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CYBERSECURITY: RESEARCH ON METHODS FOR DETECTING DDOS ATTACKS

This article describes the problem of DDoS attacks, analyzing their nature and consequences. The paper covers common DDoS attack types, such as SYN flood, ICMP flood, UDP flood. Existing methods for detecting attacks from literature are reviewed, including machine learning approaches, including artificial neural networks, support vector machines and decision trees. The paper introduces a decision tree-based machine learning model for the detection of DDoS attacks. The model is trained and tested on a publicly available dataset. The dataset consists of 1,04,345 rows of data, where every row includes 23 features, such as source IP, destination IP, port number, number of bytes transferred from the switch port, etc. A similar set of characteristics can be obtained on a real network hardware using simple calculations, which makes it possible to approximate the model evaluation to real operating conditions. SYN flood, ICMP flood and UDP flood attack types are present in the data, as well as legitimate traffic. To avoid overfitting, only some columns were used, and columns such as IP addresses were discarded. The field "label" in each row of the dataset contains either 0 or 1 where 0 corresponds to legitimate traffic and 1 to malicious one. The problem of DDoS attack detection is therefore formally reduced to the task of binary classification of each row from the dataset. The constructed model achieves an average classification accuracy of 0.94 with a standard deviation at the level of 0.06 in detecting the above mentioned types of attacks. To objectively assess the effectiveness of the model and avoid distortion of the results, stratified 5-fold cross-validation was used. The developed model can be applied in the real world network hardware to filter malicious packets or as a tool for warning the administrator about an attack. This research advances cybersecurity by enhancing DDoS attack detection.
Keywords: machine learning, DDoS, decision tree, classification.

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КІБЕРБЕЗПЕКА: ДОСЛІДЖЕННЯ МЕТОДІВ ВИЯВЛЕННЯ DDOS-АТАК

У цій статті розглядається проблема DDoS-атак, аналізується їх природа та наслідки. Стаття охоплює поширені типи DDoS-атак, такі як SYN-flood, ICMP-flood, UDP-flood. Розглядаються існуючі методи виявлення атак з літератури, включаючи методи машинного навчання, такі як штучні нейронні мережі, метод опорних векторів та дерева прийняття рішень. У статті представлено модель машинного навчання на основі дерева прийняття рішень для автоматичного виявлення DDoS-атак. Модель навчена та протестована на загальнодоступному наборі даних. Набір даних складається з 104345 рядків даних, де кожен рядок містить 23 поля, такі як IP-адреса джерела, IP-адреса призначення, номер порту, кількість байтів, переданих із порту комутатора тощо. Подібний набір характеристик можна отримати на реальному мережевому обладнанні за допомогою простих розрахунків, що дає можливість наблизити оцінку моделі до реальних умов можливої експлуатації. Типи атак SYN-flood, ICMP-flood, UDP-flood присутні в даних, а також наявний легітимний трафік. Щоб уникнути ефекту перенавчання, використовувалися лише деякі поля, а такі поля, як IP-адреси, були відкинуті. Поле «label» в кожному рядку набору даних містить 0 або 1, де 0 відповідає легітимному трафіку, а 1 — зловмисному. Тому проблема виявлення DDoS-атаки формально зводиться до здійснення бінарної класифікації кожного рядка з набору даних. Побудована модель досягає середньої точності класифікації 0,94 зі стандартним відхиленням на рівні 0,06 при виявленні зазначених типів атак. Щоб об'єктивно оцінити ефективність моделі та уникнути спотворення результатів, була використана стратифікована 5-fold кросс-валідація. Розроблена модель може бути застосована в реальному мережевому обладнанні для фільтрації шкідливих пакетів або як інструмент для попередження адміністратора про атаку. Це дослідження покращує сферу кібербезпеки, розширюючи методи виявлення DDoS-атак.
Ключові слова: машинне навчання, DDoS, дерево рішень, класифікація.

Introduction

Every year, the importance of information and network technologies in human life, as well as in the economies of the countries of the world, is growing.

Along with the growing influence of information technologies, the risks associated with information security are also growing. One of the most important threats associated with information and network technologies are Distributed Denial of Service (DDoS) attacks. The essence of such attacks is the usage of huge arrays of resources in the network to generate malicious traffic against targeted network services. Such attacks have been popular for decades. A particular difficulty in the fight against them is their indistinguishability from legitimate traffic. In addition, there are a huge number of different types of attacks, which makes it even more difficult to detect them among legitimate traffic [1].

Yearly, the complexity and magnitude of DDoS attacks show consistent growth. Notably, in 2018, a single attack reached a terabit-per-second traffic size. A concurrent trend is the expansion of economic impact. According to [3], the average damage inflicted by attacks was below $10,000 in 2017, whereas in 2018, it increased significantly, averaging between $10,000 and $100,000.

A sufficiently large number of various methods for detecting DDoS attacks have been developed. Some methods are based on data about individual packets, while others signal an attack based on the capacity of packets arriving at the server over certain periods of time. However, DDoS attacks do not share specific distinguishing features, so no systems have yet been created that can accurately detect an attack of any unusual type.

Over time, an array of different methodologies have been developed to detect DDoS attacks. Certain strategies use features of individual network packets, while others base their detection on the volumetric properties of packets arriving on servers within specific temporal windows. However, DDoS attacks do not share specific distinguishing features, so no systems have yet been created that can accurately detect an attack of any unusual type [2].

In the ever-changing world of cyber threats, understanding DDoS attacks and creating better ways to spot them are really important to protect digital systems.

Related Works

One of the most common types of DDoS attacks is the SYN flood. This attack is based on some principles of the TCP protocol, which is a transport layer protocol and one of the main protocols of the Internet protocol suite.

TCP is a connection-oriented protocol, therefore it requires the connection between two nodes to be established before the actual data transfer can take place. One of these nodes is called “server” and the second one – “client”. While the server is listening for incoming connections, clients can establish such a connection by sending the SYN packet to the server. When the server receives a SYN packer, it starts a handshake procedure which consists in sending a SYN-ACK packet back to the client. Because computer RAM is finite, any server can only process a limited number of handshakes at a time.

SYN flood attack happens when malicious clients send SYN packets to the server without finalizing the handshake procedure. When server’s connection wait slots are exhausted, denial of service is happening, because legitimate clients are unable to establish new TCP connections to the server [2, 4].

Another well-known type of DDoS attack is the ICMP flood. It is based on the exploitation of Internet Control Message Protocol (ICMP), which is the network layer protocol that is used to send service messages between hosts on the Internet. ICMP includes the specification of the so-called “echo request”, which is a method normally used to determine the latency between two hosts. When a machine receives an echo request it’s obligated to send back the correct response.

Similar to the previous type of attack, one or more malicious hosts send legitimate echo request messages in such numbers that the attacked machine's resources run out. When legitimate users can no longer access the host, the denial of service is happening [2, 5].

UDP flood is another popular type of DDoS attack. As its name implies, it uses an important transport layer protocol called UDP. User Datagram Protocol (UDP) basically is a stateless protocol, so it does not require a connection to be established between hosts to send messages, nor does it check whether messages were successfully delivered.

Using such protocol features, attackers send random UDP messages to the target host. Processing such messages, the host spends resources, which are eventually exhausted. [2, 6].

Given the variety of types of DDoS attacks, as well as their extreme similarity to legitimate traffic, their detection is not a trivial task. All existing methods are somehow related to statistical analysis or machine learning.

The simplest methods are based on the analysis of some numerical characteristics of incoming traffic per unit of time. An example of such a method is [7], which describes the construction of a fuzzy estimator based on one value – mean packet inter arrival times. Nevertheless, despite the simplicity of the model, on certain types of attacks it has an efficiency of more than 80%.

More sophisticated detection techniques utilize popular machine learning techniques for classification problems, including artificial neural networks, support vector machines and decision trees [1].

An example of a more complex system based on machine learning technologies, in particular artificial neural networks, is [8]. The paper describes the model based on the particular artificial neural networks which classifies network packets into one of 4 types: DNS DDoS attack, CharGen DDoS attack, UDP DDoS attack and legitimate traffic. The classification is based on four packet parameters, which are packet arrival time, source IP address, destination IP address, used protocol and packet length. To test the model, public datasets were used, on which the model demonstrated an overall accuracy of 95.6%. However, the model has shown lower accuracy (82.1%) in the classification of UDP DDoS attacks.

Another example of a successful model based on neural networks is [9]. It is aimed to detect DDoS attacks in real time .The model was implemented in the Apache Spark cluster and tested on a public dataset. The average detection rate of the model is over 94%.

Proposed technique

Given the growing damage that DDoS attacks inflict on the network infrastructure, and subsequently the economy every year, it was decided to develop a model, which is able to detect such attacks. Taking into account the experience of well-known systems, as well as the variety of types of DDoS attacks, it was decided to use machine learning algorithms as the basis for the developed model.

The dataset used is publicly available [10]. An important feature of the dataset is the fact that it includes examples of the most common types of attacks: SYN flood attack, UDP flood attack, ICMP flood attack. It consists of 1,04,345 rows of data, where every row includes 23 features. There are extracted features such as source IP, destination IP, port number, number of bytes transferred from the switch port, etc. And there are calculated features such as the number of packets sent per second. A similar set of characteristics can be obtained on a real network hardware using simple calculations, which makes it possible to approximate the model evaluation to real operating conditions. All fields were converted to numerical values for the correct operation of the model. In particular, the Protocol field, which stored string values, was converted to integer values, where each protocol corresponds to a separate integer. All missing values were replaced with zeros. Source IP, destination IP and date and time fields were not used in order not to create information noise during training of the model.

The field "label" in each row contains either 0 or 1 where 0 corresponds to legitimate traffic and 1 to malicious one. The problem of DDoS attack detection is therefore formally reduced to the task of binary classification of each row from the dataset, that is, to building such a model that can precisely predict the value of the label based on other fields from the same row.

Decision trees were chosen as the basis for the developed model. A decision tree is a tree-like structure, where each internal node represents a test on an attribute, each branch represents an outcome of the test, and each leaf node belongs to one of the classes. Each sample starts from the root and, being subjected to tests, eventually comes to one of the leafs, which corresponds to the result of the classification of this sample.

Decision tree models have a long history of use in the field of classification problems. Over the decades, many algorithms have been developed to build such models: ID3, C4.5, and the latest – CART. All these algorithms are based on the "greedy" principle of building trees from top to bottom, but differ in details [11].

Popular Python library Scikit-learn [12] and its implementation of the CART algorithm was used to load and preprocess the dataset, to train the model and to evaluate it.

To objectively assess the accuracy of the constructed model the Scikit-learn [12] implementation of the stratified 5-fold cross-validation was used. This technique is used to effectively eliminate random information noise that can occur when splitting a learning dataset into training and test subsets.

Finally, the model was tested, the results of which are shown in Fig. for each of the folds.

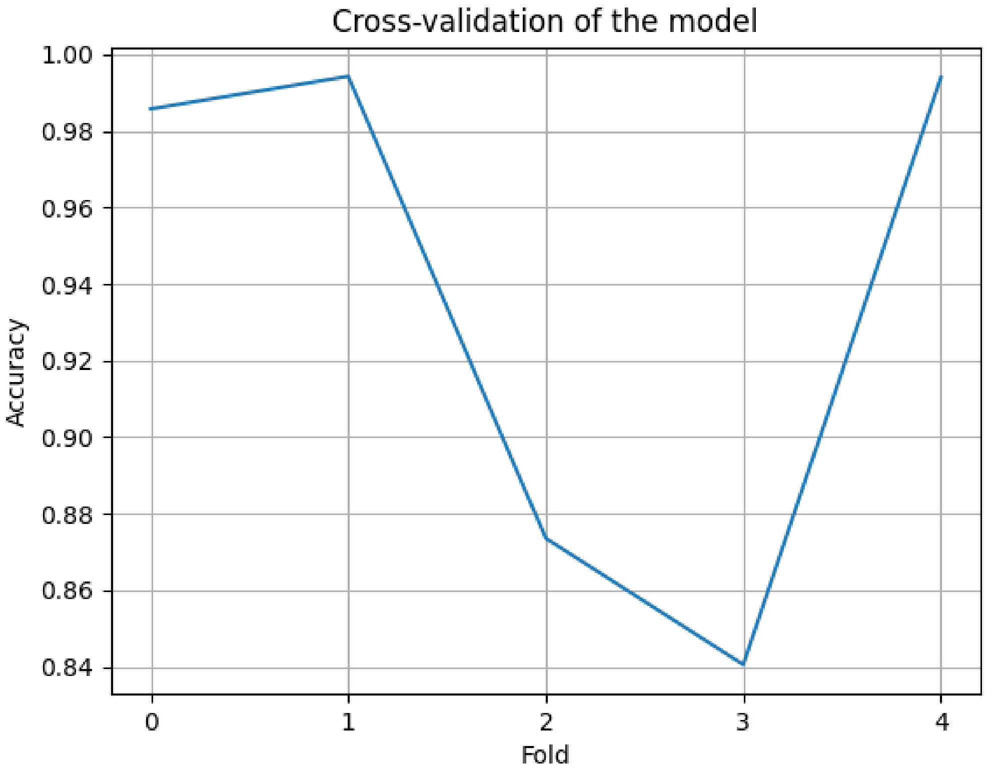

Fig. 1. The accuracy of the model during the 5-fold cross-validation

According to the test results, the average accuracy of the model was about 0.94, and the standard deviation was at the level of 0.06.

Test results point to high accuracy levels on the most popular types of attacks. It can be applied in the real world to filter malicious packets on network equipment, thereby significantly reducing the processing time for malicious packets and increasing the stability of the host during attacks by saving its resources. When used on critical infrastructure, where the accuracy of the model is insufficient, it can be used as a tool for detecting attacks for subsequent manual response to them by the administrators of the infrastructure.

Conclusions

In this paper, modern prospects for DDoS attacks and their economic impact were considered. The ever-increasing need to search for methods to protect against them, in particular their detection, was emphasized.

The main types of DDoS attacks, their nature and mechanisms are described. It is indicated that DDoS attacks are very similar to legitimate traffic, which complicates the task of detecting them.

Popular methods for detecting DDoS attacks from the literature, including methods based on machine learning algorithms, are considered.

A machine learning model based on decision trees has been developed that can effectively detect DDoS attacks. The model has been tested using a publicly available dataset [10]. The test results show a significant level of accuracy of the model, about 94%.

The constructed model is characterized by simplicity and high accuracy on the most popular types of attacks. It can be applied in the real world to filter malicious packets on network equipment. When used on critical infrastructure, where the accuracy of the model is insufficient, it can be used as a tool for detecting attacks for subsequent manual response to them.

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HANDLING THE BREAST CANCER RECURRENCE DATA FOR A MORE RELIABLE FORECAST

Breast cancer in women is a global problem that affects the gene pool. This sickness has become a prevalent cancer threat for Ukrainian women, while early detection and prophylactics notably raise survival chances, dropping the cost of treatment. Recurrence event control and forecasting are vital field areas of this problem.

This article deals with data that permits via machine-learning breast cancer recurrences in patients undergoing the therapy. The renewed data set presented in this paper contains 252 cases, of which 206 did not have recurrent events, but 46 did. This data set is an improved version of the well-known Ljubljana breast cancer data set from 1988.

The aim is a lift in the reliability of clinical prognoses of breast cancer recurrence using the updated and improved LBCD. The list of tasks accompanying this goal is as follows: Estimating relevance ranks for LBCD attributes; Evaluations of noise levels for attributes, mainly for the class attribute; Reduction of the dataset by removing irrelevant and noisy data; Imputing (restoring) the missed values for the class attribute; The simile of the performance for the initial and upgraded dataset.

Our updated dataset has fewer instances (252 instead of 286) and fewer attributes (six instead of ten), aside from the class attribute being noise-cleaned and its missed values being restored. As a result, the performance of the upgraded data set is much better than the original one, especially concerning cases of recurrence cancer. It allows clinicians a more reliable machine-learning diagnosis of breast cancer recurrence using the most known classifiers.

The used dataset is helpful in machine learning models' devising, which shall classify, detect, and forecast probabilities of recurrence events of breast cancer in clinics. The elaborated dataset ensures a much higher performance for machine learning algorithms than the initial prototype. Compared to the prototype, the dataset is more compact, comprising 252 instances instead of 286 and 6 attributes instead of 10. This dataset's class (category) attribute is entirely free of noise.

Keywords: machine learning, breast cancer dataset, recurrence events, noise cleaning, performance improving.

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ОБРОБКА ДАНИХ ПРО РЕЦИДИВИ РАКУ МОЛОЧНОЇ ЗАЛОЗИ ДЛЯ БІЛЬШ НАДІЙНОГО ПРОГНОЗУ

Рак молочної залози у жінок – глобальна проблема, яка впливає на генофонд. Ця хвороба стала основною онкологічною загрозою для українських жінок, а її раннє виявлення та профілактика значно підвищують шанси на виживання, знижуючи вартість лікування. Контроль рецмдивів та їх прогнозування є життєво важливими ділянками цієї проблеми.

Ця стаття стосується даних, які дозволяють за допомогою машинного навчання виявляти рецидиви раку молочної залози у пацієнтів, які проходять терапію. Оновлений набір даних, представлений у цій статті, містить 252 випадки, з яких 206 не мали рециливів, але 46 мали їх. Цей набір даних є вдосконаленою версією відомого набору про рак молочної залози створеного в Любляні 1988 року.

Метою є підвищення надійності клінічних прогнозів рецидиву раку молочної залози за допомогою оновленого та вдосконаленого LBCD. Перелік завдань, що супроводжують досягнення цієї мети, є наступним: Оцінка рангів релевантності для атрибутів LBCD; Оцінка рівнів шуму для атрибутів, головним чином для атрибуту класу; Скорочення набору даних шляхом видалення нерелевантних і зашумлених даних; Обчислення (відновлення) пропущених значень для атрибуту класу; Порівняння продуктивності для початкового та оновленого набору даних.

Наш оновлений набір даних має менше екземплярів (252 замість 286) і менше атрибутів (шість замість десяти), окрім мого атрибут класу очищено від шуму, і його пропущені значення відновлено. У результаті продуктивність оновленого набору даних набагато краща, ніж у прототипу, особливо щодо випадків рецидиву раку. Це дозволяє клініцистам проводити більш надійну діагностику рецидиву раку молочної залози за допомогою машинного навчання та найвідоміших класифікаторів.

Використаний набір даних є корисним для розробки моделей машинного навчання, які повинні класифікувати, виявляти та прогнозувати ймовірність рецидивів раку молочної залози в клініках. Розроблений набір даних забезпечує значно вищу продуктивність алгоритмів машинного навчання, ніж початковий прототип. Порівняно з прототипом, набір даних є більш компактним: 252 екземпляри замість 286 та 6 атрибутів замість 10. Атрибут класу (категорії) цього набору даних повністю очищений від шуму.

Ключові слова: машинне навчання, набір даних про рак молочної залози, рецидиви, очищення від шуму, підвищення продуктивності.

Introduction

Breast cancer is a highly prevalent form of cancer among Ukrainian women [1]. Women are the primary carriers of the national gene pool, which makes early diagnosis of breast cancer with the help of artificial intelligence incredibly important. Machine learning and deep learning techniques are gradually integrated into evidence-based medicine, and oncology and breast cancer diagnostics are no exception [2]. These computer-assisted techniques can improve clinical decision-making and patient outcomes[2, 3].

Our attention will be focused on the oldest among several well-known oncology breast cancer datasets, the Ljubljana Breast Cancer Dataset (LBCD). This dataset has been in use since 1988 [4], and it illustrates the cases where a node cap can occur in a female's body, which can lead to the recurrence of breast cancer. Attributes of LBCD (Meta Data) are the following:

- *Age* – Age of the patient at the time of diagnosis.
- *Menopause* – 12 months after a woman's final period.
- *Tumor size* – Tumor size represents the size of the cancer tumor at the time of diagnosis.
- *Inv-nodes*- Number of lymph nodes in the armpit that contain the spread of breast cancer visible.
- *Node caps* – Though the outside of the tumor seems to be contained, cancer may expose the risk of metastasis to the lymph node.
- *Degree of malignancy* – Grade of cancer that is visible under a microscope.
- *Breast* – Which side of the breast does breast cancer occur.
- *Breast quadrant*- Regions from the nipple area where breast cancer occurred.
- *Irradiation*: Treatment that destroys cancer cells.

The class attribute has two possible values: {no-recurrence, recurrence}. There are a total of 286 cases (instances) in the dataset. Of these, 201 belong to the first class without repeats, while 85 belong to the second class with recurrences [4]. One can see that the dataset is pretty imbalanced regarding the possible classes.

Related works

Between 2001 and 2019, the UCI machine learning repository listed 147 papers that cited the dataset [4]. This means that the dataset was referenced in approximately eight articles per year. Recently, a few dozen papers have been added to this list. As a result, it is virtually impossible to analyze each of these works individually.

However, it is noteworthy that most of these works attempted to achieve better results by improving the machine-learning algorithms while keeping the dataset unchanged. Only a few authors have taken the opposite approach, focusing on improving the dataset through optimal feature selection [2, 5, 6], denoising [7,8], or restoring missing values [9]. It is rare for authors to use a combination of these three methods.

A balanced dataset contains an equal or almost equal number of samples from the positive and negative classes. The medical datasets often are out of this rule. One can find the consequences and solutions in the review [10]. For example, AU PRC (area under the Precision-Recall Curve) is better as the integral evaluation of the performance than traditional AU ROC (area under the Receiver Operator Characteristic) in this case [11]. We are going to take these recommendations further.

The Waikato Environment for Knowledge Analysis (Weka) is a Java-based software developed at the University of Waikato, New Zealand. It is free and licensed under the GNU General Public License [12]. Its purpose is to mine data, especially from vast datasets. The latest versions of Weka contain a modern collection of various algorithms and means of machine learning with powerful visual support. Weka was used in the research displayed in this paper.

Main goal and tasks of the research

Let us formulate the primary goal of this study. The aim is a lift in the reliability of clinical prognoses of breast cancer recurrence using the updated and improved LBCD.

The list of tasks accompanying this goal is as follows:

- Estimating relevance ranks for LBCD attributes
- Evaluations of noise levels for attributes, mainly for the class attribute.
- Reduction of the dataset by removing irrelevant and noisy data.
- Imputing (restoring) the missed values for the class attribute.
- The simile of the performance for the initial and upgraded dataset.

Experimental design, datasets, and methods

The raw initial dataset (LBCD) was borrowed from [4]. This dataset has 286 instances (201 without Breast Cancer recurrence events and 85 having ones). Each instance was described by ten, including the class attributes. The code table for nine attributes of the raw dataset, excluding the class, is hosted in Table 1.

Table 1.

Coding table for nine attributes of the raw dataset

Attribute	deg–malign	irradiated	node-caps	tumor-size	inv-nodes	age	breast-quad	breast	Meno pause
Code (IDs)	1	2	3	4	5	6	7	8	9

Feature ranking and selection

As a rule, authors who work with machine learning and have performed attribute ranking exploit for this purpose one, rarer two, or three algorithms. There will be seven ranking algorithms in use. Therefore, they also need a code table, Table 2.

Table 2.

Coding table for seven algorithms (evaluators) used for attribute ranking

Evaluator	Symmetrical_ Uncert_Attribu t	Pairwise_Corr elation_Attrib	Info_Gain_Att ribut	Gain_Ratio_At trib	Classifier_Attr ibut	Correlation_At trib	Cfs_Subset
Code (IDs)	a	b	c	d	e	f	g

Thus, one can frame a rank matrix for nine attributes obtained by seven evaluating algorithms. Hence, the ranks matrix has nine columns and seven rows. The highest rank is 1, and the lowest is 9. This matrix has such a form:

$$Rm = \begin{pmatrix} 2 & 3 & 1 & 4 & 5 & 6 & 7 & 8 & 9 \\ 1 & 3 & 2 & 4 & 5 & 6 & 7 & 8 & 9 \\ 1 & 2 & 4 & 5 & 3 & 6 & 7 & 8 & 9 \\ 3 & 2 & 1 & 4 & 5 & 6 & 7 & 8 & 9 \\ 1 & 2 & 4 & 3 & 5 & 6 & 7 & 8 & 9 \\ 3 & 2 & 1 & 4 & 5 & 9 & 8 & 6 & 7 \\ 4 & 2 & 3 & 5 & 1 & 6 & 7 & 8 & 9 \end{pmatrix} \qquad (1)$$

Thence, the columns of the matrix (1) are labeled by codes from Table 1, while the rows are by codes from Table 2. Note that most evaluators rank the last four attributes by lower ranks (6-9) almost in unison, being less united for the first five.

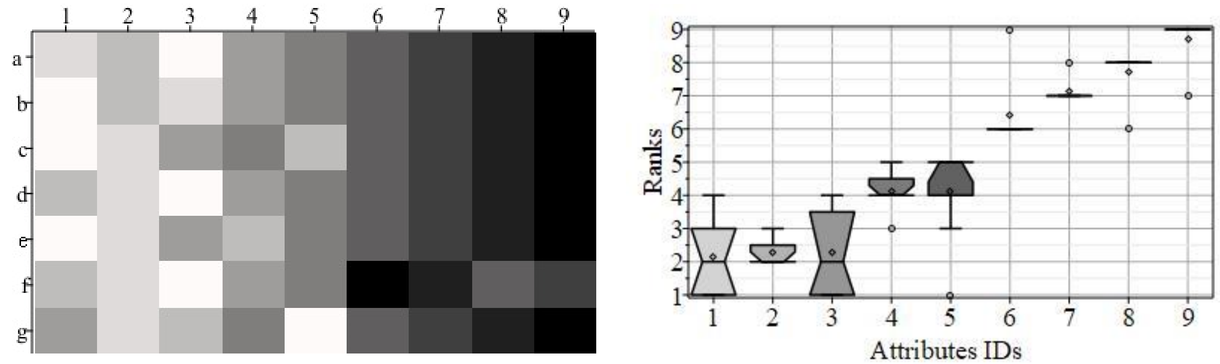

Fig 1 Heat Map of the Ranking matrice (left-hand side) and box plot (Tukey's chart) of its columns (right-hand side); the height of the boxes shows the corresponding interquartile ranges, while the horizontal segment at the boxes' "waist" is a median.

Figure 1 shows the Heat Map of the matrix (1) and the box-and-whiskers plot (Tukey's chart) for its columns. The structure of the rank's matrix, its heat map, and the box plot of its columns all testify about the presence of two subsets of attributes:

– The first five have between 1-th and 5-th ranks and manifest relatively high variability of ranks if the interquartile ranges evaluate that as in the box plot;

– The last four attributes have no visible variabilities (zero interquartile ranges), lower rank from 6 to 9, and occupy the dark side of the Heat Map.

So, the order of attributes in Table 1 corresponds to the ascending order of the rank matrix (1) columns, their medians, and the "darkening" of the heat map columns. After that, one can consider the last four attributes of Table 1 as less relevant in simile to the first five.

Noise cleaning and dataset reduction

First, we reduced the number of attributes from ten to six by removing the last four attributes with lower relevance ranks (from 6 to 9) in Table 1 from the dataset. Thus, the intermediate dataset had 286 instances and six attributes, including class.

Then, this dataset was filtered using CAIRAD (Invalid Record Analysis and Attribute Value Discovery [7]). This filter allows one to mark all questionable (incorrect) attributes as missing values. Next, all instances with three or more incorrect attributes, meaning half of them or more, were deleted. That reduced the dataset to 252 instances.

It is well-established that incorrect values in class attributes are the most harmful among all the noises present [8]. Even after applying filters, the dataset still contained 35 incorrect values, which accounted for 14% of the total values in the class attribute (see Fig.2).

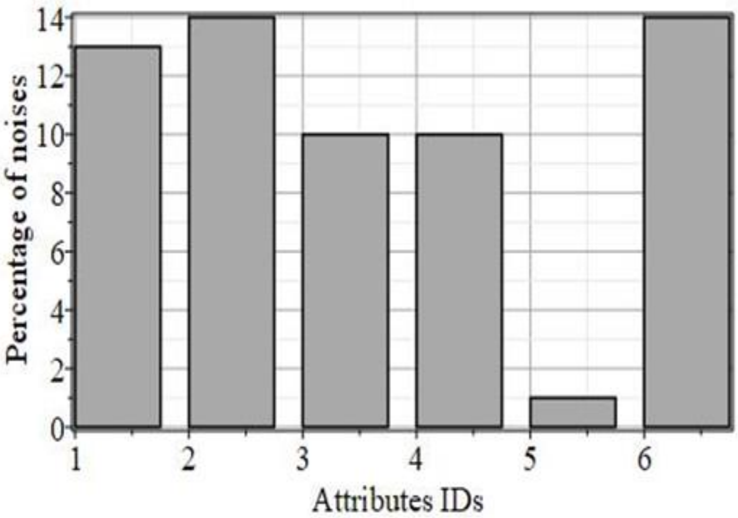

Fig. 2 Column graph for the noise levels for the first five attributes of Table 1 (1-5) and class attribute (6)

That initiated the imputation procedure (restoring correct values) for detected via filtering, denoted as missed ones. There exist many ways of such an imputation, and the algorithm [5] has been used here. The imputation was used only for the class attribute; other noises (1% to 14% dependent on the attribute) were considered missed values. As a result, the dataset was upgraded to 252 instances with six attributes each. Two hundred six of them are without recurrence events, whereas 46 have recurrence. Thus, the upgraded dataset is surely imbalanced even more than the raw one. Each instance has five nominal attributes with moderate noise levels. However, the class attribute, the sixth one, is free of noise.

The authors would like to underline two limitations of the upgraded dataset that is accessible in [13]:

First, the dataset still holds 16 instances from 252, with two missed attributes from six; perhaps these instances should also be removed.

Second, five attributes still have missing values, on a level of 1% to 14%, which may be restored.

Performance simile of datasets

To compare the performance of the two datasets, we analyzed the main performance indexes of the original [4] and upgraded [13] datasets using a version of the J48 classifier. Specifically, we used "weka.classifiers.trees.J48Consolidated -A -C 0.25 -M 2 -Q 1 -RM-C -RM-N 99.0 -RM-B -2 -RM-D 50.0".

Let us start with two confusion matrices, which serve as an origin for calculations of most performance indicators [14]. The structure of a confusion matrix is as follows :

– *True Positive (TP):* Observations are positive and are predicted to be positive. The value of TP is located in the left upper cell of the 2x2 matrix
– *False Negative (FN):* Observations are positive but are predicted to be negative. Right upper cell.
– *True Negative (TN):* Observations are negative and are predicted to be negative. Right lower cell
– *False Positive (FP):* Observations are negative but are predicted to be positive. Left lower cell.

So, the diagonal elements of the confusion matrix show the numbers of correctly classified instances for each binary class. In contrast, quantities of incorrectly classified instances are shown by non-diagonal cells. Table 3 displays both confusion matrices.

Table 3.

Confusion matrices for raw and upgraded datasets

Dataset	Raw	Upgraded
Confusion matrices	$\begin{pmatrix} 153 & 48 \\ 46 & 39 \end{pmatrix}$	$\begin{pmatrix} 190 & 16 \\ 5 & 41 \end{pmatrix}$

Note that the upgraded dataset has 252 instances instead of 286 in the raw one. Nevertheless, there is evidence that the number of correct predictions increased while the number of incorrect ones dropped. A more detailed comparison of the datasets is provided in Table 4.

Table 4

Performance indicators for raw and upgraded datasets

Datasets	Classes	Precision	Recall		F-measure	MCC	AU PRC
Raw	**no-recurrence**	0.769	0.761		0.765	0.219	0.758
	recurrence	0.448	0.459		0.453	0.219	0.434
Upgraded	**no-recurrence**	0.971	0.922		0.948	0.751	0.979
	recurrence	0.719	0.891		0.796	0.751	0.776

In evaluating prediction models, MCC (Matthew correlation coefficient) and AU PRC (area under the Precision-Recall Curve) are two critical measures. MCC considers all four elements of the confusion matrix and produces higher scores closer to 1 only if the prediction ensures reasonable rates for all four categories. In other words, MCC comprehensively evaluates the model's performance independent of a class. For the upgraded dataset, the MCC score tripled and achieved a value of 0.751, indicating a significant improvement in the model's accuracy.

Another integral but class-dependent performance indicator (AU PRC) increases, especially for the second class (cancer recurrence). Tables 3 and 4 show the higher classification performance concerning the updated data set. It means more reliable diagnostics, declared the goal in section 1.2.

Comclusions

The dataset [13] is helpful in machine learning models' devising, which shall classify, detect, and forecast probabilities of recurrence events of breast cancer in clinics.

The elaborated dataset ensures a much higher performance for machine learning algorithms than the initial prototype [4].

Compared to the prototype, the dataset is more compact, comprising 252 instances instead of 286 and 6 attributes instead of 10.

This dataset's class (category) attribute is entirely free of noise.

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MODELING AND PROCESSING OF INFORMATION FLOWS IN THE EDUCATIONAL PROCESS OF MEDICAL STUDENTS USING MIND MAPS

The fundamental principle of medical education today should be the formation of a highly qualified competitive medical professional who can conduct innovative activities and has the skills of continuous professional development, as well as increasing the transparency and clarity of the educational process for students and building confidence in achieving effective results. The creation of a modern innovative educational environment involves ensuring optimal conditions for the development and self-development of a student, which can be created, among other things, through the use of modern digital resources by both lecturers and students. Thus, the task of digitalizing the educational process of medical students is currently relevant. The purpose of this study is to model and process the information flows of the educational process of medical students.

Digitalization and visualization of the educational process at the Department of Histology of National Pirogov Memorial Medical University (Vinnytsya, Ukraine) by developing mind maps revolutionizes education, improves the teaching process, significantly increases the efficiency, effectiveness and quality of the educational process through the development of cognitive, productive, reproductive thinking in students, compliance with the intellectual capabilities of higher education students, increasing the level of involvement of students, developing digital competence in students, and so on.

The modeling and processing of information flows of the educational process of medical students has shown that students' knowledge is largely determined by the characteristics of information sources, and in order to maximize the coincidence of information flows of information sources and information flows learned by students, it is worthwhile and expedient to digitalize and visualize educational content using mind maps. It has been empirically confirmed that the use of mind maps in the study of the educational component "Histology" has increased the coincidence of information flows of information sources and information flows learned by students from one quarter to three quarters.

Keywords: digitalization of the educational process, visualization of the educational process, mind maps, modeling of information flows, processing of information flows.

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МОДЕЛЮВАННЯ ТА ОПРАЦЮВАННЯ ІНФОРМАЦІЙНИХ ПОТОКІВ ОСВІТНЬОГО ПРОЦЕСУ ЗДОБУВАЧІВ МЕДИЧНИХ СПЕЦІАЛЬНОСТЕЙ З ВИКОРИСТАННЯМ КАРТ ДУМОК

Основоположним принципом медичної освіти сьогодення має стати формування висококваліфікованого конкурентоспроможного фахівця медичної галузі, який може вести інноваційну діяльність та володіє навичками безперервного професійного розвитку, а також підвищення прозорості та зрозумілості освітнього процесу для здобувачів та формування у здобувачів впевненості у досягненні ефективних результатів. Створення сучасного інноваційного освітнього середовища передбачає забезпечення оптимальних умов для розвитку й саморозвитку людини, що навчається, які можуть бути створені в тому числі й за допомогою використання сучасних цифрових ресурсів як викладачами, так і здобувачами освіти. Отже, наразі актуальною є задача діджиталізації освітнього процесу здобувачів медичних спеціальностей. Метою даного дослідження є моделювання та опрацювання інформаційних потоків освітнього процесу здобувачів медичних спеціальностей. Діджиталізація та візуалізація освітнього процесу на кафедрі гістології Вінницького національного медичного університету ім. М. І. Пирогова шляхом розроблення карт думок революціонізує освіту, удосконалює процес викладання, значно підвищує ефективність, результативність та якість освітнього процесу завдяки розвитку в здобувачів пізнавального, продуктивного, репродуктивного мислення, відповідності інтелектуальним можливостям здобувачів вищої освіти, підвищення рівня залученості здобувачів, розвитку цифрової компетентності у здобувачів, а також за рахунок задоволення двох стійких трендів освіти сьогодення – індивідуалізація і персоналізація освітнього процесу та формування soft skills у здобувачів вищої освіти.

Моделювання та опрацювання інформаційних потоків освітнього процесу здобувачів медичних спеціальностей показало, що знання студентів значною мірою визначаються характеристиками джерел інформації, а для максимізації співпадіння інформаційних потоків джерел інформації та інформаційних потоків, засвоєних здобувачами, варто і доцільно діджиталізувати та візуалізувати освітній контент з використанням карт думок. Емпірично підтверджено, що використання карт думок при вивченні освітнього компоненту «Гістологія» дозволило підвищити співпадіння інформаційних потоків джерел інформації та інформаційних потоків, засвоєних здобувачами, з однієї чверті до трьох чвертей.

Ключові слова: діджиталізація освітнього процесу, візуалізація освітнього процесу, карти думок, моделювання інформаційних потоків, опрацювання інформаційних потоків.

Introduction

Modern education in general and medical education in particular aims to develop the personality and form the professional competence of future specialists. Society is a customer for a qualified, creative, competent specialist who is competitive in the national and European labor market.

The fundamental principle of medical education today should be the formation of a highly qualified, competitive medical professional who can conduct innovative activities and has the skills of continuous professional development, as well as increasing the transparency and clarity of the educational process for students and building confidence in achieving effective results.

Students of the new digital generation should actively participate in their own education and contribute to learning, rather than passively receive and repeat information. Lecturers of both general education and professional training components in medical higher education institutions should be aware of new trends and teaching methods to increase their effectiveness. Lecturers should help students use a variety of tools and technologies aimed at more in-depth learning. Students who do not just absorb information but actively build their own educational concepts develop skills that enable lifelong learning, which is a necessary reality for future healthcare professionals. As B. Franklin said: "Tell me and I forget; teach me and I remember; involve me and I learn".

The key to learning in the modern world is the development of digital competencies. The Law of Ukraine "On Education" considers information and communication competence to be one of the key competencies that every person needs to be successful in the modern world. The EU has recognized digital literacy (digital competence, digital skills) as one of the 8 key competencies for full life and work. Digital competence is unique in that it enables people to acquire other competencies faster and more efficiently. According to the EU and Ukraine's education development strategy, by 2030, all educational institutions should move not only to digital tools in the traditional educational process, but also to completely new digital learning models [1]. In addition, educational institutions should develop digital transformation programs to ensure the competitiveness of educational, research, and business activities at the national and global levels. The digitalization of educational institutions enhances their competitive advantages in the markets of educational services, as it promotes new forms of integration at both the national and international levels, for example, it allows the creation of virtual universities, which involve the pooling of resources of higher education institutions located in different regions (countries) for the joint implementation of certain educational programs, primarily in new technological environments.

Modern technologies are more relevant than ever in the modern educational environment - for example, Michio Kaku predicts that education will soon be based solely on Internet technologies and gadgets such as Google Glasses, which will soon be transformed into tiny lenses that will allow you to instantly download all the necessary information [2]. The fact that information technology is associated with entertainment and leisure for Generation Z, which represents the current student population, leads to high enthusiasm and enjoyment of learning with digital gadgets and information technology. Therefore, it is now very important for lecturers to use digital gadgets and information technologies to engage medical students, develop their creative and critical thinking, creativity and perseverance, teamwork and problem solving. Today, students should not be forced to simply "cram" the educational material, but should be taught to find the necessary information and use it to solve practical problems, which is a sign of the education of the future. And the freed-up mental reserve should be reoriented to develop the ability to analyze, argue, make the right decisions, and create.

Today, almost every student in Ukraine has a mobile device with Internet access (according to Ericsson ConsumerLab 2020 [3], every Ukrainian family has 2.5 devices with Internet access), but according to the results of a study of digital literacy of Ukrainians [4], another 53% of the population of Ukraine is currently below the "basic level" mark, as they use the available devices mainly for games and watching movies, to find ready-made solutions to tasks. The map of digital skills of Ukraine is shown in Fig. 1 [4].

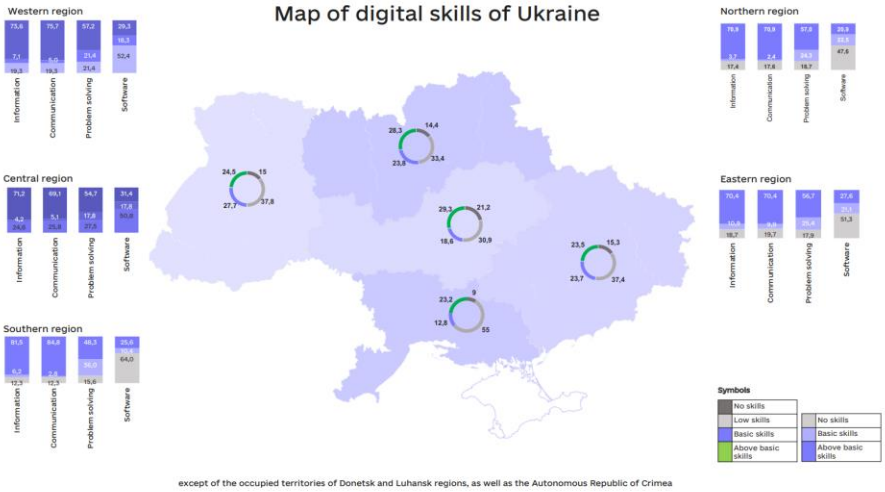

Fig. 1. Map of digital skills of Ukraine [4]

Medical students also make little use of the available mobile devices for self-education and self-development due to inability and ignorance of such opportunities. At present, even students who are considered "digital natives" are actually far from producing their own digital content – while they own their own expensive devices with the ability to write blogs, create infographics, books, and videos.

Consequently, both students and lecturers do not always use digital resources in their activities, which reduces the quality of their learning and work, limits and requires significant time to solve professional problems. This partial use of modern digital resources is primarily due to the lack of information about the availability and usefulness of digital resources, as well as the lack of skills to work with them.

Digital intelligence (DQ – Digital Quotient) includes three levels [1]: 1) digital citizenship – the use of IT in everyday life; 2) digital creativity – the creation of one's own content; 3) digital entrepreneurship – the use of IT for professional activities. Given the above, it can be concluded that currently only the first level of digital intelligence – digital citizenship – is developed in the educational environment, but the need to develop digital creativity and digital entrepreneurship is obvious.

The use of modern digital resources by lecturers and students will lead to:

1) increase of attention and interest in learning;
2) accelerating and facilitating the assimilation of knowledge;
3) development of analytical skills;
4) development of cognitive, productive thinking;
5) deeper understanding of the essence of new information;
6) promoting significant and lasting changes to improve the quality of classes;
7) simplification of preparation for classes;
8) increase of professional and scientific level;
9) increase of the efficiency of work with information;
10) increase in productivity, facilitation and acceleration of solving professional problems.

Since today's students cannot imagine their lives without digital technology, given the growth of information and the fact that digital competence has become one of the 10 key competencies of the 21st century, which is included in the Future skills you'll need in your career by 2030 [5], and all professions of the future are somehow related to digital resources, lecturers should help students use this toolkit in a new, creative and personalized way.

Thus, the task of digitalizing the educational process of medical students is *currently relevant*. Therefore, *our study is devoted* to the modeling and processing of information flows in the educational process of medical students.

Features of the organization of the educational process of medical students using mind maps

Taking into account the above requirements for the training of future specialists, including specialists in the medical field, the educational process at the Department of Histology of National Pirogov Memorial Medical University (Vinnytsia, Ukraine) is currently changing radically – it is being digitalized, individualized and intensified through the use of effective digital visualization tools that provide easier access to information, compact and concise presentation of information, systematization of information, increasing the logic of its presentation and effective teaching.

The educational component "Histology" consists of such sections as: cytology, embryology, general and special histology, and the amount of information for each section is constantly growing, which constantly motivates the introduction of new effective tools for the perfect and effective assimilation of information.

Given the huge amount of information in the modern world and the need for compact means of displaying it, when working with information, there is a need to visualize and systematize it to increase convenience and ease of perception [6].

Positive aspects of data visualization in education [6]:

1) improved understanding and interpretation of data;
2) enhanced decision-making;
3) increased student engagement;
4) personalized learning;
5) increased transparency and accountability.

Negative aspects of data visualization in education [6]:

1) privacy and security concerns;
2) data quality and accuracy;
3) overreliance on data;
4) accessibility and equity.

Effective digital visualization tools play an important role in the acquisition of competencies and programmatic learning outcomes by students. By using visualization tools, large amounts of information can be presented in a concise and logical manner, thereby contributing to the intensification of learning. Currently, there are a huge number of digital visualization tools that are presented in the "Periodic Table of Visualization Methods" [7].

An effective digital tool for visualizing the concept and structure, a new form of educational content and a new digital learning model that is actively used to individualize the educational process at the Department of Histology of National Pirogov Memorial Medical University (Vinnytsia, Ukraine), are mind maps – diagrams used to generate, present, systematize and classify concepts, ideas, thoughts [8, 9].

Mind maps enable students in distance and classroom learning to process and record a significant amount of information, assimilate it and organize it in the form of schemes and structures. The construction of mind maps is based on associative connections, which is characteristic of long-term memory. Mind maps are used to visualize thinking, develop creative thinking, brainstorm, stimulate imagination, and solve problems, etc. Mind maps are new forms of educational content that attract the attention of the audience, provide flexibility of educational content, facilitate the assimilation of educational content by students, deepen the understanding of educational content by students, and demonstrate not only facts but also the relationships between them [8, 9].

To build the mind maps, the free online graphic design platform Canva is used, which allows us to quickly create interactive mind maps with audio, video, images, and hyperlinks to map nodes that explain the concept of a node or branch of the map in more detail.

Students of specialties 222 Medicine and 221 Dentistry at National Pirogov Memorial Medical University (Vinnytsia, Ukraine) develop mind maps when studying histology to facilitate learning and deepen understanding of educational content, as well as to understand both facts and interdependencies between them.

Examples of mind maps developed using the online platform Canva are shown in Fig. 2-Fig. 5.

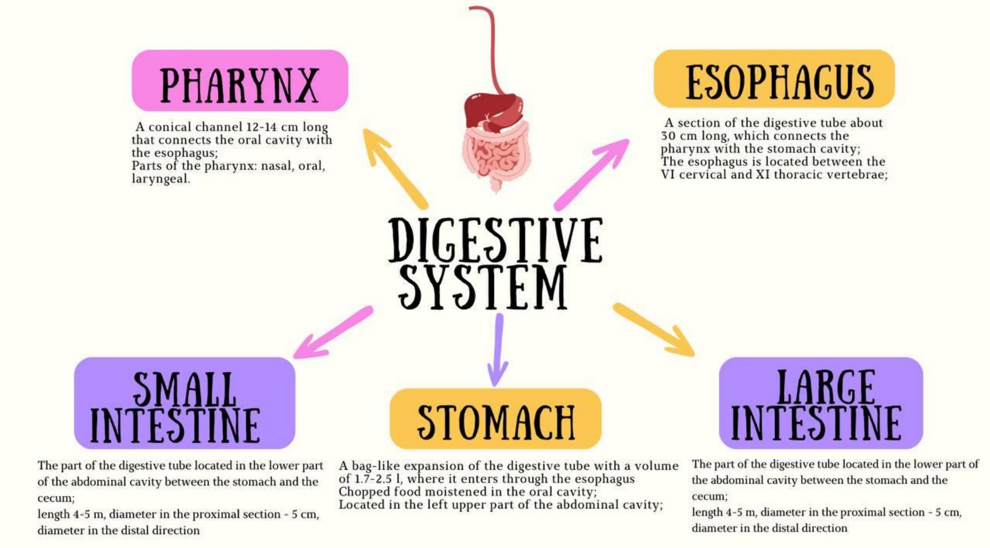

Fig.2. Mind map "Digestive system"

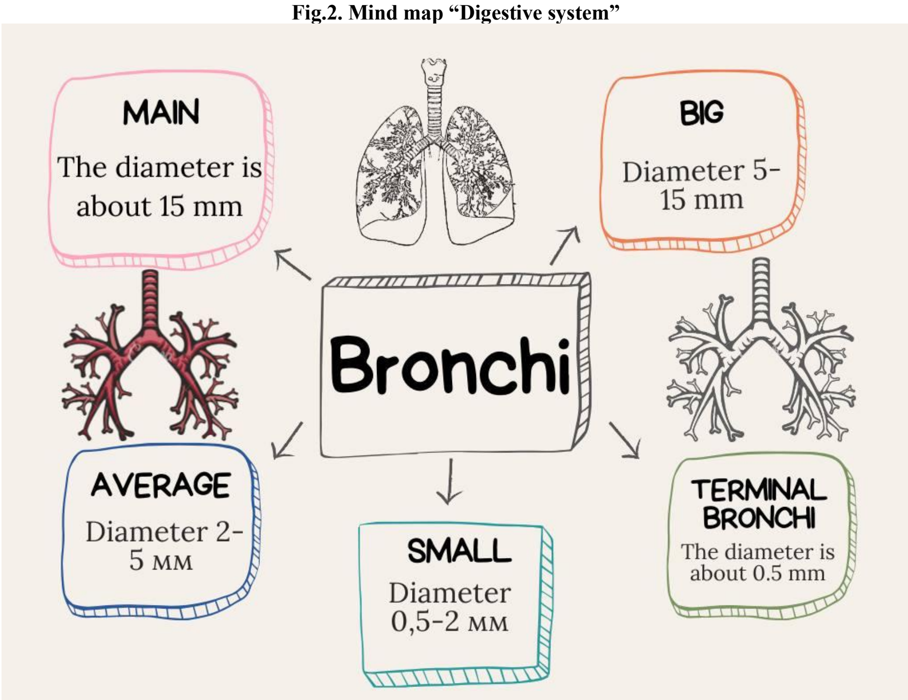

Fig.3. Mind map "Bronchus"

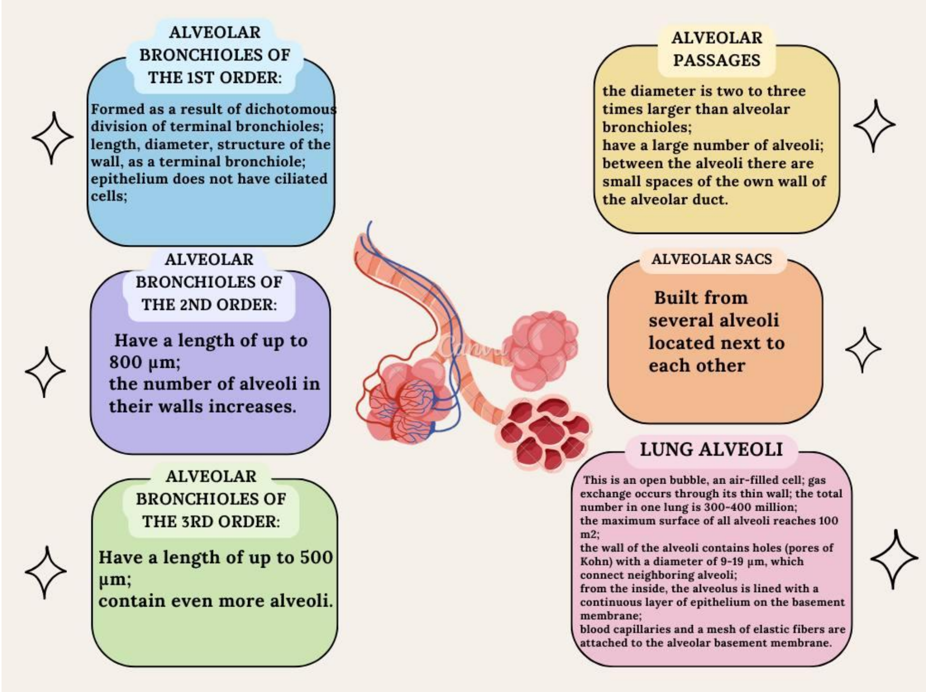

Fig.4. Mind map "Lungs"

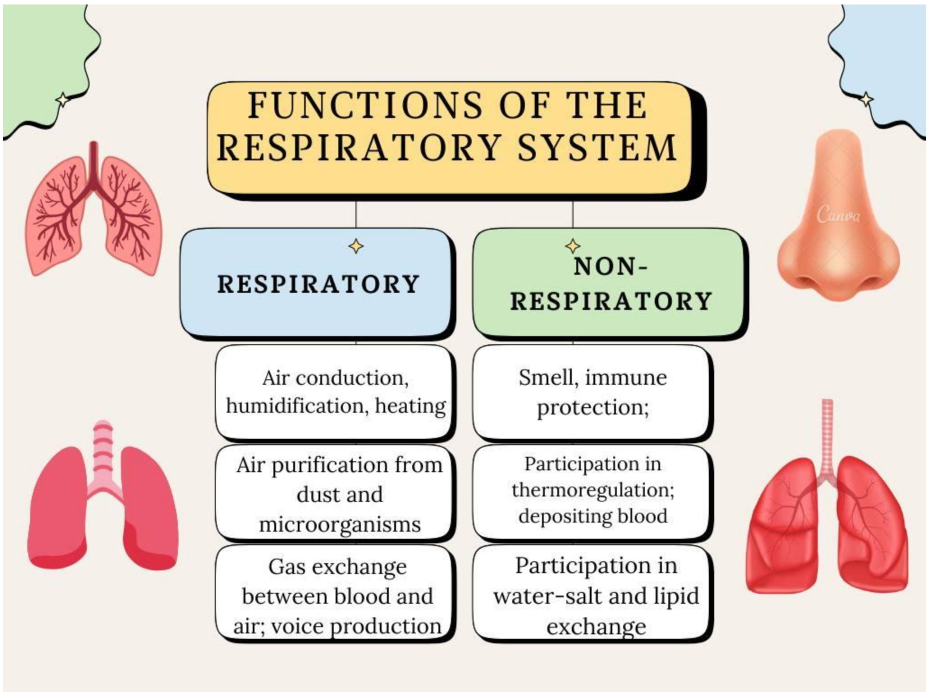

Fig.5. Mind map "Functions of the respiratory system"

The use of mind maps in the training of medical professionals provides:

- development of information literacy through the confident use of digital technologies to systematize information and the ability to create their own digital content (digital creativity)

- facilitating the understanding, interpretation and memorization of basic professional terms in both Ukrainian and English (or Latin) due to the bilingualism of mind maps (digital entrepreneurship);

- reducing the time for memorizing material due to the rapid processing of large amounts of information and the transfer of information into long-term memory and knowledge (digital entrepreneurship);

- identifying patterns, trends and deviations, which contributes to making more informed decisions based on evidence in future professional activities (digital entrepreneurship);

- structuring and systematization of students' knowledge, improving the quality of professional skills (digital entrepreneurship);

- formation of all levels of digital intelligence (DQ – Digital Quotient) in students and lecturers;

- facilitating preparation for the Unified State Qualification Exam in the form of the Krok-1 Licensing

Integrated Test Exam and the ESP Exam;

- development of self-control skills, timely identification of mistakes, their elimination and even prevention of their occurrence;
- stimulating the development of independent thinking, intellectual activity and creative approach to problem solving;
- meeting personal educational needs of each applicant, activation of individual learning and cognitive activity of applicants, adaptation of learning strategies, and as a result – individualization and personalization of the educational process of medical students by leveling the difference in perception and processes of information assimilation by applicants, analysis of the pace of mastering the material;
- promoting the development of curiosity and research interest, formation and development of initiative, creativity, visual and critical thinking, which are effective intellectual tools that will allow medical students to become specialists of the future;
- intensification, optimization, mobility and flexibility of the educational process, development of associative thinking in applicants, identification of gaps in applicants' knowledge and educational gaps.

The need for digitalization and visualization of educational content is due to the peculiarities of the modern higher education student's thinking – the ability and readiness to perceive visual and graphic information, the inability to perceive large amounts of textual information, fast information processing and short attention span. Digitalization and visualization of the educational process at the Department of Histology of National Pirogov Memorial Medical University (Vinnytsia, Ukraine) by developing mind maps revolutionizes education, improves the teaching process, significantly increases the efficiency, effectiveness and quality of the educational process through the development of cognitive, productive, reproductive thinking in students, compliance with the intellectual capabilities of higher education students, increasing the level of involvement of students, developing digital competence in students, and so on.

Modeling and processing of information flows in the educational process of medical students using mind maps

Information is a message, value, theoretical data that are objects of storage, processing and transmission and are used in the process of analyzing certain processes, objects and phenomena. Information organized in accordance with certain logical relationships is called a body of knowledge that must be obtained through systematic familiarization or study [10].

The ability to process information makes it possible to identify the problem (the essence of the contradiction), analyze the known ways and means of solving it, and generate one's own proposals and ways to solve the problem.

Information processes are performed by information processors, either physical (a device) or biological (the human brain). An abstract model of information processing includes four main elements: processor, memory, receptor, and effector (Fig. 6). A processor (a device or a human brain) performs several functions: performing elementary information processes on symbolic expressions; temporary storage of input and output expressions in short-term and/or long-term memory; scheduling the execution of information processes; changing the sequence of operations according to the contents of short-term and/or long-term memory. The memory stores symbolic expressions, including those representing complex information processes. The other two components, the receptor and the effector, are input and output mechanisms whose functions are, respectively, to receive symbolic expressions from the external environment for the processor and to transmit the processed structures back to the environment (a person receives information from his or her senses – sounds through hearing; images and text through sight; shape, temperature, and sensations through touch; smells through the sense of smell; the carriers of information signs perceived by the senses are energy phenomena – sound waves, light waves, chemical and electrochemical stimuli, i.e. information in analog form) [10]. More than 60% of information comes to us through sight and hearing. Sight and hearing are the most powerful and effective channels for transmitting and receiving information, which is why the more diverse the presentation of information, the more effective the process of its assimilation.

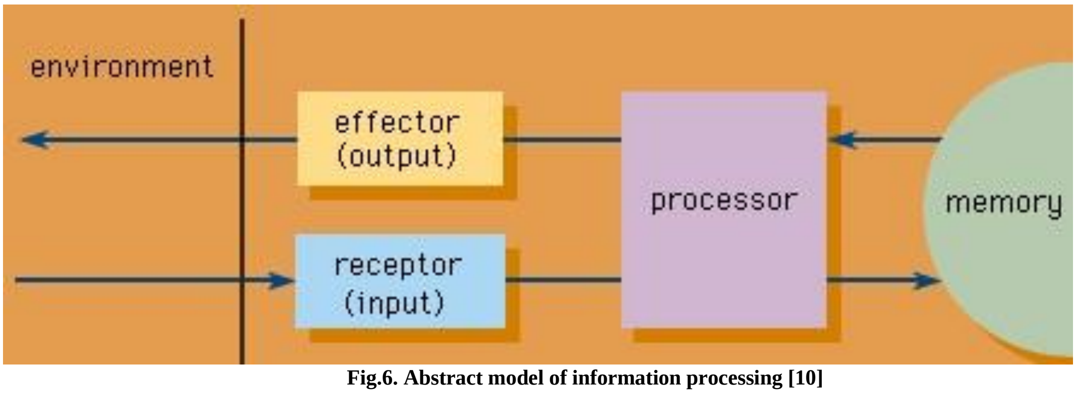

Fig.6. Abstract model of information processing [10]

To identify and study the problem and known means of solving it, certain sources of information are needed. The main sources of information of the educational process of medical students are: the lecturers of the educational components (a key link in the system of information sources); documents (textbooks, manuals, notes, scientific articles, reference books, dictionaries, encyclopedias, maps, atlases, albums, manuscripts, videos, presentations, etc.); subject-matter environment (models, layouts, devices); experience and observation; surroundings (Fig. 7). Accordingly, the ways to find the necessary information are: communicative (classes, consultation of a lecturer-practitioner, industry expert, excursion, consultation of classmates, etc.), search for documents on the Internet or in a library catalog. The main requirement for an information source is to meet the information needs of the person who accessed it.

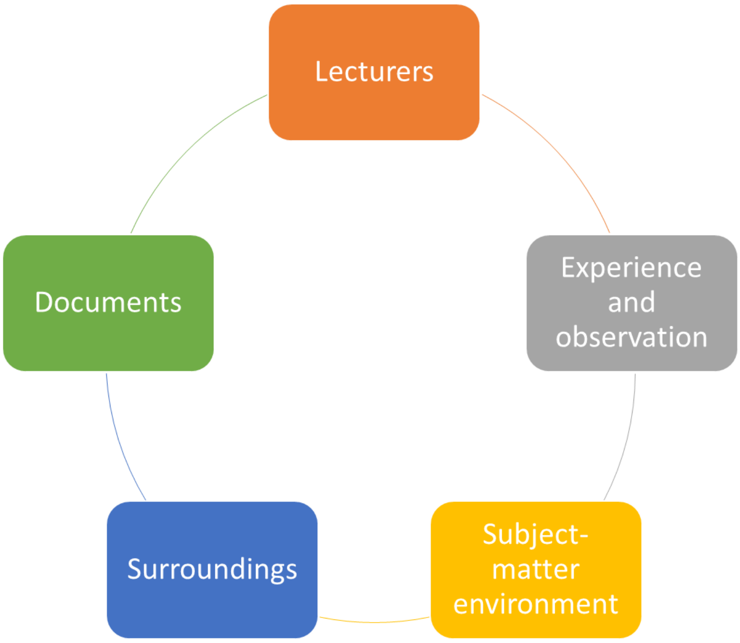

Fig.7. Sources of information of the educational process of medical students

Based on the above sources of information, the knowledge of medical students is formed (Fig. 8). Thus, students' knowledge is largely determined by the characteristics of information sources. If the source of information is insufficient, or it is inaccurate, unreliable, ambiguous or contradictory, there is a high probability that all these shortcomings will be reflected in the knowledge of students.

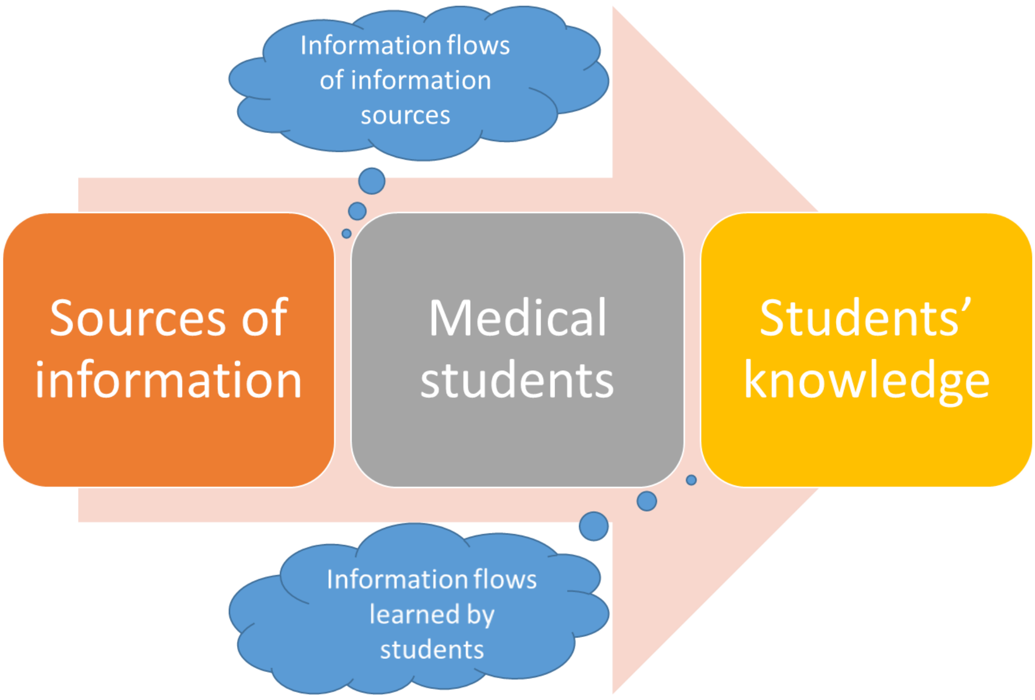

Fig.8. Structure and content of information flows in the formation of knowledge of medical students

Therefore, in order to ensure high-quality and complete knowledge of medical students, it is necessary to maximize the coincidence of information flows of information sources and information flows learned by students. As empirically confirmed during the teaching of histology at the National Pirogov Memorial Medical University (Vinnytsia, Ukraine), in the process of traditional education, students learn no more than a quarter of the proposed educational material, that is, the information flows learned by students in the process of traditional education are 1/4 of the information flows of information sources. When teaching histology at National Pirogov Memorial Medical University (Vinnytsia, Ukraine), it has also been empirically confirmed that digitalization and visualization of educational content using mind maps can increase this indicator by 2-3 times due to an increase in the efficiency of visual perception of the material, acceleration of the transfer of information into long-term memory and knowledge, and active participation in managing the presentation of educational content, that is, information flows learned by students when using visualization tools (mind maps) make up at least 2/4-3/4 of the information flows of information sources. Thus, it is the representation of information flows of information sources in a visual form (in particular, in the form of mind maps) that allows to increase the coincidence of information flows of information sources and information flows learned by students.

Taking into account the abstract model of information processing (Fig. 6), as well as the structure and content of information flows in the formation of knowledge of medical students (Fig. 8), let"s present the process of processing information flows in the educational process of medical students using mind maps in the form of such information model – Fig. 9.

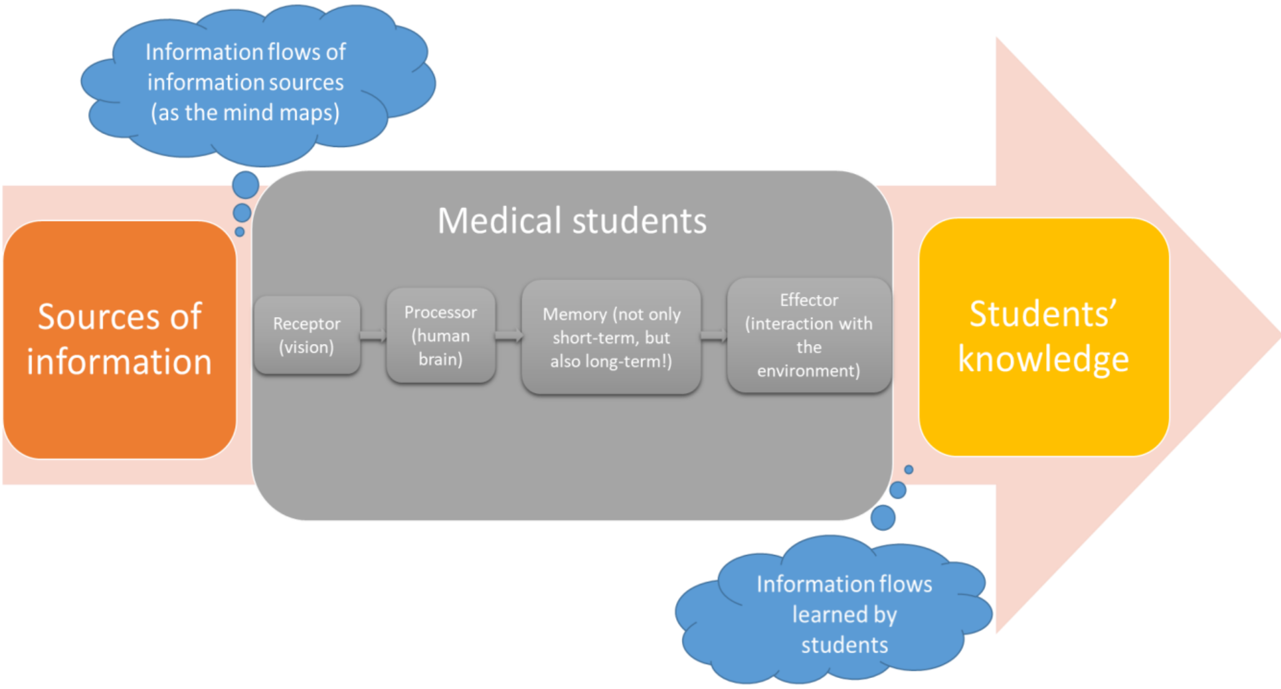

Fig.9. Information model of knowledge formation of medical students using mind maps

Thus, the modeling and processing of information flows of the educational process of medical students has shown that students' knowledge is largely determined by the characteristics of information sources, and in order to maximize the coincidence of information flows of information sources and information flows learned by students, it is worthwhile and expedient to digitalize and visualize educational content using mind maps. It has been empirically confirmed that the use of mind maps in the study of the educational component "Histology" has increased the coincidence of information flows of information sources and information flows learned by students from one quarter to three quarters.

Conclusions

The fundamental principle of medical education today should be the formation of a highly qualified competitive medical professional who can conduct innovative activities and has the skills of continuous professional development, as well as increasing the transparency and clarity of the educational process for students and building confidence in achieving effective results. The creation of a modern innovative educational environment involves ensuring optimal conditions for the development and self-development of a student, which can be created, among other things, through the use of modern digital resources by both lecturers and students. Thus, the task of digitalizing the educational process of medical students is currently relevant. The purpose of this study is to model and process the information flows of the educational process of medical students.

Digitalization and visualization of the educational process at the Department of Histology of National

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CONNECTIONIST-METAHEURISTIC APPROACH TO THE ANALYSIS OF THE GLOBAL ECONOMY'S INVESTMENT ENVIRONMENT INDICATORS

The urgent task of using new approaches to analyze the indicators of foreign direct investment and macroeconomic indicators that affect the volume of their attraction to a particular country in the world economy was solved by a connectionist-metaheuristic approach.

The connectionist-metaheuristic approach solved the urgent task of using new approaches to analyze the foreign direct investment and macroeconomic indicators that affect the volume of their attraction to a particular country in the world economy. The proposed connectionist-metaheuristic system makes it possible to improve the quality of the approximation due to: the simplification of structural identification through the use of only one hidden layer of neural network models; reduction of the computational complexity of parametric identification and the ensuring good scalability through the use of batch mode for non-recurrent neural network models and multi-agent metaheuristics for recurrent neural network models; descriptions of non-linear dependencies through the use of neural network models; high approximation accuracy due to the use of recurrent neural network models; resistance to data incompleteness and data noise due to the use of metaheuristics for parametric identification of recurrent neural network models; lack of requirements for knowledge of distribution, homogeneity, weak correlation, and optimal factors' choice. In the case of a GPU, an LSTM-based neural network with the highest approximation accuracy should be chosen. For LSTM, the coefficient of determination using the gradient method is 0.785, and using metaheuristics (modified wasp colony optimization) is 0.835. The proposed approach makes it possible to expand the scope of approximation methods' application based on artificial neural networks and metaheuristics, which is confirmed by its adaptation for an economic problem and contributes to an increase in intelligent computer systems efficiency for general and special purposes.

Keywords: artificial neural networks, approximation methods, connectionist-metaheuristic approach, wasp swarm optimization, macroeconomic indicators.

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КОНЕКЦІОНІСТСЬКО-МЕТАЕВРИСТИЧНИЙ ПІДХІД ДО АНАЛІЗУ ПОКАЗНИКІВ ІНВЕСТИЦІЙНОГО СЕРЕДОВИЩА СВІТОВОЇ ЕКОНОМІКИ

Актуальне завдання використання нових підходів до аналізу показників прямих іноземних інвестицій та макроекономічних показників, що впливають на обсяги їх залучення в ту чи іншу країну світового господарства, було вирішено за допомогою коннекціоністсько-метаевристичного підходу.

У дослідженні використано коннекціоністсько-метаевристичний підхід в ході використання нових підходів до аналізу прямих іноземних інвестицій та макроекономічних показників, що впливають на обсяги їх залучення до тієї чи іншої країни світової економіки. Запропонований коннекціоністсько-метаевристичний підхід дає змогу підвищити якість апроксимації за рахунок: спрощення структурної ідентифікації за рахунок використання лише одного прихованого шару нейромережевих моделей; зниження обчислювальної складності параметричної ідентифікації та забезпечення гарної масштабованості за рахунок використання пакетного режиму для неповторних моделей нейронних мереж і багатоагентних метаевристик для рекурентних моделей нейронних мереж; описів нелінійних залежностей за допомогою нейромережевих моделей; високої точності апроксимації за рахунок використання рекурентних нейромережевих моделей; стійкості до неповноти даних і шуму даних за рахунок використання метаевристик для параметричної ідентифікації рекурентних моделей нейронних мереж; відсутності вимог щодо знання розподілу, однорідності, слабкої кореляції та вибору оптимальних факторів. У ході використання графічного процесора запропоновано вибрати нейронну мережу на основі LSTM, яка має найвищу точність апроксимації. Для LSTM коефіцієнт детермінації за допомогою градієнтного методу становить 0,785, а за допомогою метаевристики (модифікована оптимізація колонії ос) – 0,835. Запропонований підхід дає змогу розширити сферу застосування методів апроксимації на основі штучних нейронних мереж і метаевристик, що підтверджується його адаптацією до економічної задачі, та сприяє підвищенню ефективності інтелектуальних комп'ютерних систем загального та спеціального призначення.

Ключові слова: штучні нейронні мережі, методи апроксимації, коннекціоністсько-метаевристичний підхід, оптимізація осиного рою, макроекономічні показники.

Introduction

International investment activity effectively complements international trade and contributes to the economic growth of national economies. The international investment flows from different countries intertwine and interact with each other, turning into global investment resources. An important condition for attracting investment resources is the presence of powerful economic potential, in which foreign investment flows are the foundation of global economy development. Important components of the economic potential and factors of the formation of a favorable investment environment are such as GDP volumes, the inflation rate, the unemployment rate, indicators of exports of goods and services, and others.

The object of the research is the process of analyzing statistical indicators that are indicators of the national economies' development in the context of globalization. The subject of the research is a connectionist-metaheuristic approach for the analysis of economic indicators. The aim of the research is to increase the efficiency of the analysis of economic indicators based on the connectionist-metaheuristic approach to the approximation models' creation.

The main tasks of the research:

1. To form a vector of economic indicators.
2. To create a recurrent neural network approximation model.
3. To develop a gradient method for identifying the parameters of recurrent neural network approximation models.
4. To create a metaheuristic method for the parametric identification of recurrent neural network approximation models.

Related works

The analysis of macroeconomic indicators using various methods is an important task of modern research. Nowadays various methods of economic analysis, including approximation are used to analyze such indicators.

The traditional methods of approximation are:

1. Statistical [1-3].
2. Analytical [4-6].
3. Method of group accounting of arguments (MGUA) [7, 8].

Existing traditional methods of approximation have one or more of the following disadvantages [9, 10]:

– approximation models are focused on linear dependencies;
– structural-parametric identification of the approximation model has a high computational complexity;
– approximation models cannot provide high accuracy;
– approximation models are sensitive to data noise and it is necessary to ensure data completeness for them;
– approximation models provide a priori knowledge of the type of distribution, weak correlation, uniformity, and preselection of factors.

In this regard, it is relevant to create an approximation approach that will eliminate these shortcomings.

At present, the neural network approach [11, 12] is popular, which allows using both conventional activation functions and wavelet-based activation functions. Since only a sequential learning mode is used for recurrent neural networks, metaheuristics [13-16] can be used to eliminate this drawback, which will allow them to be used in the analysis of economic indicators. Among the metaheuristics that allow parallelization on the GPU, there are multi-agent metaheuristics [17-20].

Research methods

1. Formation of the factors' vector

We used the following indicators of the national economies' investment attractiveness to form the data array: the gross domestic product volume (GDP) per capita (per year, US dollars), inflation rate (according to the consumer price index, which reflects the annual percentage change in the cost for the average consumer of purchasing a basket of goods and services, per year, %), exports of goods and services indicators (total volume, per year, USD), labor force indicators (labor force is people aged 15 years and older who provide labor for the goods and services production, per year, number of people), income tax indicators (income tax is the amount of income taxes paid by an enterprise, % of the enterprises' commercial profit in a country, per year). All indicators were formed for the 2010-2019 period.

For neural network models, to improve the approximation accuracy, the factors and responses are normalized.

2. Creating a neural network model based on long short-term memory with a forgetting gate

A long short-term memory (LSTM) neural network with a forgetting gate is a recurrent two-layer ANN [LSTM, 25, 26].

It is considered that a memory block consists of only one memory cell to reduce computational complexity.

1. The calculation of the outputs of the input layer

$$y_i^{in}(n-1) = x_i,\ i \in \overline{1, N^{(0)}}$$

2. The calculation of the forgets gates outputs

$$y_j^{g\varphi}(n) = f\left(b_j^{g\varphi} + \sum_{i=1}^{N^{(0)}} w_{ij}^{in-g\varphi} y_i^{in}(n-1)\right),\ j \in \overline{1, N^{(1)}}$$

3. The calculation of the output signals of input gateways

$$y_j^{gin}(n) = f\left(b_j^{gin} + \sum_{i=1}^{N^{(0)}} w_{ij}^{in-gin} y_i^{in}(n-1)\right),\ j \in \overline{1, N^{(1)}}$$

4. The calculation of the input signals of memory cells

$$\tilde{y}_j^{c}(n) = 2g\left(b_j^{s} + \sum_{i=1}^{N^{(0)}} w_{ij}^{in-s} y_i^{in}(n-1)\right),\ j \in \overline{1, N^{(1)}}$$

5. The calculation of the output signals of exit gates

$$y_j^{gout}(n) = f\left(b_j^{gout} + \sum_{i=1}^{N^{(0)}} w_{ij}^{in-gout} y_i^{in}(n-1)\right),\ j \in \overline{1, N^{(1)}}$$

6. The calculation of the states of memory cells

$$s_j^c(n) = y_j^{g\varphi}(n) s_j^c(n-1) + y_j^{gin}(n) \tilde{y}_j^c(n),\ j \in \overline{1, N^{(1)}}$$

7. The calculation of the output signals of memory cells

$$y_j^c(n) = y_j^{gout}(n) g\left(s_j^c(n)\right),\ j \in \overline{1, N^{(1)}}$$

8. The calculation of the output signal of the output layer

$$y^{out}(n) = b^{out} + \sum_{i=1}^{N^{(1)}} w_i^{c-out} y_i^c(n),$$

where $N^{(0)}$ – the length of the factors vector,

$N^{(1)}$ – is the number of neurons in the hidden layer memory blocks,

$b_j^{g\varphi}$ – is the threshold for the forgetting gate of the *j*-th block of memory,

b_j^{gin} – is the threshold for the input gateway of the *j*-th memory block,

b_j^{s} – is the threshold for the memory cell of the *j*-th memory block,

b_j^{gout} – is the threshold for the output gateway of the *j*-th memory block,

b^{out} – is the threshold for the neuron of the output layer,

$w_{ij}^{in-g\varphi}$ – is the weight of the connection between the *i*-th neuron of the input layer and the *j*-th memory block forgetting gate,

w_{ij}^{in-gin} – is the weight of the link between the *i*-th neuron of the input layer and the input gateway of the *j*-th memory block,

w_{ij}^{in-s} – is the weight of the link between the *i*-th neuron of the input layer and the input of the memory cell of the *j*-th memory block,

$w_{ij}^{in-gout}$ – is the weight of the link between the *i*-th neuron of the input layer and the output gateway of the *j*-th memory block,

w_i^{c-out} – is the weight of the link between the output of the memory cell of the i-th memory block and the output layer neuron,

$g(s) = \tanh(s)$ – is the activation function for memory cells,

$f(s) = \dfrac{1}{1+e^{-s}}$ – is the activation function for gateways.

3. Development of a gradient method for identifying the parameters of a neural network approximation model based on long short-term memory with a forgetting gate

1. Number of training iteration $n = 2$, initialization by uniform distribution on the interval (0,1) or [-0.5, 0.5] of offsets (thresholds) $b_j^{gin}(n), b_j^{g\varphi}(n), b_j^{gout}(n), b_{jv}^{s}(n)$ and weights $w_{ij}^{in-gin}(n)$, $w_{ij}^{in-g\varphi}(n)$, $w_{ij}^{in-gout}(n)$, $w_{ijv}^{in-s}(n)$, $i \in \overline{1, N^{(0)}}, j \in \overline{1, N^{(1)}}, v \in \overline{1, S_j}$, of offsets (thresholds) $b_j^{out}(n)$ and weights $w_{ivj}^{c-out}(n)$, $i \in \overline{1, N^{(1)}}, j \in \overline{1, N^{(2)}}, v \in \overline{1, S_j}$, where $N^{(0)}$ – the number of neurons in the input layer, $N^{(1)}$ – is the number of neurons in the hidden layer, $N^{(2)}$ – is the number of neurons in the output layer, S_j – is the number of cells in the j - th memory block.

2. The training set $\{(\mathbf{x}_\mu, \mathbf{d}_\mu) \mid \mathbf{x}_\mu \in R^{N^{(0)}}, \mathbf{d}_\mu \in R^{N^{(2)}}\}$, $\mu \in \overline{1, P}$ is specified where $\mathbf{x}_\mu$ – is the μ-th training input vector, $\mathbf{d}_\mu$ – is the μ-th training output vector, P – is the power of the training set. The number of the current pair from the training set is $\mu = 2$.

3. Initial computation of the output signal of the cell $s_{jv}^{c}(n-1) = 0$, $v \in \overline{1, S_j}$, $j \in \overline{1, N^{(1)}}$.

4. Output signal computation for each layer (forward run) $y_i^{in}(n-1) = x_{\mu-1,i}$,

$$y_j^{gin}(n) = f(net_j^{gin}(n)),\ j \in \overline{1, N^{(1)}},$$

$$f(s) = \frac{1}{1+e^{-s}},\ net_j^{gin}(n) = \sum_{i=0}^{N^{(0)}} w_{ij}^{in-gin}(n) y_i^{in}(n-1),$$

$$y_j^{g\varphi}(n) = f(net_j^{g\varphi}(n)),\ j \in \overline{1, N^{(1)}},$$

$$f(s) = \frac{1}{1+e^{-s}},\ net_j^{g\varphi}(n) = \sum_{i=0}^{N^{(0)}} w_{ij}^{in-g\varphi}(n) y_i^{in}(n-1),$$

$$\tilde{s}_{jv}^{c}(n) = g(net_{jv}^{c}(n)),\ v \in \overline{1, S_j},\ j \in \overline{1, N^{(1)}},$$

$$g(s) = 2\tanh(s),\ net_{jv}^{c}(n) = \sum_{i=0}^{N^{(0)}} w_{ijv}^{in-s}(n) y_i^{in}(n-1),$$

$$s_{jv}^{c}(n) = y_j^{g\varphi}(n) s_{jv}^{c}(n-1) + y_j^{gin}(n) \tilde{s}_{jv}^{c}(n),\ v \in \overline{1, S_j},\ j \in \overline{1, N^{(1)}},$$

$$y_j^{gout}(n) = f(net_j^{gout}(n)),\ j \in \overline{1, N^{(1)}},$$

$$f(s) = \frac{1}{1+e^{-s}},\ net_j^{gout}(n) = \sum_{i=0}^{N^{(0)}} w_{ij}^{in-gout}(n) y_i^{in}(n-1),$$

$$y_{jv}^{c}(n) = y_j^{gout}(n) h(s_{jv}^{c}(n)),\ v \in \overline{1, S_j},\ j \in \overline{1, N^{(1)}},$$

$$h(s) = \tanh(s),$$

$$y_j^{out}(n) = f(net_j^{out}(n)),\ j \in \overline{1, N^{(2)}},$$

$$f(s) = \frac{1}{1+e^{-s}},\ net_j^{out}(n) = b_j^{out} + \sum_{i=1}^{N^{(1)}} \sum_{v=1}^{S_i} w_{ivj}^{c-out}(n) y_{iv}^{c}(n).$$

It is considered that $w_{0j}^{in-gin}(n) = b_j^{gin}(n), y_0^{in}(n-1) = 1,\ w_{0j}^{in-g\varphi}(n) = b_j^{g\varphi}(n), y_0^{in}(n-1) = 1,$

$$w_{0j}^{in-s}(n) = b_j^{s}(n), y_0^{in}(n-1) = 1,\ w_{0j}^{in-gout}(n) = b_j^{gout}(n), y_i^{gout}(n-1) = 1$$

5. Calculation of ANN error energy

$$E(n) = \frac{1}{2}\sum_{i=1}^{N^{(2)}} e_i^2(n),\ e_i(n) = y_i^{out}(n) - d_{\mu-1,i}.$$

6. The adjustment of synaptic weights based on the generalized delta rule and the RTRL rule (backward movement)

$$w_{ivj}^{c-out}(n+1) = w_{ivj}^{c-out}(n) - \eta \frac{\partial E(n)}{\partial w_{ivj}^{c-out}(n)},\ i \in \overline{1, N^{(1)}},\ v \in \overline{1, S_j},\ j \in \overline{1, N^{(2)}},$$

$$b_j^{out}(n+1) = b_j^{out}(n) - \eta \frac{\partial E(n)}{\partial b_j^{out}(n)},\ j \in \overline{1, N^{(2)}},$$

$$w_{ij}^{in-gout}(n+1) = w_{ij}^{in-gout}(n) - \eta \frac{\partial E(n)}{\partial w_{ij}^{in-gout}(n)},\ i \in \overline{1, N^{(0)}},\ j \in \overline{0, N^{(1)}},$$

$$w_{ijv}^{in-s}(n+1) = w_{ijv}^{in-s}(n) - \eta e_{jv}^{c}(n) \frac{\partial s_{jv}^{c}(n)}{\partial w_{ijv}^{in-s}(n)},\ i \in \overline{1, N^{(0)}},\ v \in \overline{1, S_j},\ j \in \overline{0, N^{(1)}},$$

$$w_{ij}^{in-gin}(n+1) = w_{ij}^{in-gin}(n) - \eta \sum_{v=1}^{S_j} e_{jv}^{c}(n) \frac{\partial s_{jv}^{c}(n)}{\partial w_{ij}^{in-gin}(n)},\ i \in \overline{1, N^{(0)}},$$

$$v \in \overline{1, S_j},\ j \in \overline{0, N^{(1)}},$$

$$w_{ij}^{in-g\varphi}(n+1) = w_{ij}^{in-g\varphi}(n) - \eta \sum_{v=1}^{S_j} e_{jv}^{c}(n) \frac{\partial s_{jv}^{c}(n)}{\partial w_{ij}^{in-g\varphi}(n)},\ i \in \overline{1, N^{(0)}},$$

$$v \in \overline{1, S_j},\ j \in \overline{0, N^{(1)}},$$

where η – is a parameter that determines the learning rate (with a large learning rate is faster, but the risk of getting the wrong solution increases), $0 < \eta < 1$.

$$\frac{\partial E(n)}{\partial w_{ivj}^{c-out}(n)} = y_{iv}^{c}(n) \delta_j^{out}(n),$$

$$\frac{\partial E(n)}{\partial b_j^{out}(n)} = \delta_j^{out}(n),$$

$$\frac{\partial E(n)}{\partial w_{ij}^{in-gout}(n)} = y_i^{in}(n-1) \delta_j^{gout}(n),$$

$$\frac{\partial s_{jv}^{c}(n)}{\partial w_{ijv}^{in-s}(n)}=\begin{cases}\frac{\partial s_{jv}^{c}(n-1)}{\partial w_{ijv}^{in-s}(n-1)}y_{j}^{g\varphi}(n)+y_{i}^{in}(n-1)y_{j}^{gin}(n)g'(net_{jv}^{c}(n)), & n>2\\ y_{i}^{in}(n-1)y_{j}^{gin}(n)g'(net_{jv}^{c}(n)), & n=2\end{cases},$$

$$\frac{\partial s_{jv}^{c}(n)}{\partial w_{ij}^{in-g\varphi}(n)}=\begin{cases}\frac{\partial s_{jv}^{c}(n-1)}{\partial w_{ij}^{in-g\varphi}(n-1)}y_{j}^{g\varphi}(n)+ & \\ + y_{j}^{in}(n-1)s_{jv}^{c}(n-1)f'(net_{j}^{\varphi}(n)), & n>2\\ y_{j}^{in}(n-1)s_{jv}^{c}(n-1)f'(net_{j}^{\varphi}(n)), & n=2\end{cases},$$

$$\frac{\partial s_{jv}^{c}(n)}{\partial w_{ij}^{in-gin}(n)}=\begin{cases}\frac{\partial s_{jv}^{c}(n-1)}{\partial w_{ij}^{in-gin}(n-1)}y_{j}^{g\varphi}(n)+ & \\ + y_{j}^{in}(n-1)g(net_{jv}^{c}(n))f'(net_{j}^{gin}(n)), & n>2\\ y_{j}^{in}(n-1)g(net_{jv}^{c}(n))f'(net_{j}^{gin}(n)), & n=2\end{cases},$$

$$e_{jv}^{c}(n)=y_{j}^{gout}(n)h'(s_{jv}^{c}(n))\sum_{l=1}^{N^{(2)}}w_{jvl}^{c-out}(n)\delta_{l}^{out}(n),$$

$$\delta_{j}^{out}(n)=f'(net_{j}^{out}(n))(y_{j}^{out}(n)-d_{\mu-1,j}),$$

$$\delta_{j}^{gout}(n)=f'(net_{j}^{gout}(n))\sum_{v=1}^{S_j}h(s_{jv}^{c}(n))\sum_{l=1}^{N^{(2)}}w_{jvl}^{c-out}(n)\delta_{l}^{out}(n).$$

7. Terminating condition check

If $(n-1) \bmod P>0$, then $\mu=\mu+1$, $n=n+1$, go to step 4.

If $(n-1) \bmod P=0$ and $\frac{1}{P}\sum_{s=1}^{P}E(n-P+s)>\varepsilon$, then $n=n+1$, go to step 2.

If $(n-1) \bmod P=0$ and $\frac{1}{P}\sum_{s=1}^{P}E(n-P+s)<\varepsilon$, then terminate.

4. Development of a metaheuristic method for identifying the parameters of a neural network approximation model based on long short-term memory with a forgetting gate

For the LSTM neural network model, due to its recurrence, there is no parametric identification in the batch mode, which reduces the learning rate [29-31, 32-34]. To eliminate this shortcoming, this paper proposes a modified method for optimizing the wasp colony.

For this method, a criterion (goal function) is used, which means the choice of such values of the vector of parameters (thresholds and weights) that deliver the minimum of the mean square error (the difference between the model output and the test output).

$$F=\frac{1}{P}\sum_{\mu=1}^{P}(y_{\mu}^{out}-d_{\mu})^{2}\rightarrow\min_{\theta},$$

where y_{μ}^{out} – μ -th model response,

d_{μ} – μ -th test response.

Wasp colony optimization is based on the social behavior of wasps. The position of each wasp in space corresponds to a solution. The goal of the algorithm is to locate the optima in a multidimensional space using all the pivots. At each iteration, the strongest wasps will be determined based on the goal function. These wasps and their environment are modified. Weak wasps die and are replaced by wasps produced by crossing the best wasps. The weakest wasps are replaced with random wasps. It is proposed to decrease the parameter for generating a new position as the iteration number increases, in order to ensure the convergence of the method, in contrast to the traditional method.

1. Initialization

1.1. To set a parameter δ for generating a new position, and $0 < \delta < 1$.

1.2. To set the maximum number of iterations N, population size K, the maximum number of best wasps Q, neighborhood size Z, the length of the wasp position vector M (corresponds to the number of parameters of the neural network), the minimum and maximum values for the position vector $x_j^{\min}, x_j^{\max}$, $j \in \overline{1,M}$.

1.3. To generate randomly a vector of the best position

$$x^* = (x_1^*,...,x_M^*),\ x_j^* = x_j^{\min} + (x_j^{\max} - x_j^{\min})U(0,1),$$

where $U(0,1)$ – a function returning a uniformly distributed random number in a range $[0,1]$.

1.4. To create an initial population $P^{(0)}$

1.4.1. The wasp number $k = 1$, $P^{(0)} = \varnothing$

1.4.2. To generate randomly a position vector x_k

$$x_k = (x_{k1},...,x_{kM}),\ x_{kj} = x_j^{\min} + (x_j^{\max} - x_j^{\min})U(0,1)$$

1.4.3. $P^{(0)} = P^{(0)} \bigcup \{x_k\}$,

1.4.4. If $k \le K$, then $k = k + 1$, go to step 1.4.2

2. Iteration number $n = 0$.

3. To sort $P^{(n)}$ by target function, i.e., $F(x_k) < F(x_{k+1})$

4. To determine the best wasp in terms of the goal function

$$k^* = \arg\min_k F(x_k)$$

5. If $F(x_{k^*}) < F(x^*)$, then $x^* = x_{k^*}$

6. To apply the crossover operator Q to the best (first) wasps

6.1. The wasp number $k = 1$, $P^{(n+1)} = \varnothing$

6.2. To select randomly the -th wasp different from the k-th wasp from the best wasps, i.e. $m = round(1 + (Q-1)U(0,1))$, $k \ne m$,

where $round()$ – is the function that rounds a number to the nearest whole number.

6.3. To perform a medium crossover over x_k and x_m, and get the vector $\tilde{x}_k$

$$\tilde{x}_k = (\tilde{x}_{k1},...,\tilde{x}_{kM}),\ \tilde{x}_{kj} = 0.5(x_{kj} + x_{mj})$$

6.4. If $F(x_k) < F(\tilde{x}_k)$, then $\tilde{x}_k = x_k$

6.5. $P^{(n+1)} = P^{(n+1)} \bigcup \{\tilde{x}_k\}$

6.6. If $k < Q$, then $k = k + 1$, go to step 6.2

7. To create a neighborhood for each of the Q best wasps and apply a crossover operator to these neighborhoods.

7.1. The wasp number $k = 1$

7.2. To create a neighborhood U_{x_k} for the k-th wasp

7.2.1. $z = 1$

7.2.2. Solution generation u_z from decision x_k

7.2.2.1. $u_{zj} = x_{kj} + \delta\left(\frac{N-n}{N}\right)(x_j^{\max} - x_j^{\min})(-1 + 2U(0,1))$, $j \in \overline{1,M}$

7.2.2.2. $u_{zj} = \max\{x_j^{\min}, u_{zj}\}$, $u_{zj} = \min\{x_j^{\max}, u_{zj}\}$, $j \in \overline{1,M}$

7.2.3. If $u_z \notin U_{x_k}$, then $U_{x_k} = U_{x_k} \bigcup \{u_z\}$, $z = z+1$

7.2.4. If $z \le Z$, then go to step 7.2.2

7.3. To apply crossover to neighborhood of k-th wasp

7.3.1. $z = 1$

7.3.2. To choose randomly different from the z-th wasp m-th axis from the neighborhood U_{x_k}, i.e. , $m = round(1 + (Z-1)U(0,1))$, $z \ne m$

7.3.3. To perform a medium crossover over u_z and u_m, and get a wasp $\tilde{x}_{Q+(k-1)Z+z}$

$$\tilde{x}_{Q+(k-1)Z+z} = (\tilde{x}_{Q+(k-1)Z+z,1}, ..., \tilde{x}_{Q+(k-1)Z+z,M}),$$

$$\tilde{x}_{Q+(k-1)Z+z,j} = 0.5(\hat{x}_{kj} + \hat{x}_{mj})$$

7.3.4. If $F(u_z) < F(\tilde{x}_{Q+(k-1)Z+z})$, then $\tilde{x}_{Q+(k-1)Z+z} = u_z$

7.3.5. $P^{(n+1)} = P^{(n+1)} \bigcup \{\tilde{x}_{Q+(k-1)Z+z}\}$

7.3.6. If $z \le Z$, then $z = z+1$, go to step 7.3.2

7.4. If $k < Q$, then $k = k+1$, go to step 7.2

8. To apply the substitution operator, i.e., replace $K-(Q+Q\cdot Z)$ the worst wasps with random wasps

8.1. The wasp number $k = Q + Q\cdot Z + 1$

8.2. To select randomly two different wasps l and m from the best wasps, i.e. $l = round(1+(Q-1)U(0,1))$, $m = round(1+(Q-1)U(0,1))$, $l \ne m$

8.3. To execute crossover over x_m and x_l, and get wasp $\tilde{x}_k$

$$\tilde{x}_k = (\tilde{x}_{k1}, ..., \tilde{x}_{kM}),\ \tilde{x}_{kj} = 0.5(x_{mj} + x_{lj})$$

8.3. $P^{(n+1)} = P^{(n+1)} \bigcup \{\tilde{x}_k\}$

8.4. If $k < K$, then $k = k+1$, go to step 8.2

9. If $n < N-1$, then $n = n+1$, go to step 3

The result is x^*.

Numerical research

The numerical study of the proposed approach was carried out using the TensorFlow module and its Keras submodule. The Pandas module was used for tabular data I/O and missing value recovery through linear interpolation.

The World Bank economic indicators database (https://databank.worldbank.org/home.aspx) was used in the work. The economic indicators of 145 countries for 10 years were used. The size of the initial sample was equal to 1450. The initial sample was divided into training (P=928), verification (232) and test (290).

The length of the input layer $N^{(0)}$ for all networks was 5. The length of the hidden layer $N^{(1)}$ for the LSTM-based neural network was $N^{(0)}$. We propose a parametric identification of the LSTM neural network model based on the Adam method in batch mode to increase the learning rate. The parameter η, which determines the learning rate, was 0.001.

There is no parametric identification of these models based on the Adam method in batch mode for the LSTM neural network model, due to its recurrence, which reduces the learning rate. We propose to use metaheuristics to eliminate this shortcoming [33; 34].

It is proposed to decrease the parameter for generating a new position as the iteration number increases, in order to ensure the convergence of the method, in contrast to the traditional wasp colony optimization method. For the modified wasp colony optimization method, the parameter for generating a new position was 0.1, the population K size was 120, the maximum number of best wasps Q was 10, and the neighborhood size Z was 10. The maximum number of iterations N was 100.

Research results

To assess the quality of the approximation, the determination coefficient is calculated in the form

$$R^2 = 1 - \frac{\sum_{\mu=1}^{P} (d_\mu - f(\mathbf{x}_\mu, \mathbf{w}))^2}{\sum_{\mu=1}^{P} (d_\mu - \bar{d})^2}, \; R^2 \in [0,1],$$

$$\bar{d} = \sum_{\mu=1}^{P} d_\mu$$

The results of comparing the quantitative characteristics of the proposed methods for the parametric identification of neural network models are presented in Table 1, where *M* – is the number of parameters for a specific neural network.

Table 1

Comparison of the qualitative characteristics of the proposed methods for parametric identification of neural network models

Neural networks	Characteristics of the methods of parametric identification	
	Coefficient of determination	Computational complexity
LSTM-based neural network without the use of metaheuristics and GPU	0.785	~*NPM*, *M*=226 (forward / reverse)
LSTM based neural network using metaheuristics and GPU	0.835	~*NK*

An LSTM-based neural network using metaheuristics and a GPU has a higher determination coefficient, i.e., the highest approximation accuracy due to random search, and lower computational complexity due to the use of GPU.

Conclusions

The urgent task of using new approaches to analyze the indicators of foreign direct investment and macroeconomic indicators that affect the volume of their attraction to a particular country in the world economy was solved by a connectionist-metaheuristic approach.

The proposed connectionist-metaheuristic approach makes it possible to increase the approximation efficiency by:

– simplifying structural identification by using only one hidden layer of neural network models;

– reducing the computational complexity of parametric identification by using multi-agent metaheuristics for recurrent neural network models;

– high approximation accuracy due to the use of recurrent connections in neural network models;

– the possibility of non-linear approximation through the use of neural network models;

– lack of requirements for a priori knowledge of the distribution, weak correlation, homogeneity and preliminary selection of factors.

– resistance to data noise and data incompleteness due to metaheuristic parametric identification of recurrent neural networks models.

The proposed approach makes it possible to expand the scope of application of approximation methods based on the connectionist approach and metaheuristics, which is confirmed by its adjustment for an economic problem and contributes to an increase in the efficiency of intelligent computer systems related to the economy.

Prospects for further research are the study of the proposed approach for various problems of artificial intelligence, as well as the creation of methods for analyzing economic.

The research was carried out in accordance with the priority direction of the development of science and technology in Ukraine "Information and Communication Technologies" and contain some results of the research "Development of models and methods of biometric identification of people" (state registration number 0119U002860).

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FEATURES OF THE USE OF INFORMATION AND COMMUNICATION TECHNOLOGIES TO SUPPORT PROJECT PROCESSES IN DISTRIBUTED TEAMS

The study presents an in-depth analysis of the role of information and communication technologies (ICT) in the context of managing project processes in distributed teams. The main focus is on the classification and evaluation of the effectiveness of communication and information technologies as tools that significantly increase productivity and contribute to the optimization of work processes in such distributed teams. The main interpretations of the concept of distribution in project teams are given.

The methodological approach of the article is based on a comprehensive analysis of existing problems of communication and information exchange in distributed teams. A systematic approach was used to structure and define the main channels of communication, based on a hierarchical diagram developed on the basis of expert assessments and analysis of work processes.

The results of the study present a detailed comparative analysis of widely used platforms for project management, such as Trello, Asana, Jira, Microsoft Project, etc., with an emphasis on their functionality, areas of application, and project management models and assignments in terms of distribution in project teams.

The authors carried out a comprehensive comparison of communication and information systems, as a result, a number of main trends in the use of ICT in project management over the past four years were revealed. Special attention is paid to the most popular tools, the definition of their unique features and the potential of application in various projects. Innovative approaches to the automation of project processes in the context of project management platforms for distributed teams are also considered, with the proposal of a new algorithm for their implementation.

The conducted analysis makes an important contribution to the understanding of how information and communication technologies can be applied to improve the efficiency and productivity of distributed teams, in particular in the aspects of supporting project processes. The study contributes to a deep understanding of the key factors affecting the successful integration of the considered technologies into modern project practices.

Keywords: information technologies, communication technologies, distributed teams, platforms for project management, project management model, project management services, automation of project processes, tools for joint work, tools for documentation.

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ОСОБЛИВОСТІ ВИКОРИСТАННЯ ІНФОРМАЦІЙНИХ ТА КОМУНІКАЦІЙНИХ ТЕХНОЛОГІЙ ДЛЯ СУПРОВОДУ ПРОЄКТНИХ ПРОЦЕСІВ У РОЗПОДІЛЕНИХ КОМАНДАХ

У дослідженні представлено глибокий аналіз ролі інформаційних та комунікаційних технологій (ІКТ) у контексті управління проєктними процесами в розподілених командах. Основна увага приділена класифікації та оцінці ефективності комунікаційних та інформаційних технологій як інструментів, які значно підвищують продуктивність та сприяють оптимізації робочих процесів у таких розподілених командах. Наведено основні трактування поняття розподіленості в проєктних командах.

Методологічний підхід статті базується на комплексному аналізі існуючих проблем комунікації та інформаційного обміну в розподілених командах. Використано системний підхід для структурування і визначення головних каналів комунікації, заснованих на ієрархічній діаграмі, розробленій на основі експертних оцінок та аналізу робочих процесів.

У результатах дослідження представлено детальний порівняльний аналіз широко застосовуваних платформ для управління проєктами, таких як Trello, Asana, Jira, Microsoft Project, і ін., з акцентом на їх функціональні можливості, сфери застосування й моделі управління проєктами та призначення в розрізі розподіленості в проєктних командах.

Автори здійснили комплексне порівняння комунікаційних та інформаційних систем, в результаті виявлено ряд основних тенденцій використання ІКТ у проєктному менеджменті за останні чотири роки. Особливу увагу приділено найбільш популярним інструментам, визначенню їх унікальних особливостей та потенціалу застосування у різноманітних проєктах. Також розглянуто інноваційні підходи до автоматизації проєктних процесів в контексті платформ управління проєктами для розподілених команд, з пропозицією нового алгоритму їх імплементації.

Проведений аналіз у роботі вносить важливий вклад у розуміння того, як інформаційні та комунікаційні технології можуть бути застосовані для покращення ефективності та продуктивності розподілених команд, зокрема в аспектах супроводу проєктних процесів. Дослідження сприяє глибокому розумінню ключових факторів, що впливають на успішну інтеграцію розглянутих технологій в сучасні проєктні практики.

Ключові слова: інформаційні технології, комунікаційні технології, розподілені команди, платформи для управління проектами, модель управління проєктами, сервіси управління проєктами, автоматизації проєктних процесів, інструменти для спільної роботи, інструменти для документації.

Introduction

The use of information technologies is becoming a critical success factor in the management of project processes in today's world, which is rapidly developing and constantly changing, caused by globalization and technological progress. This is especially true for distributed teams, where coordination of efforts, parallel execution of project fragments, effective communication and integration of efforts of all participants, who may be located in different time zones and have diverse cultural and professional backgrounds, are vital.

During the COVID-19 pandemic, unpredictable military conflicts with cells in Ukraine, Israel, and other countries, it becomes clear that we are facing new challenges. The economic, business and human costs of the pandemic continue to unfold, and organizations that previously focused on office work have been forced to quickly shift to a distributed team model while trying to keep their businesses afloat during the global economic downturn. During military conflicts, the issue of relocation of offices, employees, effective communication, preservation of personnel and their potential, and effective management of project processes arises as well.

Features of the use of information and communication technologies in distributed teams gain even more weight in the light of these events. People who were previously used to office work and stability in the external environment suddenly found themselves in conditions of remote work or relocation without the appropriate training and base, many of them also faced with additional difficulties due to the closure of children's institutions and educational institutions, as well as direct threats to health or even life due to pandemics and military conflicts. Therefore, acquiring the skills to work effectively in distributed teams is more important than ever.

This problem can be traced not only in the software development industry, but also in many other industries and countries, where it is necessary to find common principles of success among a wide range of professions [1].

Information and communication technologies can contribute to the effective implementation of project processes in distributed teams, taking into account the geographical, functional and temporal distribution of their participants.

According to Maynard, distributed teams (or remote teams) are those whose members are geographically distributed, rely on ICT for communication, and face challenges in terms of reducing gaps, reducing the number of people involved, and inefficiency [2]. In Malhorta's work, a distributed team is defined as a decentralized group of people working from different geographical locations, often in different time zones and with daily schedules, interacting through technologies for communication and collaboration, with varying degrees of reliance on ICT to coordinate their activities, regardless of the team size [3].

Before considering the use of information and communication technologies for the implementation of project processes in distributed teams, it is worth highlighting the main problems that may arise in distributed teams and affect project processes (Fig. 1).

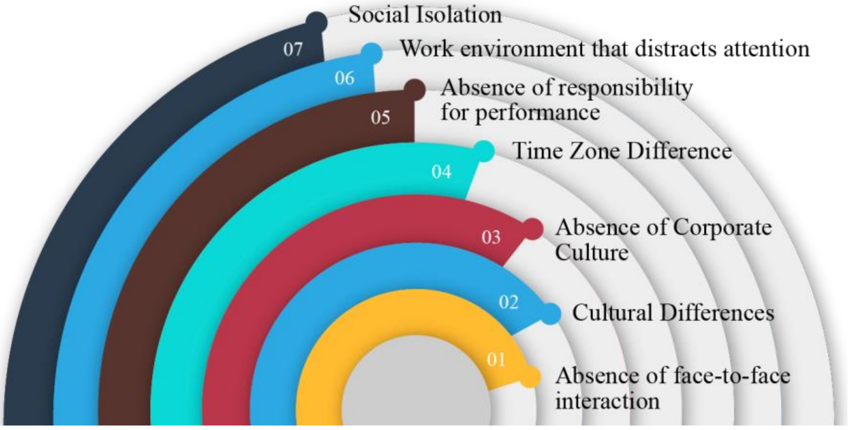

Fig. 1. Distinguishing problems that arise in distributed teams

A team is usually a group of members from different departments who work together temporarily to solve problems. The definition of distributed teams will be considered according to Margaret Boos. She defines distributed teams as groups of people who do their work in different locations and can interact primarily through communication tools such as e-mail, video conferencing, and other technological tools. This means that team members are physically dispersed, but remain connected through technology to achieve a common goal [4]. Another definition is given by Cramton. She believes that distributed teams are groups of people with a common goal who perform interdependent tasks in different locations and time zones, using technology to communicate much more than face-to-face meetings [5]. Solving problems by such teams has some advantages. First, it is possible to find the right person for almost every job. Especially if some special skills or expensive licenses are required, working in distributed teams helps to find solutions. In addition, different participants can have good knowledge and expertise in their market, so products can be adapted to the realities of the market represented by the members of the distributed team.

Apart from these advantages, there are also several disadvantages. The critical point is the participants themselves. They should be suitable for working in distributed teams. Otherwise, they jeopardize the success of the project. Another problem that can negatively affect projects is personal conflicts. To avoid this, a good identification with the team and the project is necessary. This can be ensured through personal meetings. However, such meetings are often avoided when working in distributed teams due to the associated costs. This leads to the predominance of digital communication forms that filter some important communication channels [6].

Kumar Goel believes that information and communication technology (ICT) is essential for working in distributed teams, but there are both advantages and disadvantages. As for the first, these technologies facilitate the rapid exchange of information, the sharing of files, and the clarification of doubts and the exchange of opinions [7].

M. O'Leary, J. Wilson and A. Metiu found increased communication in remote work due to the proximity effect provided by ICT, regardless of whether team members have daily contact or not. From this perspective, a cultural view of information technology (IT) that supports interpersonal dynamics can be seen as a way of enriching interactions among members, adding even more value in terms of increased productivity, enhanced communication, and the process of identification. The authors investigated that perceived proximity (i.e., cognitive and affective feelings of relational closeness) rather than physical proximity (i.e., geographic proximity measured in miles or kilometers) influences relationship quality in distributed teams. The results prove that people can form strong bonds despite great distances, and continue to shift the emphasis from information systems as “pipes” or channels to information systems as means of conveying shared meaning and symbolic value [8].

According to research by A. Reed and L. Knight, there are three factors that can lead to communication risks such as communication loss or poor communication, technical connectivity issues that hinder communication, and insufficient knowledge transfer. Some of the risks associated with perception can also lead to problems in communication. Despite the increased reliance of distributed teams on ICT, there was no evidence of significantly greater project risk due to technology failures. However, there was noticeably more risk precisely because of insufficient transfer of knowledge in the projects of distributed teams. A likely explanation is the reduction of implicit or informal knowledge transfer in virtual environments [9].

A review of communication technologies to ensure the effectiveness of distributed teams

Communication channels used by distributed teams are tools that promote effective interaction and coordination in project processes. Expert evaluations were conducted regarding the importance of each channel according to a scale from 1 to 5, where 1 indicates the minimum importance, and 5 – the maximum one, evaluations were made on the basis of the methodology of expert evaluations. Face-to-face meetings, including environment, verbal exchange, dialogue, voice communication and sign language, receive the highest score of 5, given their high effectiveness for deep understanding and complex communication in the context of project teams, but this communication channel in its classical form is extremely difficult to use for distributed teams.

Video conferences. Video conferencing with ratings of 4 for verbal and dialogue communication, and 3 for sign language, demonstrate almost the same benefits as in-person meetings, but may be limited by connection quality and technical parameters. Popular communication systems for this type of communication are Zoom, Microsoft Teams, Google Meet, etc.

Phone connection. Phone communication is rated 3 for words and dialogue and 4 for voice, identifying it as a means of direct voice communication without the possibility of visual contact. Tools for this type of communication can be standard telephone lines, VoIP services such as Skype.

Chats. Communication through chats takes an important position in interaction in distributed teams, rated at 3 points for verbal communication and dialogue. Chats allow you to conduct an immediate text exchange of information, contributing to prompt solution of issues. This is especially valuable in situations where rapid interaction between project participants is required. Despite the convenience and speed, chats can limit the possibilities of deep dialogue due to the difficulty of conveying emotional coloring and nuances in text form. Information and communication systems such as Slack or Microsoft Teams provide platforms for effective organization of chat communications.

E-mail. Email is a traditional and widely used channel for professional communication, scoring 3 for verbal communication and 2 for dialogue. E-mail is effective for documenting information exchange and provides the convenience of having organized and structured discussions. However, it may not be ideal for situations that require an immediate response, and often results in delays in communication. In addition, an excessive number of emails can cause information overload. Tools like Gmail or Outlook help you organize and manage your e-mail correspondence.

Project management platforms. Project management services play a decisive role in the coordination of distributed project teams, it should be noted that they combine the tools of both information systems and integrated elements of communication systems. Having received ratings of 4 for verbal interaction and dialogues and a maximum rating of 5 for the ability to track statuses, these services are becoming a necessary tool in modern project management. These systems simplify the process of planning, allocation of tasks, control of deadlines, and also enable careful monitoring of project progress and resources. Thanks to integrated communication tools, they allow team members to quickly exchange information and effectively manage projects regardless of geographic location. Platforms such as Jira, Asana, Microsoft Project or Trello are examples of such information systems that integrate with a wide range of tools and services, providing a high level of interaction and visualization of project processes.

Professional social networks. Professional social networks, rated 3 for verbal communication and dialogue, act as platforms for sharing knowledge, experience and creating professional connections. These networks, such as LinkedIn, allow users to post professional updates, share content, and discuss industry trends, which helps develop professional relationships and support corporate culture, especially in distributed work environments. They create a virtual space for networking, which can contribute to career growth, recruiting and increasing the company's visibility in the market.

Tools for brainstorming. Collaborative brainstorming tools play a crucial role in the phase of idea generation and creative project planning by distributed teams. With a score of 4 for visualization, such tools allow you to visually organize thoughts and ideas, facilitating deeper analysis and discussion. The dialogue component is also rated at 4 points, which emphasizes their effectiveness in supporting interaction between team members. Tools like Miro and MindMeister are examples of platforms that provide powerful real-time brainstorming capabilities, regardless of the location of participants.

Instant messaging systems. Instant messaging systems are indispensable for ensuring operational communication within distributed teams. Rated 3, they support instant text messaging, allowing participants to quickly share information and receive responses. Platforms like Slack, Telegram, Messenger or WhatsApp provide intuitive interfaces and various functions for group chats, direct messages, as well as integration with other services, which facilitates interaction within project groups.

Code version control platforms. Collaborative coding tools are the foundation for synchronous and asynchronous development in distributed teams of programmers. Rated 4 for verbal communication and dialogue, they provide effective coordination and code sharing, facilitating collective problem solving. GitHub and Bitbucket are important tools in this category, offering version control, code review, and change tracking functionality that is critical to ensuring a high-quality software product. This toolkit allows you to improve the efficiency of the communication component and synchronize work during software development, ensuring integrity and a single ecosystem.

Video and audio recording tools, rated 4 for voice and video, are essential for creating documentation, training materials, and demo presentations. They make it possible to record detailed instructions and procedures, which greatly facilitates the knowledge transmission within the team. Platforms like Zoom for video conferencing, Vimeo and Loom for recording video presentations provide powerful tools for creating and sharing multimedia content.

The different forms of communication and communication channels used in distributed teams is presented in the form of a hierarchical diagram, which is built on the basis of the expert judgments that are mentioned above (Fig. 2).

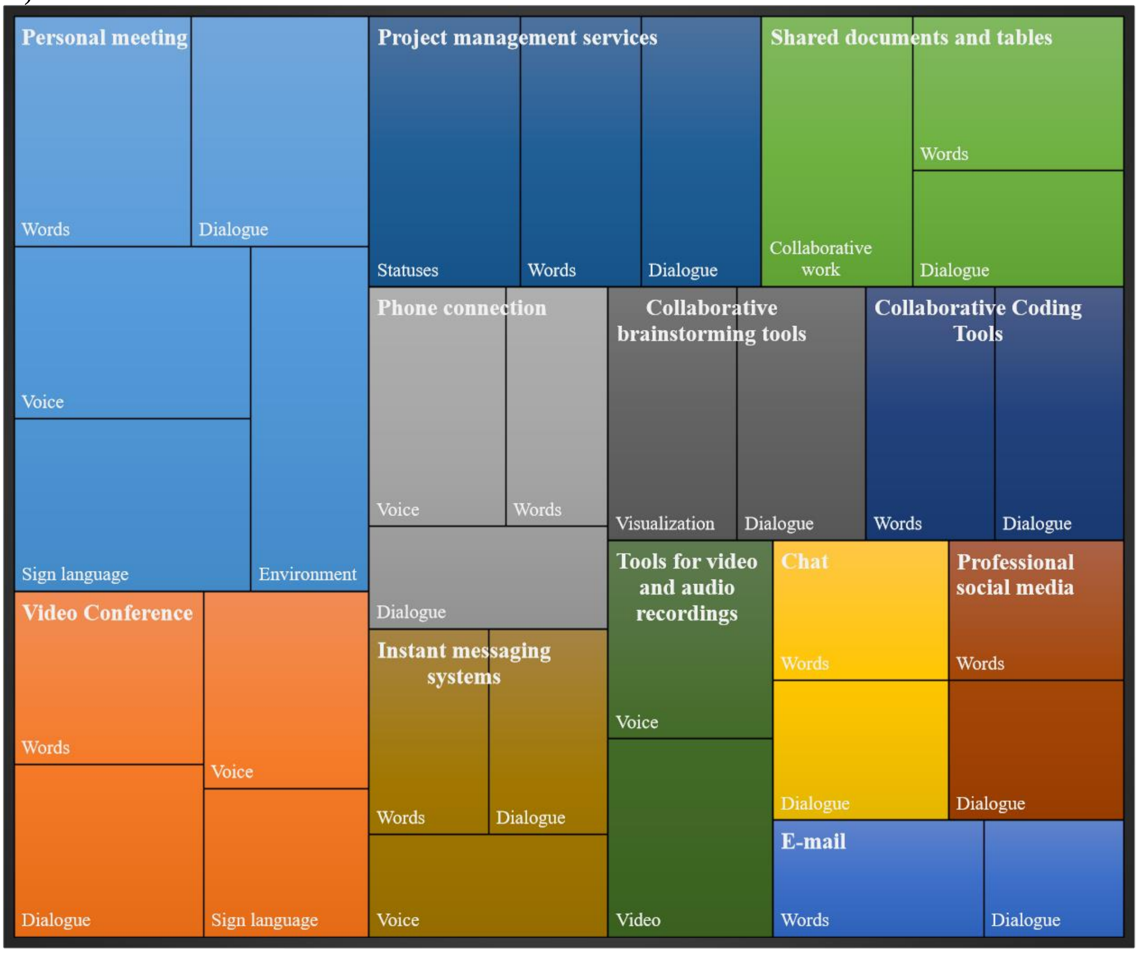

Fig. 2. A hierarchical diagram of the main communication channels used in distributed teams

In today's world of remote work and distributed teams, collaborative brainstorming tools, instant messaging systems, collaborative coding tools, and video and audio recording tools are vital to support effective interaction and collaboration. Each of these communication channels has its own specificity and a level of importance, but together they form a complex ecosystem of tools that provide successful project management in distributed teams, ensuring flexibility, responsiveness and efficiency in work processes.

The absence of one or more communication channels leads to generally limited communication. Moreover, due to the lack of communication, the project manager tends to collect most of the information about the project. This leads to the information monopoly of the project manager and supports a more hierarchical project management. Thus, the success of the project mainly depends on the skills of the manager, which may include a high risk of failure. A lean thinking approach to product development can improve teamwork [10]. The success of this approach is based on the reduction of design errors and shortening of the execution time. Since there is a timely delivery and an engineering budget that is regularly reported and visualized, the lean approach also allows you to set countermeasures in case of problems [11]. Because of the required face-to-face meetings, the approach is usually limited to local projects, but with information technology in mind, it can be adapted for distributed teams. In addition, in the future, development projects will be increasingly distributed around the world, so such project teams will have to face new challenges.

In today's world, where geographical boundaries are gradually disappearing thanks to digital technologies, the management of distributed project teams becomes especially relevant. Effective communication and coordination of the activities of such teams are critical factors for the success of projects. As a result of the analysis of the forms of communication and communication channels used in distributed teams, both traditional methods, such as e-mail and video conferencing, and modern approaches, including specialized tools for project management, which are indispensable for the collaborative work of distributed teams, were considered. The following studies will consider the formation of platforms for the integration of communication and information technologies to ensure the effectiveness of project processes in distributed teams.

To support project processes in distributed teams, various information and communication technologies are used, which are presented in Table 1. Such tools help teams to effectively manage project processes, ensure constant communication and coordination, and serve to increase productivity as well.

Table 1

Division of tools for supporting project processes into information and communication technologies

Information technologies	Communication technologies
Project Management Systems: Asana, Trello, JIRA, Microsoft Project	Tools for video conferencing: Zoom, Microsoft Teams, Google Meet, Skype та ін.
Collaboration Tools: Slack, Microsoft Teams, Discord, Miro, MindMaster	Email: Gmail, Outlook, Yahoo та ін.
Documentation Tools: Confluence, Microsoft365, Google Docs, Notion, Vimeo, Loom та ін.	Instant messages, Chats: Slack, Telegram, Viber, WhatsApp, Skype
Version Control Systems: Github, Gitlab, Bitbucket та ін.	Social networks for professional communication: LinkedIn, Facebook, Twitter та ін.
Monitoring and Reporting Systems: Datalog, New Relic, Google Analytics та ін.	Phone communication: standard telephone lines, VoIP services (Skype)
Testing Tools: Selenium, Junit, TestRail та ін.	

Research and analysis of information systems for managing project processes

It will be considered and analyzed project management platforms that are especially important when working in distributed project teams. A project management platform is an integrated information system that includes a variety of tools and techniques to facilitate the planning, execution, monitoring and completion of projects. It often includes capabilities for task management, collaboration, documentation, and resource allocation, with the goal of improving efficiency and communication within project teams. We will single out platforms for project management and list their main features.

Table 2

Comparative analysis of project management tools

Platform Name	Key Features	Project Management Model	Purpose
1	2	3	4
Trello	Different project display formats, automation, templates, integrations	Flexible, Kanban	Flexible task management for small and medium teams
Asana	AI for business solutions, workflow designer, timeline, boards, calendar, reporting	Flexible, Agile	Collaboration and task management for different team sizes
Jira	Scrum and Kanban boards, roadmaps, timelines, reports	Agile, Scrum, Kanban	Complex project management, in particular for software development
Microsoft Project	Different project display formats, resource management, integration with Microsoft 365	Traditional, Agile	Complex project management for large teams and enterprises

Basecamp	One-page dashboard, communication, task lists, file storage	Flexible	An easy-to-use tool for small teams and startups
1	**2**	**3**	**4**
Monday.com	File storage, boards, communication, integration, automation	Flexible, Agile	Universal project management, suitable for remote teams
Notion	API (Application Programming Interface), activity dashboards, budget management, templates, document management	Flexible	Organization and storage of project information, suitable for creative projects
ClickUp	AI (artificial intelligence), task management, boards, communication, automation	Agile, Scrum, Kanban	Project management using Agile methodology, suitable for different types of teams
Wrike	Dashboards, automation, kanban boards, resource planning, Gantt charts	Agile, Scrum, Kanban	Flexible project management, with an emphasis on collaboration and automation
Zoho Projects	Advanced task management, time management, charts, reports, teamwork, automation	Flexible, Agile	Multi-project management, effective planning and collaboration

A detailed analysis of the popularity of various project management services was conducted using data from Google Trends for the period from December 2019 to October 2023. The research covers platforms such as Trello, Asana, Jira, Microsoft Project, Basecamp, Monday.com, Notion, ClickUp, Wrike, and Zoho Projects. Trends in their use by project teams over recent years were analyzed and their popularity around the world was determined.

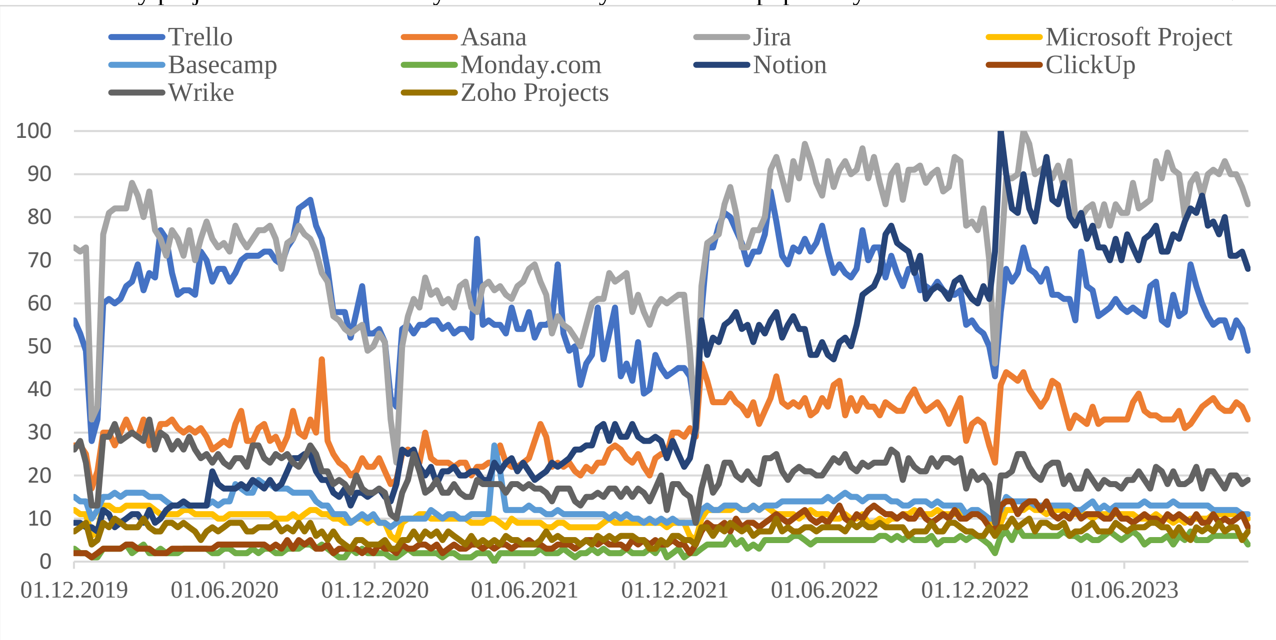

Fig. 3. Dynamics of popularity and interest in selected project management services from December 1, 2019 to October 31, 2023

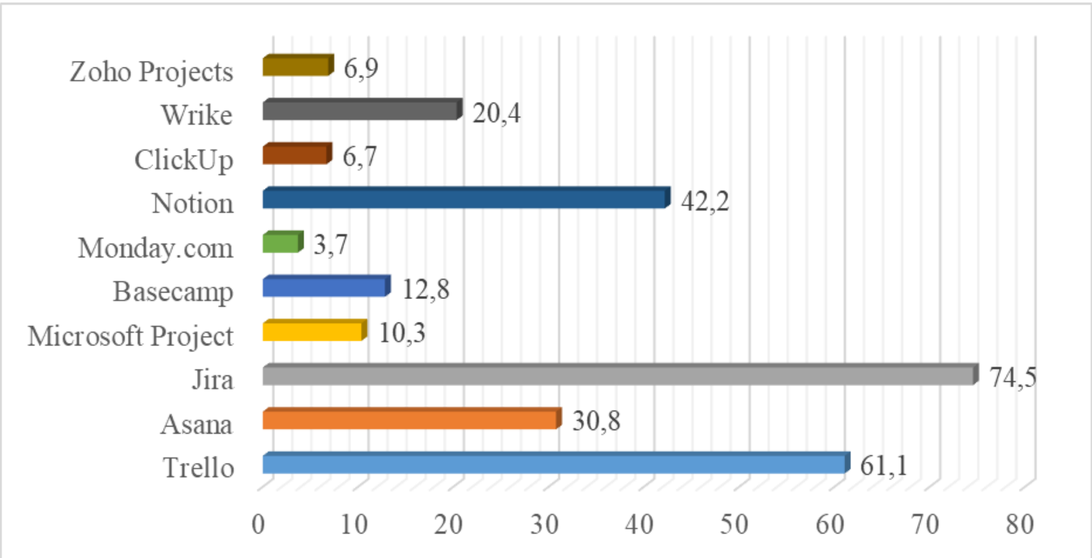

Fig. 4. Average values of the dynamics of popularity and interest of the analyzed project management services

Figures 3 and 4 present the dynamics regarding the popularity and interest in selected project management services from December 1, 2019 to October 31, 2023, based on Google Trends data [12]. The chart tracks relative search interest over time for various project management tools such as Trello, Asana, Basecamp, Monday.com, Jira, Notion, Microsoft Project, Wrike, Zoho Projects, and ClickUp.

Based on this analysis, the following patterns can be traced:

- Trello and Jira have high and variable interest levels throughout, with peaks and troughs that can indicate significant events or releases affecting user engagement.
- Asana, Basecamp, and Microsoft Project show a moderate but relatively stable level of interest, indicating an ongoing user base or market presence.
- Notion shows an increasing trend in popularity, especially in the second half of the analysis period, which may indicate a successful expansion or increase in its penetration and number of users.
- Wrike, Monday.com, Zoho Projects, and ClickUp show lower levels of search interest compared to the others, however, ClickUp has a slight upward trend over time..

For distributed teams, these trends indicate that they are more likely to consider Trello and Jira because of their high visibility and likely extensive capabilities, which may be well-suited for collaboration across geographic locations. Notion's growing popularity also points to it becoming a more popular choice, perhaps due to its flexible note-taking and organization capabilities that can be valuable to remote teams.

Variation in interest in some tools may reflect changes in market positioning, feature updates or changes in the competitive environment. Additionally, the stability of others like Asana and Basecamp indicates that they are solid options with large user bases and developed communities.

However, to make an informed decision about which service is best suited for project management of distributed teams, it is necessary to take into account not only Google Trends data [10]. Factors such as specific feature set, user experience, integration capabilities, pricing and customer support are critical to the evaluation. In further studies, a more extensive set of factors will be considered for choosing the optimal toolkit depending on the types of projects.

The results of this study highlight the importance of choosing the right project management service that meets the unique needs and workflows of each team. The results also highlight the changing demand and preferences in this area, indicating the continuous evolution of the digital project management environment.

Tools for automating project processes on project management platforms for distributed teams

To automate project processes in distributed teams and improve interaction and efficiency, it should be considered creating chatbots in popular messengers such as WhatsApp, Telegram, Viber and Messenger, etc. to integrate with project management tools such as Trello, Asana, Jira, Microsoft Project, Basecamp, Monday.com, Notion, ClickUp, Wrike, and Zoho Projects, as well as Github, Gitlab, and Bitbucket repositories, which can be an effective way to simplify workflow in distributed teams.

There are the key aspects of this process:

- Integration with project tools and repositories: Chatbots can be configured to interact with various project management tools and code repositories. Using the API of these services, chatbots can receive updates about changes in tasks, commits, pool requests and other important events.
- Customized notifications: Users can configure chatbots to receive notifications about specific events, which minimizes information noise and allows you to focus on important updates. These notifications are instant, which is an advantage over email or Slack, where delays can occur.
- Convenience and accessibility: Since most people use messengers regularly, receiving notifications through them is convenient and efficient. This is especially useful for distributed teams that work in different time zones and are geographically dispersed.
- Search functionality and autocomplete: modernized chatbots can include search and autocomplete functionality for convenient access to information about projects, tasks and documentation.
- Interactive interface: development of an intuitive interface for interaction with the chatbot ensures effective use of it, regardless of the technical experience of all team members.

Chatbots enable remote teams to quickly respond to changes in projects, improving communication and efficiency. They are also useful for various professional groups, including developers, testers, project managers, and HR professionals.

Project managers can first test chatbot solutions on small groups of users and then expand their use to the entire team, ensuring effective implementation and adoption.

Using chatbots in such scenarios significantly improves workflow, allowing teams to respond quickly to changes, manage tasks efficiently, and maintain high productivity.

Conclusions

The integration of advanced communication and information technologies becomes key in the strategy of managing project processes in distributed teams, ensuring high communication efficiency and optimization of work procedures.

In the course of the study, popular communication technologies used in distributed teams have been singled out, their advantages and bottlenecks in application have been presented, which should be taken into account when the project stakeholders select a set of tools to ensure effective communication and its success.

An analysis of project management platforms is carried out, the features of their use, popularity and interest of users in recent years are given. The basic capabilities for task management, collaboration, documentation, and resource allocation capabilities to improve efficiency and communication within project teams are covered. Options for integrating chatbots into project management platforms for automating project processes in distributed teams are offered.

Further research will focus on the comparative analysis of the effectiveness of different information platforms, developing new integration tools, adapting these platforms to unique project requirements, and evaluating their impact on team member productivity and satisfaction.

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ANALYSIS OF METRICS FOR GAN EVALUATION

Generative-adversarial networks have become quite popular in recent years. In general, these networks are based on convolutional neural networks used in classification problems. In recent years, researchers have proposed and developed many variations of GAN network architectures and techniques for their optimization, as the learning process is quite complex and unstable. Despite great theoretical advances in improving network data, evaluating and comparing GANs remains a challenge. Although several metrics have been introduced to evaluate these networks, there is currently no consensus on which metrics best reflect the strengths and limitations of models and should be used to compare models and evaluate synthesized images. This paper discusses the two most popular metrics, Inception Score (IS) and Frechet Inception Distance (FID), which are used to estimate GAN networks.

Because these metrics are based on a pre-built Google Inception model used as a classifier for IS metrics and a feature extractor for FID metrics, the goal is to develop a program module to compare metric data using the base model (Inception) and custom models.

The scientific novelty is that these metrics were first used to compare cytological images using a model different from the one proposed by the authors - Google Inception.

The practical significance of the work is the development of a software module for calculating metric data for GAN networks used for the synthesis of cytological images.

As a result, two basic models (BioCNN-1 and BioCNN-2) and a Python module for calculating IS and FID metrics for cytological images were developed. The developed module works with color images with a resolution of 64 x 64 pixels. Comparisons of metrics based on the base model and the developed models for estimating GAN networks for cytological image synthesis were compared.

It was shown that the metrics based on the developed models show better results The FID score reduced from 31.20 to 0.034 and the IS score increased from 3.52 to 3.81. A total metric calculation time reduced from 2 minutes to 15 seconds.

Keywords: GAN evaluation, metrics, inception score, frechet inception distance.

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АНАЛІЗ МЕТРИК ДЛЯ ОЦІНКИ GAN МЕРЕЖ

Генеративно-змагальні мережі стали досить популярними в останні роки. Загалом ці мережі побудовані на основі згорткових нейронних мереж, що застосовуються у завданнях класифікації. В останні роки дослідниками запропоновано та розроблено дуже багато варіацій самих архітектур GAN мереж та технік для їх оптимізації, оскільки процес навчання є досить складним та нестабільним. Незважаючи на великі теоретичні успіхи в покращенні даних мереж, оцінка та порівняння GAN залишається складним завданням. Не дивлячись на те, що було введено кілька метрик для оцінки цих мереж, наразі немає консенсусу щодо того, яка метрика найкраще відображає сильні сторони та обмеження моделей і повинна використовуватися для порівняння моделей та оцінки синтезованих зображень. У даній роботі розглянуто дві найпопулярніші метрики Inception Score (IS) та Frechet Inception Distance (FID), які застосовуються для оцінки GAN мереж.

Оскільки дані метрики базуються на використанні попередньо підготовленої моделі Google Inception, яка застосовується в якості класифікатора для метрики IS та екстрактора ознак для метрики FID, то метою роботи є розробка програмного модуля для порівняння даних метрик із використанням базової моделі (Inception) та користувацьких моделей.

Наукова новизна полягає в тому, що дані метрики вперше застосовано для порівняння цитологічних зображень з використанням моделі, що відрізняється від запропонованої авторами - Google Inception.

Практичним значенням роботи є розробка програмного модуля для обчислення даних метрик для GAN мереж, що застосовуються для синтезу цитологічних зображень.

В результаті було розроблено дві базові моделі (BioCNN-1 та BioCNN-2) та модуль на мові Python для обчислення метрик IS та FID для цитологічних зображень. Розроблений модуль працює із кольоровими зображеннями роздільною здатністю 64 x 64 пікселі. Здійснено порівняння метрик на основі базової моделі та на основі розроблених моделей для оцінки GAN мереж для синтезу цитологічних зображень.

Метрики на основі розроблених моделей показують кращі результати. Значення метрики FID зменшилося з 31.20 до 0.034, а значення метрики IS збільшилося з 3.52 до 3.81. Також загальний час обчислення метрик зменшився з 2 хвилин до 15 секунд.

Ключові слова: оцінка GAN мереж, метрики, inception score, frechet inception distance.

Introduction

In 2014, a completely new approach for image synthesis using generative adversarial networks (GAN) was invented [1]. After that, a lot of new architectures were proposed [2,3,4]. Despite the fact that a significant amount of research studies are focused mainly on the theory behind GANs, currently there are a few studies that are related to the evaluation of GAN networks [5]. The purpose of such evaluation is to measure the distance between synthesized and real images. Most existing methods use the initial Inception model to represent images in a lower dimensional space. The most popular metric at the moment is the Inception Score (IS), which measures the distance using Kullback-Leibler divergence (KL) [5]. However, this metric is based on the probability of an image belonging to one of the classes and cannot show the model overfitting. Frechet Inception Distance metric is proposed as a better alternative. This metric directly measures the Frechet distance on a feature space by approximating a single-variating Gaussian distribution.

Since these metrics are based on a pre-trained Inception model, then their values might degrade when applied to other datasets that differ from ImageNet (this dataset was used to train the Inception model). Accordingly, an urgent problem is the development of basic user models for IS and FID metrics for a specific dataset, which will allow improving the value of these metrics.

Related works

Comparing how similar two images can be is a common problem in image analysis. For this task, a variety of metrics are used.

A metric is a specific function of the distance between any two components of a collection. A metric function has to conform to three axioms. The metric has to meet the triangle inequality and be identical and symmetric. There are two types of metrics: qualitative and quantitative. Quantitative measurements are the most often utilized metrics in research [6, 7]. Qualitative metrics are metrics that are not numerical and often involve a person's subjective evaluation or evaluation by comparison. The most popular methods are Nearest Neighbors (similar images are grouped into clusters) and Rapid Scene Categorization [8]. The last one is that the experts have to make a choice between a real and a synthesized image in a short period of time. The main disadvantage of the approach based on expert evaluations is that experts can improve their skills over time [9]. For example, experts can receive feedback from other experts and receive tips on how to better detect the synthesized image.

Quantitative metrics are based on the calculation of specific numerical scores that are used to summarize the quality of synthesized images. In [10], researchers refer to such metrics as Mean Squared Error (MSE), Root Mean Squared Error (RMSE), Structural Similarity Index (SSIM), Peak Signal-to-Noise Ratio (PSNR), Coverage Metric, Inception Score, FID and others.

To evaluate images synthesized using GAN networks, researchers have developed several metrics that can be divided into model-dependent and model-independent. Model-dependent metrics usually require either an estimate of the distribution density or an analysis of the internal structure of the network used. So model-independent metrics are more popular in GAN researches [11]. Most of the independent metrics map the image to the feature space using a pre-trained model and measure the similarity of the distribution between the used dataset and the synthesized images.

Among all metrics, Inception Score (IS) and Frechet Inception Distance (FID) are the most popular and relevant metrics for evaluating the quality of images synthesized using GAN networks [12, 13]. It is necessary to perform a detailed analysis of these metrics, since they have proven themselves quite well in many studies and have shown a good correlation with experts' assessments.

Metrics overview

Inception Score. This metric is based on the Google Inception V3 image classification model. This model is designed to classify color images. The ImageNet dataset, which includes about 1.2 million RGB images divided into 1000 classes, was used as a training dataset.

This metric showed good correlation with human-made estimates on the CIFAR-10 dataset.

$$IS(G) \approx exp(E_{x \sim p_g}[D_{KL}(p(y|x) \,||\, p(y))]) = exp(H(y) - E_{x \sim p_g}[H(y|x)]),$$

where E – expected value,

$x \sim p_g$ shows that x is an image synthesized from the distribution $p_g(distribution\ of\ the\ generator)$,

D_{KL} is the Kullback-Leibler divergence between the conditional probability distribution $p(y|x)$ and marginal distribution $p(y) = E_{x \sim p_g}[p(y|x)]$,

H – entropy.

It is assumed that the conditional distribution of data, which contains significant objects, should have low entropy, and the marginal distribution (synthesized images are diverse) should have high entropy [11].

Inception Score works as follows. For example, let's take 5000 synthesized images. In order to obtain a conditional distribution of classes, it is required to classify the image data with the Inception network, which will return a vector of probabilities $p(y|x)$. In order to obtain the marginal distribution, the conditional distribution for each image should be summarized as follows $p(y) = \frac{1}{5000}\sum_{i=1}^{5000} p(y|x_i)$. Next step is to calculate the Kullback-Leibler distance between the conditional distribution of each synthesized image and the overall marginal distribution. The average value of these distances will be the value of the IS metric [12].

Therefore, IS measures the average Kullback-Leibler divergence between the conditional distribution $p(y|x)$ and the marginal class distribution $p(y)$. That is, this metric does not consider the distribution of the original samples at all, and therefore cannot assess how well the images synthesized by the generator are similar to the original samples. This metric evaluates only images diversity. The disadvantages of this metric are sensitivity to the resolution of the images themselves and to changes in the network, which is used for classification.

The minimum value of this metric is 1, and the maximum value is the number of classes that the Inception network can classify. In this case – 1000.

In order to obtain a high IS value, it is necessary that the synthesized images contain clear objects (for example, the images are not blurred) and that the generator synthesizes a variety of images from all classes [13]. Accordingly, if at least one of these conditions is unsatisfactory, the score will be low.

Frechet Inception Distance. FID compares the distributions of the original and synthesized data. In order to calculate the FID between real and synthesized images the data is transformed into a feature space using a specific layer of the Inception model, namely the *pool3* layer. Feature space is used to represent images in a lower dimensional space where similar images are represented in relatively same regions. At the output, we receive activation maps (also known as feature maps). FID metric assumes that these feature maps can be approximated using two Gaussian distributions. Then the distance between them is calculated as follows:

$$d^2((m_r C_r),(m_g C_g)) = \left\|m_r - m_g\right\|^2 + Tr(C_r + C_g - 2(C_r C_g)^{\frac{1}{2}}),$$

where $(m_r C_r)$ та $(m_g C_g)$ – average value and covariance matrix of the real and synthesized data distributions, respectively,

Tr – trace of the matrix (the sum of the diagonal elements).

The lower the value of the metric, the smaller the distance between the distributions is. Therefore, the distributions are more similar to each other [14]. The FID metric is quite sensitive to image distortions (rotation, displacement, shift, noise, etc.). The more distortions, the greater the value of the metric is [15].

A low FID value indicates that the distributions of real and synthesized images are similar to each other. However, in practice, if a model has a low FID value, it indicates that the images are of high quality or diversity, or both. This behavior can significantly complicate the diagnosis of the model.

The authors also show that this metric more closely matches human estimates and is more robust to noise than IS [11, 16].

These metrics are quite popular in the field of image synthesis using GAN networks. But they have their drawbacks [17, 18, 19].

Inception Score has the following limitations:

1) The value of the metric strongly depends on what the Inception model can classify.
2) Synthesis of images of a different set of classes that are not present in the original ImageNet dataset may cause a low IS value.
3) If the classifier cannot identify the features that belong to the training dataset, then low-quality images may receive high scores. The Inception network is trained on the ImageNet dataset. If IS is used on a completely different dataset, then the classifier may not be able to identify some features well enough, and therefore low-quality images will receive high scores.

Frechet Inception Distance is also based on the Google Inception model. But unlike IS, this metric can define dependencies between classes. That is, if the model generates only one image per class, then the IS can be quite high, but the FID will be low. Also, the FID metric degrades when various artifacts are added to the image.

The Inception Score does show a correlation with the quality and variety of images produced, which explains its widespread use in practice. However, this metric only evaluates the distribution of the synthesized images, but does not take into account how similar the synthesized and original images are. As a consequence, this may induce models to simply learn distinct and varied images (or even some noise) instead of the distribution of the original data [13].

Inception Score is limited to measuring how diverse the synthesized images are, while FID measures the distance between the distribution of synthesized and real data [14].

IS and FID calculation based on custom classification model for biomedical images

Since both metrics are based on the Inception model to obtain conditional probabilities (IS metric) and feature maps (FID metric), this can significantly affect the results when calculating these metrics for data that is not included in the ImageNet dataset on which the Inception network was trained.

A classifier architecture for biomedical images was developed, which ensures obtaining more relevant conditional probabilities for the IS metric and activation maps for the FID metric, in order to compare the values of the IS and FID metrics calculated using the Inception model and metrics calculated using a different model.

Both networks take as input color images of size 64 by 64 pixels according to the resolution of the images in the training dataset and are named BioCNN-1 and BioCNN-2.

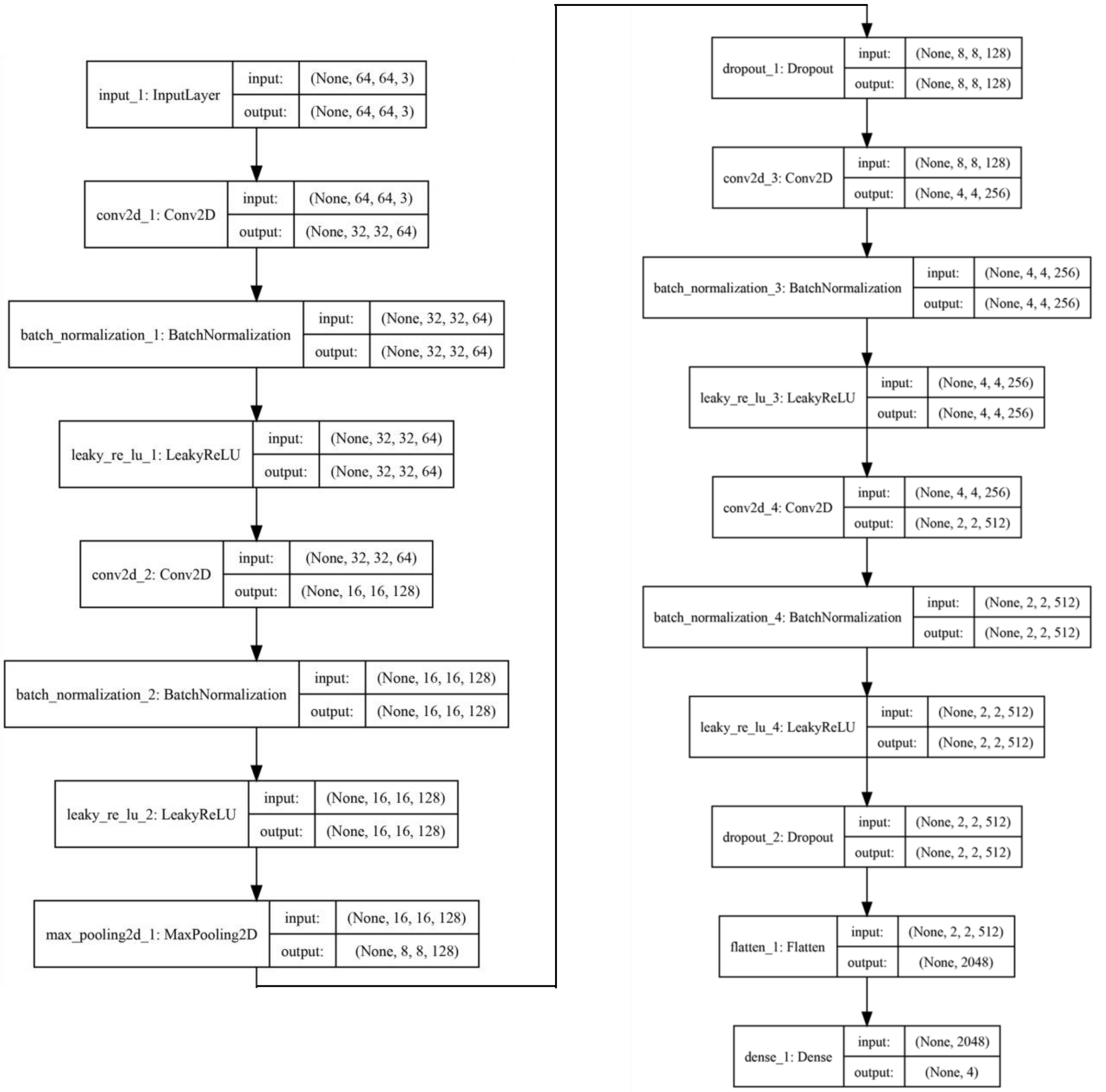

Fig. 1. Architecture of BioCNN-1

These networks are convolutional neural networks (CNNs). This type of networks is widely used in classification and pattern recognition tasks [20]. The BioCNN-1 architecture consists of a sequence of Conv, BatchNorm, and LeakyRelu activation layers. One set of these layers can be called a convolution block. BioCNN-1 consists of four such blocks.

The BioCNN-2 architecture is built using alternating VGG and ResNet blocks. These blocks are separate elements of the architecture of popular convolutional neural networks VGG and ResNet, respectively [22-25].

In general, VGG consists of a sequence of convolutional layers using a small convolutional window size (3 by 3). A subsampling (pooling) layer is placed at the end of such a block.

The ResNet block consists of two convolutional layers with the same number of filters, where the output of the second layer is added to the input of the first.

In the future, the architectures can be improved by optimizing hyperparameters, which is described in [21].

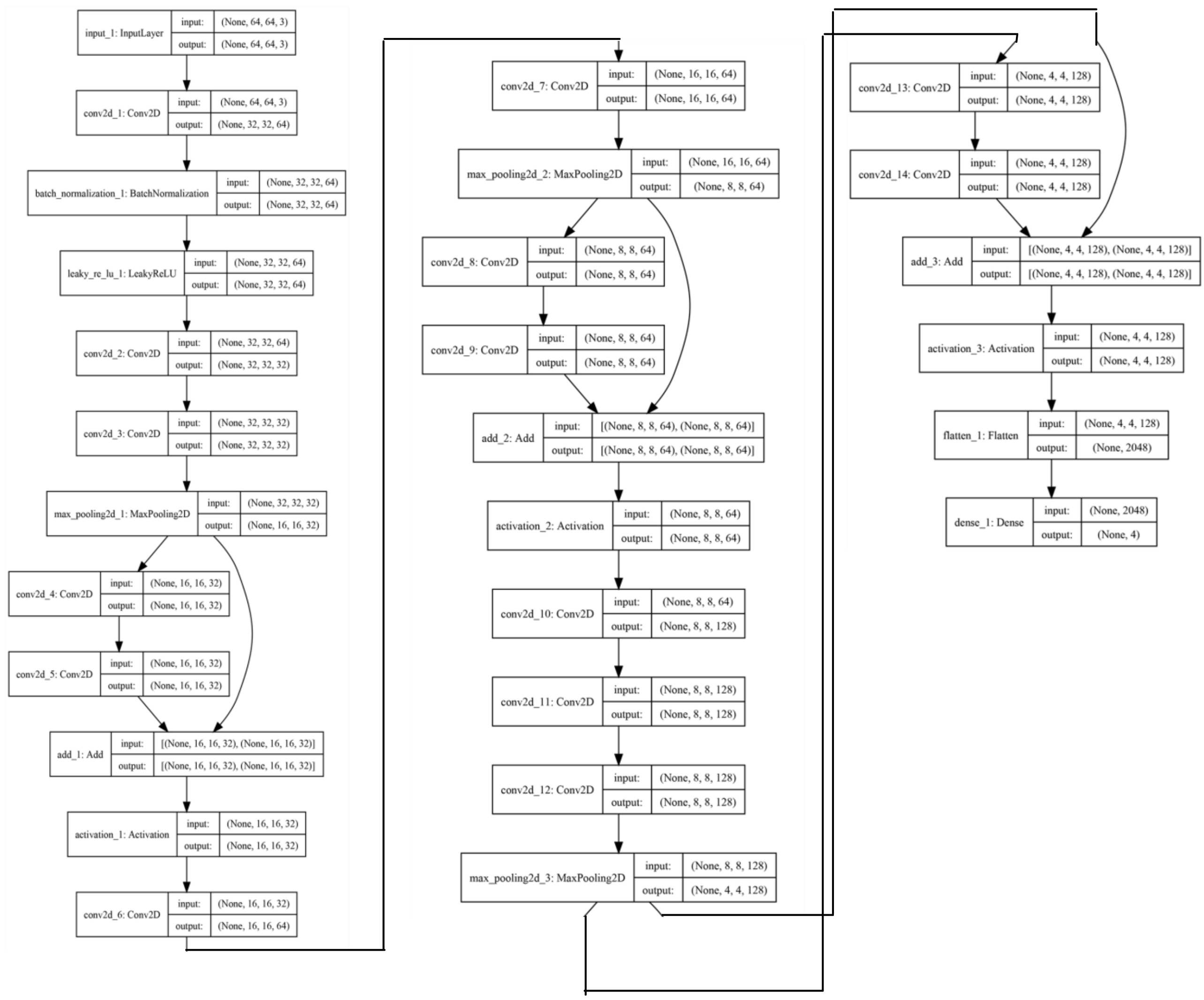

Fig. 2. Architecture of BioCNN-2

Experiments

For performing experiments, an artificial set of cytological images with a size of 64 by 64 pixels was synthesized using the GAN network [26]. Cytological images are a subset of biomedical images, which are structural and functional images of human organs and are intended for the diagnosis of diseases [27]. In general, biomedical images can be divided into three groups: cytological (images of cells), histological (images of tissues), and immunohistochemical (images of cells and their reactions and specific markers) [28, 29]. Examples of cytology images from the original and synthesized samples are shown in the figures below.

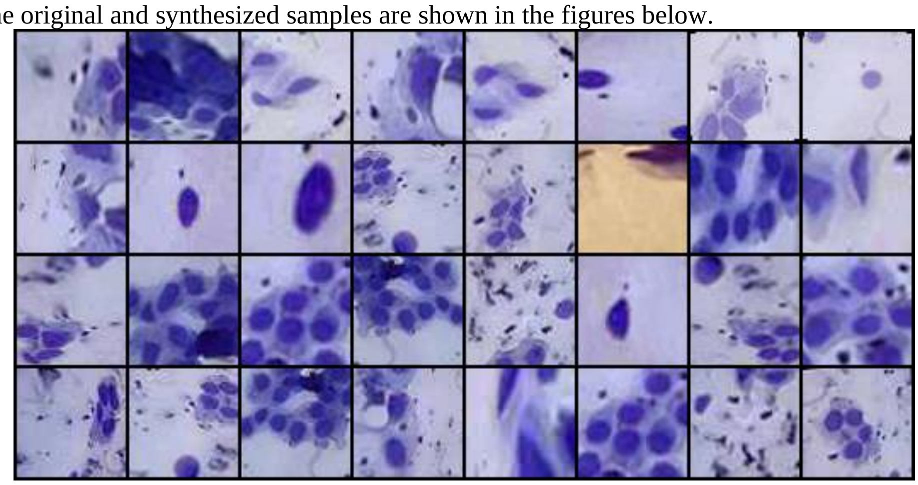

Fig. 3. Real images

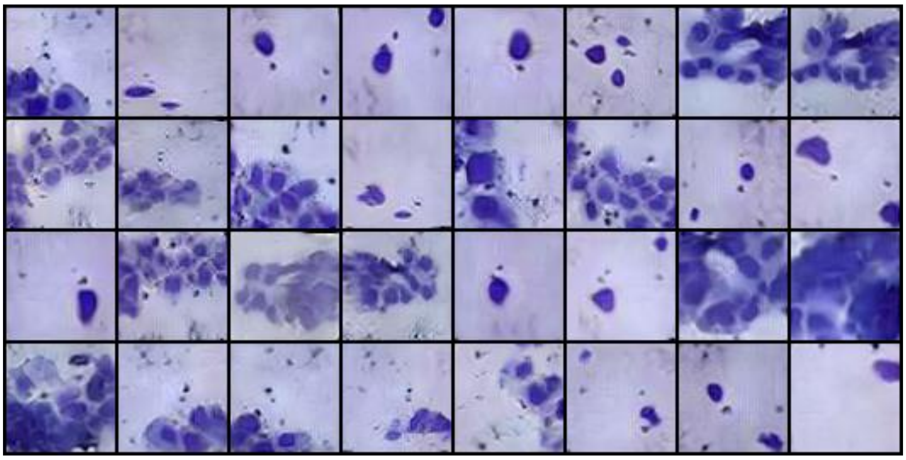

Fig. 4. Synthesized images

IS and FID metrics were used to compare the synthesized images with the original ones. To calculate the metrics based on the custom classifier, the proposed CNN architectures of the BioCNN-1 and BioCNN-2 networks are applied. To build models, train them, and calculate IS and FID metrics, a software module was developed in the Python programming language using the Keras machine learning framework. The experiments were performed on a laptop with an Intel Core i7 2.5GHz CPU and 16GB of RAM. The hyperparameters of training are listed in Table 1.

Table 1

Training parameters

Model name	Loss function	Optimizer	Learning rate	Batch size	Epochs
BioCNN-1	categorical_crossentropy	Adam	0.003	128	40
BioCNN-2	categorical_crossentropy	Adam	0.003	64	100

A sample of color cytological images divided into 4 classes with a total number of approximately 4500 images (resolution of 64 by 64 pixels) was used as a training dataset. This dataset was divided in the ratio of 80-10-10 as a training, test and validation dataset. BioCNN-1 network achieved classification accuracy of 97% and BioCNN-2 - 98.8%. The training time of the first network was approximately 15 minutes, and the second network took 45 minutes. The second network needs more time to train because its architecture is deeper. The ROC curves for both networks are shown in the figures below.

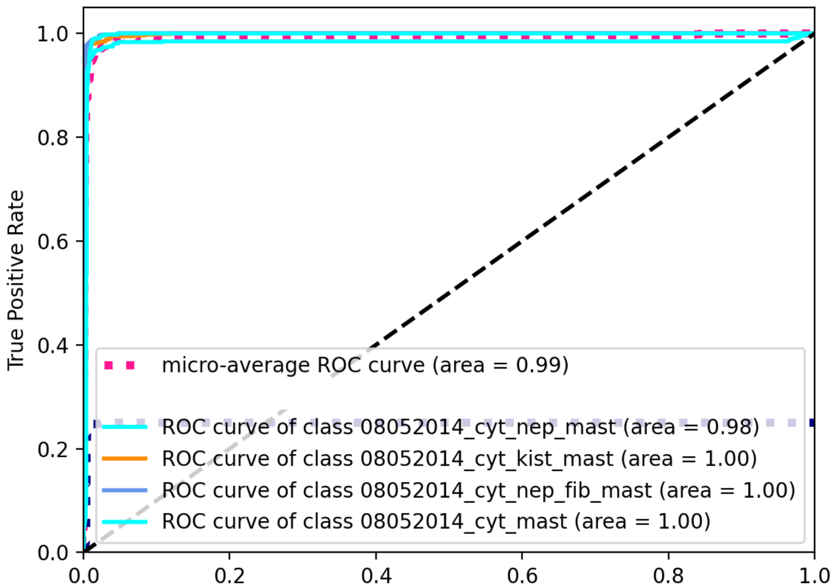

Fig. 5 ROC for BioCNN-1

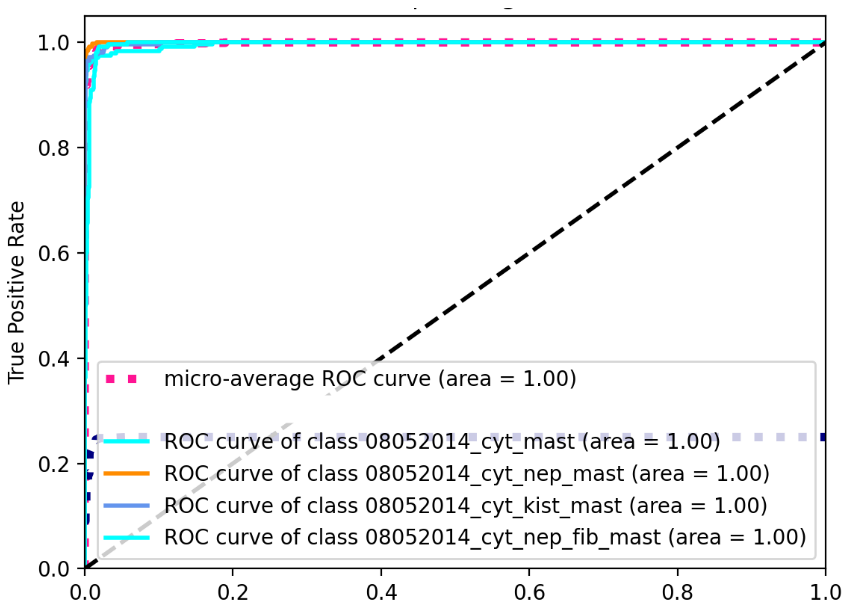

Fig. 6 ROC for BioCNN-2

After training both networks, the values of IS and FID metrics were calculated to compare the validation dataset with the synthesized images. To obtain the activation maps used in the FID metric, the fourth layer from the end (*leaky_re_lu_4*) of the BioCNN-1 model and the third layer from the end (*activation_3*) of the BioCNN-2 model were taken. The summarized results are given in Table 2.

Table 2

IS and FID scores

Inception Score, higher is better	Frechet Inception Distance, lower is better	Classification model	Total metric calculation time
3.52	31.20	Google Inception V3	~ 2 minutes
3.64	23.41	BioCNN-1	~ 8 seconds
3.81	0.034	BioCNN-2	~ 15 seconds

Discussion

As a result of the experiments, it is shown that the value of the metrics has improved when applying the developed models. There is a slight improvement in the IS metric. This indicates that the IS metric is not so dependent on the model used. The reason for this is that this metric is calculated based on the probabilities of an image belonging to one of the classes. The theoretical explanation is that similar images will be assigned to the same class regardless of the model used. However, the use of custom models did improve the IS metric, as the custom model classifies cytological images better than the Inception model.

When the BioCNN-1 model was used to calculate the FID metric compared to the Inception model, the FID value decreased from 31.20 to 23.41. However, when using the BioCNN-2 model, the metric value decreased to 0.034. To calculate this metric, feature maps obtained from a specific layer of the base model are used. The improvement of the metric values when applying the developed models indicates that the developed models provide more relevant feature maps for cytological images, since they were trained on images from this domain.

The significant difference between the values of the FID metric when using BioCNN-1 and BioCNN-2 can be explained by the architectural details of the networks themselves. Despite the fact that both networks achieved approximately the same classification accuracy on the test dataset during training, the second network is much deeper than the first. During the experiments, we also noticed a tendency for the FID value to increase significantly as the layer used as a feature extractor approaches the network input. The BioCNN-2 network demonstrates this trend in a less pronounced manner.

The fact that there is a significant difference in the FID value when using the developed networks, considering that these networks were trained on the same dataset, suggests that the deeper network (BioCNN-2) can represent the input image much better in a low-dimensional space, leading to more relevant and "informative" feature maps. In contrast to the IS metric, the FID metric is thus considerably dependent on the network utilized as a feature extractor.

Conclusions

The main results of this work are:

1. A comparison of IS and FID metrics was made for evaluating GAN networks for the synthesis of cytological images using the basic Inception model and the developed BioCNN-1 and BioCNN-2 models.

2. A Python module was developed to calculate IS and FID metrics for cytological images using the developed models.

3. The usage of the developed models, as opposed to the Inception network, greatly reduces the time required to calculate these metrics, according to actual experiments. The calculation took 15 seconds instead of 2 minutes.

4. Significant reduction in the calculation time and improvement in the values of the metrics themselves makes it possible to develop this study in the direction of using the FID metric as an additional parameter in the GAN network loss function, which would theoretically improve the quality of synthesized images.

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NEURAL NETWORK ARCHITECTURE FOR TEXT DECODING BASED ON SPEAKER'S LIP MOVEMENTS

The paper analyses the impact of using a speechless access interface (SSI), which provides the definition of the initial phase of the sound series associated with the beginning of speech based on the analysis of visemes, on the accuracy of voice command recognition in different sound environments. The analysis of the methods for recognizing the speech pattern of a speaker has shown that recent studies are based on the use of neural network architectures (CNN, LSTM) to analyze a predefined region of interest - the speaker's mouth.

In this paper, we tested a command recognition system using the SSI approach and conducted a series of experiments on modern solutions based on ALR interfaces. The main goal was to improve the accuracy of speech recognition in cases where it is not possible to use the speaker's non-noisy audio sequence, for example, at a great distance from the speaker or in a noisy environment. The obtained results showed that training the neural network on a GPU accelerator allowed to reduce the training time by 26.2 times using a high-resolution training sample with a size of the selected mouth area of 150 × 100 pixels. The results of the analysis of the selected speech recognition quality assessment metrics (word recognition rate (WRR), word error rate (WER), and character error rate (CER)) showed that the maximum word recognition rate of the speaker's speech is 96.71% and is achieved after 18 epochs of training. If we evaluate the character regonition rate of viseme recognition, the highest rate can be obtained after 13 epochs of training. Future research will focus on the use of depth cameras and stereo vision methods with increased frame rates to further improve the accuracy of voice command decoding in conditions of high background noise.

To further develop this work, we can apply noise reduction algorithms to the audio signal or solve the problem of detecting visemes in conditions of low brightness or a different angle of the face.

Keywords: NLP, automated lip reading, feature detection, audio processing, neural network, mode

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НЕЙРОМЕРЕЖЕВА АРХІТЕКТУРА ДЛЯ ДЕКОДУВАННЯ ТЕКСТУ ЗА РУХОМ ГУБ СПІКЕРА

У статті проаналізовано вплив використання інтерфейсу безмовного доступу (SSI), який забезпечує визначення початкової фази звукового ряду, що асоціюється з початком мовлення, на основі аналізу візерунків, на точність розпізнавання голосових команд у різних звукових середовищах. Аналіз методів розпізнавання мовного патерну диктора показав, що останні дослідження базуються на використанні нейромережевих архітектур (CNN, LSTM) для аналізу заздалегідь визначеної області інтересу - рота диктора.

У роботі протестовано систему розпізнавання команд з SSI-підходом та проведено ряд експериментів над сучасними рішеннями на основі ALR інтерфейсів. Головною метою було покращення точності розпізнавання мови у таких випадках, коли немає можливості використрвувати незашумлений аудіоряд спікера, наприклад на великій відстані від того, хто говорить, або у шумному оточенні. Отримані результати показали, що тренування нейронної мережі на графічному прискорювачі дозволило скоротити час навчання у 26,2 рази, використовуючи навчальну вибірку із високої роздільної здатності та розміром виділеної зони рота, що становить 150 × 100 пікселів. Результати аналізу обраних метрик оцінки якості розпізнавання мови (послівна точність розпізнавання (WRR), послівна помилка розпізнавання (WER) та посимвольна помилка розпізнавання (CER)) показав, що максимальна точність послівного розпізнавання промови спікера становить 96,71% та досягається після 18 епох навчання. Якщо оцінювати посимвольну точність розпізнавання візем, то найвищий показник можна отримати після 13 епохи навчання. Майбутні дослідження будуть зосереджені на використанні камер глибини та методів стереозору із збільшеною частотою кадрів задля подальшого збільшення точності декодування голосової команди в умовах великого фонового зашумлення.

Для подальшого розвитку цієї роботи можна застосувати алгоритми шумозаглушення до аудіосигналу або вирішити проблему виявлення виразів обличчя в умовах низької яскравості або іншого кута нахилу обличчя.

Ключові слова: NLP, автоматичне читання по губах, виявлення ознак, обробка звуку, нейронна мережа, режим

Introduction

Natural language processing is a general field of artificial intelligence and mathematical linguistics that studies the problems of computer analysis and synthesis of natural languages [1-2]. Solving these problems means creating a more convenient form of human-computer interaction, so there are SSI-based systems that use ultrasound or optical cameras and capture facial or neck movements as a signal regardless of the incoming audio.

Voice commands fit well into the concept of building a natural language user interface [3]. In addition, such technologies have already become widespread in various spheres of life (figure 1)

This list could be constantly updated, but such systems are most commonly used as voice assistants in the form of software applications on smartphones, PCs, or special devices similar to audio speakers.

This paper discusses in detail the applications where high noise levels or lack of sound signal are a problem, such as for people with disabilities, aviation, cars with insufficient noise insulation, and dialog restoration in silent movies [4-6].

Most often, speech recognition is defined as the conversion of an audio sequence of a human voice recording into text data. However, using not only audio information but also video can significantly improve the quality of recognition or even replace audio.

The main problem for a large number of SSI-based command recognition projects is that they use uncomfortable devices that need to be attached to the skin, which allows for experimental use only on patients, military, or astronauts, thus limiting mass adoption [7]. Many of these systems have a limited number of commands, such as a couple dozen in a NASA research project, and have variable accuracy for the same words from the same user due to the shifting of sensors on the body during use. Therefore, for convenience, it is better to use other devices (video camera or depth camera).

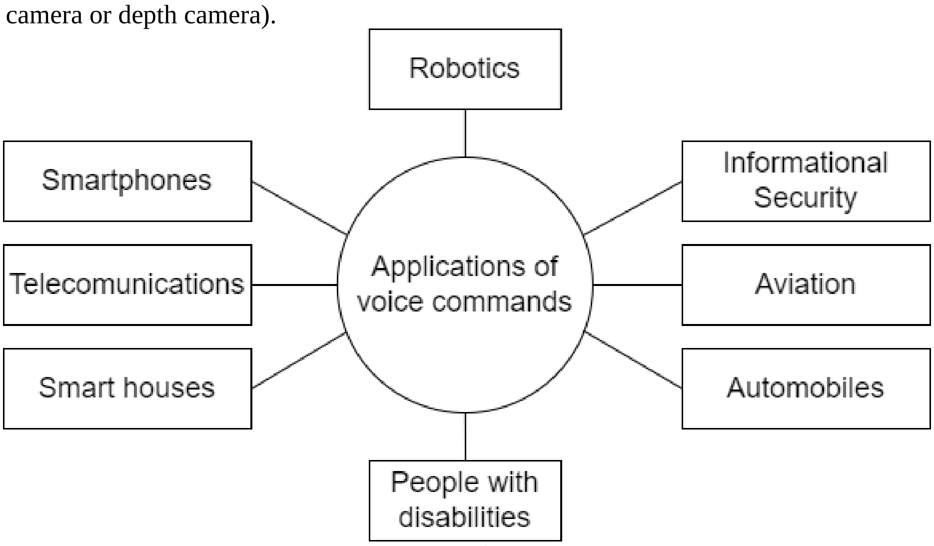


Fig.1. Applications of voice commands

The problem of high noise levels can be solved by using an algorithm for automated lip reading from a video stream, combining audio signal processing with viseme recognition in the frame [8-9]. On the other hand, such systems still have the problem of homophones, which include the same lip movements for different words, which can be solved by adding sound processing, but this method does not work well in noisy environments without additional filtering. Therefore, conducting research in this area and developing our own solution for recognizing voice commands, combining work with audio and video sequences depicting the speaker, is a relevant task.

Related works

Visual speech recognition or lip reading plays an important role in human communication, especially in noisy environments, and can be extremely useful for people with hearing impairments, so ALR technology was chosen for camera-based command recognition. To identify a word or sentence, the system must be trained using data collected for a particular language and vocabulary. However, ALR uses visemes instead of phonemes.

ALR (automated lip reading) is the process of decoding text from the speaker's mouth movement. Machine lip reading is complex because it requires extracting spatio-temporal characteristics from the video, namely the position and movement of the lips. It also complicates the process of recognizing the position of the tongue and teeth, as in many cases they are hidden behind a closed or covered mouth, so they are difficult to recognize without context.

Recent research in the field of ALR has shown a surge in end-to-end deep learning approaches for lipreading that focus on word-level prediction using a combination of convolutional and recurrent networks [10]. Therefore, in the further work we will follow this approach.

The basic detection of visemas is based on the analysis of facial geometry. When the mouth is open, the distance between the corners of the mouth increases. Even though people have different mouth sizes, you can normalize this indicator by dividing it by the distance between the jaws and get a general ratio that can be used for different faces. Each image contains a large amount of raw information that is not used in speech recognition. Therefore, it is necessary to process each image and clearly identify the AOI - the area of the lips.

Among the existing software solutions that can be used to implement certain stages of ALR systems (for example, lip area extraction), we can highlight the Dlib library, MTCNN, Openface, LFW landmarks, etc. The latter provides fast processing but low accuracy. The Dlib library is preferred because it is open source, which is important for editing algorithms or changing parameters for recognition.

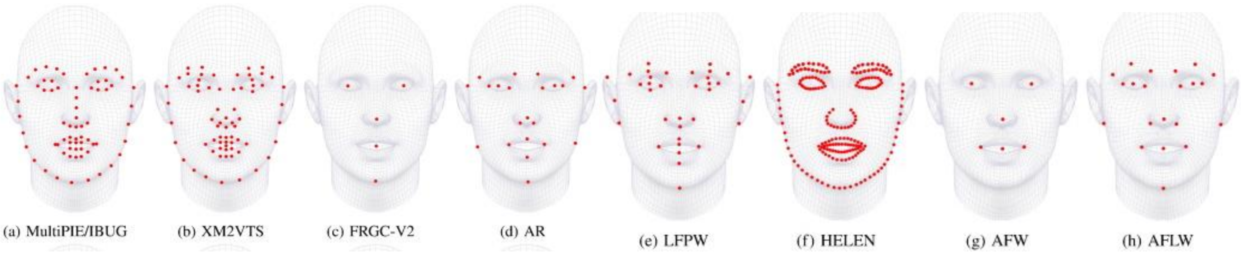


Fig.2. Examples of facial features markup

The dlib facial feature detector is developed using the classical histogram of oriented gradients (HOG) function in combination with a linear classifier, an image pyramid, and a sliding window detection scheme. The oriented gradient histogram is an image processing algorithm that performs feature extraction. Dlib contains information about the markup of dots in the face contour and applies them to the input frame, and in the output frame, it marks these dots if the image contains a mouth, eyes, or other facial features.

To recognize facial contours, including lips, we use shape_predictor_68_face_landmarks.dat, which is trained on the iBUG 300W image collection (figure 2). Other files can also be used, for example, based on HELEN, as it has a large number of dots that highlight the upper and lower lips, as well as the open mouth. Using these features, the algorithm obtains lip-centered images of 100 × 50 pixels, which will be sufficient for further processing by neural networks. The area with the detected lips is also enlarged by 10 or more pixels on each side so that the lips do not end up cropped.

To train a recognition system, a speech corpus is required, examples of which are shown in figure 3 [11-12]. GRID is a collection of tens of thousands of short videos in which 34 volunteers read nonsensical sentences in English with captions. Each file is three seconds long, and each sentence follows a pattern: command, color, preposition, letter, number, and adverb. Examples of such sentences: «place blue in M one soon», «set blue by A four please», and «place red at C zero again».

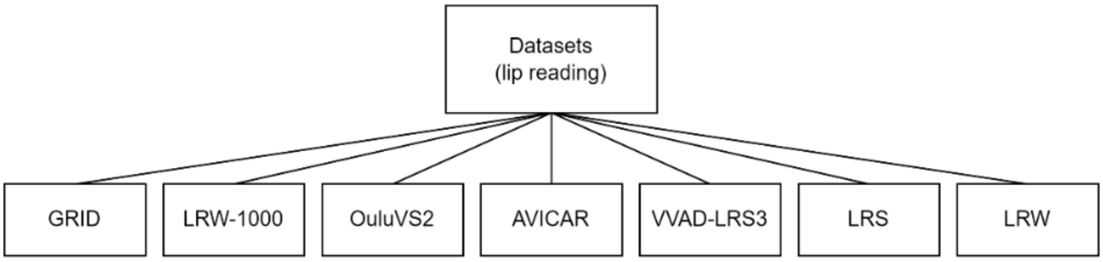


Fig.3. Examples of ALR corpora

The advantages of this corpus include a large number of videos in which the lip movements of different people are clearly visible in a bright room, which will be enough to build a recognition system, but for practical use it is better to use other corpora where the head position is not full-face, there are no template sentences and in dark lighting. To meet these conditions, we can use the OuluVS2 body, which was recorded by six cameras from five different views located between the frontal and profile views of 50 people, to analyze the non-smooth mouth movement, but the main problem will be the implementation of the ALR algorithm from the frames where the human face is in profile.

LRW-1000 used to be called CAS-VSR-W1k and is often used for recognition, but it is difficult to use for this paper because the authors of this paper do not speak Chinese, although LRW-1000 includes 18018 video samples from about 2000 people and is a good corpus for practical use because it contains different lighting, head positions and non-laboratory sentences.

The best speech corpus to compare with others in different sound conditions is AVICAR, as it records the faces of 86 people in different positions inside the car and from 7 microphones, and has 5 noise levels depending on the speed of the car. But the problem is the difficulty of obtaining all but a limited number of people's data, as links to the files were unavailable at the time of writing (last updated in 2004) or confirmation from the University of Illinois researchers is required.

Also common is the LRS corpora group, which has different versions (LRS, LRS2, LRS3-TED, MV-LRS, etc.) and was created by BBC television, with each sentence being 100 characters long. Due to the large number of camera positions, file size, and variety of content, the LRS2 dataset is more complex (75.2% of non-frontal face frames) than the LRS or MV-LRS dataset and is recommended for projects with the best recognition algorithms.

In addition to these data, there is a lack of a standardised set of similar videos in Ukrainian, which could be used to compare the results for different systems without creating our own corpus.

Aims and task of the work

The aim of this paper is to study the effect of using a speechless access interface (SSI), which provides the definition of the initial phase of the sound series associated with the beginning of speech, based on the analysis of visemes, on the accuracy of voice command recognition in different sound environments.

In order to achieve this goal, the following tasks must be solved:

- analysis of methods for recognising the speech pattern of a person speaking;
- creation of a model for recognising voice commands, improved by analysing the speech pattern of a person speaking;
- implementation of a voice command recognition model based on sound series analysis;
- implementation of a voice command recognition model based on a combination of sound series analysis and speaker's lip image;
- analysis of the obtained results.

To further develop this work, we can apply noise reduction algorithms to the audio signal or solve the problem of detecting visemes in conditions of low brightness or a different angle of the face.

Results and Discussion

To create a speech recognition system, a neural network architecture is used that maps sequences of visemes in video fragments of variable length into text sequences.

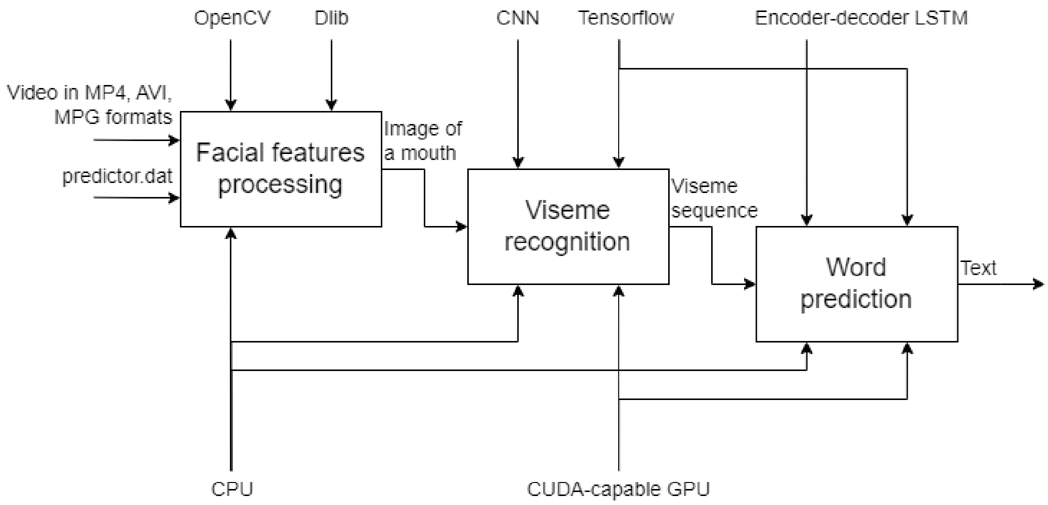


Fig.4. IDEF0 notation of the proposed system for viseme recognition

In the proposed system (figure 4), the video is decomposed into a sequence of frames containing lip images. In the next step, these frames are used as input to a convolutional neural network that has been trained on similar data. The data from the CNN is then passed through fully connected layers to form the input vector of the LSTM. The output of one layer becomes the input of the next recurrent layer. The last step is to decode the probability distribution vector of potential visemes in the LSTM, and as a result, a sequence of characters is formed, which are combined into words.

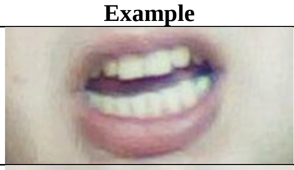
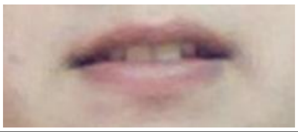
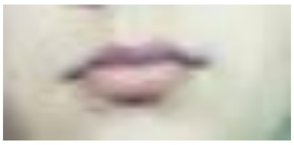
To solve the task, it is necessary to determine which words or phrases are pronounced from a fixed set of known phrases. The system's components use a sequence of images as input, and the output is words. Table 1 shows 11 visemes and a silence state that correspond to the phonemes of the English language and can be programmed into a dictionary, since phoneme groups do not differ in visual features.

The accuracy of viseme recognition will be low in cases where the distinguishing feature is the position of the tongue, such as $V_{D,T,S}$ and $V_{G,K,N}$, which requires an environment with good lighting and recognition in the dark will not be possible. For such conditions, it is possible to use a depth camera, since light does not affect the data and there are projects that use this device, such as Microsoft Kinect .

Before starting the testing, we downloaded a collection of videos with audio and text in a separate subtitle file. The training set consists of the first 30 archives of the GRID corpus without the 22nd archive (no video due to technical reasons), and the test set contains the last 3 archives, whose speakers were not considered in the training set. GRID is a collection of tens of thousands of short videos in which 34 volunteers read nonsensical sentences in English with captions. Each file is three seconds long, and each sentence follows a pattern: a command, a colour, a preposition, a letter, a number, an adverb. Examples of such sentences: «place blue in M one soon», «set blue by A four please» and «place red at C zero again». A pseudo-random number generator was also used to select a file from the test sample. The result of the system's efficiency testing in detecting the mouth area in the video and cropping it into a sequence of 150 × 100 pixels with the viseme detection is shown in table 2.

Table 1

English visemes and phonemes with examples

Consonants			Vowels		
Viseme	**Phoneme**	**Example**	**Viseme**	**Phoneme**	**Example**
$V_{J,C,H}$	/dʒ/ /tʃ/ /ʃ/ /ʒ/		V_A	/ɑ:/ /aʊ/ /aɪ/ /ʌ/	
$V_{P,M,B}$	/p/ /b/ /m/		V_E	/e/ /eɪ/ /æ/	
$V_{F,V}$	/f/ /v/		V_I	/i:/ /ɪ/	
$V_{D,T,S}$	/d/ /t/ /s/ /z/ /θ/ /ð/		V_O	/ɔ:/ /ɔɪ/ /əʊ/	
$V_{R,W}$	/r/ /w/		V_U	/ʊ/ /u:/	
$V_{G,K,N}$	/g/ /k/ /n/ /ŋ/ /l/ /y/ /h/		Silent		

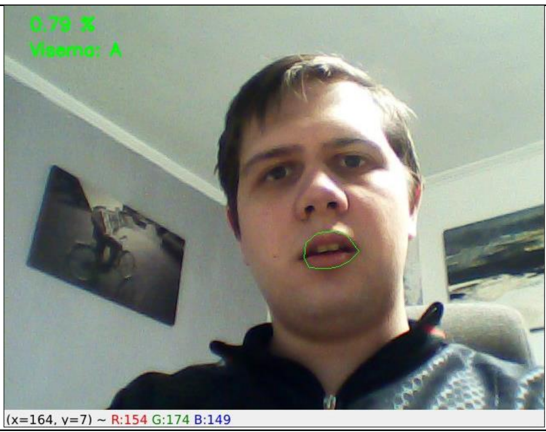
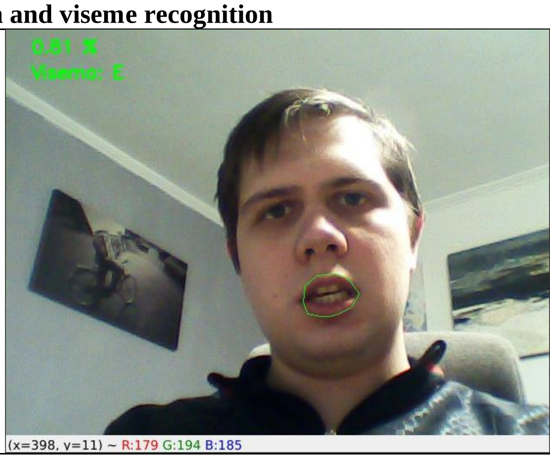
The next step is to train the neural networks on a high-resolution training set, which involves sequentially processing several hundred videos from each directory, selecting a 150 × 100 pixel mouth area. To accelerate the neural network training process and reduce the processing time by several dozen times, an NVIDIA GeForce GT 960m graphics card with Compute Capability of 5.0 was used. Training the neural network on the CPU took 64 minutes and 37 seconds, and on the above GPU – 2 minutes and 28 seconds.

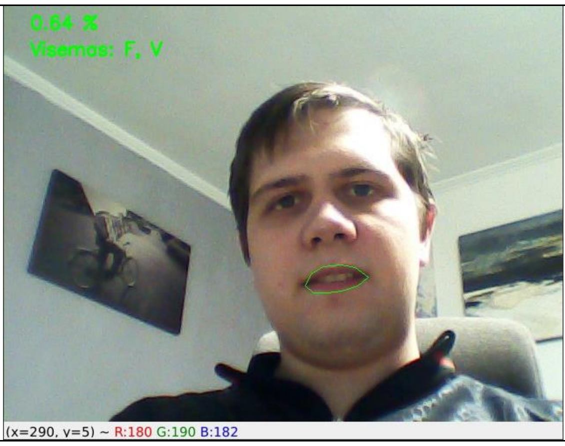
Neural networks were not trained on low-resolution video with a 75 × 50 selected mouth area, as [36] reported results showing a significant decrease in recognition accuracy when using the above settings.

The result is a text file with the corresponding recognised voice command for each video.

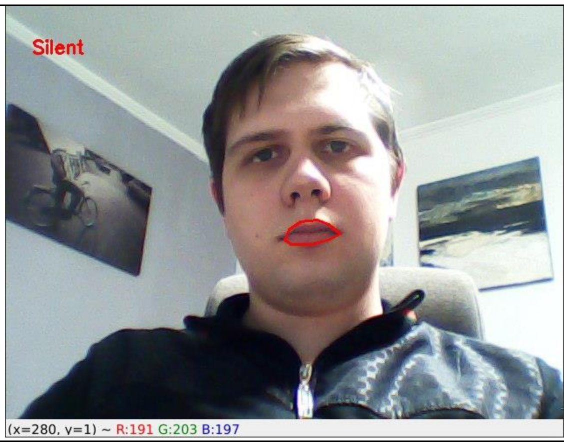
Table 2

Results of mouth area detection and viseme recognition

	
Viseme V_A	**Viseme** V_E



Viseme $V_{F,V}$



Silence

The system took 20 epochs to train, which was chosen empirically. The results are presented in table 3. We calculated the word recognition accuracy, word and character errors, and mean. The total number of video sequences for training in epoch 1 is 492 and corresponds to the total number of all videos with a speaker.

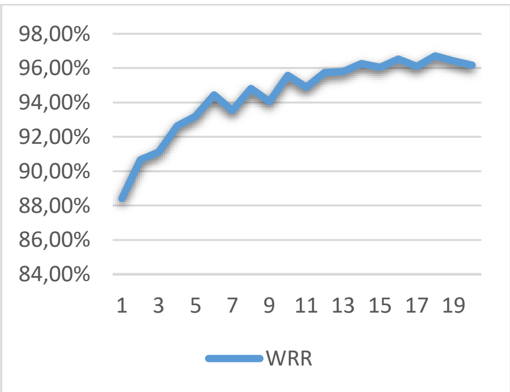
We use standard metrics for evaluating the quality of speech recognition, such as word recognition rate (WRR), word recognition error (WER) and character recognition error (CER).

Table 3

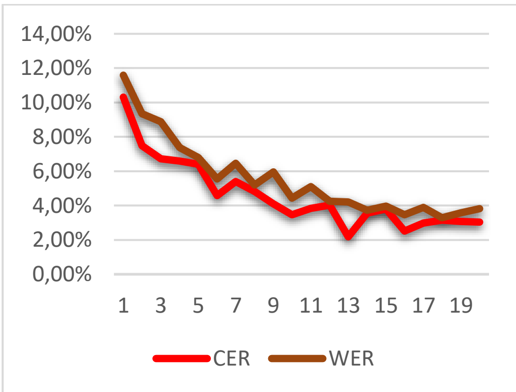
CER, WER and WRR values for 20 epochs

Epochs	**CER**	**WER**	**WRR**
1	10,31%	11,59%	88,41%
2	7,48%	9,34%	90,66%
3	6,73%	8,88%	91,12%
4	6,59%	7,37%	92,63%
5	6,41%	6,8%	93,2%
6	4,58%	5,55%	94,45%
7	5,4%	6,46%	93,54%
8	4,82%	5,19%	94,81%
9	4,1%	5,95%	94,05%
10	3,47%	4,43%	95,57%
11	3,84%	5,11%	94,89%
12	4,03%	4,25%	95,75%
13	2,18%	4,2%	95,8%
14	3,56%	3,73%	96,27%
15	3,8%	3,96%	96,04%
16	2,51%	3,47%	96,53%
17	2,98%	3,9%	96,1%
18	3,15%	3,29%	96,71%
19	3,07%	3,58%	96,42%
20	3,04%	3,82%	96,18%
Mean	4,6%	5,54%	94,46%

Increasing the number of epochs beyond 18 negatively affects the accuracy of the system and leads to network overtraining, which is evident in the last two results of table 3.



a)



b)

Fig.5. Performance dependency on 20 epochs: a) word recognition rate; b) word and character recognition error

The low accuracy with a small number of training epochs is explained by the fact that when using a recurrent neural network, input data from each frame is fed sequentially, so the system will not learn to correctly identify the word from the first frames, so further training is required to reduce the frequency of misinterpretations of the word.

We also checked the number of errors in characters and words, and found a significant impact of incorrect word recognition on the system's accuracy (figure 5). This may be due to the problem of visem-based word recognition in the module, which uses a recurrent neural network and requires changes to improve accuracy, such as replacing LSTM with bidirectional GRUs or other neural networks.

Analysis of the results showed that the largest number of errors were in homophones, for example, the letter v was replaced by f or b by p.

The average word recognition accuracy is 94.46%, which is a good indicator for modern recognition systems based on silent speech interfaces and is comparable to similar projects or software tools that recognise words based on audio only.

Conclusions

The paper analyses the impact of using a speechless access interface (SSI), which provides the definition of the initial phase of the sound series associated with the beginning of speech based on the analysis of visemes, on the accuracy of voice command recognition in different sound environments.

The analysis of the methods for recognising the speech pattern of a speaker has shown that recent studies are based on the use of neural network architectures (CNN, LSTM) to analyse a predefined region of interest - the speaker's mouth. In this work, we used the GRID corpus to perform experimental studies, since this collection of videos was taken with the best lighting conditions and short laboratory phrases, which makes it easy to test the proposed approach. In the future, at the stage of implementation of the research results, it is planned to train the proposed system with a neural network architecture on lower quality videos, for example, from the LRS collection.

Training of the neural network on a GPU accelerator allowed to reduce the training time by 26.2 times using a high-resolution training sample with the size of the selected mouth area of 150×100 pixels. The results of the analysis of the selected speech recognition quality metrics (word recognition rate (WRR), word recognition error (WER), and character recognition error (CER)) showed that the maximum word recognition rate accuracy of the speaker's speech is 96.71% and is achieved after 18 epochs of training. If we evaluate the character recognition rate of word recognition, the highest rate can be obtained after 13 epochs of training.

To further develop this work, we can apply noise reduction algorithms to the audio signal or solve the problem of detecting visemes in conditions of low brightness or a different angle of the face.

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FORMAL SPECIFICATION OF MULSEMEDIA OBJECT'S DIGITAL TWIN BASED ON DISCRETE INTERVALS TEMPORAL RELATIONS

The article proposes a modification of the relations between discrete intervals, which makes it possible to formally determine the relationship between sets of temporal data of different modalities for the formal description of a mulsemedia object`s digital twin model. A mulsemedia object is a physical object, the state of which is recorded using a set of sensors to form a temporal multimodal digital description that comprehensively defines the object as a person perceives it through the senses. A digital twin of a mulsemedia object is a complex software model of this object, which is designed to predict the possible states and behaviour of the mulsemedia object. The formal description of a mulsemedia object is based on data obtained from a set of sensors, each of which captures information of a certain modality. To combine these data into a single object specification, a temporal relationship must be established between them, since data from different modalities can be registered and be meaningful for the research in different periods of the object`s observation. Qualitative determination of the temporal relationship between sets of data can be done using relations between discrete intervals ("Is Before", "Is After", "Coincides", etc.), but quantitative determination (for example, "How much before") using existing relations discrete intervals are impossible. Therefore, the article proposes to consider existing relations of discrete intervals as qualitative relations, at the same time, introducing their modification - quantitative relations of discrete intervals. The use of quantitative relations of discrete intervals will make it possible to simplify the development of digital twin technology software by improving the quality of the formal specification of data structures that comprehensively reflect interconnected sets of temporal multimodal data obtained in the process of monitoring mulsemedia objects.
Keywords: mulsemedia, digital twins, software, discrete intervals, relations, temporal multimodal data.

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ФОРМАЛЬНА СПЕЦИФІКАЦІЯ ЦИФРОВОГО ДВІЙНИКА МУЛЬСЕМЕДІЙНОГО ОБ'ЄКТА НА ОСНОВІ КІЛЬКІСНИХ ВІДНОШЕНЬ ДИСКРЕТНИХ ІНТЕРВАЛІВ

У статті запропоновано модифікацію відношень дискретних інтервалів, яка дає змогу формально визначати зв'язок між наборами темпоральних даних різних модальностей для формального опису моделі цифрового двійника мульсемедійного об'єкта. Під мульсимедійним об'єктом розуміється фізичний об'єкт, стан якого фіксується за допомогою набору сенсорів для формування темпорального мультимодального цифрового опису, який комплексно визначає об'єкт подібно до того, як він сприймається людиною через органи чуття. Цифровий двійник мульсемедійного об'єкта є складеною програмною моделлю цього об'єкта, яка призначена для прогнозування можливих станів та поведінки мульсемедійного об'єкта. Формальний опис мульсемедійного об'єкта відбувається на основі даних, що отримуються з набору сенсорів, кожен з яких фіксує інформацію певної модальності. Для об'єднання цих даних у єдину специфікацію об'єкта між ними потрібно встановити темпоральний зв'язок, оскільки дані різних модальностей можуть реєструватися та мати сенс для дослідження у різні періоди спостереження об'єкта. Якісне визначення темпорального зв'язку між наборами даних може бути виконане за допомогою відношень між дискретними інтервалами («передує», «настає після», «збігається» та інші), проте кількісне визначення (наприклад, «наскільки передує») за допомогою існуючих відношень дискретних інтервалів неможливе. Тому у статті запропоновано вважати наявні відношення дискретних інтервалів якісними відношеннями, натомість ввести їхню модифікацію – кількісні відношення дискретних інтервалів. Використання кількісних відношень дискретних інтервалів дасть змогу спростити розроблення програмного забезпечення технології цифрових двійників за рахунок підвищення якості формальної специфікації структур даних, які комплексно відображають взаємопов'язані набори темпоральних мультимодальних даних, що отримуються у процесі моніторингу мульсемедійних об'єктів.
Ключові слова: мульсемедіа, цифрові двійники, програмне забезпечення, дискретні інтервали, відношення, темпоральні мультимодальні дані.

Introduction

Since its development, the digital twins technology has been used to solve a wide range of scientific and technical problems. One of these tasks is the task of computer modelling of mulsemedia objects. A mulsemedia object is a physical object or a composition of several physical objects, the state of which is recorded using sensors. Each sensor captures information of a specific modality. A set of sensors produce temporal multimodal information that can be used for forming a digital description which comprehensively defines the object as people can perceive it through their senses. A digital twin of a mulsemedia object is a complex software model of this object, which is designed to predict the possible states and behaviour of the mulsemedia object. To combine these data into a single object specification, a temporal relationship between them must be defined, since data from different modalities can be registered and have a specific value for the research in different periods of the object`s observation.

The research presented in this paper is aimed at the advancement of the theoretical foundations for temporal multimodal data representation that can be used for the formal specification of the mulsemedia object's digital twin.

Related works

The fundamentals of the temporal relations were proposed in works [1] and [2] where the foundations of interval algebra and interval-based temporal logic are defined. In particular, in the paper [1] thirteen relations between intervals are proposed. In the paper [2] the beginnings and endings of intervals are formally defined and associated with points on the time axis.

In the paper [3], considers three types of relations between events: temporal relations between an event and a time expression, between a pair of events and between an event and the document creation time. It proposes a Markov Logic model that jointly identifies relations of all three relation types simultaneously. It allows to improve the accuracy while solving tasks where temporal relations between events are important.

In the paper [4], a notion of a fuzzy time interval is formulated and fuzzy Allen relations which are the generalization of Allen's interval relations are proposed. The relatedness measures are applied to define fuzzy temporal relations between vague events.

The paper [5] focuses on temporal link labelling as a classification task, in particular, it considers a set of temporal relations specified in TimeML [6] that contains fourteen types of relations. The paper presents a way of choosing the right feature vectors to build the classification model.

The analysis of these and similar papers show that neither of researches deals with the temporal relations defined quantitatively. Moreover, most of the research focus on the use of interval algebra and interval-based temporal logic which consider continuous intervals. At the same time, discrete intervals can be more useful for the development of new algorithms and software for digital twins technology.

Theoretical Background

The basis for the research presented in this paper is the Algebraic System of Aggregates (ASA) [7, 8]. The ASA is an algebraic system, a carrier of which is an arbitrary set of specific structures – aggregates. In broader sense, an aggregate can be considered as a complex data structure for a consolidated representation of temporal multimodal data sets which define the same object of observation.

Mathematically, an aggregate D is a tuple of arbitrary tuples, elements of which belong to predefined sets:

$$D = [\![M_j \mid \left\langle d_i^j \right\rangle_{i=1}^{n_j}]\!]_{j=1}^{N} = [\![\{D\} \mid \langle D \rangle]\!], \tag{1}$$

where $\{D\}$ is a tuple of sets M_j, $\langle D \rangle$ is a tuple of elements tuples $\left\langle d_i^j \right\rangle_{i=1}^{n_j}$ corresponding to the tuple of sets ($d_i^j \in M_j$).

As an algebraic system, the ASA consists of three sets: a carrier (non-empty set), a set of operations, and a set of relations. This research is focused on relations of the ASA, in particular, the relations between discrete intervals.

A discrete interval (DI) [9] is a tuple, elements of which are unique values ordered either in ascending or in descending order. In broader sense, a DI is a tuple of values defining the moments of time when characteristics of the object of observation are to be measured.

In the ASA, the following relations between two DIs are defined.

The relation *Is Before* means that the first DI ($\overline{t^1}$) finishes before the second DI ($\overline{t^2}$) starts:

$$\overline{t^1} \leftarrow \overline{t^2} \text{ if } t_{n_1}^1 < t_1^2 . \tag{2}$$

The relation *Is After* means that the first DI ($\overline{t^1}$) starts after the second DI ($\overline{t^2}$) finishes:

$$\overline{t^1} \rightarrow \overline{t^2} \text{ if } t_1^1 > t_{n_2}^2 . \tag{3}$$

The relation *Coincides With* means that two DIs ($\overline{t^1}$ and $\overline{t^2}$) start and finish at the same time:

$$\overline{t^1} \leftrightarrow \overline{t^2} \text{ if } t_1^1 = t_1^2, t_{n_1}^1 = t_{n_2}^2 \text{ and } n_1 = n_2 . \tag{4}$$

The relation *Meets* means that the first DI ($\overline{t^1}$) finishes at the same time moment as the second DI ($\overline{t^2}$) starts:

$$\overline{t^1} \mapsfrom \overline{t^2} \text{ if } t^1_{n_1} = t^2_1 . \tag{5}$$

The relation *Is Met By* means that the first DI ($\overline{t^1}$) starts at the same time moment as the second DI ($\overline{t^2}$) finishes:

$$\overline{t^1} \mapsto \overline{t^2} \text{ if } t^2_{n_2} = t^1_1 . \tag{6}$$

The relation *Overlaps* means that the second DI ($\overline{t^2}$) starts during the first DI ($\overline{t^1}$) and it finishes after the first DI finishes:

$$\overline{t^1} \hookleftarrow \overline{t^2} \text{ if } t^1_1 < t^2_1 \text{ and } t^1_{n_1} < t^2_{n_2} \text{ and } t^2_1 < t^1_{n_1} . \tag{7}$$

The relation *Is Overlapped By* means that the first DI ($\overline{t^1}$) starts during the second DI ($\overline{t^2}$) and it finishes after the second DI finishes:

$$\overline{t^1} \hookrightarrow \overline{t^2} \text{ if } t^2_1 < t^1_1 \text{ and } t^2_{n_2} < t^1_{n_1} \text{ and } t^1_1 < t^2_{n_2} . \tag{8}$$

The relation *During* means that the first DI ($\overline{t^1}$) starts after the second DI ($\overline{t^2}$) starts and it finishes before the second DI finishes:

$$\overline{t^1} \curvearrowleft \overline{t^2} \text{ if } t^1_1 > t^2_1 \text{ and } t^1_{n_1} < t^2_{n_2} . \tag{9}$$

The relation *Contains* means that the first DI ($\overline{t^1}$) starts before the second DI ($\overline{t^2}$) starts and it finishes after the second DI finishes:

$$\overline{t^1} \curvearrowright \overline{t^2} \text{ if } t^1_1 < t^2_1 \text{ and } t^1_{n_1} > t^2_{n_2} . \tag{10}$$

The relation *Starts* means that the first DI ($\overline{t^1}$) starts at the same moment of time as the second DI ($\overline{t^2}$) starts and it finishes before the second DI finishes:

$$\overline{t^1} \leftarrowtail \overline{t^2} \text{ if } t^1_1 = t^2_1 \text{ and } t^1_{n_1} < t^2_{n_2} . \tag{11}$$

The relation *Is Started By* means that the first DI ($\overline{t^1}$) starts at the same moment of time as the second DI ($\overline{t^2}$) starts and it finishes after the second DI finishes:

$$\overline{t^1} \rightarrowtail \overline{t^2} \text{ if } t^1_1 = t^2_1 \text{ and } t^1_{n_1} > t^2_{n_2} . \tag{12}$$

The relation *Finishes* means that the first DI ($\overline{t^1}$) starts after the second DI ($\overline{t^2}$) starts and it finishes at the same moment of time as the second DI finishes:

$$\overline{t^1} \looparrowleft \overline{t^2} \text{ if } t^1_1 > t^2_1 \text{ and } t^1_{n_1} = t^2_{n_2} . \tag{13}$$

The relation *Is Finished By* means that the first DI ($\overline{t^1}$) starts before the second DI ($\overline{t^2}$) starts and it finishes at the same moment of time as the second DI finishes:

$$\overline{t^1} \looparrowright \overline{t^2} \text{ if } t_1^1 < t_1^2 \text{ and } t_{n_1}^1 = t_{n_2}^2 . \quad (14)$$

All the abovementioned relations are qualitative. The further research offers the new approach that enables modifying these relations to make them quantitative.

Proposed Approach

The following quantitative relations are proposed in this research to enable defining relations between two discrete intervals by a specific number of time moments.

The relation *Is Quantitively Before* means that the DI $\overline{t^1}$ finishes τ moments of time before the DI $\overline{t^2}$ starts:

$$\overline{t^1} \underset{\tau}{\leftarrow} \overline{t^2} \text{ if } t_1^2 = t_{n_1}^1 + \tau . \quad (15)$$

The relation *Is Quantitively After* means that the DI $\overline{t^1}$ starts τ moments of time after the DI $\overline{t^2}$ finishes:

$$\overline{t^1} \underset{\tau}{\rightarrow} \overline{t^2} \text{ if } t_1^1 = t_{n_2}^2 + \tau . \quad (16)$$

The relation *Quantitively Overlaps* means that the DI $\overline{t^2}$ starts τ_s moments of time after the DI $\overline{t^1}$ starts and it finishes τ_f moments of time after the DI $\overline{t^1}$ finishes:

$$\overline{t^1} \underset{(\tau_s,\tau_f)}{\hookleftarrow} \overline{t^2} \quad \text{if} \quad t_1^2 = t_1^1 + \tau_s \text{ and } t_{n_2}^2 = t_{n_1}^1 + \tau_f . \quad (17)$$

The relation *Is Quantitively Overlapped By* means that the DI $\overline{t^1}$ starts τ_s moments of time after the DI $\overline{t^2}$ starts and it finishes τ_f moments of time after the DI $\overline{t^2}$ finishes:

$$\overline{t^1} \underset{(\tau_s,\tau_f)}{\hookrightarrow} \overline{t^2} \quad \text{if} \quad t_1^1 = t_1^2 + \tau_s \text{ and } t_{n_1}^1 = t_{n_2}^2 + \tau_f . \quad (18)$$

The relation *Quantitively During* means that the DI $\overline{t^1}$ starts τ_s moments of time after the DI $\overline{t^2}$ starts and it finishes τ_f moments of time before the DI $\overline{t^2}$ finishes:

$$\overline{t^1} \underset{(\tau_s,\tau_f)}{\curvearrowleft} \overline{t^2} \quad \text{if} \quad t_1^1 = t_1^2 + \tau_s \text{ and } t_{n_2}^2 = t_{n_1}^1 + \tau_f . \quad (19)$$

The relation *Quantitively Contains* means that the DI $\overline{t^1}$ starts τ_s moments of time before the DI $\overline{t^2}$ starts and it finishes τ_f moments of time after the DI $\overline{t^2}$ finishes:

$$\overline{t^1} \underset{(\tau_s,\tau_f)}{\curvearrowright} \overline{t^2} \quad \text{if} \quad t_1^2 = t_1^1 + \tau_s \text{ and } t_{n_1}^1 = t_{n_2}^2 + \tau_f . \quad (20)$$

The relation *Quantitively Starts* means that the DI $\overline{t^1}$ starts at the same moment of time as the DI $\overline{t^2}$ starts and it finishes τ moments of time before the DI $\overline{t^2}$ finishes:

$$\overline{t^1} \underset{(\tau)}{\leftarrowtail} \overline{t^2} \quad \text{if} \quad t_1^1 = t_1^2 \text{ and } t_{n_2}^2 = t_{n_1}^1 + \tau . \quad (21)$$

The relation *Is Quantitively Started By* means that the DI $\overline{t^1}$ starts at the same moment of time as the DI

$\overline{t^2}$ starts and it finishes τ moments of time after the DI $\overline{t^2}$ finishes:

$$\overline{t^1} \underset{(\tau)}{\rightarrowtail} \overline{t^2} \quad \text{if} \quad t_1^1 = t_1^2 \text{ and } t_{n_1}^1 = t_{n_2}^2 + \tau . \tag{22}$$

The relation *Quantitively Finishes* means that the DI $\overline{t^1}$ starts τ moments of time after the DI $\overline{t^2}$ starts and it finishes at the same moment of time as the DI $\overline{t^2}$ finishes:

$$\overline{t^1} \underset{(\tau)}{\hookleftarrow} \overline{t^2} \quad \text{if} \quad t_1^1 = t_1^2 + \tau \text{ and } t_{n_1}^1 = t_{n_2}^2 . \tag{23}$$

The relation *Is Quantitively Finished By* means that the DI $\overline{t^1}$ starts τ moments of time before the DI $\overline{t^2}$ starts and it finishes at the same moment of time as the DI $\overline{t^2}$ finishes:

$$\overline{t^1} \underset{(\tau)}{\looparrowright} \overline{t^2} \quad \text{if} \quad t_1^2 = t_1^1 + \tau \text{ and } t_{n_1}^1 = t_{n_2}^2 . \tag{24}$$

The relations *Coincides With*, *Meets*, and *Is Met By* do not have their qualitive and quantitative versions as these relations are always defined by specific moments of time and, thus, they can be considered either as qualitive or as quantitative depending on the context.

The proposed quantitative relations between discrete intervals can be useful for the formal specification of a complex data structure based on a multi-image concept [8].

A multi-image is a complex representation of temporal multimodal data sets which describe an object. In mathematical sense, the multi-image *MI* is an aggregate, the first data tuple of which is a non-empty tuple of time values.

$$MI = [\![T, M_1, .., M_N | \langle t_k \rangle_{k=1}^{\tau}, \langle d_{k_1}^1 \rangle_{k_1=1}^{n_1}, .., \langle d_{k_N}^1 \rangle_{k_N=1}^{\mathrm{N}}]\!], \tag{25}$$

where T is a set of time values; $\tau \geq n_i, i \in [1, \ldots, N]$.

Thus, T is a mathematical representation of the common time scale which defines the whole period of the object's observation. However, for the development of an algorithm of the object's multi-image processing, it can be useful to present in an evident way the interrelation of different data modalities in terms of time. The definition of the multi-image as the formula (25) does not provide such representation. Let us use the quantitative relations to advance the definition of the multi-image.

Firstly, let us define a sub-multi-image SMI_i which presents temporal data of i-modality as:

$$SMI_i = [\![T_i, M_i | \langle t_{k_i}^i \rangle_{k_i=1}^{\tau_i}, \langle d_{k_i}^i \rangle_{k_i=1}^{n_i}]\!], \tag{26}$$

where T_i is a set of time values which defines the time moments $\langle t_{k_i}^i \rangle_{k_i=1}^{\tau_i}$ when the data $\langle d_{k_i}^i \rangle_{k_i=1}^{n_i}$ of i-modality (the modality is defined by a set M_i) is to be measured; $i \in [1, \ldots, N]$.

Then, the multi-image *MI* can be defined as:

$$MI = SMI_{i_1} \left(R_{i_1 i_2}\right) SMI_{i_2}, \;\; i_1 \neq i_2, \;\; \forall i_1, i_2 \in [1, \ldots, N], \tag{27}$$

where $R_{i_1 i_2}$ is a quantitative relation between discrete intervals $\langle t_{k_i}^{i_1} \rangle_{k_i=1}^{\tau_{i_1}}$ and $\langle t_{k_i}^{i_2} \rangle_{k_i=1}^{\tau_{i_2}}$ of SMI_{i_1} and SMI_{i_2} accordingly.

The interpretation of the multi-image concept defined by the formula (27) enables establishing of temporal relationships between data sets of different modalities. In turn, this can allow to simplify the formal specification of a complex data structure for mulsemedia object's digital twin description.

The visualization of a formal specification based on the modified definition of a multi-image can be presented as an oriented graph. This specification is further called a *temporal specification* of a multi-image. The following example demonstrates how a temporal specification can be defined.

Let the mulsemedia object be a real nature scene where forest fire appears during the process of the forest massif observation. The observation is carried out by using the following devices: two video cameras, four audio recorders, a smell detector, and an air motion detector. Later, the data recorded using these devices are used for creating mulsemedia content (mulsemedia movie) for its reproduction in an educational immersive environment. According to the proposed approach, the mulsemedia object must be described by a temporal specification with the purpose of the creation of such a mulsemedia product – the mulsemedia movie.

Let us specify the following SMIs to be used for the mulsemedia object's specification: SMI_1 is the first video; SMI_2 is the second video; SMI_3 is the first audio; SMI_4 is the second audio; SMI_5 is the third audio; SMI_6 is the forth audio; SMI_7 is the smell record; and SMI_8 is the air motion record. Each of these SMIs has its own DI when the modality data of this SMI is obtained. The modalities timing is shown on Fig. 1.

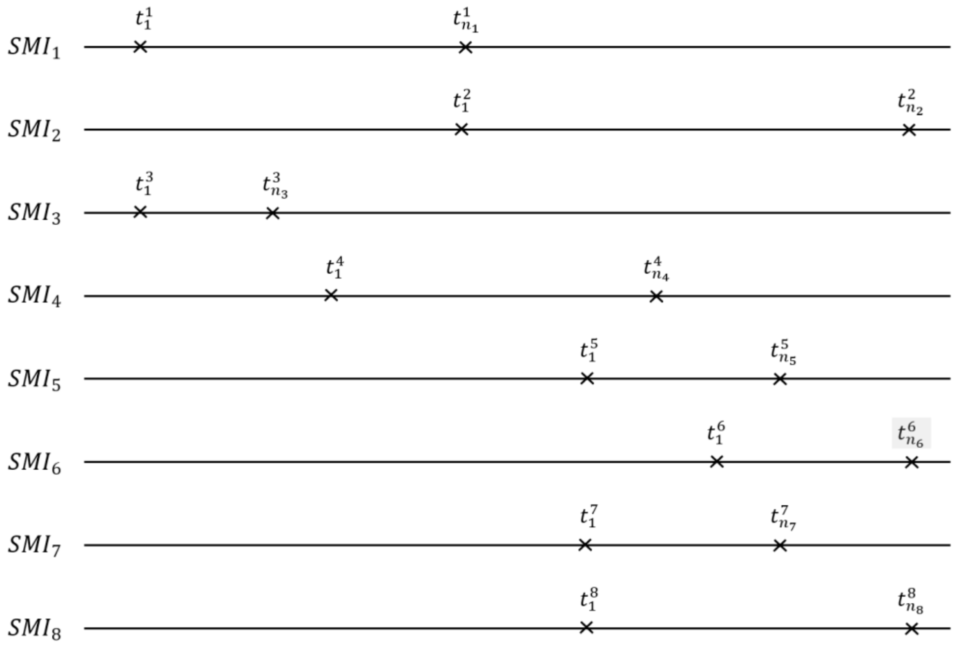

Fig. 1. The scheme of modalities timing

This scheme of modalities timing allows to calculate the following time values which are necessary for defining the qualitive relations between the DIs:

$$\begin{cases} w_1 = t_{n_1}^1 - t_{n_3}^3 \\ w_2 = t_1^4 - t_{n_3}^3 \\ w_3 = t_1^4 - t_1^1 \\ w_4 = t_{n_4}^4 - t_{n_1}^1 \\ w_5 = t_1^5 - t_1^4 \\ w_6 = t_{n_5}^5 - t_{n_4}^4 \\ w_7 = t_1^5 - t_1^2 \\ w_8 = t_{n_2}^2 - t_{n_5}^5 \\ w_9 = t_1^6 - t_1^5 \\ w_{10} = t_{n_6}^6 - t_{n_5}^5 \\ w_{11} = t_1^6 - t_1^2 \\ w_{12} = t_{n_8}^8 - t_{n_7}^7 \\ w_{13} = t_{n_8}^8 - t_{n_5}^5 \end{cases} \quad (28)$$

Then the multi-image for the given example can be defined by the temporal specification depicted on Fig. 2.

The next step is the realization of the obtained temporal specification in a program code. It can be done by using either a general-purpose programming language, or a domain-specific programming language ASAMPL 2.0 [10]. The advantage of using ASAMPL is that it is optimized for processing specifically temporal multimodal data. To support further simplification of the realization of the temporal multimodal data processing algorithms for the development of the mulsemedia software, the proposed quantitative relations need to be implemented in the syntax of the programming language ASAMPL.

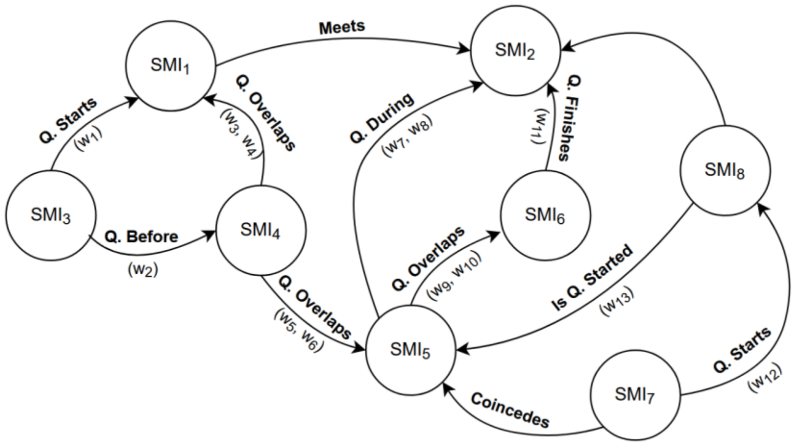

Fig. 2. The multi-image temporal specification ("Q." means "Quantitative")

Conclusions

The research presented in this article enables improving the mathematical apparatus for processing discrete intervals, which is a development of Allen's interval algebra. Unlike Allen's intervals, discrete intervals allow to determine discrete events, which in turn enables using the interval relations defined in the Algebraic System of Aggregates for the development of software for a mulsemedia object's digital twin implementation and usage.

The distinguishing feature of the new approach presented in this paper is that two types of relations between discrete intervals have been introduced; they are qualitative relations and quantitative relations. The qualitative relations are relations originally defined for discrete intervals in the Algebraic System of Aggregates. The quantitative relations are introduced in this paper for the first time. These relations enable defining how close or far the beginning and ending points of two discrete intervals are on the time axis. This allows to simplify the formal specification of the complex data structure for a mulsemedia object's digital twin representation based on temporal multimodal data to be received from a set of sensors which monitor the mulsemedia object.

Further research can be focused on the development of new advanced algorithms for temporal multimodal data processing as well as it must include the implementation of the quantitative relations in the syntax of the programming language ASAMPL 2.0.

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AN UNSUPERVISED-SUPERVISED ENSEMBLE TECHNOLOGY WITH NON-ITERATIVE TRAINING ALGORITHM FOR SMALL BIOMEDICAL DATA ANALYSIS

Improving the accuracy of intelligent data analysis is an important task in various application areas. Existing machine learning methods do not always provide a sufficient level of classification accuracy for their use in practice. That is why, in recent years, hybrid ensemble methods of intellectual data analysis have begun to develop. They are based on the combined use of clustering and classification procedures. This approach provides an increase in the accuracy of the classifier based on machine learning due to the expansion of the space of the input data of the task by the results of the clustering.

In this paper, the tasks of modification and improvement of such technology for small data analysis are considered. The basis of the modification is the use of clustering with output at the first step of the method to increase the accuracy of the entire technology. Despite the high accuracy of the work, this approach requires a significant expansion of the inputs of the final linear classifier (labels of the obtained clusters are added to the initial inputs). To avoid this shortcoming, the paper proposes an improvement based on the introduction of a new classification procedure at the first step of the method and replaces all the initial inputs of the task with the results of its work. In parallel with it, clustering is performed taking into account the original attribute, the results of which are added to the output of the classifier of the first step. In this way, the formation of an expanded set of data of significantly lower dimensionality in comparison with the existing method takes place (here there is no longer a large number of initial features, which is characteristic of biomedical engineering tasks). This reduces the training time of the method and increases its generalization properties.

Modeling of the method was based on the use of a short dataset contained in an open repository. After the preprocessing procedures, the dataset has only 294 vectors, each of which was characterized by 18 attributes. Data classification was done using an SGTM-based neural-like structure classifier. This linear classifier provides high accuracy of work. In addition, it does not provide for the implementation of an iterative training procedure and additional adjustment of work parameters. Data clustering was performed using the k-means method. This choice is due to both the simplicity and speed of its work.

The search for the optimal number of k-means clusters was carried out using 4 different methods. They all showed different results. That is why, some experiments were conducted to assess the influence of different numbers of clusters (from 3 to 7) on the accuracy of all 4 algorithms of the developed technology. The accuracy of the proposed technology has been established experimentally in comparison with the linear classifier and the existing hybrid method. In addition, by reducing the inputs of the final classifier, the developed technology reduces the duration of the training procedure compared to the basic method. All this ensures the possibility of using the proposed technology when solving various applied problems of medical diagnostics, in particular, based on the analysis of small data.

Keywords: small data approach, non-iterative training, ensemble learning, unsupervised-supervised technology, biomedical engineering.

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АНСАМБЛЕВА ТЕХНОЛОГІЯ БЕЗ ВЧИТЕЛЯ-З ВЧИТЕЛЕМ З НЕІТЕРАТИВНИМ АЛГОРИТМОМ НАВЧАННЯ ДЛЯ АНАЛІЗУ КОРОТКИХ НАБОРІВ БІОМЕДИЧНИХ ДАНИХ

Підвищення точності інтелектуального аналізу даних є важливою задачею в різних прикладних областях. Існуючі методи машинного навчання не завжди забезпечують достатній рівень точності класифікації для їх використання на практиці. Саме тому, в останні роки почали розвиватися гібридні ансамблеві методи інтелектуального аналізу. В їх основі покладено сумісне використання процедур кластеризації та класифікації. Такий підхід забезпечує підвищення точності класифікатора на основі машинного навчання за рахунок розширення простору вхідних даних задачі результатами роботи кластеризатора.

У цій роботі розглядаються завдання модифікації та удосконалення подібної технології аналізу коротких даних. В основі модифікації покладено використання кластеризації з виходом на першому кроці методу для підвищення точності роботи усього методу. Незважаючи на високу точність роботи, такий підхід вимагає суттєвого розширення входів фінального лінійного класифікатора (до початкових входів додаються мітки отриманих кластерів). З метою уникнення цього недоліку, у статті запропоновано удосконалення, в основі якого покладено введеня нової процедури класифікації на першому кроці методу та використання результатів її рботи для заміни усіх початкових входів задачі. Паралельно з нею виконується кластеризації з врахуванням вихідного атрибуту, результати якої додаються до вихода класифікатора першого кроку. Таким чином відбувється формування розширеного набору даних суттєво меншої вимірності в порівнянні із існуючим методом (тут вже немає великої кількості початкових ознак, що характерно для задач біомедичної нженерії). Це зменшує час роботи методу і збільшує його генералізаційні властивості.

Моделювання роботи методу відбувалося на основі використання корткого набору даних, який міститься у відкритому репозиторії. Після процедур попереднього опрацювання, набір даних налічував лише 294 вектори кожен з яких характеризувався 18 атрибутами. Класифікація даних відбувалася із використанням SGTM neural-like structure. Цей лінійний класифікатор забезпечує високу точність роботи. Окрім цього він не передбачає виконання ітераційної процедури навчання та додаткового налаштування параметрів роботи. Кластеризація даних відбувалася із використанням методу k-means. Такий вибір обумовлено як простотю так і швидкодією його роботи.

Пошук оптимальної кількості кластерів методу k-means відбувався із використанням 4 різних методів. Усі вони *продемонстрували різні результати. Саме тому, у статті проведено експерименти щодо оцінки впливу різної кількості кластерів (від 3 до 7) на точність роботи усіх 4 алгоритмів розробленої технології. Експериментальним шляхом встановлено підвищення точності роботи запропонованої технолоігї у порівнянні з лінійним класифікатором та існучим гібридним методом. Окрім цього, за рахунок зменшення входів фінального класифікатора, розроблена технологія зменшує тривалість процедури навчання в порівнянні з базовим методм. Все це забезпечує можливість використання запропонованої технології під час розвязання різноманітних прикладних задач медичної діагностики, зокрема на основі аналізу коротких наборів даних..*

Ключові слова: підхід до малих даних, неітеративне навчання, ансамблеве навчання, технологія без вчителя-з вчителем, біомедична інженерія.

Introduction

The topicality of the task of increasing the classification accuracy in the biomedical engineering area is extremely important due to many factors [1] that affect the quality of diagnosis, prognosis, and treatment of various diseases.

Correct classification of biomedical data, such as biomarkers or genetic data, can help detect diseases such as cancer, heart disease, and neurological disorders faster and more accurately [2]. In addition, thanks to accurate classification, it is possible to develop personalized approaches to treatment. Knowledge about the nature of the disease at the individual level allows us to choose the optimal methods of treatment and the dose of medicines [3,4]. Here it should be taken into account that incorrect classification can lead to serious consequences for patients.

The high accuracy of classification models based on machine learning helps to reduce the risk of diagnostic errors and incorrect treatment assignments. In addition, accurate classification models allow rational use of medical resources, such as the time of medical professionals, equipment, and material resources, reducing the number of unnecessary diagnostic procedures [5]. However, the effectiveness of machine learning methods largely depends on the data set for analysis.

Biomedical sets of tabular data have their characteristics due to the specificity of the source and purpose of these data in biomedical research and medical practice. In particular, they have a multidimensional nature [4]. This is explained by the need to take into account during the analysis a large number of parameters measured as part of medical research. Such data may include clinical, laboratory, and other medical parameters that require a specific understanding of the medical context for effective analysis and interpretation.

Tabular sets of biomedical data can contain different types of features, including both numeric and categorical features. Effective analysis may require the use of different methods for different types of features [6]. In addition, such data may be collected from a sample of patients or studies, which may affect their representativeness.

The problem discussed above deepens in the case of the analysis of short biomedical datasets. In particular, there may be a limited number of examples for each or one of the classes. This leads to insufficient representativeness of the data, which leads to many problems when building machine learning models, especially for complex classes. In particular, in the conditions of analysis of a limited amount of data, the risk of overfitting increases significantly, when the model can correctly generalize to new examples. On the other hand, underfitting can occur here if the model is not complex enough to solve complex tasks.

Among other problems of classification of short sets of biomedical data using machine learning methods, the problem of automatic selection/extraction of important features for classification should be highlighted, taking into account the multidimensionality of such data [7]. Additionally, models trained on short datasets can be more vulnerable to outliers, noise, and anomalies in the input data. [8].

All this requires specialized approaches, methods, and an understanding of the specifics of the medical context to achieve reliable and valuable results when analyzing biomedical data sets of small volumes. That is why, to increase the accuracy of classification in biomedical engineering, new hybrid methods of data analysis are constantly being developed, which include machine learning, fuzzy logic [9], deep learning [10], kernel methods [11], and statistical approaches [12].

In particular, in [13] the authors considered a problem of classification using a hybrid, hierarchical approach. The authors proposed the use of clustering at the first step of the hierarchical method to select clusters in a given data set. In the second step of the method, the classifier is used within each separate separated cluster. This approach provides a significant increase in classification accuracy. However, in the case of analyzing short data sets, the selected clusters may be very small. This will make it impossible to use classifiers based on machine learning

To overcome this limitation, another approach was developed in [14]. The dataset according to [14] is not divided into clusters here, which is a significant advantage in the case of analysis of short data sets. In this case, clustering is also performed, but its results are used to expand the space of the input data of the problem by the observation belonging to each of the selected clusters.

This approach provides the possibility of intellectual analysis of small volumes of data, and significantly increases the accuracy of classification. However, it also expands the already multidimensional feature space of each vector in a biomedical dataset. This causes several problems when analyzing short sets of biomedical data using machine learning tools.

That is why this paper aims to improve the unsupervised-supervised classification technology for the case of the analysis of multidimensional short sets of biomedical data.

The main contribution of this paper can be summarized as follow:

1. The two-step method of intelligent data analysis [14] was modified by performing a data clustering procedure taking into account the original attribute, which allowed to increase the accuracy of classification in the field of biomedical engineering;
2. The two-step classification method has been improved due to the parallel execution of the data classification and data clustering procedures in the first step of the method, taking into account the original attribute, and the formation of a new dataset of significantly reduced size from their output signals for training the final classifier. This provides a significant reduction in the duration of the training procedure of a non-iterative classifier while increasing the accuracy of its work in the case of analysis of short sets of biomedical data.

Materials and methods

This paper is devoted to the development of unsupervised-supervised ensemble technology for data classification in medicine. It is based on several modifications and improvements of the hybrid method of data classification based on the consistent use of clustering and classification to improve the accuracy of the latter.

Let us consider the adaptation (Basic method, algorithm 1) and modification (Basic method, algorithm 2) of the method from [14] to increase the accuracy of solving classification problems.

Let a training sample of medical data be given in the form of a set of vectors of the form $x_1, x_2, ..., x_n \to y$. The task consists in assigning an observation with an unknown output to one of the K known classes

So, the main steps of the Basic method's (algorithm 1) training procedure are as follows:

1. We perform clustering of the training data sample using the selected method for selection C clusters. For this, we use vectors of the form $x_1, x_2, ..., x_n$. It should be noted that unlike [14], the next condition must be met here: $C > K$.
2. We calculate the centers for each of the found clusters C : $x_1^c, x_2^c, ..., x_n^c$
3. We form a new, expanded training dataset by adding to each observation the labels, belonging to each of the obtained clusters $m_l, l = 1,...C$. As a result, we obtained new vectors in the form $x_1, x_2, ..., x_n, m_1, ..., m_C \to y$. It should be noted that in the case when the current vector belongs to a cluster l, $l = 1,...C$, then $m_l = 1$. In all other cases $m_l = 0$.
4. We train the final classifier on extended vectors of the species $x_1, x_2, ..., x_n; m_1, ..., m_c \to y$ using the selected machine learning method.

The procedure for applying the Basic method (algorithm 1) requires the following steps:

1. We assign the current vector of the test sample $u_1, u_2, ..., u_n$ with an unknown output to one of the defined clusters C. To do this, we calculate the Euclidean distance between the current vector and each of the cluster centers found in step 2 of the training procedure. The smallest value of the Euclidean distance will determine whether the observation belongs to the corresponding cluster.
2. We form a new, expanded data vector by adding the membership labels of each of the obtained clusters to the current vector $u_1, u_2, ..., u_n, m_1, ..., m_C$.
3. We apply the final classifier to the formed vectors $u_1, u_2, ..., u_n, m_1, ..., m_C$ using the selected machine learning method for searching y^{final_pred}.

The modification of the basic method (algorithm 2) consists in using the data clustering procedure taking into account the initial value. In this case, we enter the initial value known for the training sample as an additional feature and perform step 2 of the training procedure of the previous method.

In the case of solving a classification task, the output value is the class to which the observation belongs. Therefore, each input vector of the training sample is expanded by a set of observation membership labels $m_q, q = 1,...K$ to each of the classes K defined by the stated task ($m_q = 1$, if the vector belongs to q-th class, and $m_q = 0$ in all other cases). Thus, clustering according to algorithm 2 will be performed on the vectors of the training set of the species $x_1, x_2, ..., x_n; m_1, ..., m_K$.

The application procedure of the basic method (algorithm 2) corresponds to the application procedure according to algorithm 1. It should be noted that the first step of the application procedure of algorithm 1 will be performed for cluster centers $u_1^c, u_2^c, ..., u_n^c$, without use $m_1, ..., m_K$.

The advantage of using clustering with output is the possibility of increasing the accuracy of this procedure, in particular with linear methods of machine learning, and, as a result, increasing the accuracy of the entire method. From a theoretical point of view, this effect can be explained by Cover's theorem [15]. However, the main drawback of both algorithms is a significant increase in the number of features of each data vector, which depends on the optimal number of clusters of the training sample. In addition, biomedical datasets are characterized by a large number of independent attributes that must be considered during analysis. All this together will increase the training time of the selected classifier. In addition, this approach can be accompanied by a deterioration of the generalization properties of the classifier and even cause overfitting.

To avoid such shortcomings, this paper also proposes a technology for improving the basic method (both algorithms). It is based on the need to reduce the dimensionality of the space of extended vectors while ensuring high classification accuracy. For this, at the first step of the method, an additional classification procedure is introduced, the results of which will replace all the initial independent attributes of the initial dataset. In parallel with it, clustering will be performed, the results of which will expand each vector as in the basic method. Thus, the final classifier of the second step of the technology will receive a significantly smaller number of inputs, which will reduce the duration of the training procedure.

Let's take a closer look at the main steps of the Proposed technology (algorithm 3)**.**

1. We train the linear classifier on the vectors $x_1, x_2, ..., x_n \to y$.
2. We apply the training data sample to the previously trained classifier to obtain $y^{pred^{(1)}}$ for each data vector.
3. We perform clustering of the training data sample using the selected method for selection C clusters. For this, we use vectors of the form $x_1, x_2, ..., x_n$. It should be noted that unlike [14], the next condition must be met here: $C > K$.
5. We calculate the centers for each of the found clusters C: $x_1^c, x_2^c, ..., x_n^c$
4. We form a new, expanded training dataset, replacing all initial independent attributes with new ones. This happens by adding to $y^{pred^{(1)}}$ labels belonging to each of the obtained clusters $m_l, l = 1,...C$. As a result, we will receive a new training data set for the final classifier in the form of a set of vectors in the form $y^{pred^{(1)}}, m_1, ..., m_C \to y$. It should be noted that in the case when the current vector belongs to a cluster l, $l = 1,...C$, then $m_l = 1$. In all other cases $m_l = 0$.
5. We train the final classifier on extended vectors $y^{pred^{(1)}}, m_1, ..., m_C$ using the selected machine learning using the selected method of machine learning.

The structural diagram of the developed technology is shown in Fig. 1.

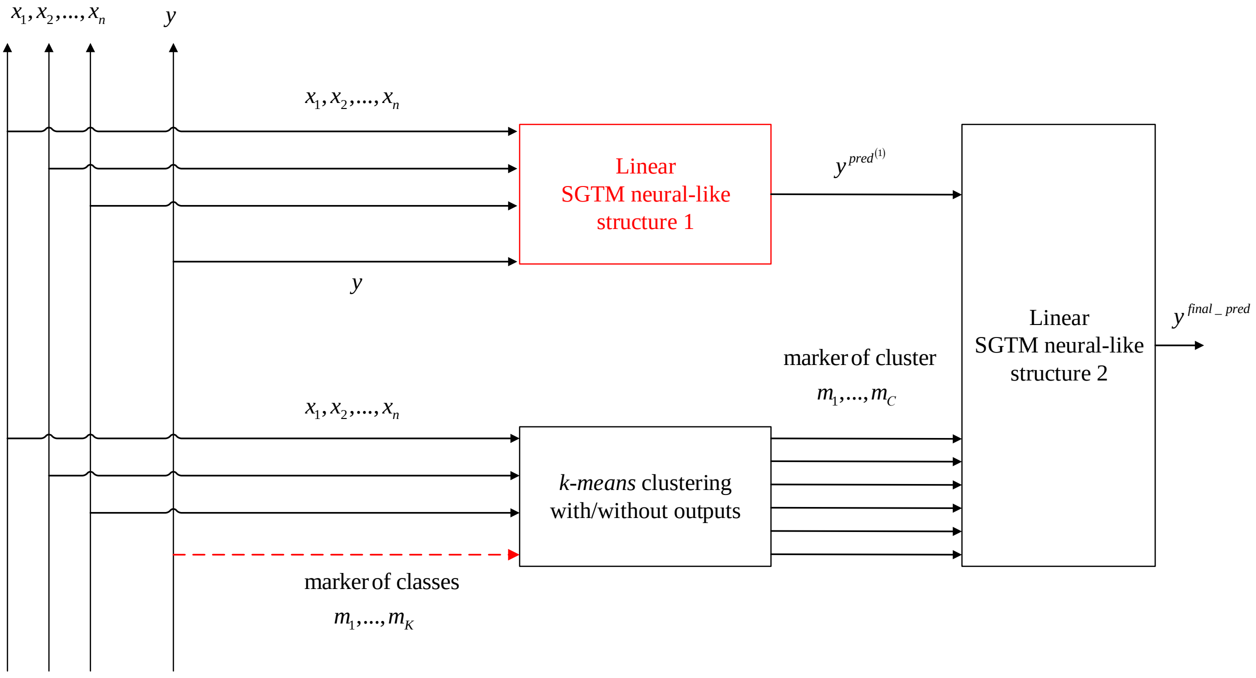


Fig. 1. Flow-chart of the improved unsupervised-supervised technology with non-iterative training algorithms

The application procedure of the Proposed technology (algorithm 3) requires the following steps.

1. We apply the current vector of the test sample to the previously trained first classifier. We get the predicted value $y^{u-pred^{(1)}}$,
2. We find the membership of the current vector of the test sample $u_1, u_2, ..., u_n$ with an unknown output to one of the defined clusters. To do this, we calculate the Euclidean distance between the current

vector and each of the cluster centers found in step 2 of the training procedure. The smallest value of the Euclidean distance will determine whether the observation belongs to the corresponding cluster.

3. We form a new, expanded data vector by adding labels of belonging to each of the obtained clusters to the corresponding $y^{u-pred^{(1)}}$. As a result, we get $y^{u-pred^{(1)}}, m_1, ..., m_C$.
4. We apply the final classifier to the formed vectors $y^{u-pred^{(1)}}, m_1, ..., m_C \rightarrow y$ using the selected machine learning method for searching y^{final_pred}.

An obvious advantage of the proposed technology would be a significant reduction of inputs for the final classifier. This will ensure the possibility of using the proposed technology for the analysis of short datasets in the tasks of medical diagnostics. However, to increase the accuracy of the technology, this article proposed the Proposed technology (algorithm 4). It consists in performing the clustering procedure with output, with identical steps as in the basic method (algorithm 4)**.**

Modeling, results, and comparison.

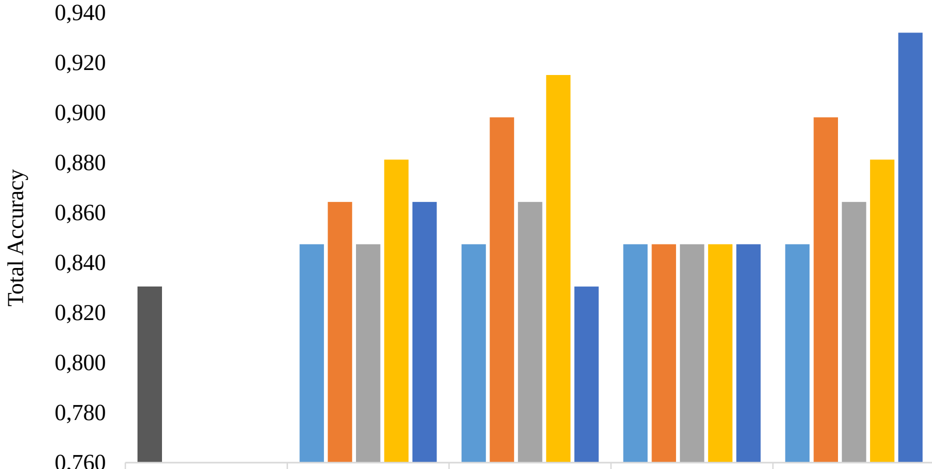
Both methods and their algorithms were modeled using a short set of medical data. An applied binary classification task, considered in this paper is to predict a heart attack based on 14 input attributes of a short dataset. The dataset is contained in an open repository [16].

The selected dataset contains a considerable number of gaps and categorical variables. In addition, the authors of the dataset did not specify which attributes are the most important. That is why the author carried out preliminary processing of the data, which consisted of:

- Removal of columns that contained a large number of omissions;
- Filling of missing values with average values for some observations;
- Conversion of categorical features into numerical ones;
- Performance of feature selection technique to select the most significant features for analysis.

After performing all the above procedures, the dataset contained 18 features and 294 observations. It was randomly divided into training and test samples in the ratio of 80% to 20%, respectively.

Data classification in this paper was done using SGTM neural-like structure. This linear classifier ensures high accuracy of work. In addition, it does not provide for the implementation of an iterative training procedure and additional adjustment of work parameters. Details of learning algorithms and the application of this classifier can be found in [17,18]. Data clustering was done using the *k-means* method. This choice is due to both the simplicity and speed of its work.



	Linear SGTM neural-like sctructure	Basic method - algorithm 1	Basic method - algorithm 2	Proposed technology - algorithm 3	Proposed technology - algorithm 4
3 clusters	0,831	0,847	0,847	0,847	0,847
4 clusters	0,831	0,864	0,898	0,847	0,898
5 clusters	0,831	0,847	0,864	0,847	0,864
6 clusters	0,831	0,881	0,915	0,847	0,881
7 clusters	0,831	0,864	0,831	0,847	0,932

Fig. 2. Comparison of the classification accuracy for all investigated methods using different numbers of clusters

The search for the optimal number of *k-means* clusters was carried out using 4 different methods. They all showed different results. That is why, in this paper, experiments were conducted on the assessment of the effect of different numbers of clusters (from 3 to 7) on the accuracy of all 4 algorithms of the developed technology.

Fig. 2 shows the total accuracy indicator for all investigated methods (Linear SGTM-based classifier and 4 algorithms developed in this paper) when using different numbers of clusters.

From the results presented in Fig. 2 the following conclusions can be drawn:

- Linear SGTM-based classifiers provide fairly high accuracy when analyzing a short dataset;
- The adapted method (algorithm 1) demonstrates an increase in the accuracy in comparison with the Linear SGTM-based classifier using any of the studied numbers of clusters;
- The use of clustering with output (algorithm 2) provides both a significant increase in the accuracy of work in particular in comparison with algorithm 1 and a slight deterioration. It depends on the number of clusters of the clustering procedure;
- The proposed technology (algorithm 3) increased the accuracy of the Linear SGTM-based classifier. However, the number of clusters here did not affect the change in this indicator's value;
- The use of the proposed technology (algorithm 4), which uses clustering with output, increased the accuracy of all previous methods. It should be noted that this improvement is characteristic of all values of the clusters studied in the paper;
- The highest classification accuracy was obtained using the proposed technology (algorithm 4) for seven clusters. In particular, it was possible to obtain a 10.1 higher accuracy compared to the Linear SGTM-based classifier.

In addition to the accuracy of work, an important indicator of the effectiveness of all studied algorithms is their training time. Since the training procedures of all four algorithms differ slightly, their training time was calculated as the duration for the final linear classifier at the second step of all methods.

Fig. 3 summarizes the results of this experiment.

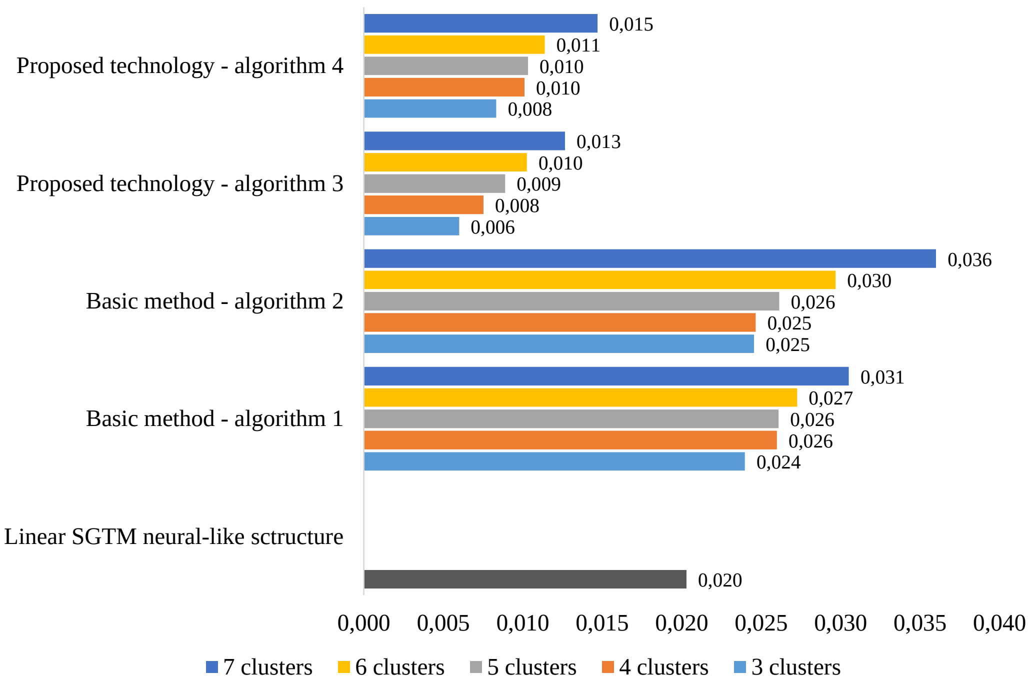


Fig. 3. Comparison of the training time (in seconds) for all investigated methods using different numbers of clusters

From the results presented in Fig. 3 the following conclusions can be drawn:

- Linear SGTM-based classifier provides the highest speed during the analysis of the studied short dataset;
- The adapted method (algorithm 1) demonstrates an increase in the duration of training time, in particular, when the number of clusters of this method increases;
- The use of clustering with output (algorithm 2) is accompanied by a slight increase in the training time of the method in comparison with algorithm 1;
- The proposed technology (algorithm 3) significantly reduced the duration of training time both in comparison with algorithm 1 and algorithm 1. This is explained by a significant reduction in the number of features used for analysis;
- The use of the proposed technology (algorithm 4), which applies clustering with output, does not significantly increase the duration of the training procedure compared to algorithm 3**.**

If we summarize the results presented in both figures, it should be noted that the developed technology (algorithm 4) demonstrated more than 10% higher classification accuracy with an insignificant increase in the duration of the training procedure, compared to the basic linear classifier. All this provides several advantages for the use of the proposed technology when solving various applied tasks of medical diagnostics, in particular, based on the analysis of small data.

Conclusions

The modern development of the field of biomedical engineering is characterized by the appearance of an increasing number of tasks, including the processing of tabular datasets, with a limited amount of data for the implementation of training procedures by artificial intelligence tools. This imposes several limitations on the application of existing machine learning tools. The problem is deepened by the fact that this area is characterized by the presence of a large number of independent variables necessary for analysis.

To analyze short datasets of large dimensions, the paper proposes a hybrid technology of the combined use of clustering and classification. The author considers modified and improved algorithms that demonstrate a significant increase in classification accuracy during expert diagnostics.

The simulation was carried out on a real dataset to solve the binary classification task. Experimentally, it was established that the improved technology demonstrated more than 10% higher classification accuracy with an insignificant increase in the duration of the training procedure, compared to the basic linear classifier. Summarizing the advantages of improved technology, the following should be highlighted. It provides:

- a significant reduction of the space of input data for the classifier in comparison with the basic method of classification for tabular datasets [14];
- reducing the computational complexity of the improved method due to a significant reduction in the space of input data for further analysis by the selected classifier based on machine learning;
- a significant increase in the accuracy of solving the classification tasks in comparison with the existing method from [1];
- the possibility of processing data of small volumes with a large number of input attributes;
- the possibility of processing tabular datasets with a critically small number of observations in comparison with the hierarchical classifier from [13];
- the possibility of effective processing of datasets of large volumes due to an insignificant increase in the space of the input data of the task, but with a significant increase in the accuracy of the work of this approach;
- the possibility of building different combinations of clustering-classification methods depending on the research area, the task, and the volume and specificity of the available dataset.

All this ensures the possibility of using the proposed technology when solving various applied problems of medical diagnostics, in particular, based on the analysis of short data sets

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STUDY ON THE BASIS OF COMPUTER MODEL OF STEEL HEATING PROCESS IN ORDER TO REDUCE RESOURCE COSTS

Steel is one of the most important materials in the modern world, used in various industries and construction. Steel production starts with heating steel melt in steel ladles, the equipment used in the steel industry to produce various types of steel. The ladle plays a key role in this process, as it is the place where the steel melt is heated. The search for rational technological layouts that ensure the economical use of material and energy resources in the manufacture of high-quality steel products is an urgent scientific and technical challenge facing the engineering staff of steelmaking and high-quality competitive steel products. Random increases and decreases in steel temperature can lead to deterioration in steel quality, accelerated erosion of refractory materials, and increased energy consumption. Steel heat losses depend on the ladle's thermal state, thermal and physical properties of the steel, and slag. The thermal state and thermal properties of molten steel and slag need to be quantified to better control the production process, the final steel composition, and the desired pouring temperature.

The experimental results, their analysis and systematization are presented. It is concluded that the most suitable materials for the melt heating process are ladles with the smallest geometric parameters together with RESISTAL B80 lining. In turn, the largest ladle during the experiments produces in most cases the highest resource costs with a steel casing – 498-1972 UAH and 0.18-0.74 MJ. In some results, comparing the steel casing with RESISTAL B80, the resource costs make up a slight difference – 3-7 UAH. and 0.001-0.003 MJ, and in others – 24-704 UAH and 0.009-0.266 MJ. At the same time, the bucket with medium geometric dimensions shows average indicators of resource costs – 423-1255 UAH and 0.16-0.47 MJ.

Software for modeling an industrial process has been developed that allows conducting numerical experiments for a particular steel melt with different input parameters to determine their impact on resource consumption. Saving the results of the experiments, it is possible to analyze the impact of input parameters on a particular melt and make the right decisions for further experiments.

Keywords: computational fluid dynamics, melt, cost reduction, steel ladle.

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ДОСЛІДЖЕННЯ НА ОСНОВІ КОМП'ЮТЕРНОЇ МОДЕЛІ ПРОЦЕСУ НАГРІВАННЯ СТАЛІ З МЕТОЮ ЗМЕНШЕННЯ ВИТРАТ РЕСУРСІВ

Сталь – один з найважливіших матеріалів у сучасному світі, який використовується в різних галузях промисловості та будівництві. Виробництво сталі починається з нагрівання металевого розплаву в сталерозливних ковшах – обладнанні, що використовується в металургійній промисловості для виробництва різних видів сталі. Ковш відіграє ключову роль у цьому процесі, оскільки саме в ньому відбувається нагрівання металевого розплаву. Пошук раціональних технологічних схем, що забезпечують економне використання матеріальних і енергетичних ресурсів при виробництві високоякісної металопродукції, є актуальним науково-технічним завданням, що стоїть перед інженерно-технічним персоналом сталеплавильного виробництва і якісної конкурентоспроможної металопродукції. Випадкові підвищення і зниження температури сталі можуть призвести до погіршення якості сталі, прискореної ерозії вогнетривких матеріалів і підвищених енерговитрат. Теплові втрати сталі залежать від теплового стану ковша, теплофізичних властивостей металевого розплаву та шлаку. Тепловий стан і теплофізичні властивості розплавленої сталі та шлаку необхідно визначати кількісно, щоб краще контролювати виробничий процес, кінцевий склад розплаву і бажану температуру розливання.

Представлено результати експериментів, їх аналіз та систематизація. Зроблено висновок, що найбільш придатними матеріалами для процесу нагріву розплаву є ковші з найменшими геометричними параметрами в поєднанні з футеровкою RESISTAL B80. У свою чергу, найбільший ківш під час експериментів дає в більшості випадків найбільші ресурсні витрати зі сталевою оболонкою - 498-1972 грн і 0,18-0,74 МДж. В одних результатах, порівнюючи сталевий кожух з RESISTAL B80, ресурсні витрати складають незначну різницю - 3-7 грн. і 0,001-0,003 МДж, а в інших - 24-704 грн. і 0,009-0,266 МДж. При цьому ківш із середніми геометричними розмірами демонструє середні показники ресурсних витрат - 423-1255 грн та 0,16-0,47 МДж.

Розроблено програмне забезпечення для моделювання промислового процесу, що дозволяє проводити чисельні експерименти для конкретної плавки сталі з різними вхідними параметрами для визначення їх впливу на витрати ресурсів. Зберігаючи результати експериментів, можна аналізувати вплив вхідних параметрів на конкретну плавку і приймати правильні рішення для подальших експериментів.

Ключові слова: комп'ютерне моделювання, розплав, зменшення витрат, сталерозливний ковш

Introduction

Reducing resource costs at steelmaking companies is a crucial task. Production efficiency and cost management play a key role in ensuring the competitiveness of enterprises engaged in industrial processes. To achieve these goals, it is important to analyze and optimize various aspects of production processes, such as temperature control, heat loss, and energy management. These measures can improve product quality and help reduce resource costs.

Related works

Most of the solutions found in the literature refer to three stages of the steel production process: melting in arc furnaces [1], refining [2] and continuous casting [3]. On the other hand, the analysis of heat losses in ladles is mainly considered from the point of view of their design.

Such a model was presented in work [4], where the optimal parameters of bucket lining were determined with minimal energy consumption. The model describes the heat exchange of molten steel during ladle transportation between stations. The ladle of the refining unit can determine the temperature of the molten steel under various production parameters, such as the steel grade and the weight of the molten steel. Predicting the temperature at which the ladle arrives at the continuous steel casting station (CSST) is important to plan for overheating during casting and to ensure sufficient time for the ladle to leave the steel casting station at the steel plant.

One of the main approaches used to calculate the required amount of electricity consumed by industrial equipment of metallurgical enterprises is the approach based on the use of regression dependencies of electricity consumption on important factors of the production process. The solution to the problem of electricity consumption based on the forecasting of electricity based on multivariate regression and correlation analyses was also carried out in [5-6].

In [7] emphasizes that the most energy-intensive steelmaking process using electric arc furnaces (EAFs) is subject to automation limitations and decisions related to furnace loading volume, while operators typically make decisions about electrode placement time. The authors proposed a recommendation system based on an economically optimal operating model to support the operator's real-time decision-making for an economically optimal process.

Purpose

A mathematical modeling method was used to predict the thermal state of the liquid metal in the ladle. The calculations took into account the geometric parameters of the steel ladle, thermal properties of the steel melt, slag and lining. For the purpose of this study, the ladle is an open container that receives the molten steel and some slag. In the ladle, 3 graphite electrodes are placed, which are designed to supply electric current to the melt to heat it. The total power of these electrodes is 25000000 W. There are assumptions for mathematical model:

1) View of a steel ladle in the form of a cylinder (Fig. 1).
2) Geometric properties of a steel ladle, which are presented in table 1.
3) Thermal properties of steel melt, slag and lining, which are presented in tables 2-4.

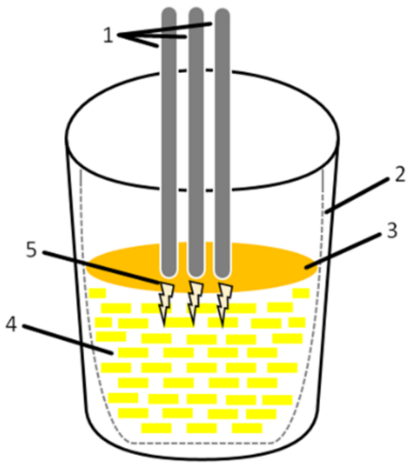

Fig.1. Simplified scheme of a steel ladle
1 - graphite electrodes, 2 - lining, 3 - slag, 4 - liquid metal (melt), 5 - electric current

Table 1

Geometric dimensions of the steel ladle

Ladle number, №	Capacity, t	Height, mm	Average diameter, mm
1	50	2800	2480
2	100	3450	3175
3	250	4350	3885
4	480	5660	4977

Table 2

Thermal properties of melts

Steel melt	Thermal conductivity, $W/(m \cdot K)$	Heat capacity, $Joule/(kg \cdot K)$	Density, kg/m^3	Temperature, K
Iron	50	85	7000	1815,5
Structural steel	30	500	7000	1998,15
Carbon steel	35	550	7500	1723,15
High strength cast iron	40	650	7900	1673,15
Gray cast iron	25	500	6950	1533,15
White cast iron	40	550	7100	1482,15

Table 3

Thermal properties of slag

Material	Thermal conductivity, $W/(m \cdot K)$	Heat capacity, $Joule/(kg \cdot K)$	Density, kg/m^3	Temperature, K
Slag	1,8	1	2675	1473,15

Table 4

Thermal properties of lining

Lining	Thermal conductivity, $W/(m \cdot K)$	Heat capacity, $Joule/(kg \cdot K)$	Density, kg/m^3	Temperature, K
RESISTAL B80	1,8	1212	7000	1815,5
	1,8	1342	2750	1873, 15
	2	1070	2200	673, 15
Steel casing	42	430	7730	673, 15

The heat conduction equation was used to model the process of heating the steel melt and the change in the temperature of the materials over time:

$$\frac{du}{dt} = \frac{k}{cp}\frac{d^2u}{dx^2} - \frac{\mu}{cp}(u^4 - v^4) \tag{1}$$

where $\frac{du}{dt}$ – rate of change of melt temperature over time; k – coefficient of thermal conductivity of the melt; cp – specific heat capacity of the melt; d^2x/dx^2 – dispersion of the melt temperature along the x coordinate; μ – heat transfer coefficient, which characterizes the amount of heat radiated from a unit of material surface per unit of time; u^4 – fourth degree of the melt temperature function; v^4 – the fourth degree function of ambient temperature.

Emissivity is the degree of an object’s ability to absorb and emit energy, i.e. how well the body emits and absorbs energy. In this study, we chose this coefficient of 0.3, and its consideration gives a more accurate result and optimization of resource costs.

The Stefen-Boltzmann constant (law, proportionality coefficient) associated with the blackness coefficient was also taken into account in the thermal process:

$$\sigma = 5{,}6 \cdot 10^{-8} \cdot \frac{Vatt}{m^2 \cdot T^4} \tag{2}$$

To calculate the flows between two points in the system (upstream and downstream), taking into account temperature differences, distance, and thermal conductivity, the Fourier's law (heat conduction) was used. Since the system used layers of air, slag, molten steel, and lining, this law was used to calculate the heat flow between adjacent layers:

$$q = -k\nabla T \tag{3}$$

where q – heat flux; k – thermal conductivity coefficient; ∇T – temperature gradient (temperature difference in space).

In addition, the volume of steel melt in the ladle (75%) was taken into account for all experiments. This made it possible to take into account the volume of liquid steel to heat it, which affected the thermal state and temperature gradient. The area of the bottom and side walls of the ladle was also calculated. In this case, the heat flow calculations are determined in relation to these geometric parameters.

Based on this mathematical model, software was developed to perform numerical studies and analyze the melt heating process with various parameters and their combinations. The main task of this software is to analyze and search for parameters that meet the requirements of the industrial process to reduce resource consumption.

The program has a user-friendly interface through which the user explores the industrial process to find and analyze parameters for certain conditions in order to reduce resource costs. To start the study, the user must select a specific ladle, metal melt, slag and enter such input parameters as: process duration, initial temperature of melt, slag and lining, temperature above slag, room temperature, temperature of electrodes on and off.

After the experiment, the user can save it to the database for further analysis and compare it with others to find the optimal melt heating option. The results obtained can be useful and used for further research on this topic.

During the experiment, the graph displays changes in the temperature of the materials in real time, which makes it possible to study and analyze thermal processes and their dynamics during the experiment.

The C# programming language was chosen to create the software, SQL Server was chosen to store and manage data, and the SQL Server Management Studio (SSMS) environment was chosen as the interface for managing and creating queries. A logical model of the data base is presented in figure 2.

To display the modeling results, we used the chart component, a control for building various types of graphs and charts.

The graphical user interface was developed using Windows Forms technology, which is part of the Microsoft .NET Framework platform, which has a large set of controls, convenient and wide functionality that allows you to quickly and easily create an attractive and functional user interface.

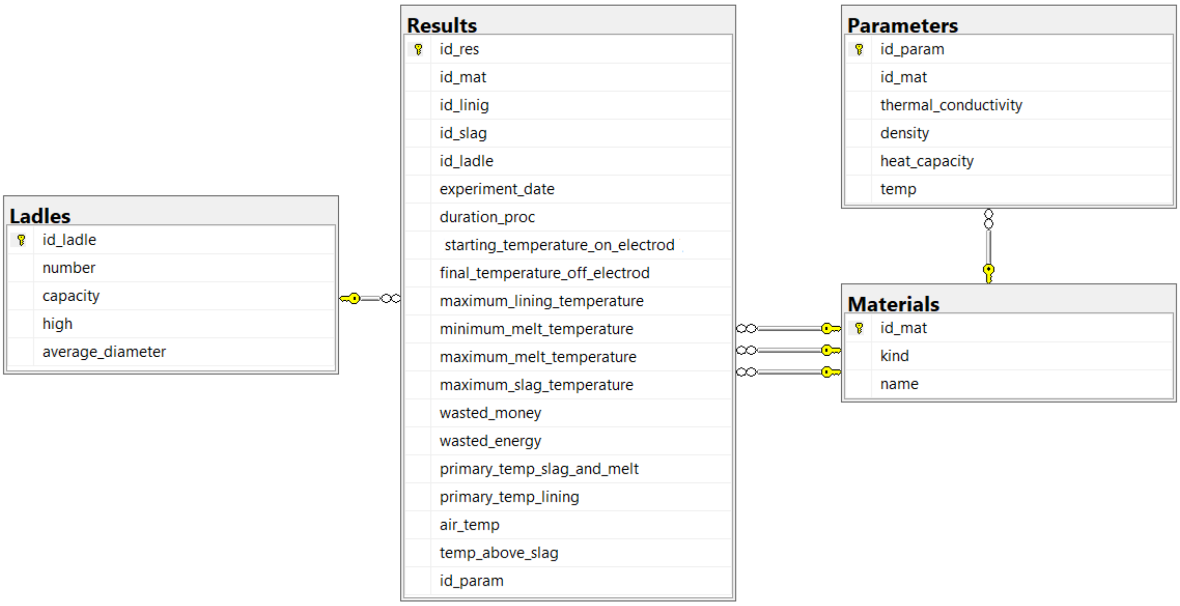

Fig. 2. Logical model of the database

Results

To conduct experiments on the process of heating the steel melt, the heat conduction equation was chosen as the basis for the experiments. During the experiments, the data given in the tables 1-4 and the input data such as: process duration, initial temperature of melt, slag and lining, temperature above slag, room temperature, temperature of electrodes on and off. During the experiments, 100 results were obtained. The duration of each experiment was 10 minutes

Based on the results of the iron melt, we can conclude that the optimal parameters for its heating in terms of resource costs are the following: ladle № 2, RESISTAL B80 lining, electrode exclusion temperature – 1815 and 1830, K; initial melt and slag temperature – 1820, K. In the course of this, 0.16 MJ and 423 UAH were spent. The result of this experiment is shown in figure 2.

The most costly result of heating an iron melt, the graph of which is shown in figure 3, is the following experiment with the following parameters: ladle № 4, steel casing, electrode shutdown temperature – 1812 and 1820, K; initial melt and slag temperature – 1815, K As a result, 0.232 MJ and 612 UAH were spent. The result of this experiment is shown in figure 3.

These results show that in most cases, the materials that have a more costly impact on resource costs are bucket No. 4, which has the highest geometric properties throughout the study, together with the steel casing. In turn, buckets No. 1 and 2, which have the smallest dimensions and are lined with RESISTAL B80, show more favorable results.

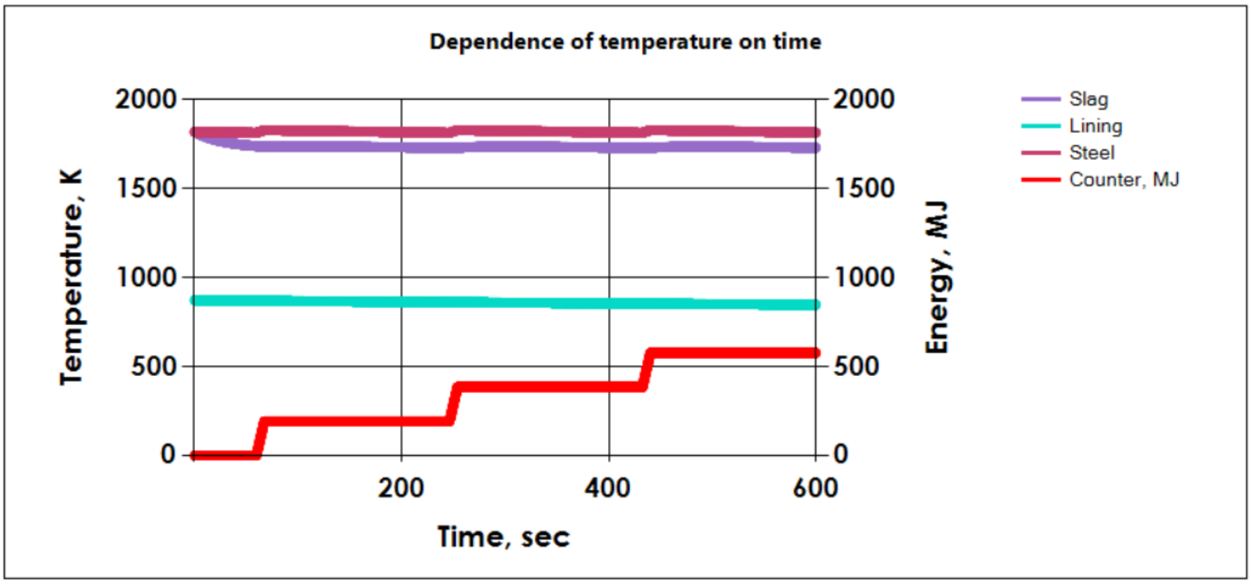

Fig. 3. Chart of experiment with the most energy-efficient consumption of resources for melting iron

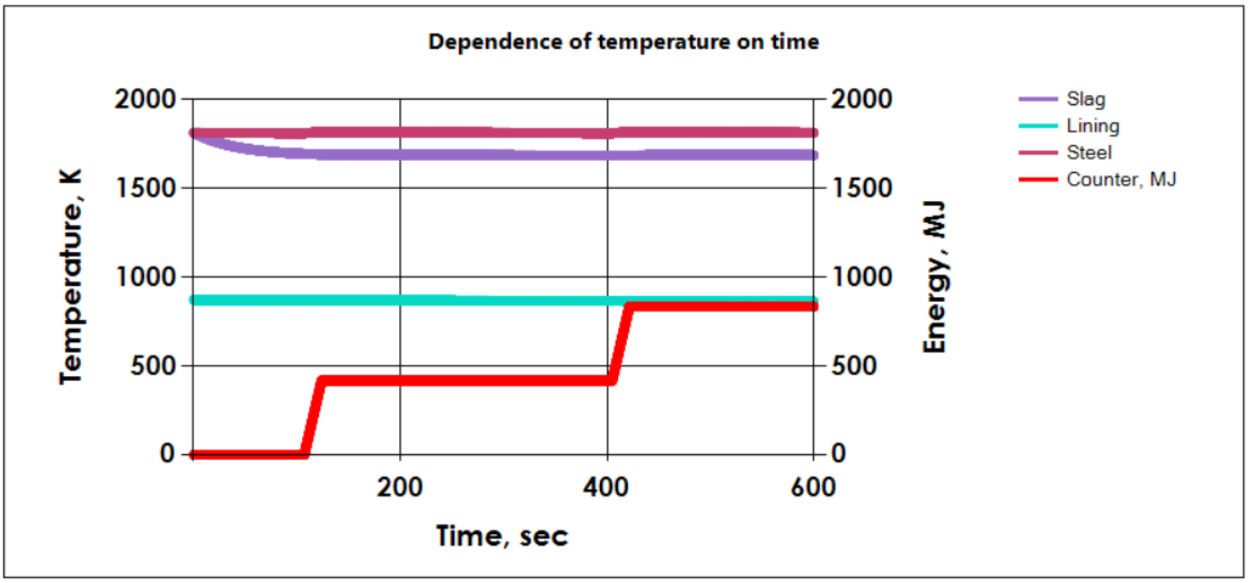

Fig. 4. Chart of the experiment with the largest resource costs for melting iron

Conclusions

The experimental results, their analysis and systematization are presented. It is concluded that the most suitable materials for the melt heating process are ladles with the smallest geometric parameters together with RESISTAL B80 lining. In turn, the largest ladle during the experiments produces in most cases the highest resource costs with a steel casing – 498-1972 UAH and 0.18-0.74 MJ. In some results, comparing the steel casing with RESISTAL B80, the resource costs make up a slight difference – 3-7 UAH. and 0.001-0.003 MJ, and in others – 24-704 UAH and 0.009-0.266 MJ. At the same time, the bucket with medium geometric dimensions shows average indicators of resource costs – 423-1255 UAH and 0.16-0.47 MJ.

Software for modeling an industrial process has been developed that allows conducting numerical experiments for a particular steel melt with different input parameters to determine their impact on resource consumption. Saving the results of the experiments, it is possible to analyze the impact of input parameters on a particular melt and make the right decisions for further experiments.

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MULTI-CRITERIA ASSESSMENT OF THE CORRECTNESS OF DECISION-MAKING IN INFORMATION SECURITY TASKS

Theoretical optimization models assume the presence of a single criterion. Therefore, the solution of the problem by the method of vector (multi-criteria) optimization is of particular interest in the problems of cybersecurity and information security. Especially when it is necessary to evaluate the correctness of the made decisions (CMD). In the paper this problem is solved so that it can be asserted that the decision was made correctly in this particular case when solving a problem while ensuring the information security of a particular object. The problems of developing and using means of protection against "weapons of mass destruction" - information weapons, which are widely used in modern conditions, are becoming relevant. Understanding and analyzing the negative consequences associated with the vulnerability of computer equipment and various information technologies, the problem arises of the need to carry out work to ensure information and cyber security. It is necessary to conduct research and work in many areas - from the development of the theoretical foundations of the information content of computer systems to the development of domestic programs and hardware for technical protection. The solution of these problems may have specific features for individual computer equipment, for automated systems, for local and distributed computing networks, and especially for the Internet. The implementation of models is possible only in the form of a complex of software and hardware based on computer technology with the obligatory use of digital maps of the area. It is necessary to take into account the usefulness of the decisions made. The decision-making problem often encounters a situation, and in our case it is very often when there are several criteria for evaluating a decision. This is due to the multipurpose nature of the situation.

Keywords: correctness of decision-making, multi-criteria assessment, information security.

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БАГАТОКРИТЕРІАЛЬНА ОЦІНКА ПРАВИЛЬНОСТІ ПРИЙНЯТИХ РІШЕНЬ У ЗАДАЧАХ ІНФОРМАЦІЙНОЇ БЕЗПЕКИ

Теоретичні моделі оптимізації припускають наявність єдиного критерію. Тому розв'язання задачі методом векторної (багатокритеріальної) оптимізації становить особливий інтерес у задачах кібербезпеки та інформаційної безпеки. Особливо, коли необхідно оцінити правильність прийнятих рішень (ППР). У роботі дана задача розв'язана таким чином, що можна стверджувати, що в даному конкретному випадку було прийнято правильне рішення при розв'язанні задачі при забезпеченні інформаційної безпеки конкретного об'єкта. Актуальними стають проблеми розробки та використання засобів захисту від «зброї масового ураження» – інформаційної зброї, яка широко використовується в сучасних умовах. Розуміючи та аналізуючи негативні наслідки, пов'язані з уразливістю комп'ютерної техніки та різних інформаційних технологій, постає проблема необхідності проведення робіт із забезпечення інформаційної та кібернетичної безпеки. Необхідно проводити дослідження і працювати за багатьма напрямками - від розробки теоретичних основ інформаційного наповнення комп'ютерних систем до розробки вітчизняних програмно-апаратних засобів технічного захисту. Рішення цих завдань може мати особливості для індивідуального комп'ютерного обладнання, для автоматизованих систем, для локальних і розподілених обчислювальних мереж і особливо для Інтернету. Реалізація моделей можлива лише у вигляді комплексу програмно-технічних засобів на базі комп'ютерної техніки з обов'язковим використанням цифрових карт місцевості. Необхідно враховувати корисність прийнятих рішень. Проблема прийняття рішення часто стикається з ситуацією, а в нашому випадку дуже часто, коли є кілька критеріїв оцінки рішення. Це пов'язано з багатоцільовим характером ситуації.

Ключові слова: правильність прийняття рішень, багатокритеріальна оцінка, інформаційна безпека.

Introduction

Information has become an important strategic resource that is necessary for the successful operation of the state, society and man. At the same time, the information society implies not only the development of the technological component, but also the appropriate level of knowledge development, the highest level of education, the rapid pace of development of science and high technologies.

Now the problems of developing and using means of protection against "weapons of mass destruction" - information weapons, which are widely used in modern conditions, are becoming relevant.

Already now, understanding and analyzing the negative consequences associated with the vulnerability of computer equipment and various information technologies, the problem arises of the need to carry out work to ensure information and cyber security. In general, these problems are multifaceted. It is necessary to conduct research and work in many areas - from the development of the theoretical foundations of the information content of computer systems to the development of domestic programs and hardware for technical protection.

It should be noted that the solution of these problems may have specific features for individual computer equipment, for automated systems, for local and distributed computing networks, and especially for the Internet.

Therefore, a rather important problem that needs to be solved is to determine the list of necessary measures for cybersecurity and technical protection of information in each specific case, determining the list of threats. Such a definition is possible based on the analysis of threat models and protection tools.

A modern approach to solving these problems requires that these models to be modern and combined. The main difference between these models is that they must be dynamic in nature, i.e. so that, along with static information of a general nature, they would allow situational modeling of defense processes using specific means, taking into account existing means of reconnaissance and attack, with reference to a specific object of protection. In this case, it becomes possible to obtain a specific threat model for each specific object in which information needs to be protected, based on the use of technical threat models and object protection. Of course, the implementation of models is possible only in the form of a complex of software and hardware based on computer technology with the obligatory use of digital maps of the area. And at the same time, it is necessary to take into account the usefulness of the decisions made. It should also be taken into account that when developing models, the decision-making problem often encounters a situation, and in our case it is very often when there are several criteria for evaluating a decision. This is due to the multipurpose nature of the situation. At the same time, theoretical optimization models assume the presence of a single criterion. Therefore, the solution of the problem by the method of vector (multi-criteria) optimization is of particular interest in the problems of cybersecurity and information security, especially when it is necessary to evaluate the correctness of the made decisions (CMD).

Related works

The whole set of vector optimization methods, despite their diversity, can be classified as follows:

1) methods of multi-criteria CMD functions, characterized by the synthesis of a single generalized criterion based on a given set of local criteria [1,2];
2) algorithmic methods that regulate a certain sequence of solving specially formulated optimization problems [3,4].

The advantage of methods belonging to the first class is the numerical evaluation of the optimal solution, as well as its numerical comparison with other solutions of interest and with the "ideal" (if it is known).

The theoretical basis for constructing the SPR function was laid down in [5], where a system of rational behavior axioms was formulated, on the basis of which the existence and uniqueness of an individual (local) CMD function was proved. These axioms have the following meaning.

Axiom 1. Comparability of objects of evaluation and transitivity of preferences.

For each pair ω_1, ω_2 only one of the relations is satisfied $\omega_1 \leftarrow \omega_2$, $\omega_1 \rightarrow \omega_2$, $\omega_1 \sim \omega_2$. Moreover, from $\omega_1 \leftarrow \omega_2$, $\omega_2 \leftarrow \omega_3$, it follows $\omega_1 \leftarrow \omega_3$.

Axiom 2. If $\omega_1 \leftarrow \omega_2 \leftarrow \omega_3$, then there is such a parameter $r \epsilon [0,1]$, that $\omega_2 \sim [r\, \omega_1 + (1- r)\, \omega_3]$.

Axiom 3. Validity of commutative and distributive laws:

$[r\omega_1 + (1-r)] \sim [(1-r)\omega_2 + r\omega_1]$;

$\{r[q\omega_1 + (1-q)\omega_2\} + (1-r)\omega_2\} \sim [p\omega_1 + (1-p)\omega_2]$, $(p = rq)$.

When axioms 1-3 are satisfied, there is a CMD function that maps the set of evaluation objects to real numbers. For it $u(\omega_1) < u(\omega_2)$ if $\omega_1 \leftarrow \omega_2$;

$$u(\omega_1) = u(\omega_2) \text{ if } \omega_1 \sim \omega_2. \quad (1)$$

This expression transforms into the next form:

$$u(\omega) = u[r(\omega_1) + (1-r)\omega_2] = [ru(\omega_1) + (1-r)u(\omega_2)]. \quad (2)$$

The CMD expression u is unique up to a positive linear transformation, i.e. for any other expression u satisfying these axioms,

$$u(\omega) = \alpha u(\omega) + \beta, \alpha > 0. \quad (3)$$

In [6] and other works, the parameter r in (2) was interpreted as the value of the probability in a lottery with two outcomes (ω_1, ω_2). However, the theory of fuzzy sets [7] allows to propose a different interpretation: if $\omega_1 \rightarrow \omega \rightarrow \omega_2$, then the parameter $r \in [0,1]$ is the degree of belonging of the object ω_1 to the fuzzy set of CMD, for which the highest degree of membership belongs to the object ω_1, the lowest - object ω_2. Then $r(\omega)$ is a membership function of ω in the same fuzzy set.

Let there be a set of local evaluation criteria *N=(1,2,3,…,n)*. Then the vector estimation problem includes two stages:

1) the stage of assessing the object ω for each *i*-th local criterion $x_i = u_i(\omega)$, $x_i \in X_i$;

2) the stage of assessing the object $x_N = (x_1, x_2, x_3, \dots, x_n) \in X_N$, where X_N - Cartesian product of measuring scales of local criteria $X_N = X_1 * X_2 * X_3 * \dots * X_n$.

Let introduce the assumption that axioms 1-3 are valid not only for objects ω, but also for vectors of estimates $x_N \in X_N$, which means that there is a mapping

$$U: X_N \to R^1. \tag{4}$$

This is a very strong assumption, and the most likely objections to it are: X_N objects are non-transitive. The answer to the first objection is that X_N objects are a reflection of various ways to achieve the goal, each of which is characterized by its degree of achievement. Therefore, they are just from the point of view of this purpose. Therefore, objects that are not related to this goal will be incomparable from this point of view. The case of incomparability is the absence of a goal, but here there is no need to determine the CMD in relation to objects. It is difficult to give a categorical answer to the second objection. However, experiments show that the made decisions are usually transitive [8][9].

Main part

To obtain the form of the multicriteria CMD function, we formulate two additional axioms.

Axiom 4. Symmetry. Changing the designations of local criteria does not change the nature of preferences:

$$(x_1, x_2, \dots, x_i, \dots, x_j, \dots, x_n) \sim (x_1, x_2, \dots, x_j, \dots, x_i, \dots, x_n).$$

This axiom is somewhat analogous to the commutative law from Axiom 3, which implies that no restriction is imposed on the method of numbering local criteria. In what follows, based on Axiom 4, we will use the following notation: x_N- is the vector of ratings by all local criteria, x_P- is the vector of ratings by local criteria from the non-empty set $P \subset N$, $x_{\frac{N}{P}}$- is the vector of ratings by local criteria from set that is the difference N\P. Then $x_N = (x_P x_{N\backslash i})$, if *P*- is a one-element set, $x_N = (x_i x_{N\backslash i})$.

Axiom 5. Monotony of group preferences. Any improvement in the rating vector for one or more local criteria, with the level of ratings for the rest unchanged, leads to the fact that the new rating vector will be at least no worse than the original one, i.e., from $x_p' \leftarrow x_p''$ it follows $(x_P x_{N\backslash P}) \precsim (x_p'' x_{N\backslash P})$.

Suppose, for the values of each *i*-th local criterion, a range is given

$$x_i' \precsim x_i \precsim x_i''. \tag{5}$$

Then, based on Axioms 2 and 5, for any value of $x_{N\backslash i}$ we have

$$(x_i x_{N\backslash i}) \sim [\lambda_i (x_i'' x_{N\backslash i}) + (1 - \lambda_i)(x_i' x_{N\backslash i})], (i \in N)\ . \tag{6}$$

In accordance with (2), the CMD function of the *i*-th local criterion, taking into account the influence of $x_{N\backslash i}$ on x_i, has the form

$$U(x_i x_{N\backslash i}) = \lambda_i(x_i | x_{N\backslash i}) U(x_i'' x_{N\backslash i}) + [1 - \lambda_i(x_i | x_{N\backslash i})] U(x_i' x_{N\backslash i}), \tag{7}$$

where $\lambda_i(x_i | x_{N\backslash i}) \in [0,1]$ – conditional membership function of the vector $(x_i | x_{N\backslash i})$ to the fuzzy set of CMD defined by the boundaries $(x_i'' x_{N\backslash i})$ and $(x_i' x_{N\backslash i})$. The term "conditional" here is understood in the same way as in probability theory in relation to distribution functions. If the *i*-th criterion does not depend on the others in terms of correctness, then expression (7) is simplified:

$$U(x_i x_{N\backslash i}) = \lambda_i(x_i) U(x_i'' x_{N\backslash i}) + [1 - \lambda_i(x_i)] U\left(x_i' x_{\frac{N}{i}}\right).$$

Function (7) is indeed a function of the CMD of a local criterion, despite the use of the designation of the multi-criteria correctness function U. This is obvious if, using property (3), we denote $U(x_i'' x_{N\backslash i}) = 1$, $U(x_i' x_{N\backslash i}) = 0$, whence it follows $U(x_i x_{N\backslash i}) = \lambda_i(x_i x_{N\backslash i})$.

Proceeding from these provisions, we will prove the main property of the function of multi-criteria decision-making correctness.

Theorem. There is an analytical expression for the multi-criteria CMD function from the set of CMD functions of local criteria.

Proof. First consider the two-dimensional case $x_N = (x_1 x_2)$, and then extend the result to any N.

Let us write expression (7) for the correctness function of the second criterion, provided that the evaluation of the first x_1

$$U(x_1 x_2) = \lambda_2(x_2|x_1)U(x_1 x_2'') + [1 - \lambda_2(x_2|x_1)]U(x_1 x_2). \quad (8)$$

Similarly, we write expressions for the CMD function of the first criterion for x_2'', x_2':

$$U(x_1 x_2'') = \lambda_1'(x_1|x_2'')U(x_1'' x_2'') + [1 - \lambda_1(x_1|x_2'')]U(x_1' x_2''); \quad (9)$$
$$U(x_1 x_2') = \lambda_1(x_1|x_2')U(x_1'' x_2') + [1 - \lambda_1(x_1|x_2')]U(x_1' x_2'). \quad (10)$$

Using Axiom 3, substituting (9) and (10) into (8). Thus, we supplement the preference characteristic according to the second criterion (8) with the corresponding characteristics according to the first criterion (9) and (10). As a result, we obtain the CMD function of the object $(x_1 x_2)$ according to two local criteria:

$$\begin{gathered} U(x_1 x_2) = \lambda_1(x_1|x_2'')\lambda_2(x_2|x_1)U(x_1'', x_2'') + \\ +[1 - \lambda_1(x_1|x_2'')]\lambda_2(x_2|x_1)U(x_1' x_2'') + \\ +\lambda_1(x_1|x_2')[1 - \lambda_2(x_2|x_1)]U(x_1'', x_2') + \\ +[1 - \lambda_1(x_1|x_2')][1 - \lambda_2(x_2|x_1)]U(x_1' x_2'). \end{gathered} \quad (11)$$

Based on Axioms 2 and 5, we express $U(x_1' x_2'')$ and $U(x_1'', x_2')$ in terms of boundary values:

$$U(x_1' x_2'') = \lambda_{(12)}(x_1' x_2'')U(x_1'' x_2'') + \left[1 - \lambda_{(12)}(x_1' x_2'')\right]U(x_1' x_2'); \quad (12)$$

$$U(x_1'' x_2') = \lambda_{(12)}(x_1'' x_2')U(x_1'' x_2'') + \left[1 - \lambda_{(12)}(x_1'' x_2')\right]U(x_1' x_2'). \quad (13)$$

Using Axiom 3, we substitute (12) and (13) into (4). As a result, we get

$$U(x_1 x_2) = \lambda_{(12)}(x_1 x_2)U(x_1'' x_2'') + \left[1 - \lambda_{(12)}(x_1 x_2)\right]U(x_1' x_2'). \quad (14)$$

where $\lambda_{(12)}(x_1 x_2) = \{1 - [1 - \lambda_1(x_1|x_2'')][1 - \lambda_{12}(x_1'|x_2'')]\}\lambda_2(x_2|x_1) + +\lambda_1(x_1|x_2')\lambda_{(12)}(x_1'' x_2')[1 - \lambda_2(x_2|x_1)]$, $\lambda_{(12)}(x_1 x_2) \in [0,1]$. (15)

Therefore, the resulting function (14) implements U: $(X_1 X_2) \to R^1$. This means that the set of the first and second local criteria can be replaced by a new scalar criterion $x_{(12)}$, for which $x_{(12)}' \precsim x_{(12)} \precsim x_{(12)}''$. Then similar reasoning for criteria $x_{(12)}$, x_3 will lead to the CMD function of three criteria $x_{(123)}$. After performing this procedure *(n-1)* times, we obtain the correctness function for N local criteria:

$$U(x_N) = \lambda_N(x_N)U(x_N'') + [1 - \lambda_N(x_N)]U(x_N'), \quad (16)$$

where $x_N'' = (x_1'' x_2'' x_3'' \dots x_n'')$, $x_1' x_2' = (x_1' x_2' \dots x_n')$.

When implementing the mapping p: $\lambda_{I|i}(x_{I|i}) \to \lambda_{I|i}(x_{I|i}|x_i)$; the value $\lambda_N(x_N)$ is determined similarly to (15) by the recursive formula

$$\begin{gathered} \lambda_I(x_I) = \{1 - [1 - \lambda_{I|i}(x_{I|i}|x_i'')][1 - \lambda_I(x_{I|i}' x_i'')]\}\lambda_i(x_i|x_{I|i}) + \\ +\lambda_{I|i}(x_{I|i}|x_i')\lambda_I(x_{I|i}'' x_i')[1 - \lambda_i(x_i|x_{I|i})],\ \lambda_I(x_I) \in [0,1). \end{gathered} \quad (17)$$

In this formula $I = (1,2,3, \dots, i)$, $I|i = (1,2,3, \dots, i-1)$.

The CMD function (16) is the only one up to a positive linear transformation (3), which is obvious from $U(x_N) = \lambda_N(x_N)[U(x_N'') - U(x_N')] + U(x_N')$. This means that the choice of the beginning and end of the scale of the correctness of decision-making is not fundamental, only the function $\lambda_N(x_N)$, which is determined by the set of N CMD functions of local criteria according to the rule (17). The theorem has been proven.

Using a similar technique, it is easy to show that for $(x_i x_{N|i}) = \alpha_i U(x_i x_{N|i}) + \beta_i$, $\alpha_i > 0$ there is $V(x_N) = \alpha_N U(x_N) + \beta_N$, where α_N, β_N are determined by recursive formulas

$$\alpha_I = \alpha_{I|i}\alpha_i, \beta_I = \beta_{I|i}\alpha_i + \beta_i.$$

The proved theorem fundamentally solves the question of the uniqueness of the multicriteria CMD function. However, the resulting expression (17) is inconvenient for analysis in real problems. In [10], it is shown that the fulfillment of Axiom 5 generates three goal-forming principles in multicriteria problems. For each of the principles, its own multi-criteria correctness function is synthesized, which is a special case of (17), which is constructive.

Conclusions

It should be noted that, in contrast to [9], the term "correctness independence" of the i-th criterion means that the utility function of the SPR is unchanged for any value of the evaluation vector $x_{N|i}$, i.e. the condition (18) is met

$$\lambda_i(x_i|x_{N|i}) = \lambda_i(x_i). \tag{18}$$

This is a less stringent condition than the equivalence of various combinations of vector objects [11]. Therefore, in this setting, independence does not mean the additivity of local estimates.

To check the possibility of fulfilling condition (18), we write the CMD function of i-th local criterion (7) in the form:

$$\lambda_i(x_i|x_{N|i}) = \frac{U(x_i x_{N|i}) - U(x_i' x_{N|i})}{U(x_i'' x_{N|i}) - U(x_i' x_{N|i})}. \tag{19}$$

Differentiating (19) in the direction determined by the vector $x_{N|i}$, and equating the numerator to zero, we obtain the required condition

$$\begin{gathered} \frac{\partial U(x_i x_{N|i})}{\partial x_{N|i}}\left[U(x_i'' x_{N|i}) - U(x_i' x_{N|i})\right] - \\ -\frac{\partial U(x_i'' x_{N|i})}{\partial x_{N|i}}\left[U(x_i x_{N|i}) - U(x_i' x_{N|i})\right] - \\ -\frac{\partial U(x' x_{N|i})}{\partial x_{N|i}}\left[U(x'' x_{N|i}) - U(x_i x_{N|i})\right] = 0. \end{gathered} \tag{20}$$

For each goal-forming principle [10], condition (20) is satisfied if the change in the correctness of the vector x_N with a change in only one i-th component can be described by a function only from this component $U(x_i x_{N|i}) = \alpha_i(x_i x_i') U(x_i x_{N|i}) + \beta_i(x_i x_i')$. That is, the correctness of decision-making allows us to assert that the decision was made correctly in this particular case when solving a problem while ensuring the information security of a particular object.

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SELECTION OF THE ARTIFICIAL INTELLIGENCE COMPONENT FOR CONSULTATIVE AND DIAGNOSTIC INFORMATION TECHNOLOGY FOR GLAUCOMA DIAGNOSIS

The most important areas of application of consultative and diagnostic systems are urgent and life-threatening conditions characterized by a lack of time, limited opportunities for examination and consultations, and often little clinical symptoms with a high level of threat to the patient's life and the rapid pace of development of the process. The experience of using consultative and diagnostic systems proves a significant improvement in the quality of diagnostics, which not only reduces unjustified losses, but also allows more effective use of aid resources, regulates the volume of necessary research, and finally, increases the professional level of doctors for whom such a system serves at the same time and educational. Consultative diagnostic systems and technologies are currently rarely and insufficiently used in ophthalmology, although the field of ophthalmology in general and glaucoma diagnosis in particular are in great need of them.

Currently, the problem of using artificial intelligence for the problem of glaucoma analysis is faced with the fact that neural networks themselves and the methods of their use are not made suitable for mass use, with the complexity of development for certain models, with the inaccessibility for mass use, and the difficulty of collecting data for training neural models due to "confidentiality" of data. There is also the issue of cost and diagnostic availability — the availability of a trained professional, the means to collect data, and the time it takes for a patient to receive a diagnosis.

The author's further research will be aimed at creating the neural network itself for the diagnosis of glaucoma with different approaches from the available data types for each individual case, as well as creating programs and instructions for deploying such a neural network in places of use and using it with minimal requirements and resource needs. Compared to other similar products, this will be such an introduction of artificial intelligence that will allow to incorporate all the available experience into a small number of lines of code and will have pros in low budget and mass use.

Keywords: consultative and diagnostic information technology, ophthalmology, glaucoma diagnostics, artificial intelligence.

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ВИБІР КОМПОНЕНТУ ШТУЧНОГО ІНТЕЛЕКТУ ДЛЯ КОНСУЛЬТАТИВНО-ДІАГНОСТИЧНОЇ ІНФОРМАЦІЙНОЇ ТЕХНОЛОГІЇ ДІАГНОСТУВАННЯ ГЛАУКОМИ

Найбільш важливі області застосування консультативно-діагностичних систем – невідкладні та загрозливі для життя стани, що характеризуються дефіцитом часу, обмеженими можливостями обстеження і консультацій і нерідко малою клінічною симптоматикою при високому рівні загрози для життя хворого і швидких темпах розвитку процесу. Досвід використання консультативно-діагностичних систем доводить суттєве підвищення якості діагностики, що не лише зменшує невиправдані втрати, але і дозволяє більш ефективно використовувати ресурси допомоги, регламентувати об'єм необхідних досліджень, і нарешті, підвищити професійний рівень лікарів, для яких така система слугує одночасно і навчальною. В офтальмології наразі рідко та недостатньо ефективно використовуються консультативно-діагностичні системи та технології, хоча галузь офтальмології в цілому та діагностування глаукоми зокрема дуже їх потребують.

Наразі проблема використання штучного інтелекту для проблеми аналізу глаукоми полягає в тому, що самі нейромережі та методи їх використання є мало придатними для масового використання, зі складністю розробки для певних моделей, з недоступністю для масового використання та важкістю збору даних для навчання нейронних моделей через "конфіденційність" даних. Також є проблема вартості та можливості діагностики — наявність кваліфікованого спеціаліста, засіб для збору даних та час, необхідний для пацієнта, щоб отримати діагностику.

Подальші дослідження авторів будуть спрямовані на створення самої нейромережі для діагностики глаукоми з різними підходами від наявних типів даних для кожного окремого випадку, а також створення програм та інструкцій для розгортання такої нейромережі на місцях використання та використання її з мінімальними вимогами та потребами в ресурсах. В порівнянні з іншими подібними продуктами це буде таке впровадження штучного інтелекту, яке дозволить втілити весь наявний досвід у невелику кількість рядків коду і буде відрізнятись бюджетністю та масовістю використання.

Ключові слова: консультативно-діагностична інформаційна технологія, офтальмологія, діагностування глаукоми, штучний інтелект.

Introduction

Modern information technologies are increasingly more often used in the field of health care, which is convenient, and sometimes simply necessary. Thanks to this, medicine, including non-traditional, acquires completely new features today. In many medical studies, it is simply impossible to do without a computer and special software for it. This process is accompanied by significant changes in medical theory and practice, associated with the introduction of corrections both at the stage of training medical workers and for medical practice.

Historically, consultative diagnostic systems began to develop as one of the first medical diagnostic systems. Currently, consultative and diagnostic systems are represented by numerous systems for diagnosing pathological conditions (including prognosis) in diseases of various profiles and for different categories of patients. The input information for such systems is data on the symptoms of diseases, which are entered into the computer in dialog mode, or in the format of specially developed information cards. Diagnostic conclusions, in addition to the diagnosis (or possible diagnoses), as a rule, also contain recommendations for choosing a tactical solution and therapeutic measures.

The most important areas of application of consultative and diagnostic systems are urgent and life-threatening conditions characterized by a lack of time, limited opportunities for examination and consultations, and often little clinical symptoms with a high level of threat to the patient's life and the rapid pace of development of the process.

The experience of using consultative and diagnostic systems proves a significant improvement in the quality of diagnostics, which not only reduces unjustified losses, but also allows more effective use of aid resources, regulates the volume of necessary research, and finally, increases the professional level of doctors for whom such a system serves at the same time and educational

Consultative diagnostic systems and technologies are currently rarely and insufficiently used in ophthalmology, although the field of ophthalmology in general and glaucoma diagnosis in particular are in great need of them.

In the field of eye health, glaucoma stands out as a silent threat to vision, often progressing imperceptibly until irreversible damage occurs.

Glaucoma is known for its insidious onset, with patients often experiencing no symptoms until significant vision loss occurs. Traditional diagnostic methods such as intraocular pressure measurement and visual field tests are important, but in some cases may not be sufficient for early detection. The elusive nature of glaucoma makes timely diagnosis a serious challenge for medical professionals. In order to detect glaucoma, it is necessary not only to use traditional diagnostic methods, but also to take pictures and diagnose pictures of the patient's fundus. In order to take pictures of the fundus, expensive equipment is needed, which not every state medical institution of Ukraine can afford. In addition, high-quality diagnosis requires extensive experience in recognizing and diagnosing similar diseases. Also, patients need to allocate time and money for diagnosis, which also reduces the likelihood of timely diagnosis of glaucoma.

Challenges related to the diagnosis of glaucoma (difficulty of early diagnosis, asymptomatic early stages, the need for a complex technique and sufficient qualification for diagnosis, the allocation of time by the patient for diagnosis) require the search for innovative solutions for the early diagnosis of glaucoma.

One of the promising and innovative ways to process diagnostic data in order to detect minor and barely noticeable changes to the human eye are components of artificial intelligence, since artificial intelligence ensures the accumulation of experience, the absence of forgetting experience with insufficient use, and the ability to freeze the training of an artificial intelligence unit at the highest point of efficiency. In addition, for example, machine learning algorithms (as one of the components of AI) have the ability to analyze huge amounts of data with unprecedented speed and accuracy.

Therefore, *the task of this study* will be the selection of an artificial intelligence component for consultative and diagnostic information technology for diagnosing glaucoma.

Analysis of known methods and solutions

Analysis of known works and solutions for detecting eye diseases by fundus imaging:

1) Algorithm based on artificial intelligence for early detection of glaucoma. Used by a hospital in Singapore for diagnosis. Created by scientists from Nanyang Technological University (Singapore) in collaboration with doctors at Tan Tok Seng Hospital. Claimed accuracy of 97%. Pros: all the above-mentioned advantages of artificial intelligence [1];
2) Algorithm for screening diabetic retinopathy in the early stages with the help of artificial intelligence. Created by the Ukrainian medical IT startup CheckEye in association with the private medical center "Zakarpatska Endoclinic". For screening using this method/algorithm, it is possible to make an appointment by phone on the website check-eye.com in the version of the website localized in the Ukrainian language. Pros: localized in Ukraine Disadvantages: personal data is required (personal data is not required for fundus screening), small distribution of places of use/examination, a certificate from a doctor about diabetes is required, does not apply to glaucoma [2];
3) Intelligent technology of computer diagnostics of eye pathologies. Accuracy: not specified. Pros: detailed mathematical description [3];
4) Computer tools for diagnosing diseases based on a neural network. Accuracy: not specified. Pros: mathematical description [4];
5) Artificial intelligence in glaucoma: posterior segment optical coherence tomography. Pros: The standard machine learning pros. Disadvantages: the requirement of expensive equipment to obtain tomography [5];

6) Using machine learning with regular positive reinforcement and feedback from doctors. Pros: Feedback to improve accuracy [6];
7) Comparison of different machine learning classifiers for glaucoma diagnosis based on the SPECTRALIS retinoscope. Pros: description of different methods [7];
8) Overview of data processing of different machine learning methods for ophthalmology. Pros: Using different methods and recording results [8];
9) Development and verification of a deep learning optical glaucoma diagnosis system using coherence tomography. Pros: detailed description of the results, partial description of the method [9];
10) Investigating the potential of neural networks for the identification of eye diseases. Pros: ready-made code with a solution [10];
11) Glaucoma detection on retinal fundus images based on transfer learning and fuzzy clustering. Pros: the transfer method allows you to reduce the time of study [11];
12) Segmentation and Classification Algorithms for Glaucoma Detection Based on Machine Learning. Pros: A list of approaches leading to the highest accuracy is provided [12];
13) Detection of glaucoma using a hybrid deep learning model. Pros: the specified method for the least data loss when moving between model layers [13];
14) IoT-Based Predictive Modeling for Glaucoma Detection in Optical Coherence Tomography Images Using a Hybrid Genetic Algorithm. Pros: high accuracy of the method, clear description of the approach [14];
15) Advances in glaucoma detection using deep machine learning [15];
16) An online platform for early detection of eye diseases using deep machine learning. Pros: mass approach to using the result of machine learning [16].

Role of artificial intelligence in the diagnosis of glaucoma

As the analysis showed, in the context of glaucoma diagnosis, artificial intelligence can solve several key problems:

1) Early diagnosis detection – one of the main advantages of artificial intelligence in the diagnosis of glaucoma is its ability to detect subtle changes in the eye that may not be visible to the human eye. By analyzing image data, such as optical coherence tomography (OCT) scans or images taken during fundus screening, artificial intelligence algorithms can identify early signs of glaucomatous damage, allowing for intervention before irreversible vision loss occurs;
2) Personalized diagnostics and risk detection – AI systems can integrate a variety of patient data, including medical history, genetics and lifestyle factors, to create personalized health records with risk information for various diseases. This specialized approach enables healthcare professionals to identify individuals at increased risk of developing glaucoma, facilitating early monitoring and early intervention;
3) Increased accuracy when analyzing the field of view – traditional visual field tests are subjective and can vary depending on the patient's interpretation of the words. AI-based algorithms can improve the accuracy of visual field testing, minimizing variability and providing more reliable results. This may lead to more accurate and consistent monitoring of glaucoma progression;
4) Optimization of the diagnostic process – artificial intelligence can significantly reduce the burden on healthcare professionals by automating time-consuming tasks such as image analysis and data interpretation. This efficiency allows physicians to focus on patient care and decision making, ultimately improving the overall diagnostic process. Also, artificial intelligence can be combined with existing means of information dissemination for mass application and simplifying obtaining advice from an experienced and qualified mind to determine glaucoma;
5) Medical ethics – although the potential benefits of artificial intelligence in glaucoma diagnosis are exciting, ethical issues must be acknowledged. Ensuring the privacy and security of patient data, eliminating errors in AI algorithms, and establishing clear guidelines for the integration of AI into clinical practice are key aspects that require close attention. And all medical ethics depends little on artificial intelligence to diagnose diseases. Moreover, personal information is important for artificial intelligence only from the point of view of making a diagnosis — any person is a separate case with a set of information based on which a diagnosis can be made and no more.

The integration of artificial intelligence into the diagnosis of glaucoma represents a transformative step forward in the search for early detection and effective treatment of this sight-threatening condition. By using machine learning, healthcare professionals will be able to overcome diagnostic challenges, offering hope for a future where glaucoma is much less of a threat to vision, as prevention of glaucoma will occur much earlier than the negative consequences of late detection.

Conclusions

Currently, the problem of using artificial intelligence for the problem of glaucoma analysis is faced with the fact that neural networks themselves and the methods of their use are not made suitable for mass use, with the complexity of development for certain models, with the inaccessibility for mass use, and the difficulty of collecting data for training neural models due to "confidentiality" of data. There is also the issue of cost and diagnostic availability—the availability of a trained professional, the means to collect data, and the time it takes for a patient to receive a diagnosis.

The author's further research will be aimed at creating the neural network itself for the diagnosis of glaucoma with different approaches from the available data types for each individual case, as well as creating programs and instructions for deploying such a neural network in places of use and using it with minimal requirements and resource needs. Compared to other similar products, this will be such an introduction of artificial intelligence that will allow to incorporate all the available experience into a small number of lines of code and will have pros in low budget and mass use.

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