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ORGANIZATIONAL STRUCTURE OF TECHNICAL PROTECTION OF INFORMATION AT THE NETWORK LEVEL USING VPN TECHNOLOGY

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Abstract. Recently, connecting employees to the company's internal network remotely through public resources has become widespread among small and medium-sized companies. In this case, the issue of information protection has become acute since a certain share of information may circulate through an unprotected network. Currently, VPN technology, which has many options for implementing networks for different purposes of use, is widely used. Among the variety of implementations, this research has chosen the construction of a VPN network based on Cisco equipment as an object of research. This approach has been chosen because of the prevalence and availability of equipment, and the availability of a simulator to design, set up and test the network. The organization structure, in which employees can work both inside and outside the corporate network, has been described. At the same time, each of the employees is supposed to have equal opportunities to connect to servers securely and work with data related to the organization's activities. Accordingly, for the employees who work remotely, the issue of information security is specifically acute. Therefore, the authors propose a network model, which consists of three zones: the main office, the remote worker's workplace, and a segment with servers located in the demilitarized zone (DMZ). The demilitarized zone provides an additional level of security for the local network, which minimizes damage in the event of an attack on one of the publicly available services: an external attacker has direct access only to the equipment in the DMZ. The VPN technology will be used as a means of protecting the connection of employees to servers with the organization's data. The network hardware is selected. The Cisco 2811 router which is used to cover the needs of small organizations (up to 36 workplaces) is chosen to combine all segments into one network. Practical implementation of the VPN technology settings in the presented distributed network of the organization has been conducted. The computer network is simulated in the Cisco Packet Tracer environment. As a result of fulfilling the assigned tasks, security policies have been implemented in the network based on the use of Cisco VPN technology. This tool makes it possible to organize a secure VPN channel for connections from within the organization's network, which, in turn, allows a remote employee to access the organization's servers and data. The results of this work can be used by the companies or individual users who plan to integrate the VPN architecture, based on Cisco equipment, into their network infrastructure.

Keywords: network, demilitarized zone, Packet Tracer simulator, Cisco, VPN tunnel, cryptographic map.

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Introduction

Modern business is reaching out far beyond the region and country borders. As a result, the enterprises' structural components have become more distributed. Accordingly, communication and exchange of information between the enterprise's branches is realized through the Internet. The pandemic also contributed to the trend when remote work became the norm for many organizations. In Ukraine, this phenomenon received an additional impetus with the full-scale war of the Russian Federation against Ukraine, which spurred an extensive migration of specialists, posed threat to the employees' safety during missile attacks, which made remote work a new reality. Organizations introduced special policies regarding remote employees. It is obvious that the growth of the number of users, the amount of information and its value naturally requires a solution to the problem of information protection (Zhilin *et al.*, 2021). Information in the modern world has become a value that must be reliably protected (Buriachok *et al.*, 2019). Every year, huge amounts of money are spent on the information security of enterprises, state institutions and organizations, but does not guarantee a complete protection of information systems, since the methods of external intervention are being improved, the initiators of which can be either ordinary cybercriminals who aim to enrich themselves or obtain a competitive advantage, or even organized groups of specialists acting in the interests of the country, whose policies and activities are aimed at the infrastructure and critically important information resources of another state (Mohan *et al.*, 2015). It is obvious that protection should be targeted at the main properties of information: integrity, confidentiality, and availability (Mykytyshyn *et al.*, 2016).

The relevance of information protection at the network level lies in the fact that there is a key need to ensure the confidentiality of data transmitted within the network (Graivoronsky *et al.*, 2009). On the scale of the office, it is quite possible to create a secure network, but this will only partially solve the security problem, because in modern conditions some employees have remote access, so it is necessary to expand the security policy of the organization to the entire network infrastructure (Semenov *et al.*, 2014).

The security policy of the organization is developed in accordance with the provisions of ND TZI 1.1-002-99 and recommendations of ND TZI 1.4-001-2000.

Literature review

One of the common approaches to solving the problem of information security is setting up and using virtual private networks (Virtual Private Network or VPN) (Galkin *et al.*, 2016; Vasylyna *et al.*, 2013). This technology is widely spread since, in addition to the security advantages it offers, it allows the user to bypass certain network restrictions, for example, it provides access to sites and resources that are prohibited in the country or by organization regulations. With this aim, for example, you can use the Opera browser above version 40 to easily enable a free VPN option. In addition to specialized software that complements the operating system with VPN functions. In addition, there are other methods, including software and hardware and integrated solutions that employ various tools, such as a router with the function of filtering network traffic, network screens, proxy servers, software-hardware encryptors etc. (A Framework for IP Based Virtual Private Networks; Pure hardware VPNs uale high-availability tests).

The idea of building virtual VPN networks is based on a fairly simple reasoning about building a secure tunnel between two nodes of an open network, which, through cryptographic algorithms, is inaccessible to outside observers, which will ensure confidentiality and integrity of information (Medvedev *et al.*, 2002).

Cisco Systems (Cisco IOS Quality of Service Solutions Configuration Guide) is the leader in the market of network equipment used in creating and using VPN technology. The company has specifically implemented the following technologies: Cisco ASA for network screens, Cisco Secure IDS for the intrusion detection system, Cisco VPN for virtual private networks (Bartlett *et al.*, 2016; Bollapragada *et al.*, 2005).

VPN technology offers an opportunity to establish a network connection over another network. A VPN connection provides users with secure access to an organization's corporate network while limiting access for the attackers. To equip a network connection with such a property, it is necessary to implement three basic principles: tunneling, encryption, and authentication (Douglas Crawford). Data transfer between sender and receiver network nodes takes place through multiple nodes of an open public network, but due to tunneling, the traffic passes as if they were combined into one local network. This is implemented due to an asymmetric cryptographic encryption algorithm, which generates additional information transmitted along with the main data packet. On the receiving side, this additional information is used for data authentication, which ensures their security.

The most commonly used protocols to establish a VPN are IPSec, PPTP, PPPoE, L2TP, L2TPv3 and OpenVPN (VPN protocols; We choose the VPN protocol; What is SSL?).

VPN service providers use encryption and a set of IPSec protocols to encapsulate user data for reliable protection (IPSec is a protocol for protecting network traffic at the IP level). Cisco IOS SSL VPN technology provides access to the corporate network using the SSL cryptographic protocol and provides data transmission of various types, including those with increased bandwidth requirements (audio and video files).

Materials and methods

The purpose of the research: building a model of information protection at the network level using Cisco VPN technology.

Research objectives:

- 1) describe the organization (institution) and construct a model of its distributed network, where the information protection system is implemented;
- 2) implement the VPN technology settings in the presented distributed network of the organization and test the information protection system.

When developing an information protection system, the developer should be guided by regulatory documents that stipulate the minimum requirements for its creation.

Here, we consider a simple model of the organization, which can be expanded and supplemented in the future. This approach will demonstrate the basic principles of implementing information protection based on Cisco VPN technology. Suppose that the institution for which an information protection system is being implemented is engaged in work related to commercial secrets and at the same time has a limited budget funding and a small staff. Therefore, for the proper functioning of the system, it is necessary to take maximum security measures, which would not exceed the limited budget.

Suppose that the staff in this organization consists of three workers who are installed in the main office and an employee who performs the duties remotely. At the same time, each of the employees must be equally enabled to securely connect to servers and work with data related to the company's activities.

One of the factors contributing to better information protection from unauthorized access and interference from the outside is to divide the network into three zones: the main office (LAN), the remote worker's workplace (Branch) and the premises with servers located in the demilitarized zone.

The Demilitarized Zone (DMZ) is a network with limited access that separates a private network from a public network. The DMZ hosts various servers, such as: file (FTP), domain name (DNS), mail (MTA), proxy, IP telephony (VoIP), etc. The purpose of DMZ is to ensure the security of a private network by providing the company with access to untrusted networks (the Internet). If you provide open access to the necessary resources of the external network, then the internal network will be at risk. The solution to this complication can be to install the necessary servers in an isolated DMZ network, which is separated from the private one by means of a firewall that will filter the traffic between them. In turn, the DMZ server is protected by another firewall, which acts as a buffer between the restricted access network and the external network. Thus, the existence of a DMZ creates two additional barriers for an attacker, whose task is to compromise the system's operation in the DMZ first, then break the protection of the internal security system, and gain access to confidential information. At the same time, if the first barrier is broken, a security breach notification will be issued. To monitor the state of the system, companies can install a proxy server inside the DMZ, which will allow monitoring user activity and filtering traffic, giving employees access to the global network. However, the efficiency of DMZ protection does not include private networks and cannot guarantee information protection in case of internal attacks.

VPN technology will be used as a means of protecting the employees' connection to servers containing the company's data. The structure of the company's distributed network built in the Cisco Packet Tracer environment (Melnik *et al.*, 2018; Cisco Packet Tracer) is shown in Fig. 1. This simulator allows you to design network models, configure its components (routers and switches) using Cisco IOS commands, and simulate interaction between several users. The addressing of devices in the network is presented in Fig. 2.

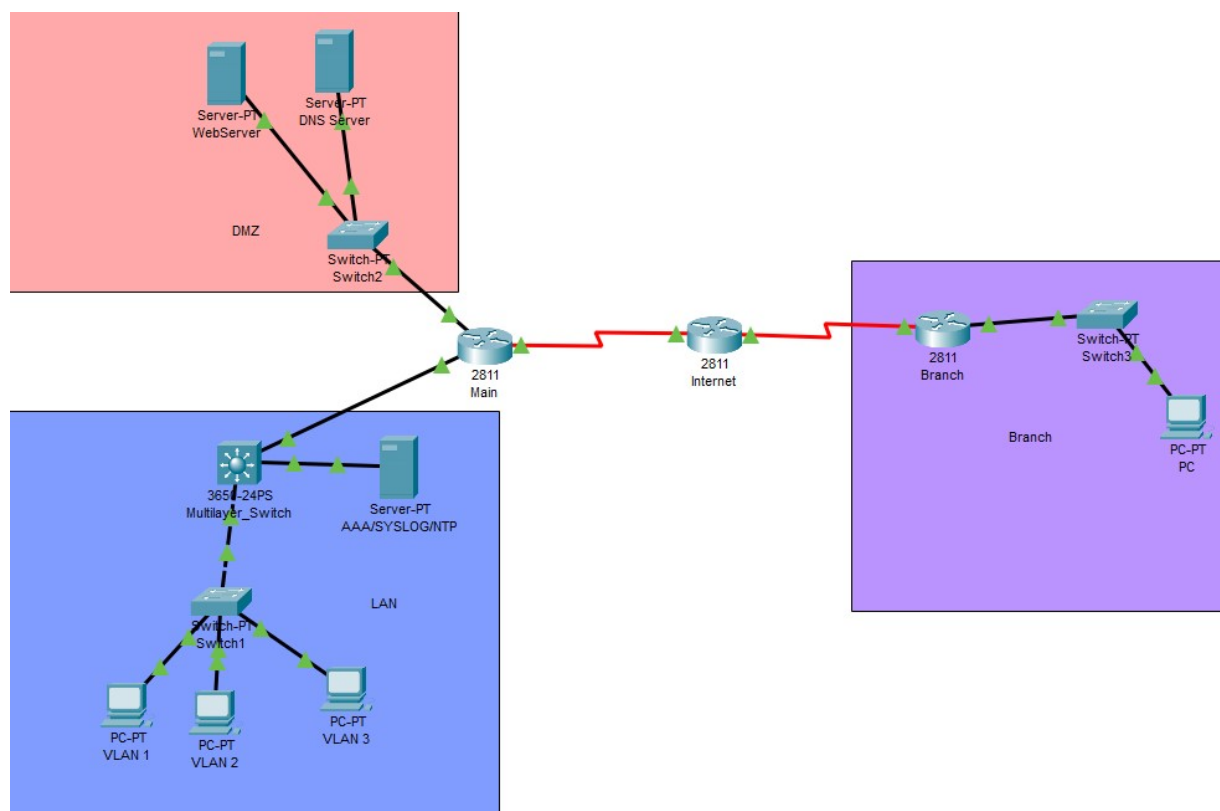


Figure 1. Scheme of the company's distributed network

Пристрій	Інтерфейс	IP-адреса	Маска підмережі	Шлюз за замовчуванням	Порт комутатора
Main	F0/0	172.30.66.1	255.255.255.252		G1/0/1
	F0/1	172.30.10.1	255.255.255.0		F0/1
	S1/0	194.11.166.66	255.255.255.240		S1/0
Internet	S1/0	194.11.166.65	255.255.255.240		S1/0
	S1/1	172.30.1.1	255.255.255.252		S1/0
Branch	S1/0	172.30.1.2	255.255.255.252		S1/1
	F0/0	172.30.1.33	255.255.255.224		F0/1
PC	F0	172.30.1.34	255.255.255.224	172.30.1.33	F1/1
WebServer	F0	172.30.10.2	255.255.255.0	172.30.10.1	F1/1
DNS Server	F0	172.30.10.3	255.255.255.0	172.30.10.1	F2/1
Multilayer_Switch	G1/0/1	172.30.66.2	255.255.255.252		F0/0
	G1/0/2				F0/1
	G1/0/3	172.30.66.33	255.255.255.224		F0
	VLAN10	172.30.0.1	255.255.255.0		
	VLAN20	172.30.15.1	255.255.255.0		
	VLAN30	172.30.55.1	255.255.255.0		
AAA/SYSLOG/NTP	F0	172.30.66.34	255.255.255.224	172.30.66.33	G1/0/3
VLAN 1	F0	172.30.0.2	255.255.255.0	172.30.0.1	F1/1
VLAN 2	F0	172.30.15.2	255.255.255.0	172.30.15.1	F2/1
VLAN 3	F0	172.30.55.2	255.255.255.0	172.30.55.1	F3/1

Figure 2. Representation of addressing in the network

Next, we briefly consider the main segments of the network presented in Fig. 1.

- Central network device – Cisco 2811 router (connects all network segments into one) (Overview of Cisco Interface Cards for Cisco Access Routers).
- The LAN zone (highlighted in blue) is the main office (the workplaces of three employees are located).
- Demilitarized zone (highlighted in pink).
- Branch (highlighted in purple) is the branch where the remote employee's workplace is located.

A VPN tunnel is to be established between the Branch and the central device of the network called Main, because in this case, the employee from the branch will be protected from attacks on the data transmitted as a result of working inside the network and, at the same time, will be able to remotely access the company's data and work with it safely (Construction of a secure Internet access node).

Practical implementation of VPN technology settings. Network configuration will take place in the Cisco Packet Tracer environment. The simulator has a device library that contains all the necessary components, including various series of Cisco routers, switches and firewalls, servers for various purposes and other network equipment. The repository also presents a wide nomenclature of various types of connections between computer network elements (Melnik *et al.*, 2018). To add a new network element, the user may simply drag the desired element to the workspace and set the connection type by clicking on the corresponding devices in turn. The Cisco Packet Tracer simulator allows you to successfully create complex network layouts, check network topology for operability. However, the implemented functionality of the devices is limited and corresponds to the equipment capacity in the real-life setting.

Configuring security policies including VPN. ISAKMP (Internet Security Association and Key Management Protocol) and IPSec are required to build and encrypt a VPN tunnel. ISAKMP, an alternative name for which is IKE (Internet Key Exchange), is a negotiation

protocol that allows two nodes to agree on how to establish an IPsec tunnel. ISAKMP alignment consists of two phases: Phase 1 and Phase 2.

During phase 1, the first tunnel is established to protect subsequent ISAKMP negotiation messages. During phase 2, a tunnel is established to protect the data. Then, IPsec is launched to encrypt the data using appropriate algorithms, provide authentication, and replay protection.

For further correct operation of the VPN configuration, the Security Technology package must be installed. This step may not be necessary with some versions of Cisco routers. Therefore, enter the following commands:

```
Main(config)# license boot module c1900 technology-package securityk9
```

```
Main(config)# exit
```

After that, the router needs to be rebooted: *Main# reload*

The first step is to configure the ISAKMP Phase 1 policy:

```
Main(config)# crypto isakmp policy 10
```

```
Main(config-isakmp)# encryption aes 256
```

```
Main(config-isakmp)# authentication pre-share
```

```
Main(config-isakmp)# group 5
```

```
Main(config-isakmp)# exit
```

In the above commands, the individual parameters mean the following:

AES 256 is the encryption method that will be used in Phase 1 (state-of-the-art encryption methods are recommended).

Pre-Share implies using a pre-shared key (PSK) and as an authentication method.

Group 5 is the Diffie-Hellman group that will be used.

It is possible to use the commands *hash md5* (hashing algorithm) and *lifetime 86400* (the lifetime of the session key, which is expressed in seconds. This value is set by default).

It is necessary to create extended access lists of ACL access rights to sort potentially dangerous traffic (traffic that needs to be filtered):

```
Main(config)# access-list 110 permit ip 172.30.0.0 0.0.0.255 172.30.1.32 0.0.0.31
```

```
Main(config)# access-list 110 permit ip 172.30.15.0 0.0.0.255 172.30.1.32 0.0.0.31
```

```
Main(config)# access-list 110 permit ip 172.30.55.0 0.0.0.255 172.30.1.32 0.0.0.31
```

```
Main(config)# access-list 110 permit ip 172.30.66.32 0.0.0.31 172.30.1.32 0.0.0.31
```

The next step is to create a transformation set (Transform Set) used for data protection (named VPN-SET):

```
Main(config)# crypto ipsec transform-set VPN-SET esp-aes esp-sha-hmac
```

In the above command, ESP-AES is the encryption method, and SHA is the hashing algorithm.

The next step is to create a Crypto Map. Crypto Map represents the last step of configuration and combines the previously specified ISAKMP and IPsec configurations.

```
Main(config)# crypto map VPN-MAP 10 ipsec-isakmp
```

```
Main(config-crypto-map)# description VPN to Branch
```

```
Main(config-crypto-map)# set peer 172.30.1.2
```

```
Main(config-crypto-map)# set transform-set VPN-SET
```

```
Main(config-crypto-map)# match address 110
```

```
Main(config-crypto-map)# exit
```

In the given sequence of commands, the name of the VPN-MAP cryptographic map is specified. The *ipsec-isakmp* tag tells the router that this corresponding map is an IPsec cryptographic map. Match address is a command that applies an access list to a cryptographic transformation.

The last step is to apply a cryptographic map to the router interface through which the traffic passes. In this case, the output interface is Serial1/0:

```
Main(config)# interface Serial1/0
Main(config-if)# crypto map VPN-MAP
Main(config-if)# exit
```

It should also be considered that only one cryptographic map can be applied to one interface.

At this point, the configuration on the Main device is completed, it is necessary to perform similar actions for the Branch device but specify unique IP addresses of ports and ACLs. The commands to configure VPN on the Branch device are given below:

```
Branch(config)# access-list 110 permit ip 172.30.1.32 0.0.0.31 172.30.0.0 0.0.0.255
Branch(config)# access-list 110 permit ip 172.30.1.32 0.0.0.31 172.30.15.0 0.0.0.255
Branch(config)# access-list 110 permit ip 172.30.1.32 0.0.0.31 172.30.55.0 0.0.0.255
Branch(config)# access-list 110 permit ip 172.30.1.32 0.0.0.31 172.30.66.32 0.0.0.31
Branch(config)# crypto isakmp policy 10
Branch(config-isakmp)# encryption aes 256
Branch(config-isakmp)# authentication pre-share
Branch(config-isakmp)# group 5
Branch(config-isakmp)# exit
Branch(config)# crypto isakmp key vpnpa55 address 194.11.166.66
Branch(config)# crypto ipsec transform-set VPN-SET esp-aes esp-sha-hmac
Branch(config)# crypto map VPN-MAP 10 ipsec-isakmp
Branch(config-crypto-map)# description VPN to Main
Branch(config-crypto-map)# set peer 194.11.166.66
Branch(config-crypto-map)# set transform-set VPN-SET
Branch(config-crypto-map)# match address 110
Branch(config-crypto-map)# exit
Branch(config)# interface Serial1/0
Branch(config-if)# crypto map VPN-MAP
Branch(config-if)# exit
```

Testing of the information protection system. It is advisable to ensure that the VPN settings are correct using the show crypto map command. The result of the setting is shown in Fig. 3 and Fig. 4.

```
Main#show crypto map
Crypto Map VPN-MAP 10 ipsec-isakmp
  Peer = 172.30.1.2
  Extended IP access list 110
    access-list 110 permit ip 172.30.0.0 0.0.0.255 172.30.1.32 0.0.0.31
    access-list 110 permit ip 172.30.15.0 0.0.0.255 172.30.1.32 0.0.0.31
    access-list 110 permit ip 172.30.55.0 0.0.0.255 172.30.1.32 0.0.0.31
    access-list 110 permit ip 172.30.66.32 0.0.0.31 172.30.1.32 0.0.0.31
  Current peer: 172.30.1.2
  Security association lifetime: 4608000 kilobytes/3600 seconds
  PFS (Y/N): N
  Transform sets={
    VPN-SET,
  }
  Interfaces using crypto map VPN-MAP:
    Serial1/0
```

Figure 3. Result of VPN setup on Main device


```

Branch#show crypto map
Crypto Map VPN-MAP 10 ipsec-isakmp
  Peer = 194.11.166.66
  Extended IP access list 110
    access-list 110 permit ip 172.30.1.32 0.0.0.31 172.30.0.0 0.0.0.255
    access-list 110 permit ip 172.30.1.32 0.0.0.31 172.30.15.0 0.0.0.255
    access-list 110 permit ip 172.30.1.32 0.0.0.31 172.30.55.0 0.0.0.255
    access-list 110 permit ip 172.30.1.32 0.0.0.31 172.30.66.32 0.0.0.31
  Current peer: 194.11.166.66
  Security association lifetime: 4608000 kilobytes/3600 seconds
  PFS (Y/N): N
  Transform sets={
    VPN-SET,
  }
  Interfaces using crypto map VPN-MAP:
    Serial1/0

```

Figure 4. Result of VPN configuration on Branch device

Results and discussion

Considering the growing trend of introducing remote work in many companies, this paper considers one of the possible options for protecting company information using VPN technology, which allows creating secure networks and significantly reduces possible threats of information leakage. The research was conducted with the equipment of the Cisco family.

With the help of the Cisco Packet Tracer simulator, a practical computer model of the company's distributed network was built, and its operation was simulated taking into account the capacity of real equipment from the same manufacturer.

The configuration of security policies, including VPN, is considered, which includes establishing and encrypting a VPN tunnel, specifying the AES 256 encryption method, using a pre-shared key (PSK) as an authentication method, filtering traffic, creating a transform set (Transform Set) used for protection of personal data, creating a cryptographic map and applying it to the interface of the router through which the traffic passes.

The Cisco Packet Tracer simulator assesses the correctness of VPN settings and, if necessary, introduces appropriate adjustments.

Conclusions

The current study implemented the security policies in the company's network based on the use of Cisco VPN technology. This tool made it possible to organize a secure VPN channel for connections from within the company's network, which in turn allows a remote employee to access the company's servers and data.

The scientific novelty of the study consists in the construction of a model of information protection at the network level using Cisco VPN technology, which involves dividing the network into three zones and creating a VPN tunnel, which allows organizing a secure remote connection of users to their workplaces.

The practical significance of the obtained results is a test-verified model, which can be promptly implemented for practical use because it is oriented towards real equipment, taking into account its possible limitations of work in real conditions. This is especially important for companies whose employees connect remotely over unsecured network infrastructure, such as using public Wi-Fi networks.

Prospects for further research. The proposed model of information protection in a company where some employees work remotely is a complete, but basic model, but due to its flexibility, it can be scaled according to the requirements of a specific customer, taking into account their needs and wishes. A wide range of Cisco equipment will satisfy the needs of the most demanding customer. The described procedures for the practical implementation of the network infrastructure, the configuration of security policies and testing the correctness of the settings remain unchanged and will be extended to the added new devices.

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Conflict of Interest

The authors have no conflict of interest.

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ОРГАНІЗАЦІЙНА СТРУКТУРА ТЕХНІЧНОГО ЗАХИСТУ ІНФОРМАЦІЇ НА МЕРЕЖЕВОМУ РІВНІ З ВИКОРИСТАННЯМ ТЕХНОЛОГІЇ VPN

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Анотація. В останні роки для малих і середніх компаній поширилася практика дистанційного підключення працівників до внутрішньої мережі компанії через загальнодоступні ресурси. В цьому випадку гостро постає питання захисту інформації, оскільки її частина може циркулювати у незахищеній мережі. Нині широко використовується технологія VPN, яка має багато варіантів реалізації мереж для різних цілей використання. Серед різноманіття реалізацій в роботі розглянуто побудову VPN мережі на базі обладнання компанії Cisco. Такий підхід обумовлений поширеністю та доступністю устаткування, наявністю симулятора для проектування, налаштування та апробації мережі. Здійснено опис структури організації, особливістю якої є те, що співробітники можуть працювати як всередині корпоративної мережі, так і за її межами. При цьому кожен із працівників повинен мати однакові можливості для захищеного підключення до серверів та роботи з даними, що фігурують при роботі організації. Відповідно для фахівців, що працюють дистанційно, гостро постає питання безпеки інформації. Тому була запропонована модель мережі, яка розділяється на три зони: головний офіс, місце роботи віддаленого працівника та сегмент із серверами, які знаходяться у демілітаризованій зоні (DMZ). Наявність демілітаризованої зони надає додатковий рівень безпеки в локальній мережі, який дозволяє мінімізувати збитки в разі атаки на один із загальнодоступних сервісів: зовнішній зловмисник має прямий доступ тільки до обладнання в DMZ. Як засіб, що буде захищати підключення працівників до серверів з даними організації, буде використовуватись технологія VPN. Здійснено вибір апаратного забезпечення мережі. Для поєднання усіх сегментів в одну мережу обрано маршрутизатор Cisco 2811, який використовується для потреб невеликих організацій (до 36 робочих місць). Проведено практичну реалізацію налаштувань технології VPN у представленій розподіленій мережі організації. Проведено моделювання комп'ютерної мережі в середовищі Cisco Packet Tracer. В результаті виконання поставлених завдань було впроваджено політики безпеки в мережі на основі використання технології Cisco VPN. Цей засіб дозволив організувати захищений VPN канал для підключень зсередини мережі організації, що, в свою чергу, дає змогу працівнику, який працює віддалено, отримати доступ до серверів та даних організації. Результати цієї роботи можуть використати компанії чи окремі користувачі, які планують інтегрувати архітектуру VPN, на базі обладнання Cisco, до своєї мережевої інфраструктури.

Ключові слова: мережа, демілітаризована зона, симулятор Packet Tracer, Cisco, VPN-тунель, криптографічна мапа.

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TECHNICAL FEATURES OF BUILDING A LI-FI NETWORK USING SDN MANAGEMENT METHODS

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Abstract. The construction of LI-FI wireless access networks using open source platforms offers very good prospects for communication operators. At the same time, it is necessary to develop system models and describe management methods. For this purpose, the paper proposes to use a centralized management system based on SDN principles. Having complete information about the state of network elements allows you to ensure optimal use of network resources, increase throughput and quality of service. The analysis of the principles of building a LI-FI office network using the management level based on SDN principles to reduce interference in cells, increase throughput and quality of service has been made. The analysis of well-known publications devoted to the methods of construction and management of load flows in LI-FI networks using centralized control systems, reducing the level of interference in cells due to the optimal use of network resources has been carried out. Based on the analysis of the LI-FI network operation process using centralized management systems, limitations are determined and recommendations are developed regarding the order of user service at access points. Building an access network based on Li-Fi technology is a very promising direction for solving the problems of existing wireless access networks based on radio frequency technologies. To manage such a network, it is advisable to use open source SDN platforms, and, in particular, the ONOS operating system. The proposed solutions require the development of mathematical models and methods for the optimal solution of control problems in different operating conditions.

Keywords: OWC, Li-Fi, SDN, ONOS, management methods, PoE.

Introduction

Currently, there is a sharp increase in traffic in wireless access networks of systems for various purposes. These are Industry 4.0, Internet of Things (IoT) systems and others. For example, it is predicted that by the end of 2022 the IoT market will have 20-30 billion active hosts (Chowdhury *et al.*, 2018). Studies show that the generated traffic in wireless access networks has been growing exponentially in recent years. At the same time, a critical task is to ensure the specified throughput and quality of service (QoS) indicators for users in the system (Haas, 2018; Romanov *et al.*, 2020).

One of the main components that determine the level and quality of the services provided is a wireless access telecommunications system that ensures the interaction of all elements. In this area, a number of shortcomings can be noted that may slow down the development of systems and the provision of modern services in the near future. The main ones are (Wang *et al.*, 2022; Romanov, & Miklaiv, 2021; Huang *et al.*, 2022).

1. Limited capabilities of the used wireless access technologies in terms of throughput and quality of service.

2. Construction of existing telecommunication networks based on specialized monolithic network elements, such as switches, routers, which requires large time and material costs when introducing new technologies.

3. Low level of intelligence of telecommunications network management systems.

Let us briefly analyze the impact of these shortcomings and ways to overcome them.

Currently, wireless access is mainly carried out using radio frequency technologies such as Wi-Fi, Bluetooth, RFID. And the leader in this area is WiFi technology. However, radio technologies in access networks are already at the limit of their capabilities in terms of throughput and quality of service. Therefore, further development requires the search for new, more efficient wireless access technologies. As the analysis of modern literature shows, one of the directions for solving this problem can be considered the use of the optical frequency spectrum for building future wireless access networks with high density and throughput.

The second drawback is related to the fact that the existing networks were created on the basis of specific software and hardware platforms from different manufacturers. This has led to low flexibility, poor scalability and dependence of telecom operators on equipment vendors. The solution to this problem can be the use of SDN technology when building networks. This allows you to significantly increase the efficiency of their functioning due to the centralization of management; virtualization of functions of network elements, applications and services; separation of hardware and software functions. With this approach, operators have the opportunity to independently develop applications and implement them as an addition to the basic software. This allows you to significantly speed up the process of providing new modern services to network users.

The third disadvantage associated with the low level of intelligence of control systems requires the development of new models and methods for solving control problems that allow optimizing the efficiency of using network infrastructure resources and network equipment. The principle of centralized management, embedded in the SDN network management system, has ample opportunities to improve the efficiency of the network.

However, in order to use these opportunities, it is necessary to develop models and methods for solving problems of intelligent control. At the same time, special attention should be paid to the methods of collecting initial data, the timeliness of their submission to the authorities and the assessment of their reliability. In addition, indicators reflecting the actual parameters of the network should be used as initial data:

It should be noted that in order to solve these problems, the hardware and software structure of the network, the composition of the functional blocks of the network elements,

their purpose and functions should be determined. It is also necessary to describe the relationship of elements in the process of solving problems in various network operating conditions.

Materials and methods

One of the possible ways to increase the throughput and quality of service of wireless access systems is to use Li-Fi (Light Fidelity) technology, where instead of radio frequencies, VLC (Visible Light Communication) visible light spectrum waves are used for data transmission.

Although the practical use of the technology is still in its early stages, much research is being done to achieve high data rates and reliable delivery to users. In this case, ordinary light emitting diode (LED) lamps can be used as devices for transmitting and receiving light waves. This approach makes it possible to use the lighting infrastructure as a ready-made telecommunications environment.

Significant results in the practical application of Li-Fi technology have been achieved in the field of building ITS (Intelligent Transportation Systems). Here solutions are obtained for the use of lighting infrastructure, car headlights and traffic lights for communication and compliance with road safety requirements. In addition, there are patents for the use of Li-Fi technology in aircraft, offices, and large shopping centers. The use of Li-Fi technology in wireless access networks provides significant advantages over other technologies. The main ones are:

1) Availability. Li-Fi uses LEDs as a data carrier, which allows us to use the lighting system as a ready-made data network. This easy accessibility results in significant cost savings.

2) Capacity. The available radio frequency spectrum for wireless communications can be expanded by a factor of 10,000 by using the visible light spectrum. It can be street light, LED table lamp and other light sources.

3) Security. When transmitting with Li-Fi technology, you can ensure security by simply blocking the light, thus allowing for an easy implementation of security, and therefore a more secure way of transmitting data.

4) An environmentally friendly system that reduces health risks. RF signals are carcinogenic and may pose a threat to human health, while visible light is safe for your life.

5) Ability to use existing infrastructure. For Li-Fi, we can use existing LED light sources as hotspots, thus reducing the cost of infrastructure development.

6) High rates of energy saving and energy efficiency:

Results and discussion

In modern wireless communications, a large amount of energy is spent on infrastructure and its maintenance. For example, a lot of energy is spent on cooling base stations and keeping them in working order. Whereas when using LiFi technology, it is enough to have a 60-watt LED light bulb that can be used as an access point.

Thus, the LiFi technology itself can significantly improve the efficiency of the access network. We can get further efficiency gains by implementing advances in SDN technology. Especially the management principles embedded in this technology. Today, research is underway and proposals are being developed for the practical implementation of this technology within the framework of a number of projects. These projects cover the creation of the next generation broadband access infrastructure, the construction of a service platform (services platform) for the provision of services, a platform for building SD-RAN and Core RAN networks of 5G / 6G mobile operators, a platform for building basic fixed networks, SD-FABRIK and other important telecommunications industries. Representatives of the Open

Networking Foundation (ONF) consortium make the greatest contribution to the development of this area. ONF is at the head of all projects to build SDN and is engaged in accelerating the processes of their practical implementation (Chowdhury *et al.*, 2018).

A number of documents describing the principles of construction and operation of SDN networks have been published. In (Romanov *et al.*, 2020; Wang *et al.*, 2022; Romanov, & Miklaiv, 2021; Huang *et al.*, 2022) general requirements, system approaches and generalized architecture of SDN networks are considered. The papers (Haas, 2018; Xu *et al.*, 2017; Romanov *et al.*, 2018; ONF TR-539, 2016) consider the tasks and features of the protocols used to solve various problems in SDN networks. The works (Zeng *et al.*, 2017; Geldard *et al.*, 2022; Alowa *et al.*, 2020) describe the features of building SDN network elements and the order of their interaction in the process of servicing information flows. In (ONF TR-525, 2015; Das, 2020; Romanov *et al.* Principles of Building, 2022; Romanov *et al.* SDN network modeling, 2022; Romanov *et al.* Construction, 2021), the principles of building an optical transport network are considered and recommendations are given to ensure the safety of their operation. The most complete and systematized material is presented in (Romanov *et al.* Mathematical description, 2021 Phemius *et al.*, 2013). Articles (Lam *et al.*, 2016; Comer *et al.*, 2019) explore various aspects of servicing information flows and focus on the need to meet network security requirements.

The most complex tasks in SDN networks are faced by the control layer, which acts as a centralized control system. Consider how the structure of the LiFi transmission path will change when using the management principles adopted in SDN networks.

Figure 1 shows a possible structure of the signal transmission path in a wireless Li-Fi network using the SDN control plane. Signal transmission through the Li-Fi network path is based on VLC (Visible Light Communication) where light acts as the communication medium. The light source is a Led Lamp controlled by a Lamp Driver. The data sources can be the Server or the Internet, which are connected via an SDN switch. The Lamp Driver adjusts the blinking speed of the LEDs and controls the modulation of the transmitted signals. Modulated signals control the speed at which light flickers when transmitting digital data (values 0 and 1). The data emitted by the LED is received by a light-sensitive device called a photodetector, which processes and amplifies the signal. Next, the light signals are converted into digital signals. Thus, the received signals are converted to the form in which they came from the information source.

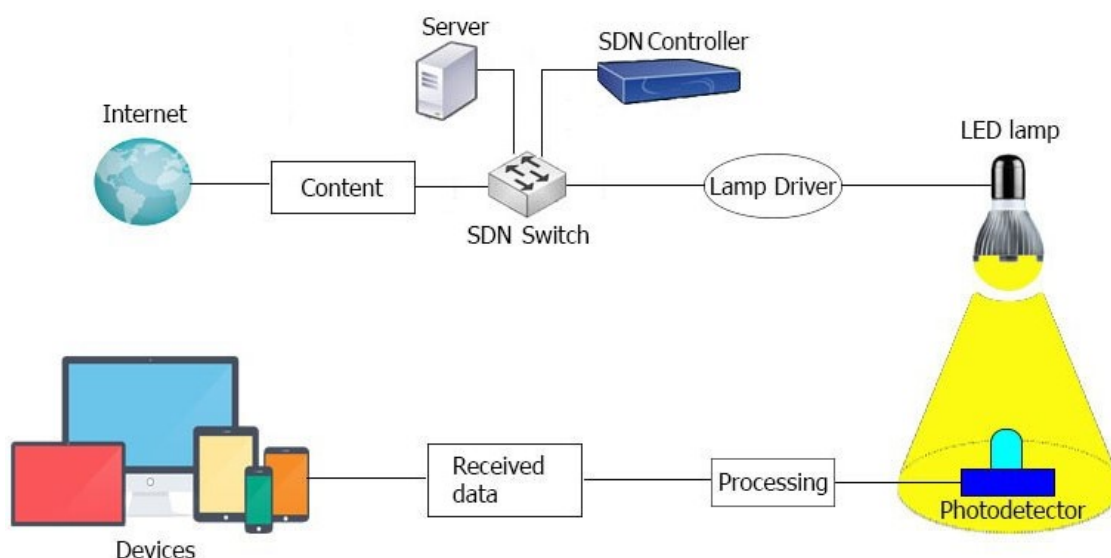


Figure 1. Signal transmission path in Li-Fi

Li-Fi can provide simultaneous network access to many users because it is a broadband wireless technology. In Li-Fi technology, an optical space division multiple access (SDMA) scheme can be implemented using transmitters with an angular separation. Compared to optical time division multiple access (TDMA), SDMA can achieve a tenfold increase in throughput in a Li-Fi network. Using OFDM provides a simpler multiple access technique, that is, orthogonal frequency division multiple access (OFDMA), in which users are served and separated by a plurality of orthogonal signal subcarriers.

In addition, the performance of the Li-Fi network path can be improved by using NOMA non-orthogonal multiple access. Different from conventional OFDMA technologies, NOMA can serve a much larger number of users by allocating non-orthogonal frequency resources. It is possible to use other modulation methods.

As a rule, all studies of Li-Fi networks are focused on the transmission path from the LED to the photodetector. However, for a comprehensive study of the system, it is necessary to consider the service process in all elements of the network. Let's consider a possible option for building a campus Li-Fi optical access network with SDN elements, which is shown in Figure 2.

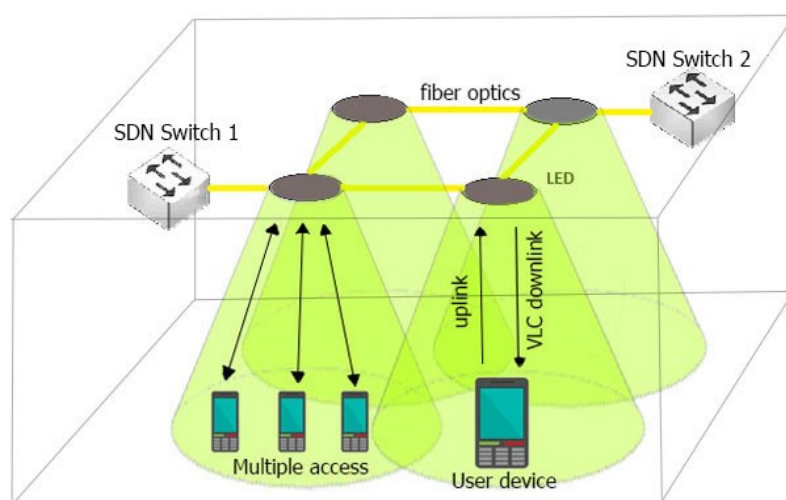


Figure 2. Variant campus Li-Fi network with SDN elements

The Li-Fi network shown in Figure 2 includes multiple access points for uplink, downlink, and reverse link connections. In addition, the system provides functions for transmitting and receiving information, support for user mobility and the possibility of flexible access to resources. To do this, the network has the following elements:

1. LED lamp that provides wireless information transmission using VLC.
2. Fiber optics - lines connecting LED lamps, switches and other network elements.
3. SDN Switch, - switches that provide the establishment of a data transfer path between access points.
4. User device - mobile devices of users that connect to an access point and then to the global network
5. Uplink. An uplink for transmitting data from a user's mobile device to a network. It provides a request for various services, confirmation of data receipt, transmission of information about the state of the channel.
6. VLC downlink. Downlink for downloading data from the network.
7. Interaction lines between access points, network switches and other network elements.

Access points (APs) form ultra-small cell networks to provide high-density wireless communications services to mobile users. The Li-Fi network must support data service when users move through different light coverage regions. In a Li-Fi network, a two-way communication is established between an AP and a UE, making it possible for the AP to serve multiple users at the same time. In addition, the backhaul links between access points and the network gateway are essential to enable cooperation between access points and establish communication with the external network. These feedbacks can be implemented by optical fiber, Power-over-Ethernet network or power lines. The downlink Li-Fi is powered by the existing LED lighting system. This is due to the fact that LED lighting is becoming more and more popular. In addition, transmission at a rate of several tens of Gbit/s through LEDs was demonstrated.

On a Li-Fi network, an uplink connection is required to send requests for certain content, send acknowledgments, send Channel State Information (CSI) and download files, and enable voice and video calls. The principle of information exchange in the network is as follows. The user connects to a specific LiFi hotspot in the same way as a WiFi hotspot. Thanks to this, he gains access to the network. It can download a file on the downlink, or vice versa upload information on the uplink. The user in the process of moving changes his access point. Switching is performed automatically without breaking the connection. The interconnection of network elements can be provided by a fiber optic line or via a power supply network. If you want to establish communication between access points in different rooms, SDN Switches are used. Since the use of visible light in the uplink may cause distraction to the mobile user, the use of infrared is considered to be the most appropriate for this link direction. This also has the added benefit that the uplink and downlink do not interfere with each other, and simultaneous communication with different entities can be established.

It should be noted that despite the presence of several publications in the field of research on the transmission of information on the uplink based on infrared radiation, further comprehensive investigations are required in this direction. In addition, radio based communication technologies such as Bluetooth, ZigBee and especially Wi-Fi can also be considered. There are publications which state that an RF/VLC hybrid communication system with a downlink-only VLC is capable of offloading a significant amount of data traffic while still having low latency.

The process of network functioning is quite complicated. Users move around the room. This changes the angles of transmission and reception of signals, the distance between the elements of the system, LED service areas. At the same time, it is necessary to ensure the requirements for the level of lighting at each point of the room. Therefore, to address these issues in the network, it is proposed to use the principles of SDN management. Today, the ONF consortium develops a number of open source platforms. Therefore, an SDN controller can be recommended as a centralized LiFi network management device. As a basis, you can take a controller designed to control the data center. Then the structure of the LI-FI network will look like shown in Figure 3.

Building a LiFi network using the SDN control plane requires more research. It is necessary to provide a system of multiple user access and interference coordination in public channels. Consider use cases: horizontal and vertical handover. At the same time, in case of horizontal handover, provide for the possibility of changing the serving access point, for example, to radio access technology. Vertical handoff may refer to a change in a serving AP belonging to a different radio or optical device. For example, mobile users can be transferred from a Li-Fi hotspot to a Wi-Fi hotspot when none of the Li-Fi hotspots can offer a reliable link or the user's speed is too high. At the same time, the residence time in the cell is too short

to establish a high quality of communication. When the user slows down and enters the coverage of a lightly loaded Li-Fi hotspot, it may be better to transfer that Li-Fi hotspot to a lighter Wi-Fi network for more efficient operation (for example, to ensure less packet collisions).

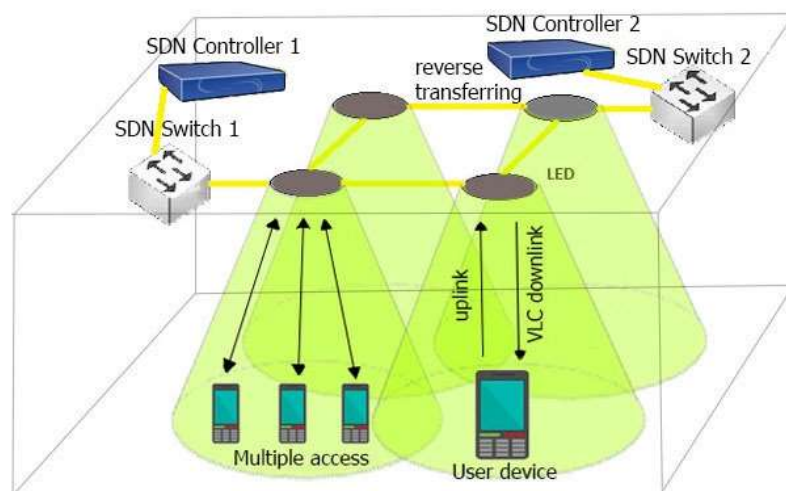


Figure 3. LiFi campus network using SDN controllers

It should be borne in mind that the efficiency of such a complex network will largely depend on the level of intelligence of the controller. At the same time, the main element of the controller is ONOS. A possible version of the ONOS architecture is shown in Figure 4.

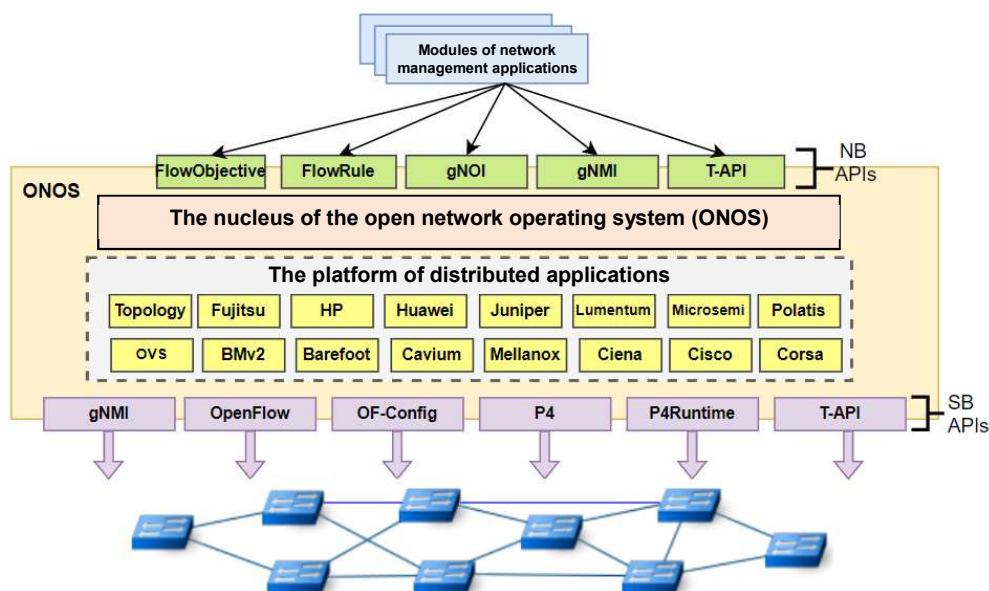


Figure 4. ONOS architecture

As can be seen from Figure 4, the ONOS design is modular. In this case, a particular deployment is designed to include the necessary subset of modules.

Three features should be noted.

The first feature is that the horizontal plane of the NBI is quite large. Any access to the underlying equipment, whether it is a control program or a human operator, is carried out through ONOS. This means that the totality of all northern APIs should be sufficient to set up, operate and manage the network. For example, NBI includes gNMI and gNOI for setup and operations, respectively. This also means that NBI includes a topology API, which management applications use to get information about changes in the underlying network state (for example, ports go up and down), as well as a Flow Objective API, which is used to manage underlying switches.

It should be noted that there is a wide range of applications that run directly on ONOS. These applications may have a graphical interface that can be used to monitor network status. Applications may have a command line interface that operators can use to issue directives. These issues are discussed in more detail in (Romanov *et al.*, 2020; Zeng *et al.*, 2017; Das *et al.*, 2020).

Conclusions

1. Building an optical access network based on Li-Fi technology using SDN management methods is a very promising direction for solving the problems of existing wireless access networks based on radio frequency technologies.

2. Comparative characteristics of performance indicators of optical access networks with wireless access networks based on radio frequency technologies shows that LiFi has advantages in most performance indicators.

3. Given that wireless access based on radio technologies today has a large coverage, these networks will be used together during the transition phase. At the same time, the priority in the use of a particular technology will be determined by the network operating conditions.

4. For management, it is advisable to use open source platforms for SDN networks, and, in particular, ONOS, which are now being actively developed by the ONF community.

5. For the further development of this direction, it is necessary to develop mathematical models and methods for optimally solving control problems under different operating conditions, which will later become software modules at the application level.

Acknowledgements

None.

Conflict of Interest

None.

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ТЕХНІЧНІ ОСОБЛИВОСТІ ПОБУДОВИ LI-FI МЕРЕЖІ ЗА ДОПОМОГОЮ МЕТОДІВ КЕРУВАННЯ SDN

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Анотація. Побудова мереж бездротового доступу Li-Fi з використанням платформ із відкритим кодом дає дуже добрі перспективи операторам зв'язку. При цьому необхідні розробка моделей системи і опис методів управління. Для цього в роботі пропонується використовувати централізовану систему управління на принципах SDN. Наявність повної інформації про стан елементів мережі дозволяє забезпечити оптимальне використання мережевого ресурсу, підвищити пропускну здатність та якість обслуговування.

Зроблено аналіз принципів побудови офісної мережі Li-Fi з використанням рівня управління на принципах SDN для зменшення перешкод у стільниках, підвищення пропускну здатності та якості обслуговування.

Проведено аналіз відомих публікацій, присвячених методам побудови та управління потоками навантаження в мережах Li-Fi з використанням систем централізованого управління, зменшення рівня перешкод у стільниках за рахунок оптимального використання мережевого ресурсу. Завдяки технології Li-Fi значно підвищується ефективність мережі доступу; ще більше підвищити ефективність мережі можна, впровадивши принципи керування, закладені у технології SDN. Найскладніші завдання в мережах SDN стоять перед рівнем управління, який діє як централізована система керування. Розглянуто, як зміниться структура тракту передачі Li-Fi при використанні принципів управління, прийнятих у мережах SDN.

На базі аналізу процесу функціонування мереж Li-Fi з використанням систем централізованого управління визначено обмеження та розроблено рекомендації щодо порядку обслуговування користувачів у точках доступу.

Побудова мережі доступу на базі технології Li-Fi є дуже перспективним напрямом вирішення проблем існуючих бездротових мереж на базі радіочастотних технологій. Для управління такою мережею доцільно використовувати платформи з відкритим кодом мереж SDN і, зокрема, операційну систему ONOS. Запропоновані рішення вимагають розробки математичних моделей та методів оптимального вирішення завдань управління у різних умовах функціонування.

Ключові слова: OWC, Li-Fi, SDN, ONOS, методи управління, PoE.

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MATHEMATICAL MODEL OF THE ASSOCIATED PROCESSES OF DENITRIFICATION AND RENEWAL OF SULFATES IN AN INNOVATIVE BIOFILTER

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Abstract. The problem of pollution of underground water sources with nitrates, as well as geogenic compounds (sulfates, hydrocarbonates) is of interest to researchers around the world. Nitrates represent a particular risk to the health of the population living in places without centralized water treatment. In this case, post-treatment of water at the point of use is recommended using both technologies for the removal of nitrates from treated water and their biological conversion into nitrogen. Without downplaying the role of the former, the latter technologies are seen as promising, requiring research and improvement.

The purpose of the work is to study the process of nitrate biotransformation in a small submersible biofilter in the presence of basic groundwater anions (sulfates and hydrocarbonates) and their effect on the quality of treated water. The shift of sulfate-sulfide balance in aquatic environment of the biofilter and the influence of the concentrations of sulfate ions and the substrate of bacterial nutrition on the accumulation of hydrogen sulfide and its consumption in the volume of the biofilter have been studied. It is shown that the processes of denitrification and reduction of sulfates to hydrogen sulfide proceed sequentially. The reduction of sulfates to hydrogen sulfide begins after the removal of nitrates from the treated water at a dosage of the nutrient substrate that exceeds the stoichiometric requirement for denitrification. Hydrogen sulfide, which is formed in the zone of connection of inlet and outlet knees of the biofilter, is practically not detected at its outlet. The reduction of sulfates associated with the removal of nitrates can be a useful tool for additional treatment of water from impurities of heavy and polyvalent metal ions.

Keywords: decentralized water treatment, nitrates, hydrogen sulfide, bacterial nutrition, water quality.

Introduction

The growth of the population and the demand for food contribute to the intensification of agriculture, in particular, through the use of fertilizers based on both organic and inorganic compounds of nitrogen. This is one of the main causes of groundwater pollution with nitrates. According to estimates (Matei *et al.*, 2021; Benes *et al.*, 1989), only 40-60% of the total amount of nitrate fertilizers applied to the soil is consumed by plants, the latter in the form of nitrate ions (NO_3^-) entering water sources (soil and underground), which leads to their contamination.

Nitrate ions are a stable form of bound nitrogen, poorly sorbed by water-bearing soils, capable of migrating over aquifers over long distances, penetrating deep-lying strata, which leads to permanent nitrate pollution (Besser *et al.*, 2022) of underground water sources. This limits their use for domestic and drinking water supply due to serious risks to human health, and also provokes a number of environmental problems.

Literature review

The main danger of nitrates entering the human body is associated with the occurrence of methemoglobinemia in young children (Fewtrell, 2004). Based on this, WHO recommended a limit of nitrate content in drinking water of $\leq 50 \text{ mg/dm}^3$ in the form of (NO_3^-). However, the consequences for human health, the appearance of which is likely at lower concentrations of nitrate ions in water and may be associated with the immunosuppressive effect of nitrates, a decrease in the body's resistance to the action of mutagenic and carcinogenic agents, malignant tumors, reproductive risks, etc., continue to be studied (Ward *et al.*, 2018; Noori *et al.*, 2022; Temkin *et al.*, 2019; Grout *et al.*, 2023).

The concentration of nitrates in groundwater is affected by climate change (Sidiropoulos *et al.*, 2019; Paradis *et al.*, 2016). Its growth is predicted as a result of a decrease in groundwater level due to the degradation of water resources (a decrease in the amount of groundwater in the future water balance). Despite the adopted legislation (Nitrate Directive, 1991/676/EEC; Water Framework Directive, 2000/60/EEC), nitrate pollution of groundwater in the world (Abascal *et al.*, 2022) is a global problem, which is also inherent in Ukraine (Romanchuk *et al.*, 2021; Herasymchuk *et al.*, 2022). The work (Romanchuk *et al.*, 2021) shows that in 10 out of 15 studied regions of Ukraine, the nitrate content in drinking well water in rural settlements was exceeded both during traditional and organic farming. According to (Natsionalna dopovid, 2022), only 23.5% of Ukrainian villages are provided with centralized water supply. The rest of the population of rural residential areas uses drinking water from wells, boreholes, catchments. From 14.2% to 45.6% (depending on the type of source) of drinking water samples did not meet the standards (DSanPiN, n.d.) for sanitary and chemical indicators, including nitrate content from 13.4 to 36.3%. There are cases when this indicator reached 63.9% (Herasymchuk *et al.*, 2022). The use of such water for drinking is possible only after its purification. In places where there are no centralized drinking water treatment sites and water distribution networks, to reduce high levels of concentrations of nitrate and other harmful impurities, it is recommended to use water purification devices at points-of-use (POU) and at points-of-entry (POE). Most often, reverse osmosis and ion exchange devices are used. Their advantages and disadvantages are described in (Matei *et al.*, 2021; Jensen *et al.*, 2021). High investment and operating costs are a deterrent to the use of such devices in regions with low population incomes (Grout *et al.*, 2023). The use of biofiltration can be an alternative.

The study (Alguacil-Duarte *et al.*, 2022) of life cycle assessment (LCA) and economic efficiency analysis of two processes of drinking water treatment (reverse osmosis and biological purification) has shown that biological technology allows to produce drinking water in a more *environmentally safe, economical and efficient way*.

Currently, slow sand filters (SSF) and biological sand filters (BSF) are increasingly being considered as one of the available alternatives to POU. Recently published reviews (Freitas *et al.*, 2022; Maiyo *et al.*, 2023) note that these filters were originally focused on removal of silted particles, turbidity, color, and pathogenic microorganisms. However, thanks to the improvement of the design, construction of filter loads, water purification modes, the capabilities of biofilters have been significantly expanded, including for nitrate removal

(Romero *et al.*, 2020; Mutsvangwa *et al.*, 2017; Aslan *et al.*, 2007; Mohobane *et al.*, 2022; Roshanravan *et al.*, 2021).

At the same time, the control over microbiological processes taking place and the management of clogging (clogging) of the filter layer remain the weak point of biological filtration (Rocher *et al.*, 2019). As an alternative to the existing POU biofilters, the concept of a biofilter with minimal additional maintenance (Gevod *et al.*, 2021), resistance to clogging of its filter layer was evaluated. The latter consisted of elements of a certain size and configuration with a highly developed surface and colonies of heterotrophic denitrifying bacteria attached to it. Loading elements ensured the creation of channels in the filter layer for unhindered movement of denitrified water along the path of biofiltration and the release of gaseous products of microbial metabolism, in particular molecular nitrogen, from the biofilter into atmospheric air. The change of filtration mode from continuous direct flow to piston (displacement) minimized the formation of excess biomass entering the filtrate.

However, in addition to nitrates, groundwater also contains other inorganic compounds (salts of heavy and polyvalent metals, carbonates, sulfates, etc.), which take part in associated processes (methanogenesis, sulfate reduction, ureolysis) in the biofilter. Therefore, the study of these processes that can affect the quality of treated water is relevant.

The purpose of the study was to reveal additional possibilities of denitrification small-sized, submersible biofilter, namely, biotransformation together with nitrates of sulfates to hydrogen sulfide, which can contribute to the removal of ions of heavy and polyvalent metals from water.

It is known that the increased content of nitrates suppresses the activity of sulfate-reducing bacteria (He *et al.*, 2010) in the immobilization of heavy and polyvalent metal ions in the form of insoluble sulfides and oxides.

The object of research was a shift in the sulfate-sulfide balance in aqueous environment of the biofilter and the influence of concentrations of sulfate ions and the substrate of bacterial nutrition, in particular ethanol, on the accumulation of H_2S and its consumption in the biofilter volume during biofiltration denitrification.

Experimental part. Materials and methods

The microbiological reduction of sulfates to hydrogen sulfide H_2S with its subsequent transformation into colloidal sulfur in the process of denitrification of water in a biofilter operating in displacement (piston) mode was studied. The design of the biofilter, the type of filter load, and the mode of incubation of biofouling were described in detail in (Gevod *et al.*, 2021). Samples of purified water were taken for analysis (Fig. 1) from inlet zone (1) of inlet elbow, outlet zone (3) of outlet elbow, and from connection zone (2) of inlet and outlet elbows. The sample volume from each sampling point was 150 ml. During the research, 5 liters of water for denitrification were supplied to the biofilter in a "volley" at a given time every day, and the same amount of filtrate (denitrified water) was simultaneously received. Time of hydraulic water retention in the biofilter was determined by its volume supplied to biofiltration, the length of the filtration path, did not depend on other parameters of the process and was two and a half days, which exceeded the necessary time for exhaustive denitrification of water.

Model solutions of nitrate water were used in the work. They were prepared on the basis of tap water containing sulfates (125 mg/dm^3) by adding ($NaNO_3$) to it. The concentration of the latter was 250 mg/dm^3 . In separate experiments, distilled water was used to prepare sulfate-free nitrate water. Ethyl alcohol (C_2H_5OH) was used as a nutrient substrate. Its

concentration during the research was 60 mg/dm^3 and 125 mg/dm^3 . The choice of the type of nutrient substrate was determined by the target (drinking) purpose of the treated water and existing recommendations in the literature (Mutsvangwa *et al.*, 2017; Mohseni-Bandpi *et al.*, 2013).

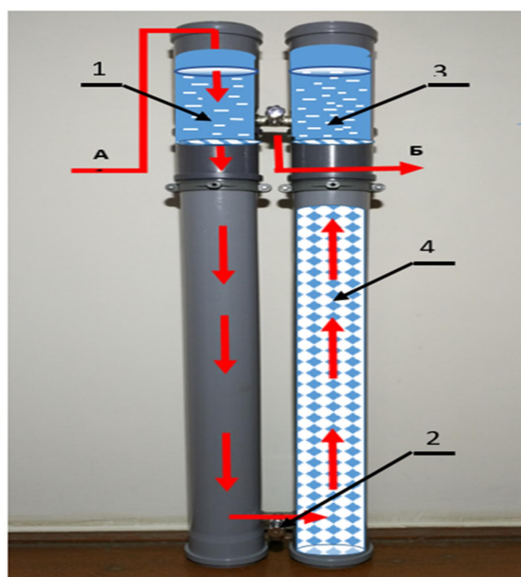


Figure 1. General view of the biofilter with a cross-section of its outlet elbow and the positions of sampling sites for analyzes:

1 - inlet zone; 2 - zone of connection of inlet and outlet elbows; 3 - output zone of outlet elbow; 4 - biofilter loading: A-B – direction of water movement through the biofilter

The concentration of nitrates in water was measured by I-160 MI ionometer with ELIS-121NO₃ ion-selective electrode and EVL1-M reference electrode. The working range of nitrate ion concentration measurements was 10^{-1} - $5 \cdot 10^{-5}$ M. The sensitivity was $5 \cdot 10^{-6}$ M.

The concentration of ethanol in water samples from 1-3 zones of the biofilter was determined using GC9790 III gas chromatograph with flame ionization detector and short packed column (diameter is 3 mm, length is 500 mm). Chromosorb W treated with polyethylene glycol (PEG 20M) was the packing material. The temperatures of the ejector, detector, and column were kept constant and were, respectively, 160°C, 200°C, and 120°C. Molecular nitrogen (N₂) of 99.995 qualification was the mobile phase. The dosage of liquid samples into the ejector liner was equal to 0.2 µl and 0.1 µl. Samples were entered manually. A microsyringe with a volume of 1 µl was used. Processing of chromatograms was carried out automatically according to the algorithms of "FL9790 chromatogram Workstation" software.

The appearance and consumption of hydrogen sulfide in the connection zone of inlet and outlet elbows were monitored based on the results of measurements of the value of redox potential (Eh). For this purpose, ERP-101 measuring electrode and EVL1-M silver chloride reference electrode, which were connected to I-160MI ionometer, and also - by the reaction of qualitative determination of hydrogen sulfide using a solution of [Pb(NO₃)₂] lead nitrate and by characteristic smell of water sample, were used. In the cells of the potentiometer, selected water samples from three zones of the biofilter were mixed with magnetic stirrers at a speed of 120 rpm and atmospheric air was freely accessible to them. The area of the sample mirror was 0.2 dm². When measuring (Eh), the electrode pair, pre-exposed in tap water with an equilibrium concentration of dissolved oxygen in it, was moved into the cell with the test sample and potentiometer readings were taken after 5 minutes of exposure time.

pH control was carried out with I-160MI ionometer with ESK 10603 pH glass electrode and EVL1-M silver chloride reference electrode. Concentrations of nitrate ions, Eh and pH were measured and recorded automatically according to a given algorithm using the "Analytics" software.

Results and discussion

During denitrification, the reduction of sulfates manifests itself in that part of the filter load, where the biofiltered water contains a sufficient amount of dissolved sulfates and bacterial nutrients (donors of assimilated carbon and electrons), but has practically no dissolved oxygen. Under anaerobic conditions, sulfate-reducing bacteria split oxygen from (SO_4^{2-}) sulfate ions and produce (HS^-) hydrosulfide ions. The latter undergo hydrolysis and hydrogen sulfide is formed in water. Its presence in water samples is revealed by a qualitative reaction using $[Pb(NO_3)_2]$ and by the results of redox potential (Eh) measurements.

Natural water that does not contain hydrogen sulfide, at neutral, weakly acidic and weakly alkaline pH values, is characterized by redox potentials (Eh) in the range from plus 50 mV to plus 300 mV on the hydrogen scale (Piskarev *et al.*, 2010). Eh value depends on the content of dissolved mineral and organic impurities with different degrees of oxidation in water. Positive values of redox potentials are determined in water by impurities in an oxidized state. The appearance of hydrogen sulfide, which is a strong reducing agent, shifts the redox potential of water in negative direction to values in the range from minus 250 mV to minus 300 mV.

Fig. 2 shows measured concentrations of nitrate ions, Eh, and pH in the samples taken for analysis from positions 1, 2, and 3 (Fig. 1) before supplying another new portion of water for biofiltration. It was supplied daily (stationary mode of functioning of the biofilter) at a given time. The output water contained 250 mg/dm^3 of sodium nitrate, 125 mg/dm^3 of sulfates, and 125 mg/dm^3 of ethanol (carbon/nitrogen ratio $C/N = 1.56$), which is excessive compared to the stoichiometry of biological denitrification (28) when $C/N = 0.94$. Columns of different heights in sector (a) in Fig. 2 show nitrate concentrations in water samples that have been taken for research at the biofilter inlet (position 1), from the sampler at the junction of inlet and outlet elbows of the biofilter (position 2) and at the biofilter outlet (position 3). As can be seen, during the operation of the biofilter in the displacement biofiltration mode, a multiple (by more than an order of magnitude) reduction in the concentration of nitrate ions in denitrified water is achieved. At the same time, the main share of the observed decrease in the concentration of nitrate ions falls on the inlet elbow of the biofilter. In sectors (b) and (c) of the diagram field, the results of Eh and pH measurements are presented. In the water supplied to the biofilter and in the resulting filtrate, redox potentials have positive values, which on the hydrogen scale range from plus 90 mV to plus 135 mV. In the water sampled for analysis from the connection zone of inlet and outlet elbows of the biofilter, Eh have negative values, which vary in the range from minus 230 mV to minus 265 mV.

The hydrogen index (pH) of the water supplied to the biofilter and in the obtained biofiltrate is in the range of 8.1-8.3 and 8.45-8.7, respectively, and in the sample from the zone of connection of inlet and outlet elbows - 7.6-7.8.

The results of Eh measurements indicate the presence of hydrogen sulfide in the zone of connection of inlet and outlet elbows of the biofilter. Samples of denitrified water from this zone have a characteristic odor. The presence of hydrogen sulfide in them is confirmed by a qualitative reaction using lead nitrate.

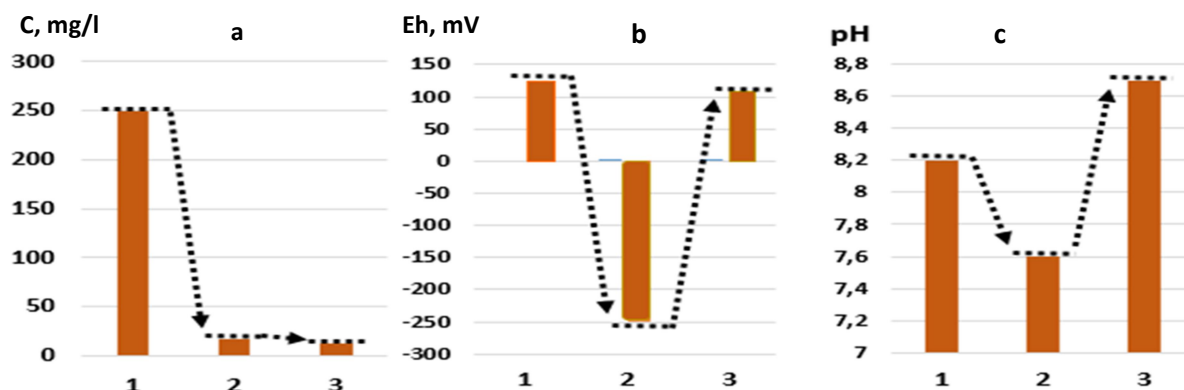


Figure 2. Change in nitrate concentration (a), redox potential (b), and pH (c) in water samples: 1 - inlet zone; 2 - zone of connection of inlet and outlet elbows; 3 - output zone of outlet elbow

Thus, during biofiltration denitrification of water with ($NaNO_3$) initial concentration – 250 mg/dm^3 , sulfate concentration – 125 mg/dm^3 and ethanol dosage – 125 mg/dm^3 , in the lower part of the biofilter (anaerobic zone) the presence of sulfate-reducing bacteria is observed. The latter separate oxygen from sulfate ions for their respiration and release (HS^-) hydrosulfide ions that undergo hydrolysis into the filtered water, which is accompanied by the appearance of hydrogen sulfide in denitrified water along the path of biofiltration.

Between hydrosulfide ions and hydrogen sulfide molecules, a dissociation equilibrium is established, and between sulfate ions, hydrosulfide ions, and hydrogen sulfide, a redox equilibrium, associated with the functioning of sulfate reductases in bacterial cells that reduce (SO_4^{2-}) ions to (HS^-), is established.

The ($H_2S \rightleftharpoons HS^-$) dissociation equilibrium depends on pH and the ionic strength formed by salts dissolved in water. If the ionic strength is neglected, then the equilibrium between (HS^-) and (H_2S) depends only on pH and is described by the equation:



For this reaction, the standard Gibbs potential (ΔG°_{298}) is:

$$\Delta G^\circ_{298} = 40.27 \text{ kJ/mol.} \quad (2)$$

The ratio of the standard Gibbs potential (ΔG°_{298}) to the energy of thermal motion (RT) is the logarithm of the dissociation equilibrium constant, i.e.:

$$\lg K = \frac{-\Delta G^\circ_{298}}{2.303RT}. \quad (3)$$

So, in this way:

$$\lg K = -7.05; \text{ and } K = 8.91 \cdot 10^{-8}, \quad (4)$$

however

$$K = \frac{[H^+][HS^-]}{[H_2S]}, \quad (5)$$

and

$$\lg \frac{[HS^-]}{[H_2S]} = \lg K + pH. \quad (6)$$

Equation (6) reveals the relationship between pH and the concentration ratio of hydrosulfide ions to hydrogen sulfide in their presence in water. In particular, if $[H_2S] = [HS^-]$, then:

$$\lg K + pH = 0, \text{ and } pH = 7.05. \quad (7)$$

If $pH < 7.05$, the hydrogen sulfide equilibrium according to reaction (1) shifts to $[H_2S]$, and when $pH > 7.05$ - to $[HS^-]$.

Concentrations of hydrogen sulfide and hydrosulfide ions at different pH values are found as follows:

$$K_1 = \frac{[H_2S][OH^-][H^+]}{[HS^-][H^+]} = \frac{K_W}{K} = \frac{\alpha^2[HS^-]^2}{(1-\alpha)[HS^-]}, \quad (8)$$

where: K_W is ionic product of water; K_1 is a constant of H_2S dissociation reaction according to the first degree; α^* is a degree of hydrolysis of hydrosulfide ions; $[HS^-](1 - \alpha^*)$ is a concentration of hydrosulfide ions that have not undergone hydrolysis; $\alpha^*[HS^-]$ is a concentration of formed (H_2S) and (OH^-).

Then:

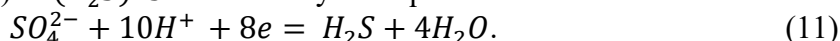
$$[HS^-] = \frac{[OH^-]^2}{K_1} = \frac{10^{-2(14-pH)}}{K_1} \quad (9)$$

or

$$[H_2S] = \alpha[HS^-] = \sqrt{K_1[HS^-]}. \quad (10)$$

If sulfate ions are present in water together with hydrogen sulfide and hydrosulfide ions, then the situation changes. In sulfate ions, sulfur has a (+6) oxidation state, and (-2) in hydrogen sulfide molecules and hydrosulfide ions. The equilibrium in water between (SO_4^{2-}) and (HS^-) ions, as well as between (SO_4^{2-}) and (H_2S) ions depends on both pH, as well as energy expenditure required for the reduction of sulfate ions. Sulfate-reducing bacteria obtain energy for the work of enzyme complexes that split oxygen from (SO_4^{2-}) ions and produce (H_2S) ions from nutrient substrates.

The recovery of (SO_4^{2-}) to (H_2S) is described by the equation:



The standard Gibbs potential for this reaction is equal to:

$$-\Delta G^\circ_{298} = 233.91 \text{ kJ/mol}, \quad (12)$$

and, thus, the standard redox potential is described by the expression:

$$Eh^0 = \frac{-\Delta G^\circ_{298}}{8F}. \quad (13)$$

Then, according to the Nernst equation, the relationship between [SO_4^{2-}] and [H_2S] concentrations with redox potential and pH is as follows:

$$Eh = Eh^0 - \frac{2.3R}{nF} \lg \frac{[H_2S]}{[SO_4^{2-}]} - \frac{2.3RT}{F} \frac{(n_H)}{(n_e)} pH \quad (14)$$

or

$$Eh = 0.303 + 0.0074 \lg \frac{[SO_4^{2-}]}{[H_2S]} - 0.074 pH \quad (15)$$

and

$$\lg \frac{[SO_4^{2-}]}{[H_2S]} = \frac{Eh - 0.303 + 0.074 pH}{0.0074} = Q. \quad (16)$$

Assuming that

$$[H_2S] + [SO_4^{2-}] = \text{const},$$

and imagining the concentrations of indicated components as fractions from the unit, we get:

$$[SO_4^{2-}]^* + [H_2S]^* = 1 \quad (17)$$

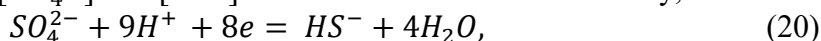
or

$$[SO_4^{2-}]^* = \frac{10^Q}{1 + 10^Q} \quad (18)$$

and

$$[H_2S]^* = \frac{1}{1 + 10^Q}. \quad (19)$$

The equilibria between [SO_4^{2-}] and [HS^-] can be described in a similar way, i.e.:



$$-\Delta G^\circ_{298} = 194.54 \text{ kJ/mol}, \quad (21)$$

$$Eh^0 = \frac{-\Delta G_{298}^0}{8F} = 0.252 \text{ V}, \quad (22)$$

$$Eh = Eh^0 - \frac{2.3RT}{nF} \lg \frac{[HS^-]}{[SO_4^{2-}]} - \frac{2.3R}{F} \frac{(n_H)}{(n_e)} pH \quad (23)$$

and

$$Eh = 0.252 + 0.0074 \lg \frac{[SO_4^{2-}]}{[HS^-]} - 0.066 pH. \quad (24)$$

Then:

$$\lg \frac{[SO_4^{2-}]}{[HS^-]} = \frac{Eh - 0.252 + 0.066 pH}{0.0074} = Q_1 \quad (25)$$

and by analogy with (17)-(19):

$$[SO_4^{2-}]^* = \frac{10^{Q_1}}{1 + 10^{Q_1}}, \quad (26)$$

$$[HS^-]^* = \frac{1}{1 + 10^{Q_1}}. \quad (27)$$

Equation (9) indicates that in a hydrogen sulfide system, a shift in pH by one unit causes a change in the concentration of hydrosulfide ions by two orders of magnitude. At the same time, the concentration of hydrogen sulfide also changes proportionally, as follows from equation (10).

Fig. 3A shows how relative concentrations of sulfate ions and hydrosulfide ions change depending on pH at redox potentials equal to 0.2 V; 0.25 V and 0.3 V, respectively, and Fig. 3B - how decimal logarithms of the ratio of concentrations of sulfate ions to hydrosulfide ions change depending on the values of redox potentials at pH = 6.6; 7.6 and 8.6.

The ratios of concentrations of sulfate ions to hydrosulfide ions, depending on redox potentials, are exponential functions. In semi-logarithmic coordinates, their graphs are straight lines with a slope: $nF/2.3RT$. Their location occurs with a displacement along the ordinate axis proportional to pH, as shown by equations (23)-(25). At a given pH value, an increase or decrease in redox potential by 0.01 V leads to a change in the concentration ratio more than twenty times. Therefore, the processes occur most dynamically in the hydrogen sulfide system near the points of concentrations equality $[SO_4^{2-}]$ and $[HS^-]$, or $[SO_4^{2-}]$ and $[H_2S]$. This is illustrated in Fig. 3A. On it, black dashed curves 1*, 2*, 3* demonstrate how the concentration of sulfate ions can change at redox potentials equal to minus 0.2 V; minus 0.25 V; and minus 0.3 V, when the hydrogen index increases from 6.5 to 7.0, respectively; also from 7.5 to 8.0 and from 8.0 to 8.5. Red continuous lines show, at the same time, the change in relative concentrations of hydrosulfide ions. Calculations have been made according to equations (26) and (27) using the values obtained in (25). It can be seen that an increase in the hydrogen index by 0.5 units leads to a change in relative concentrations of $[SO_4^{2-}]$ and $[HS^-]$ from almost zero to one and vice versa.

The course of calculated curves 2 and 2* in Fig. 3A corresponds to the results of experimental measurements, which have shown a shift of redox potential to minus 260 mV and pH to 7.6 (Fig. 2b, c). Their intersection occurs at pH 7.6-7.62, which corresponds to the possibility of achieving the same relative concentrations of hydrosulfide ions and sulfate ions at $Eh = 0.25 \text{ V}$. In fact, the concentration of hydrosulfide ions produced by sulfate-reducing bacteria is related to the amount and quality of the substrate for their nutrition. In denitrification biofilter, ethanol, part of which from denitrification zone, under conditions of excess, enters sulfate reduction zone, is such a substrate of bacterial nutrition. Therefore, real concentrations of hydrosulfide ions and, accordingly, hydrogen sulfide, compared to the initial amount of sulfate ions in water fed to the biofilter for processing, are not large.

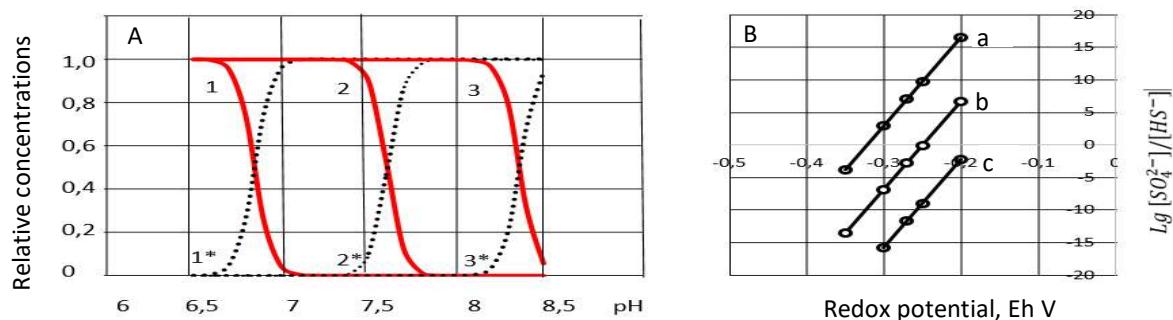


Figure 3. Calculated dependences of relative concentrations of hydrosulfide ions and sulfate ions and decimal logarithms of their ratios depending on pH at given Eh:

A - 1, 2, 3 - change in relative concentrations of hydrosulfide ions and 1*, 2*, 3* - sulfate ions depending on pH at Eh = -0.2 V; -0.25 V; -0.3 V respectively
 B - $\lg [SO_4^{2-}]/[HS^-]$ on Eh at pH=6.6 (a); 7.6 (b); 8.6 (c)

Fig. 4 shows the dependence of the change of redox potentials (Eh) on time in water samples taken for analysis from zones of: a) inlet elbow; b) connection of inlet and outlet elbows of the biofilter; c) outlet elbow of the biofilter. Measurements of redox potentials were carried out in samples that were in states of rest (1), stirring with magnetic stirrer (2), as well as mixing a stream of air bubbles (3) with additional blowing through the sample of filtered water.

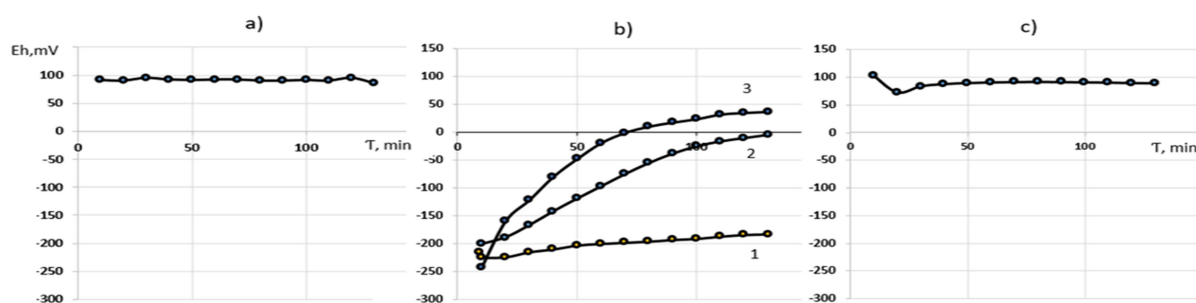


Figure 4. Dynamics of changes in redox potentials in water samples taken for analysis from different zones of the biofilter:

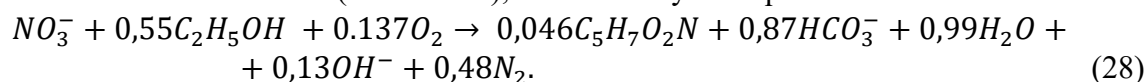
a) zone of inlet elbow; b) zone of connection of inlet and outlet elbows;
 c) zone of outlet elbow of the biofilter

The graphs of the "Eh - τ " function in Fig. 4 show that Eh in samples of water entering biofiltration (a) and in the obtained biofiltrate (c) practically do not differ from each other and are stable over time. Therefore, the conditions of the experiment (state of rest or mixing of water samples with magnetic stirrer) do not have a noticeable effect on Eh indicators. Such dynamics of changes in redox potentials over time indicates the absence of significant amounts of reduced sulfur compounds, in particular hydrosulfide ions and hydrogen sulfide, in water entering biofiltration and in denitrified water. On the other hand, a different picture is observed in biofiltrate samples obtained from the zone of connection of inlet and outlet elbows of the biofilter (b). The course of changes in the "Eh - τ " functions in these samples is significantly influenced by hydrodynamic conditions. If water sample in the measuring cell of the potentiometer is at rest (magnetic stirrer is turned off), redox potential during its measurement changes as shown by curve 1 (sector b). When water sample is mixed with

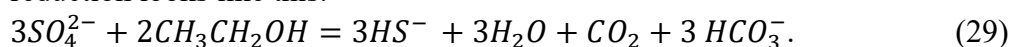
magnetic stirrer, redox potential changes as shown by curve 2. Under the conditions of blowing the water sample with a stream of air bubbles in addition to mixing, effective surface area of water-air phase separation in the measuring cell increases significantly and the change in Eh values is demonstrated by curve 3.

The results of this experiment testify to the process of sulfate reduction with the formation of H_2S . During the contact of filtrate samples containing hydrogen sulfide with atmospheric air, hydrogen sulfide is weathered. The difference in its concentrations (partial pressures) in the sample volume and in atmospheric air is the driving force. The process is accelerated by convective transfer of dissolved hydrogen sulfide to the surface of "water-air" phase interface during mixing and additional blowing of the samples with atmospheric air.

From the obtained data, it is possible to conclude that during the daily supply of portions of nitrate water of the above composition to the biofilter the formation of hydrogen sulfide is observed in the zone of connection of its inlet and outlet elbows. Its appearance is caused by the fact that the dosage of ethanol in denitrified water, which is 125 mg/dm^3 , exceeds the stoichiometric one ($C/N = 0.94$), calculated by the equation:



Due to the biotransformation of nitrates into molecular nitrogen in the presence of ethanol, the concentration of nitrate ions in the filtrate decreases. This contributes to the activation of sulfate-reducing bacteria (He *et al.*, 2010), which are localized in the zone of connection of inlet and outlet elbows of the biofilter. In the presence of ethanol, they produce hydrogen sulfide, releasing oxygen from sulfate ions for their respiration. The equation of bacterial sulfate reduction looks like this:



Hydrogen sulfide, which is formed in the zone of connection of inlet and outlet elbows of the biofilter, is practically not observed at its outlet. It can be assumed that in the filter loading after the zone of operation of sulfate-reducing bacteria, there is a zone of prevalence of sulfur bacteria that oxidize hydrogen sulfide, which hasn't been spent on the formation of insoluble sulfides, to elemental sulfur.

Sulfate reduction is suppressed if the addition of ethanol to denitrified water is less (60 mg/dm^3 , i.e. $C/N = 0.75$) than is required for exhaustive microbiological reduction of nitrate to molecular nitrogen according to equation (28).

Fig. 5 shows "Eh - τ " chronopotentiograms of filtrate samples taken for analysis from zone (2) of the biofilter during the decade of the experiment. The course of obtained "Eh - τ " dependences, as expected, confirms that with a decrease in the dosage of ethanol in denitrified water, sulfate-reducing bacteria stop producing hydrogen sulfide. Its accumulation in the biofiltrate decreases as the period of "starvation" of the microbial community increases, and already after five days of the biofilter's work, under certain conditions, the chronopotentiograms record the disappearance of hydrogen sulfide. This is demonstrated by the general course of the curves with indices from 0 to 5 in Fig. 5a. However, if ethanol dosage is restored to the original value of 125 mg/dm^3 , then the picture is reversed. In working biofilter, the production of hydrogen sulfide is resumed in the zone of connection of its inlet and outlet elbows. This demonstrates the course of "Eh - τ " curves with indices from 5 to 10 in Fig. 5b.

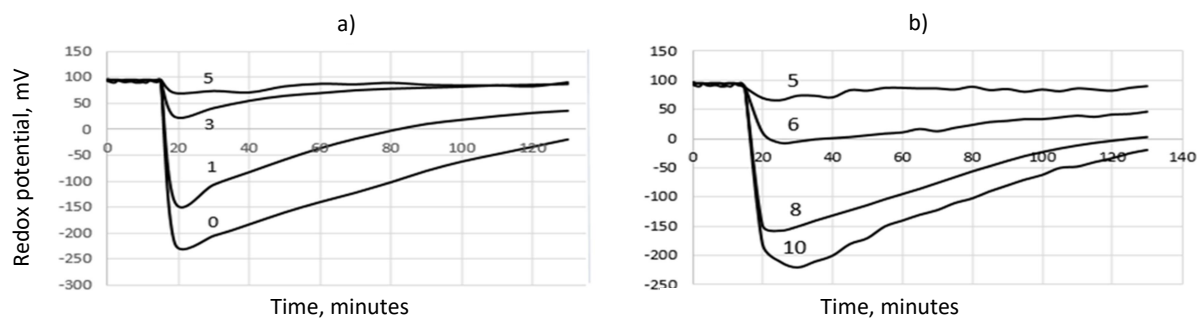


Figure 5. Dynamics of the change in redox potentials during 10 days in biofiltrate samples stirred with magnetic stirrer at different doses of ethanol:

a) curve 0 - dose of ethanol is 125 mg/dm^3 ; curves 1, 3, 5 - dose of ethanol is 60 mg/dm^3

b) curve 5 - dose of ethanol is 60 mg/dm^3 ; curves 6, 8, 10 - dose of ethanol is 125 mg/dm^3

The numbers near the curves correspond to the sequence of the experiments (day of the experiment)

Similarly, sulfate reduction is affected by the concentration of sulfate ions. The denitrification of model water that does not contain sulfates (nitrate-containing water with the addition of ethanol was prepared on a distillate) is accompanied by the suppression of sulfate-reducing bacteria, and hydrogen sulfide is not detected in biofiltrate samples. It is important to note that ethyl alcohol, which is dosed into denitrified water, is almost completely consumed in the biofilter. It is always assimilated by the microbiome during the time the treated water is inside the biofilter. This is confirmed by the results of chromatographic studies of water samples supplied to biofiltration denitrification and biofiltrate samples that have been taken from functioning filter at its outlet and from zones of connection of inlet and outlet elbows.

Conclusions

Recently, biological denitrification is increasingly considered as one of available alternatives to decentralized water treatment. Therefore, it is relevant to study the impact of other impurities contained in natural waters, in particular sulfates, carbonates, etc., both on the removal of nitrates directly from the treated water and on its quality. The paper presents the results of denitrification of water in the presence of sulfates in a small-sized submersible biofilter. It is shown that the processes of biotransformation of nitrates and sulfates follow the trajectory of water movement in the biofilter sequentially. Reduction of sulfates to hydrogen sulfide begins after removal of nitrates from the treated water. This happens when the dosage of nutrient substrate (ethanol) added to the biofilter exceeds the stoichiometric amount required for denitrification. The obtained results in subsequent studies can be used to further improve the quality of the obtained biofiltrate due to the additional removal of impurities of salts of heavy and polyvalent metals from it.

Acknowledgements

None.

Conflict of Interest

None.

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МАТЕМАТИЧНА МОДЕЛЬ СПОЛУЧЕНИХ ПРОЦЕСІВ ДЕНІТРИФІКАЦІЇ ТА ВІДНОВЛЕННЯ СУЛЬФАТІВ В ІННОВАЦІЙНОМУ БІОФІЛЬТРІ

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Анотація. В роботі із застосуванням математичного моделювання розкрито особливості біологічного перетворення нітратів і сульфатів до нітрогену та сірководню під дією гетеротрофних денітрифікаційних і сульфат-відновлювальних бактерій в малогабаритному заглибному біофільтрі при різних співвідношеннях «карбон/нітроген». Технологія біофільтрації дає змогу виробляти питну воду більш екологічно безпечним, економічним та ефективним способом. Однак підземні води, окрім небезпечних для здоров'я людини нітратів, містять й інші неорганічні сполуки (солі важких та полівалентних металів, карбонати, сульфати і т. д.), що беруть участь у супутніх процесах (метаногенезу, сульфат-відновлення, уреолізу) в біофільтрі. Під час дослідження було розкрито додаткові можливості денітрифікаційного малогабаритного заглибного біофільтра, а саме, біотрансформації разом із нітратами сульфатів до сірководню, який може сприяти видаленню іонів важких та полівалентних металів з води. Досліджено зрушення сульфат-сульфідної рівноваги у водному середовищі біофільтра та вплив концентрацій сульфат-іонів і субстрату бактеріального живлення, зокрема етанолу, на накопичення і його витрачання в об'ємі біофільтра при здійсненні біофільтраційної денітрифікації. Результати моделювання сполучених процесів денітрифікації води у малогабаритному інноваційному біофільтрі у присутності сульфатів дали змогу встановити можливість і чинники їх керованого відновлення. Показано, що перевищення дозування субстрату живлення (етанолу) у вихідну воду порівняно зі стехіометричним, коли «карбон/нітроген» дорівнює 0,94, призводить до появи у фільтраті сірководню, який продукують сульфат-відновлювальні бактерії за рахунок живлення залишками етанолу. Сірководень у фільтраті не з'являється при дозуванні субстрату живлення у вихідну воду в кількості, що відповідає показнику «карбон/нітроген» меншому, ніж потребує стехіометрія біологічного відновлення нітратів. Кероване відновлення сульфатів до сірководню може бути корисним додатковим інструментом поліпшення якості фільтрату при сумісній денітрифікації і вилученні з води домішок солей важких металів. Розроблена модель і отримані результати можуть бути використані для подальшого поліпшення якості одержуваного біофільтрату за рахунок додаткового видалення з нього домішок солей важких і полівалентних металів.

Ключові слова: децентралізоване водоочищення, нітрати, сірководень, бактеріальне живлення, якість води.

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MALWARE DETECTION MODEL BASED ON MACHINE LEARNING

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Abstract. Every year, malware authors create more and more sophisticated and clever malware that can harm our computers. Traditional methods, which are based on searching for program signatures are no longer effective in solving the problem of malware detection. It is being replaced by automated file analysis, which is a more promising approach to detecting suspicious files. Machine learning methods are increasingly used to detect such malware programs. However, such solutions may require a lot of computing resources to perform their operations. Therefore, the task of creating an optimal machine learning model in terms of learning speed and malware detection accuracy arises. In addition, usually one method of data representation is not sufficient to detect malicious features of files. Therefore, this paper will describe two different methods: one method is based on the binary information of the file, the other one is based on disassembled code of executable files. The purpose of this work is to improve the efficiency of malware detection by optimising feature extraction methods and applying machine learning. The main tasks of the study include: extracting features from exe files, creating several machine learning models and comparing them to determine the most effective one. The dataset used in this study has been collected from various online sources and consists of 12824 executable files in .exe format, of which 11844 files are malicious and 980 are benign. This paper presents recommended methods of feature extraction and input data generation for machine learning models based on the support vector machine algorithm. These methods allow to find the best way to process the features describing a malicious file. Six machine learning models, each of which performed well in terms of F-score, precision, and recall metrics, were created. The model that was created based on the binary type of data representation showed the highest results for all metrics.

Keywords: intrusion detection, PE format, feature extraction, disassembled instructions, support vector machine.

Introduction

Every year there are more and more methods for detecting malicious software that abandon traditional signature approaches. Instead, a bet is made on heuristic analysis, behavioral methods or their combinations (Abri *et al.*, 2019). These methods have gained particular attention due to their ability to detect zero-day malware. This is software whose signature is not available to antivirus systems (Handa *et al.*, 2019; Alazab *et al.*, 2011). The use of machine learning models is the key point of these methods, but it is not without certain challenges. The main ones are the selection and formation of an optimal set of features

(features of the file) that allow to best represent the input data set. In addition, it is important to effectively adapt these features for machine learning models to improve the overall accuracy of the models and optimize the learning time. Our work is focused precisely on these aspects. In particular, in the world scientific literature there are already works that offer various solutions to these issues (Chaudhary, 2021; Kutlay *et al.*, 2020; Al-Khshali *et al.*, 2020). In our previous study, we have analyzed a set of .exe files with the help of different machine learning algorithms using the binary code of the file as key features (Nafiev *et al.*, 2022). We have considered the executable file in PE format, and also selected the most optimal parameters for classification algorithms. The algorithm based on support vectors turns out to be particularly effective. Therefore, in this work, we will build several machine learning models based on this algorithm. The main purpose of this research is to improve the process of detecting malware with the help of modernized feature extraction methods and the use of machine learning models. Within the framework of this study, we have identified the following tasks:

1. Formation of the input data set for the support vector machine.
2. Research and adaptation of methods for extracting features from files.
3. Construction and evaluation of several machine learning models based on extracted features.
4. Comparison of models in order to choose the most effective one for detecting malware.

1 Materials and methods

This section describes the main stages of our research. Section 1.1 covers the basics of PE format. In Subsection 1.2, we consider the formation of the input data set. Subsection 1.3 describes data representation and feature extraction methods, and Subsection 1.4 introduces the basics of the support vector machine algorithm.

1.1 Description of PE format

There is no doubt that Portable Executable (PE) file format plays a key role in the execution of software in the Windows operating system. It is universal file format for executable files, dynamic link libraries (DLLs) and drivers (Microsoft, n.d.). Structural organization of PE format, which is depicted in Fig. 1, is one of its main features. PE file consists of different sections containing different types of information. For example, PE header contains metadata about the file, such as the date of its creation, file size, version, and so on (Sikorski *et al.*, 2012). Import address table indicates external functions that the program uses, and export address table indicates the functions that the program exposes for use by other programs. These tables can provide important information about the behavior of a program because they indicate the interaction of the program with other programs or with the operating system (Sikorski *et al.*, 2012; Bilar, 2007). Resource sections can contain different types of data, such as icons, fonts, images, text lines, etc. These resources can be analyzed to obtain additional features for static analysis. Using n-grams of bytes or n-grams of instructions, certain patterns in binary code contained in PE files can be detected. These patterns may indicate typical behavior of a benign program or behavior specific to malware, such as exploitation of known vulnerabilities, attempts to bypass antivirus programs, or the presence of malicious content (Abdessadki *et al.*, 2019). Ultimately, the analysis of PE format can provide a significant amount of information that can be used to classify a file as malicious or safe one.

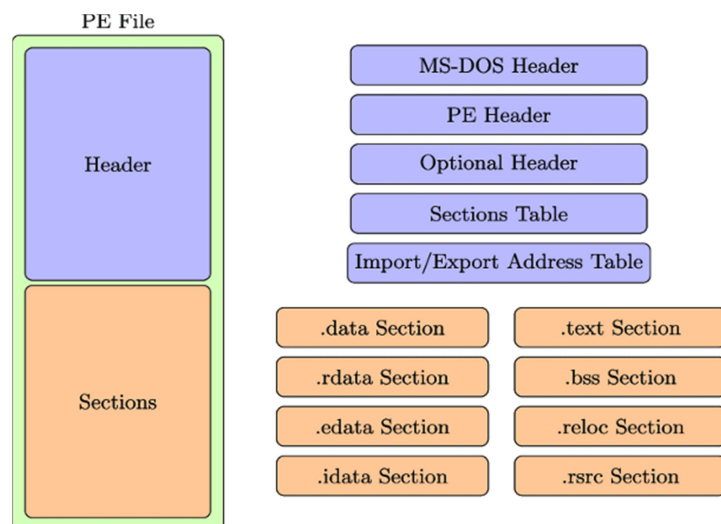


Figure 1. Structure of PE format

1.2 Formation of the input data set

The creation of the input data set is one of the most important steps in building a machine learning model. It is also necessary that such a set is well balanced to obtain the most representative results. The input data was represented by a dataset containing 11,844 malicious .exe files and 980 benign ones. Malicious files were divided into 5 different families: CryptoRansom (5856), Zbot (1973), Zeus (1413), InstallCore (731), Winwebsec (657), Mediyas (463), Zeroaccess (407), Locker (300). An infographic of the distribution of files by type can be seen in Fig. 2.

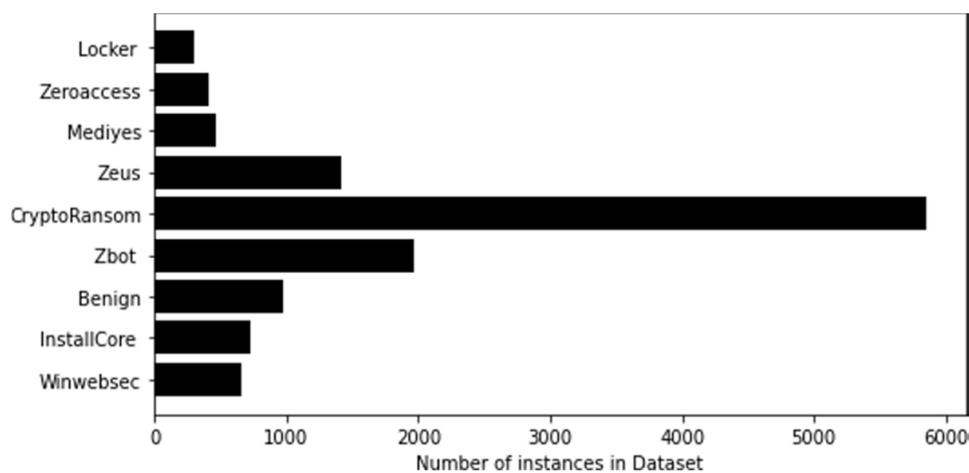


Figure 2. Infographic of distribution of files by type

It is worth noting that in the used data set there are significantly fewer safe files than malicious ones. In real system, this may be a problem, but in our case, such a distribution is acceptable, since our main task in this work is to investigate methods of feature formation. All malicious files were taken from "malicia-project.com" and "virusshare.com" websites. Benign files were taken from the folders of installed legitimate software applications of various categories. They can be downloaded at "download.cnet.com/windows".

1.3 Identification of features

As already mentioned in this Section, PE executable files contain a lot of different information that can be used to detect malware. We can consider each file as a sequence of

bytes, a set of trace instructions, or function calls. Different types of file representation require different approaches to information extraction, selection, and preprocessing. This Section is aimed at solving these tasks.

1.3.1 Binary data representation

To generate input data for a machine learning model, you need to extract useful bit information from the executable file. To do this, each file is processed in turn using the pefile library from the Python programming language. The functions of this module allow to get the bytes of certain fields from different sections of PE-file in the form of a line. For each file from the data set, a list containing the sequence of bytes of this file is formed. A visualization of this process can be seen in Fig. 3.



Figure 3. The process of forming a byte vector, which is filled with different fields of PE file structure

This study examines two models of binary data representation. The first model uses only the byte sequence from the header (purple cells in Fig. 1): DOS_HEADER, FILE_HEADER, OPTIONAL_HEADER, SECTION_HEADER, Export, and Import. The second model uses the entire header and resource section (.rsrc) as it is available in the file module (orange cells in Fig 1). Fig. 4 shows an example of the fields used for the DOS Header (The fields, 2016).

```
typedef struct _IMAGE_DOS_HEADER {
    WORD    e_magic;          /* 00: MZ Header signature */
    WORD    e_cblp;           /* 02: Bytes on last page of file */
    WORD    e_cp;             /* 04: Pages in file */
    WORD    e_crlc;           /* 06: Relocations */
    WORD    e_cparhdr;        /* 08: Size of header in paragraphs */
    WORD    e_minalloc;       /* 0a: Minimum extra paragraphs needed */
    WORD    e_maxalloc;       /* 0c: Maximum extra paragraphs needed */
    WORD    e_ss;             /* 0e: Initial (relative) SS value */
    WORD    e_sp;             /* 10: Initial SP value */
    WORD    e_csum;           /* 12: Checksum */
    WORD    e_ip;             /* 14: Initial IP value */
    WORD    e_cs;             /* 16: Initial (relative) CS value */
    WORD    e_lfarlc;         /* 18: File address of relocation table */
    WORD    e_ovno;           /* 1a: Overlay number */
    WORD    e_res[4];         /* 1c: Reserved words */
    WORD    e_oemid;          /* 24: OEM identifier (for e_oeminfo) */
    WORD    e_oeminfo;        /* 26: OEM information; e_oemid specific */
    WORD    e_res2[10];       /* 28: Reserved words */
    DWORD   e_lfanew;         /* 3c: Offset to extended header */
} IMAGE_DOS_HEADER, *PIMAGE_DOS_HEADER;

#include <poppack.h>
```

Figure 4. Example of DOS_HEADER fields from PE file structure

Data representation using n-grams was one of the first feature generation methods used to detect malware (Raff *et al.*, 2018). In this work, we will use a Markov chain, which can be represented as a graph, in which the vertices are the states of the process (all possible 256 bytes), and the edges are the transitions between the states. As a result, we get a square matrix of $P = \|p_{ij}\|$ transitions with a dimension of 256×256 , where each p_{ij} cell contains the probability of transition from one byte to another. The transition matrix is subject to the following conditions:

$$p_{ij} \geq 0, \quad (1)$$

$$\forall i \sum_j p_{ij} = 1. \quad (2)$$

To build such a matrix of transitions, first, based on the collected sequence of bytes for each file, it is necessary to build an adjacency matrix of the form (00, 01, ..., ff)*(00, 01, ..., ff). In this adjacency matrix, the number of times one byte was immediately followed by another byte is counted in each cell. And only then, after the formation of adjacent matrices, transition matrices are built for all files.

At the final stage, a final matrix with dimensions 12824 (the number of all files)* 256^2 is formed, in which each line corresponds to one file and includes its transition matrix converted into vector form. Each such vector contains 65536 values. A diagram of this process can be seen in Fig. 5.

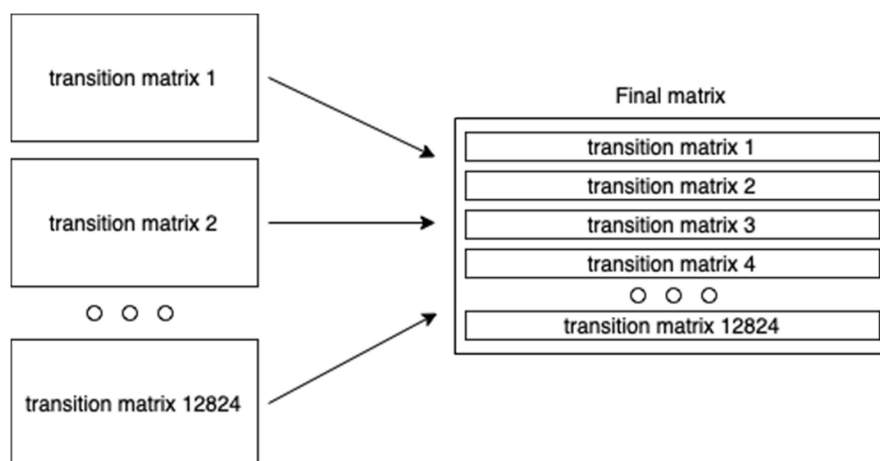


Figure 5. Diagram of formation of the final matrix

Before passing the resulting matrix to the machine learning algorithm, you must first split this matrix into two parts. One part will be used for learning the model and the other part for testing. Since our dataset does not contain a large number of different types of malicious files, it was decided to use 60% of the final matrix for learning and 40% for testing.

1.3.2 Instruction tracing

Executable instruction tracing is also used to detect malware. We generate disassembled code using IDA Pro, which is opened for each file via the command line using a python script. The program saves disassembled instructions of each element in .asm files. This is a file format in which text information is stored. An example of an .asm file is shown in Fig. 6.


```

; -----
loc_4112BC:                                ; CODE XREF: sub_411239+70\u2191j
mov     [ebp+var_48], 0
mov     [ebp+var_48], 1
push    14h                               ; dwMilliseconds
call    ds:Sleep
call    sub_411565
mov     [ebp+var_48], eax
cmp     [ebp+var_48], 0
jz      short loc_4112FB
mov     eax, [ebp+var_28]
mov     [ebp+var_24], eax
mov     [ebp+var_4], 3D63h
mov     ecx, [ebp+var_24]
push    ecx
call    sub_411000
add     esp, 4
jmp     short loc_411302
; -----

```

Figure 6. A fragment of the .asm file

Note: Used instructions are marked in red

After that, instructions (push, call, cmp, mov, jz, etc.), which are assembled into a two-dimensional matrix, are sent to each file in turn. Each line of this matrix corresponds to a sequence of instructions of a specific file. Now the task is to form adjacency matrices for all files. In binary data representation, we used the number of all existing bytes as the dimension of the adjacency matrix. However, in the case of instruction tracing, we cannot use all existing instructions, as their number is counted in the thousands. And this will have a very negative effect on the learning speed of the model. Therefore, it is necessary to limit the set of instructions based on which the adjacency matrix is built. To solve this problem, it was decided to choose the instructions that appear in all files the most times in total. Four sets of instructions containing 74, 126, 187 and 272 elements were formed. Based on each such set, a machine learning model will ultimately be built.

Finally, an adjacency matrix is built for each file in the same way as in binary data representation. The four sets of instructions determine the dimensionality of two-dimensional square adjacency matrices, in which for each pair of instructions in the matrix, the number of times the first instruction followed the second is counted. Now, transition matrices are constructed using adjacency matrices. Transition matrices form the final matrix, as in Fig. 5. As in binary data representation, the final matrix is divided into two parts - learning and testing ones, and the share of the learning sample is 60% of the entire data set.

1.4 Machine learning algorithm

For file classification, we use the support vector machine (SVM) algorithm. This algorithm searches for a hyperplane in the feature space that separates the points of two classes with the maximum distance (Lifshits, 2006; Burges, 1998). The hyperplane found by the SVM is a linear combination of data instances, x_i , with weights, α_i . It is important to note that only points close to the hyperplane will have nonzero values of α . These points are called support vectors. Therefore, the goal of SVM learning is to find the weight vector α that describes the contribution of each data instance to the hyperplane. Using quadratic programming, you can effectively solve the following optimization problem:

$$\max_{\alpha} \left(\sum_{i=1}^n a_i - \frac{1}{2} \sum_{i=1}^n \sum_{j=1}^n \alpha_i \alpha_j y_i y_j \langle x_i, x_j \rangle \right). \quad (3)$$

Under the conditions:

$$\sum_{i=1}^n \alpha_i y_i = 0, \quad (4)$$

$$0 \leq \alpha_i \leq C, \quad (5)$$

where y_i is the label of the class of the x_i instance, $\langle \cdot, \cdot \rangle$ is the scalar product, and C is the regularization parameter that allows "soft fields". That is, some instances may fall between fields, which helps prevent data overlearning and provides better accuracy. The weight vector of the hyperplane is calculated as follows:

$$\omega = \sum_i \alpha_i y_i x_i. \quad (6)$$

In the current state of affairs, only linear hyperplanes are possible in the d -dimensional space determined by x feature vectors. Using the kernel trick, data instances can be projected into a higher-dimensional space and find a linear hyperplane in it that will be equivalent to a nonlinear hyperplane in the original d -dimensional space. A new optimization problem arises:

$$\max_{\alpha} \left(\sum_{i=1}^n a_i - \frac{1}{2} \sum_{i=1}^n \sum_{j=1}^n \alpha_i \alpha_j y_i y_j K(x_i, x_j) \right). \quad (7)$$

The replacement of the scalar product with $K(x_i, x_j)$ kernel function is the only difference from formula (3). In our case, a Gaussian kernel is used, where transition matrices for two instances are taken and their kernel function (kernel) is calculated according to the following formula:

$$K(x, x') = \delta^2 e^{-\frac{1}{2\lambda^2} \sum_{i,j} (x_{ij} - x'_{ij})^2}. \quad (8)$$

Now, taking into account α found in equation (7), our solution is given by:

$$f(x) = \text{sgn} \left(\sum_{i=1}^n \alpha_i y_i K(x_i, x_j) \right), \quad (9)$$

where class +1 (benign file) is returned if $\text{sum} \geq 0$, and class -1 (malicious file) is returned if $\text{sum} < 0$.

2 Results and discussion

In this study, six machine learning models, four of which are trace representation type and two are binary type, were created. The indicators of the main metrics can be seen in Table 1. In this table, Binary_r is a model that includes the file resource section. Binary_wr model does not include it. Models called Trace_74 and similar ones are based on the trace type of data representation, where 74 means the number of instructions used as features. Time means the learning time of the model, measured in seconds. ROC and Precision-Recall curves can

also be observed in Fig. 7. The results show that all our models have fairly close indicators. However, it is still possible to select the best model, relying on the F-score metric, which is the harmonic mean between precision and recall. Models based on binary data representation have proven to be quite effective, especially when a resource section is used. A slight advantage in all metrics was shown by the Binary_r model. However, the learning time of this model also increased slightly as more data was used. These high metrics are explained by the fact that binary code often displays file properties that are specific for malware, such as specific coding pattern, specific libraries, or command sequences. For security systems that rely on speed of response and high accuracy, models learned on binary representation, especially with the resource section, should be used. Among the models based on disassembled instructions, the model with 74 instructions (Trace_74) turned out to be the most efficient one. In addition, the learning time of this model is significantly less than that of the variants with 126, 187 and 272 features, which is a significant plus. This proves that it is not always necessary to use a large amount of learning data for high classification quality. More precisely, the correct selection of "important" instructions can give an advantage over a large volume. When developing systems for detecting malicious files based on trace instructions, we recommend focus on the quality, not the quantity, of data. This not only improves the accuracy, but also reduces the computational cost and learning time of the model. It is also worth noting that binary representation models have shown a comparable accuracy result to the best model learned on trace instructions.

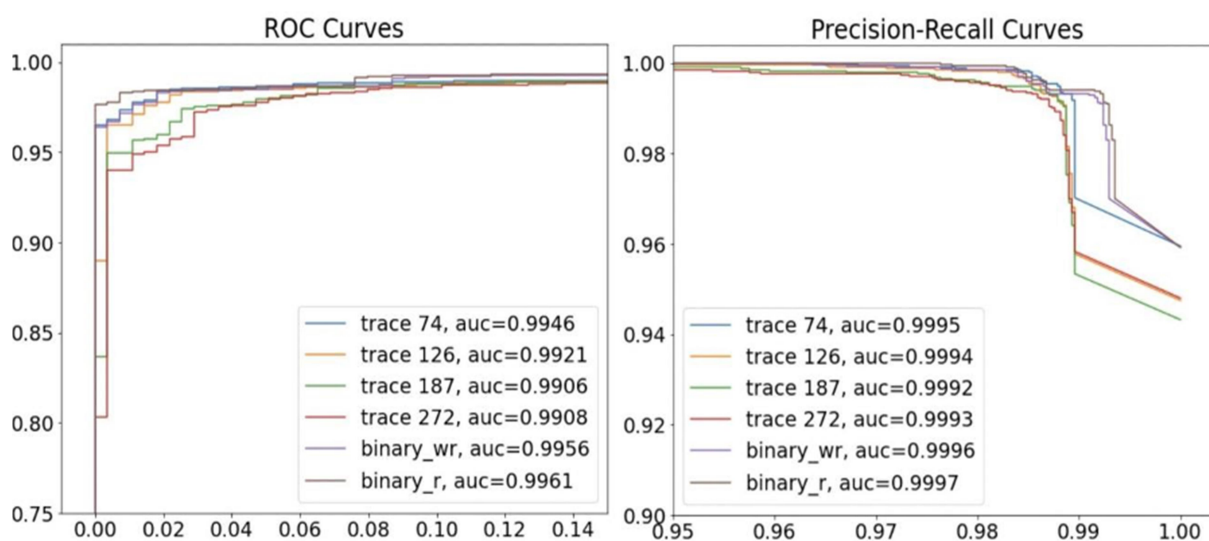


Figure 7. ROC and Precision-Recall curves

The results of our models accuracy may seem too high (Table 1), but some limitations should be taken into account. First, the data set used is not well balanced. Benign files are an order of magnitude fewer than viral ones, so the machine learning model will be better able to recognize malicious files. This is acceptable in our research, but a real file recognition system should use a balanced and carefully filtered data set. Second, there are not many different types of malicious files in the collected data set. Viruses of the same type are very similar to each other, which makes it easy for a machine learning algorithm to recognize such files. Future studies should use as many varieties of malicious files as possible to obtain a more representative result of the detection accuracy.

Table 1. Results of evaluation of machine learning models

	recall		precision		F-score		roc_auc	pr_auc	Time
	0	1	0	1	0	1			
Binary_wr	0.9130	0.9909	0.8873	0.9932	0.9000	0.9921	0.9956	0.9996	795
Binary_r	0.9239	0.9915	0.8947	0.9940	0.9090	0.9928	0.9961	0.9997	816
Trace_74	0.9130	0.9893	0.8689	0.9932	0.8904	0.9912	0.9946	0.9995	99
Trace_126	0.9094	0.9873	0.8479	0.9929	0.8776	0.9901	0.9921	0.9994	255
Trace_187	0.8695	0.9887	0.8571	0.9898	0.8633	0.9893	0.9906	0.9992	490
Trace_272	0.8369	0.9882	0.8461	0.9873	0.8415	0.9877	0.9908	0.9993	747

Conclusions

In this work, a method for detecting malicious programs based on machine learning was presented. We analyzed machine learning models that were built based on two different feature extraction approaches. The first approach used bitwise file information obtained from the PE structure using the Python pefile library. Two models were generated, one of which used the resource section of the file for learning. The second approach used executable instruction tracing. The disassembled code was generated using the IDA Pro program. 4 sets of features, each of which contained a different number of instructions (74, 126, 187 and 272) and corresponded to one machine learning model, were formed. All six models showed a good result of the accuracy of detecting malicious files. Our study demonstrates the importance of choosing a feature extraction approach when building machine learning models. Models based on the binary representation showed the best accuracy, especially the one that included the resource section. On the other hand, there was an opportunity to optimize the malware detection process through instruction tracing, especially when a limited number of instructions was used. It was found that the model learned on the least number of instructions (Trace_74) showed the highest values for all metrics. In addition, this model requires the least time for its learning, which is a significant advantage for using such a model in real file classification systems. Thus, it can be argued that the principle of using all possible data for classification does not always give the best accuracy result. Sometimes it is useful to select a small part of the entire set of features on which the learned model will show the highest accuracy result.

Acknowledgements

None.

Conflict of Interest

None.

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МОДЕЛЬ ВИЯВЛЕННЯ ШКІДЛИВОГО ПРОГРАМНОГО ЗАБЕЗПЕЧЕННЯ НА ОСНОВІ МАШИННОГО НАВЧАННЯ

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Анотація. З кожним роком автори шкідливого програмного забезпечення створюють все більш досконалі та хитромудрі шкідливі програми, які можуть завдати шкоди нашим комп'ютерам. Традиційні методи, які ґрунтуються на пошуку сигнатур програм, перестають бути ефективними для вирішення проблеми детекції шкідливого програмного забезпечення. На зміну приходить автоматизація аналізу файлів, яка є більш перспективним підходом для виявлення підозрілих файлів. Для виявлення таких програм все частіше використовують методи машинного навчання. Однак для виконання своїх операцій такі рішення можуть потребувати багато обчислювальних ресурсів. Тому виникає задача створення оптимальної моделі машинного навчання з погляду швидкості навчання і точності детекції шкідливого програмного забезпечення. Крім того, зазвичай одного методу представлення даних недостатньо для якісного виявлення шкідливих ознак файлів. Тому в цій роботі буде описано два різні методи: один підхід ґрунтується на бінарній інформації файлу, другий полягає у використанні трасувальних інструкцій. Мета цієї роботи – підвищення ефективності виявлення шкідливого програмного забезпечення шляхом оптимізації методів вилучення ознак та застосування машинного навчання. Основні задачі дослідження включають: вилучення ознак з exe-файлів, створення кількох моделей машинного навчання та їх порівняння для визначення найефективнішої моделі. Використаний у цьому дослідженні набір даних був зібраний з різних інтернет-джерел та складається з 12824 виконуваних файлів у форматі .exe, з яких 11844 файлів є шкідливими, а 980 – доброякісними. У статті представлено рекомендовані методи вилучення ознак та генерації вхідних даних для моделей машинного навчання на основі алгоритму машини опорних векторів. Ці методи дозволяють знайти найкращий шлях для обробки ознак, що описують шкідливий файл. Було створено шість моделей машинного навчання, кожна з яких показала високі показники метрик F-score, precision та recall. Модель, яка була створена на основі бінарного типу представлення даних, показала найвищі результати по всіх метриках.

Ключові слова: виявлення вторгнень, PE формат, вилучення ознак, дизасембльовані інструкції, машина опорних векторів.

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SPADE SOFTWARE AGENTS AND THEIR IMPACT ON HARDWARE RESOURCES

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Abstract. Eliminating the disadvantages of updating prices with a large number of products in the online store, we have found a solution in the application of the Smart Python Agent Development Environment (SPADE). The article presents the process of collecting data on SPADE and Openfire Server performance metrics in order to determine and analyze the consumption of system resources when connecting software agents with different types of behavior, in different numbers, as well as during interaction with a web application.

In current study, JMeter is used as a tool for data collection and performance testing (including load and stress). Quantitative and qualitative methods of data analysis are used. When processing the collected values of indicators for the use of hardware resources, methods of mathematical statistics have been used to identify relations between indicators. To compare the behaviors of the SPADE software agent, to determine the effectiveness of one over the other, as well as to determine the effectiveness of using the agent interface in command line mode compared to its web counterpart in the form of a graphical user interface (in terms of performance), formulas for calculating the growth rate are used.

During the study, the advantage of SPADE in the speed of program code execution; the difference in performance between agent behaviors, as well as between agent web user interface (AWUI) and command line interface (CLI) modes; features of using the CLI mode of the agent for interactive user interaction with the application in order to quickly fix errors that occur during the interaction of the agent with the web application have been determined.

Integration of SPADE agents into the pricing process has practical implications for retailers, opening up opportunities to study and develop new tools for subsequent application in solving specific problems.

Keywords: XMPP, Python, behavior, web, JMeter, CPU, RAM.

Introduction

Solving the problem of pricing in the absence of up-to-date data, an integrated approach was used using correlation and data monitoring through the application programming interface (API) (Zelenko, 2022). Despite the profitability, the developed software prototype (the minimum viable product (MVP) (Graffius, 2023; Umbreen *et al.*, 2022), which was used by the German company for two years (Zelenko *et al.*, Classification, 2023), had several limitations, the main of which was associated with a large time spent on executing the program code for updating prices ($\approx 100-110$ s) and, as a result, an increase in the load on the web server. Other important disadvantages include the cost of additional time and financial

resources for the development and support of: a method for reporting errors that require a human decision; graphical user interface (GUI) for making these decisions as well as for interacting with the software during the price update process.

The capabilities of the technologies used did not allow eliminating the first disadvantage and made it difficult to eliminate the second one, so it was decided to make changes to the application architecture. In the process of searching for new technologies, a solution was found, which consisted in the use of SPADE.

The **goal** is to study the impact of SPADE software agents on PC hardware resources and determining the effectiveness of their use compared to the web user interface (UI) in terms of performance. The **tasks** are: collect data on XMPP server performance metrics during its testing (including load and stress testing); determine the amount and analyze the consumed hardware resources over a certain time interval when connecting SPADE software agents with different basic types of behavior, in different quantities, as well as during interaction with a web application when performing the main function – updating prices.

Materials and methods

Software agent (hereinafter – agent) can be considered as a software object that can exhibit the above multi-dimensions or as an encapsulated computer system that is situated in some environment, and that is capable of flexible, autonomous action in that environment in order to meet its designed objectives. Researchers consider agent-oriented development as a natural and a logical evolution of the current software development paradigms, such as structured and object-orientated approaches, as it presents a higher-level of abstraction and encapsulation. Agent-oriented approaches can significantly enhance our ability to model, design and build complex, distributed software systems (Slhoub, 2018).

Agent orientation represents a higher-level abstraction that is more flexible than the prior programming paradigms, such as object abstraction. The agent technology is going to be the next significant breakthrough in software development and the new revolution in software (Slhoub, 2018). The software agents and multi-agent systems (MAS) (Holgado-Terriza *et al.*, 2020) will be one of the landmark technologies in computer science that will bring extra theoretical power, methods and techniques that will broaden the field of computer applications (Ajitha *et al.*, 2016).

Smart Python Agent Development Environment (SPADE) is a free MAS platform written in Python (n.d.) under MIT license and based on instant messaging (XMPP) (Spade-BDI, n.d.; Spade, n.d.; Pal *et al.*, 2020; Palanca, 2018; SPADE – SPADE 3.3.0, n.d.; Donancio *et al.*, 2019). And since Python is the language widely used in most machine learning framework (Lyu *et al.*, 2020) as well as in web development, this will allow the software (developed using the SPADE platform) to be easily integrated into a large number of web applications, as well as to use the software in conjunction with a large number of machine learning (ML) libraries provided by Python.

Some features: flexibility, agent model based on behaviors, web-based interface, use any XMPP server, BDI support (Spade, n.d.; Pal *et al.*, 2020; Palanca, 2018; SPADE – SPADE 3.3.0, n.d.; GitHub - javipalanca/spade_bdi, n.d.; Palanca *et al.*, 2022; Palanca *et al.*, 2023; Pérez, 2023). Behavior-based architectures are conceptually more capable, since they remove some of the limitations of reactive systems (Palanca *et al.*, 2022).

Five most commonly used SPADE behavior types were chosen for the experiment: Cyclic, Periodic, One-Shot, Time-Out, The Finite State Machine (FSM) (Palanca, 2018; Advanced Behaviours, n.d.; Palanca *et al.*, 2020; The SPADE agent model, n.d.).

The SPADE technology was chosen for the MVP upgrade for a complex reason that includes fundamental benefits (some of which are driven by Python):

1. An increase in the speed of script execution (described in the course of the current study).
2. No need to increase the script execution time and memory limit, reducing the load on the web server.
3. The possibility of interactive interaction with the agent (in this case, in the process of updating prices), which allows a person to quickly make a decision in case of errors or situations when the decision cannot be made by the agent.
4. Reduction of time and, as a result, *ceteris paribus*, financial costs due to the absence of the need to develop and maintain a graphical user interface (GUI) for software agents, compared with the development and support of such for web applications. Nevertheless, the SPADE technology has a built-in GUI, which, if necessary, allows you to speed up interaction with the agent and expand its functionality.

To implement the 3rd point, when executing the price updating algorithm (PUA; which uses cost-based method (CBM) for goods in the amount of 47817 units) in PHP/Python instead of an agent, for example, through cron, it is necessary to develop an alert functionality that will be limited in capabilities compared to the potential of SPADE BDI. Also, in the case of using PHP, GUI development will be required, however, the CLI mode UI for the SPADE agent is implemented faster, providing the user with quick access as a separate, more distinct system process (both visually and programmatically; compared to the web GUI). In the case of using SPADE, the notification option may be needed only if a user needs to make a decision remotely.

The following advantages also served as a reason for choosing this technology:

1. Potential for software development using Artificial Intelligence (AI) or Distributed Artificial Intelligence systems (DAI; due to the use of Python and agent technology (agent-oriented software engineering (AOSE) (Slhoub, 2018), the link for which is SPADE). It is planned to apply in the next version of the software in the form of monitoring the prices of competitors, allowing the use of the competitive-based method (Zelenko *et al.*, Overview, 2023).
2. Ability to delegate user requirements to an agent (Jubilson *et al.*, 2016), allowing the agent to make decisions independently.
3. The ability to develop software at a higher level of abstraction, which is more flexible than the prior programming paradigms (Slhoub, 2018).
4. Widespread use of its programming language (Python).

Software testing is defined as an activity to check whether the actual results match the expected results and to ensure that the software system is defect free. Software testing also helps to identify errors, gaps or missing requirements in contrary to the actual ones. In simple terms, Software Testing means Verification of Application Under Test (AUT). Testing is important because software bugs could be expensive or even dangerous. It can be either done manually or using automated tools (Nordeen, 2020).

During manual testing, there are a lot of problems faced by testers like it is very time taking and consuming, no reusability, has no scripting feature, much human effort required, and still major or minor bugs remain unexplored. Therefore to cover all types of errors and bugs automation testing has introduced that explores all the issues exist in manual testing. Automation testing is 70% faster than the manual testing, ensures consistency, saves cost, improves accuracy, increases efficiency, et al. All automation testing tools test software in less time, produce more reliable, repeatable and reusable final product (Abbas *et al.*, 2017; Nordeen, 2020).

Performance testing is defined as a type of software testing to ensure software applications will perform well under their expected workload. It is also performed in order to

determine how fast system responds under a particular workload. The goal of this testing type is not to find bugs, but to eliminate performance bottlenecks (Dilshan de Silva *et al.*, 2023). It is done to provide stakeholders with information about their application regarding speed, stability and scalability (Nordeen, 2020; Mokhamd *et al.*, 2023). And since these three components were considered important in the development and maintenance of the MVP, this type of testing was chosen for the experiment.

Performance testing is an important and necessary test process to ensure that there are no problems with the performance of the product, such as: long download time, poor response time and poor scalability. In addition, these types of testing activities help to identify bottlenecks that interfere with the operation of the hardware-software platform of the product resource and can lead to significant delays in performance and even to the failure or crash of the resource as a whole (Ali *et al.*, 2020).

The focus of the performance test: Scalability determines maximum user load the software application can handle; Stability determines if the application is stable under varying loads; Speed determines whether the application responds fast enough (Nordeen, 2020; Mokhamd *et al.*, 2023).

Methods used to implement performance testing are load and stress testing (they are performance testing techniques). Load testing is necessary to know that a software solution will perform under real-life loads (Nordeen, 2020; Mokhamd *et al.*, 2023). It measures the response of a system under various load conditions. This test helps determine how the software behaves when multiple users are using the software at the same time. Load testing is required to simulate concurrent usage. Stress uses virtual users who exceed the maximum number until system/application downtime occurs and is typically used for a longer period of time. It is needed to test stability and reliability of the system or it can be called as testing system durability (Mokhamd *et al.*, 2023). Both performance and therefore load testing are categorized as non-functional testing (the technique which focuses on testing of a software application for its non-functional requirements) (Nordeen, 2020).

In any case, exhaustive testing is not possible. Instead, an optimal amount of testing is needed, based on the application's risk assessment. The answer to the question "How to determine the risk?" leads to the defect clustering principle (the application of the Pareto principle) (Nordeen, 2020).

The layout and hardware/software list of the tested environment are shown in Figure 1 and in Table 1.

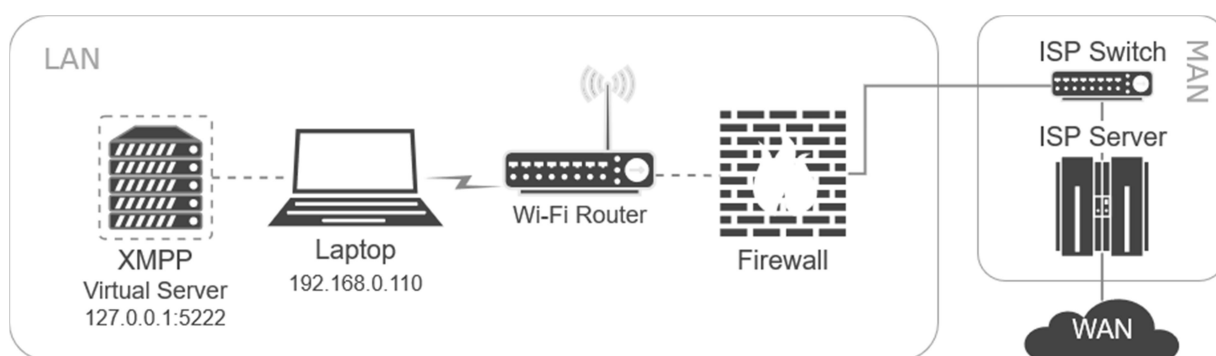


Figure 1. Testing environment network architecture layout (based on (Ali *et al.*, 2020))

JMeter was chosen as the most suitable and effective performance (including load and stress) testing tool based on competitive analysis results and comparison testing tools

(including those for web services) (Ali *et al.*, 2020; Abbas *et al.*, 2017; Dilshan de Silva *et al.*, 2023).

Table 1. Hardware/Software test environment

#	Required hardware/software	Description/Type of hardware/software
1	Hardware	Laptop: AMD Ryzen 5 4500U with Radeon Graphics, 2.38 GHz, RAM: 16.0 GB (13.9 GB usable), SSD 512 GB.
2	Operation System	Microsoft Windows 10 Pro, Version 20H2 (OS Build 19042.1466), 64-bit.
3	An Instant Messaging (IM) server	Openfire (XMPP) Server v4.7.4, build 51b9db9.
4	Execution environment language	Java (JRE/JDK v1.8.0_202).
5	Agent Development Environment	SPADE v3.2.3 (Palanca, 2023; SPADE, n.d.)
6	Agent Development Environment programming language	Python v3.7.9.
7	Test scenario recording/execution tools	Apache JMeter v5.5 (plugins: XMPP Protocol Support (bzm) v1.5.1, 3 Basic Graphs v2.0, jp@gc - PerfMon Metrics Collector v2.1, Dummy Sampler v0.4).
8	Server metrics fetching tool	PerfMon Server Agent (JP@GC) v2.2.3.
9	Browser	Mozilla Firefox v114.0.2 (64-bit).

The Apache JMeter™ application is open source software, a 100% pure Java application that is considered an automated tool for testing performance, load and stress as well, and along with BlazeMeter are considered sufficient automation tools to accelerate and utilize performance-testing processes (Abbas *et al.*, 2017; Dilshan de Silva *et al.*, 2023; Mokhamd *et al.*, 2023; Ali *et al.*, 2020; Apache JMeter, n.d.). And since load and stress testing are methods used to implement performance testing, JMeter can be used to implement all of them, as well as to perform Application Performance Monitoring (APM) refers to managing the performance of a software application to ensure the expected level of service, as measured by performance metrics and user experience monitoring. The APM solution aims to detect and determine application performance issues before users are actually impacted by them (Mokhamd *et al.*, 2023).

It was originally designed for testing Web Applications but has since expanded to other test functions (Apache JMeter, n.d.). JMeter integration with Agile and DevOps processes improves tool utilization (Ali *et al.*, 2020).

As a tool for collecting data on CPU/RAM (Central Processing Unit and Random Access Memory) metrics, in addition to Apache JMeter, the PerfMon Server Agent software agent was used (Table 1), sometimes called JP@GC Agent (where JP@GC means JMeter Plugins at Google Code) (GitHub - undera/perfmon-agent, n.d.; Documentation: JMeter-Plugins.org/wiki/PerfMon/, n.d.; Matam *et al.*, 2017; Pohilko, n.d.). It is a server metrics fetching agent for server performance monitoring, written in Java and based on SIGAR (System Information Gatherer And Reporter (GitHub - hyperic/sigar, n.d.).

All tests were preceded by smoke testing (Nordeen, 2020). Objects, types, test tools and their descriptions are provided in Table 2.

Based on 10 results of the price update function execution (Figure 2), using the Dummy Sampler plugin (Documentation: JMeter-Plugins.org/wiki/DummySampler/, n.d.), the average value $\bar{t}_0 = 104.46$ was determined. Taking into account that the minimum required time for this operation is more than 100 s, it was decided to collect data within this time interval (always from the beginning of the update process; thus ensuring data normalization for their subsequent analysis).

Table 2. Test plan for XMPP server testing

#	Testing object	Testing type	JMeter testing tool	Description / Features
1	XMPP server	Performance	Dummy Sampler	Difference between two conditions (when the agent is running and not).
2	XMPP server	Load	OS Process Sampler (JMeter - OS Process Support)	While connecting a large number of agents.
3	XMPP server	Load	bzm - XMPP Sampler (XMPP Protocol Support)	XMPP Connection.
4	XMPP server	Performance/Load	Dummy Sampler	Load comparison on XMPP server with different agent behaviors (outside and during the price update process).

A comparison was made (according to the average values of the speed of the price update process) between three variants of the architecture of the software being developed, which differ in the location of the PUA: on the side of the web server with a call via cron (a test run through the browser is shown in Figure 2); with the same location, but with a call through the SPADE agent (Figures 3, 4; this architecture was used for most tests); PUA is aggregated by the SPADE agent (Figure 5). The script execution speed in the second case is approximately equal to that for the first one, which is natural, given the invariability of the PUA location. This architecture option allows you to quickly incorporate SPADE technology into a web project (approximately within 5 minutes). The script execution speed in the third case is $\bar{t}_1 = 43.24$.

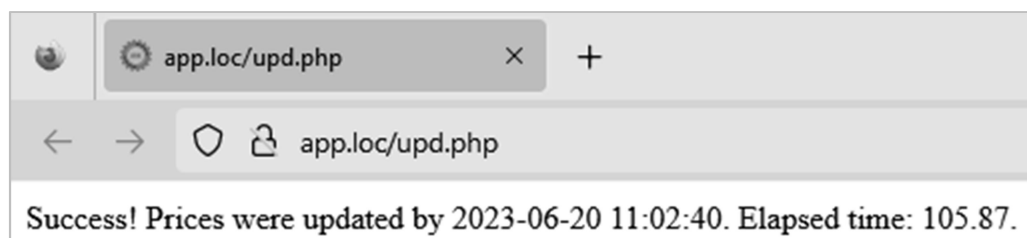


Figure 2. Pricing update information message displayed as a result of a request via the Mozilla Firefox web browser

```

Agent starting...
Wait until user interrupts with Ctrl+C
Starting behaviour...
Counter: 0
There's no new file!
Counter: 1
Counter: 2

```

Figure 3. Launching the agent

```

Counter: 321
Counter: 322
Counter: 323
Counter: 324
Counter: 325
Success! Prices were updated by 2023-06-20 11:35:35. Elapsed time: 106.729.

```

Figure 4. Successful price update by an agent through a request to an MVC controller aggregating PUA

```
Counter: 79
Counter: 80
Success! Prices were updated by 2023-06-20 12:13:14. Elapsed time: 42.74.
```

Figure 5. Successful price update by PUA aggregating agent

Let us substitute the average values of the indicators of the execution time of the price update process $\bar{t}_0, \bar{t}_1$ displayed in Figures 3 and 5 into (1) (percentage decrease, % decrease) in order to determine the efficiency. Thus, we determine $\Delta M(\%) = 58.61$. An additional run of the script outside the agent showed the same results, therefore, this growth rate is due to the difference between the speed of executing PHP and Python code, and not the work of the agent.

$$\Delta M(\%) = \frac{M_{n-1} - M_n}{M_{n-1}} \times 100\%, \quad (1)$$

where M is mean, M_n is n^{th} sequence term (“final” value), M_{n-1} is a previous term in sequence (“initial” value), $M_{n-1} - M_n$ is ΔM or decrease. (1) is based on (2) (percentage increase, % increase) (Dueñas *et al.*, 2021; Mahadevan *et al.*, 2022) to determine growth and growth rate (comparative performance indicator). In the case of a negative value of the denominator, it must be taken modulo.

$$\Delta M(\%) = \frac{M_n - M_{n-1}}{M_{n-1}} \times 100\%, \quad (2)$$

or $(M_n/M_{n-1} - 1) \times 100\%$, where $M_n - M_{n-1}$ is ΔM or increase. The test results are shown in Figures 8, 9.

Let us substitute the CPU and RAM load indicators displayed in Figure 9 into (2) in order to determine the increase and % increase. Results are shown in Table 3.

Table 3. Increase display for average CPU and RAM load (Figure 9)

Metrics	CPU, %			RAM, MB		
	M	ΔM	$\Delta M(\%)$	M	ΔM	$\Delta M(\%)$
Agent using features						
Without using an agent	0.08	—	—	287.32	—	—
With using an agent	0.18	0.1	125	289.07	1.75	0.61
With using an agent while price update	0.19	0.01	5.56	290.6	1.53	0.53

Based on the values of ΔM and $\Delta M(\%)$ from Table 3, it is concluded that the use of hardware resources (by the XMPP server during connection with the agent) is negligible in terms of modern PC computing power.

To determine the effectiveness of SPADE in terms of hardware resource usage (HRU) for user PC, the SPADE web interface was chosen as an object for comparison (Palanca *et al.*, 2020) (agent web UI (AWUI) (Palanca, 2017).

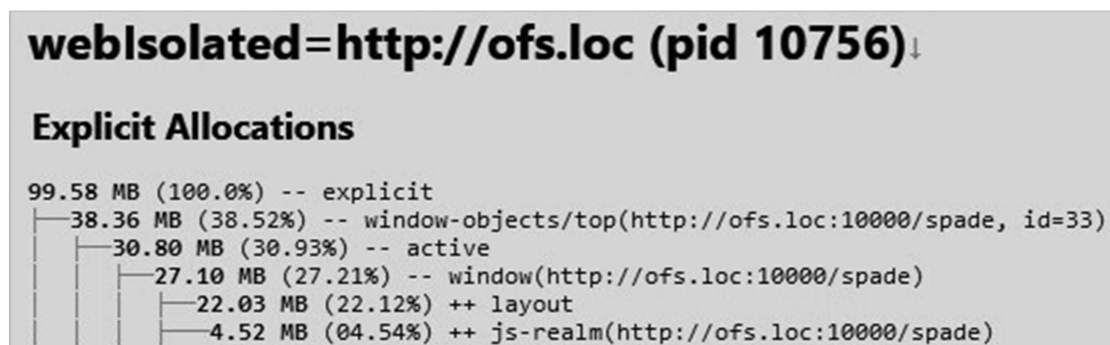


Figure 6. Detailed measurements of Firefox’s memory usage via “about:memory” special page (about:memory, n.d.) for the SPADE web interface tab

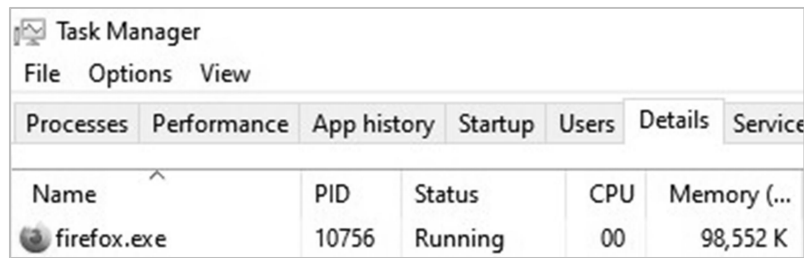


Figure 7. System process firefox.exe (i.e., browser tab) with PID 10756

According to Figure 10, the mean for CPU used resources is 0.16%, for RAM is 98.21 MB. Since the server does not use the hardware resources of the user's PC, only the resources used by the agent (CLI mode) were taken into account to determine the efficiency. Substituting these values (as well as those for SPADE in CLI mode: CPU – 0.2%, RAM – 85.77 MB) into (1), we get the efficiency when the SPADE agent works in CLI mode compared to AWUI: for CPU – $(0.16 - 0.2) / 0.16 * 100\% = -25\%$, for RAM – $(98.21 - 85.77) / 98.21 * 100\% = 12.67\%$. It is worth noting that AWUI was used for the example, which was not loaded with script libraries. In the case of using a more complex GUI developed using modern front-end frameworks, it is expected to increase the efficiency of using SPADE agents in CLI mode compared to the web version of the UI.

The purpose of the next load test is to show the load on the XMPP server as it grows as agents connect. An exhaustive description of the “bzm – XMPP Connection” plugin settings can be obtained from the source (XMPP Load Testing, n.d.). The test results are shown in Figure 11.

The purpose of this test is to display the difference between HRU for different types of agent behavior; the task is to collect data on performance metrics for different behaviors of the SPADE software agent using the OS Process Sampler plugin. The results are displayed in Figures 12-14.

By ordering the average HRU values (Figure 14) and substituting them into (1), we obtain the results presented in Table 4.

Table 4. Comparison of percentage decrease for agent behaviors

ΔRAM (%)				ΔCPU (%)			
Out of the price update		During price update		Out of the price update		During price update	
Behavior type	value	Behavior type	value	Behavior type	value	Behavior type	value
One shot	-	FSM	-	FSM	-	Cyclic	-
FSM	0.40	One Shot	2.14	One Shot	10.26	One Shot	8.11
Timeout	2.18	Timeout	1.75	Cyclic	5.71	FSM	11.76
Periodic	1.05	Periodic	1.45	Periodic	21.21	Timeout	3.33
Cyclic	1.68	Cyclic	1.66	Timeout	15.38	Periodic	24.14

From Table 4, we can draw conclusions about the effectiveness of one agent's behavior compared to another. For example, the FSM behavior is 0.4% (RAM) more efficient than One Shot when the agent is running outside the price update process.

Stress testing of the launch and operation of the XMPP server, as well as a large number of agents (with sending requests to the Open Server) was performed 8 times (with a duration of 100 seconds for each iteration) with two settings - with a limit on the frequency

of launching agents ($f_l = 1$ Hz, where f is the frequency, l is the launch (abbreviated from the “launch”)) and without it. The results are presented in Table 5 and Figures 15, 16.

Table 5. Stress test results

ID	Number of launches			Result
	General	Successful	Failed	
1	166	127	39	JMeter crash.
2	144	109	34	
3	1265	137	1128	
4	107	84	23	
5	98	76	22	
6	116	97	19	JMeter crash, XMPP server crash.
7	267	247	20	Stable performance of applications (with the ability to save CPU/RAM load metrics).
8	98	95	3	

During all tests, the Open Server remained in working condition (in order to save space and due to the repetition of the result for 8 tests, this information was not indicated in the table), which can be explained by the frequency of requests by each of the agents on the Open Server – $f_r = 0.2$ Hz, where r is a request (abbreviated from “request”), which is at least 5 times less than the frequency of agent launches (the values of the “General” column, indicated in Table 5, divided by 100). In addition, the load on the XMPP server increases not only at the moment the agent starts, but also during the processing of other processes (e.g., behavior). Testing Open Server is out of the scope of this work.

Having removed the main noise at the end of the 3rd test (after about 230 agent launches), in order to avoid excessive stretching of the plot along the Y axis and in order to more clearly view the test results, we display the launch errors on a scatter plot (Figure 17).

The reason for the appearance of errors in the application is presumably due to the consumption of RAM (XMPP server: 287.32 MB + 1.75 MB (for each agent); 85.77 MB (for each SPADE agent in CLI mode)), despite the fact that 70 software agents can occupy ≈ 6 -6.5 GB of RAM (provided that the agent and server are running on the same PC), which is acceptable in terms of the environment under test and modern computing power in general.

Based on the RAM load metric (Figure 16), namely the lack of indicators of hardware resource consumption after the 47th second during the 7th test, we can conclude that XMPP Server has crashed. Nevertheless, the application continued to successfully execute the function of launching agents, despite the stop of data collection by CPU load metric at the 51st second.

Results and discussion

In the course of this work, the following were carried out:

1. Data collection on XMPP server performance metrics in order to analyze and determine the amount of hardware resources consumed over a certain time interval when connecting SPADE software agents with different basic types of behavior, in different amounts, as well as during the execution of their main function – price update.
2. Comparison (according to the average values of the speed of the price update process) between the three variants of the architecture of the software being developed, which differ in the location of the price updating algorithm (PUA).

3. Stress test of launching agents, on the basis of which a scatter diagram of launch errors was built.

In the course of performing a qualitative and quantitative analysis of the data, it was found that:

1. The percentage increase in the speed of the price update process using SPADE compared to the web version was 58.61% (due to the use of Python).
2. The hardware resources used by SPADE are acceptable in terms of modern PC computing power (on average for XMPP server: 0.08% of CPU and 287.32 MB of RAM + 0.1% of CPU and 1.75 MB of RAM for each agent; 0.2% of CPU and 85.77 MB of RAM for each SPADE agent in CLI mode). Efficiency (in terms of HRU) when running a SPADE agent in CLI mode compared to AWUI: for CPU – -25%, for RAM – 12.67%.
3. Mean/min/max values, medians and modes are determined based on performance data for different types of behavior of SPADE agents. Based on ascending averages, a percentage increase is determined for RAM/CPU resource consumption during and outside of the price update process. Based on these values, one can draw a conclusion about the effectiveness of one type of agent behavior compared to another (in terms of HRU).
4. Most launch errors falls on the set of active software agents in the amount of ≈ 70 -240 units with the result in the form of hanging OS processes and with the subsequent fall of the JMeter and XMPP server applications. The limited frequency ($f_l = 1 \text{ Hz}$) of launching agents allows you to reduce the number of errors and application crashes.
5. The trend (steady upward) in Figure 11 differs significantly from that (partially downward/absent) in Figure 16 when agents are sequentially launched with a difference in frequency ($f_l = 1 \text{ Hz}$ for the first and $f_l = 0.31 \text{ Hz}$ for the second case). Based on the current and previous paragraphs, we can conclude that with a decrease in the value of f_l , the stability of applications and the accuracy of the collected data increase.
6. Because of the use of SPADE and, as a result, the absence of the need to develop a GUI, the time spent on developing a UI is reduced (hence the labor intensity; compared to developing one for web applications).

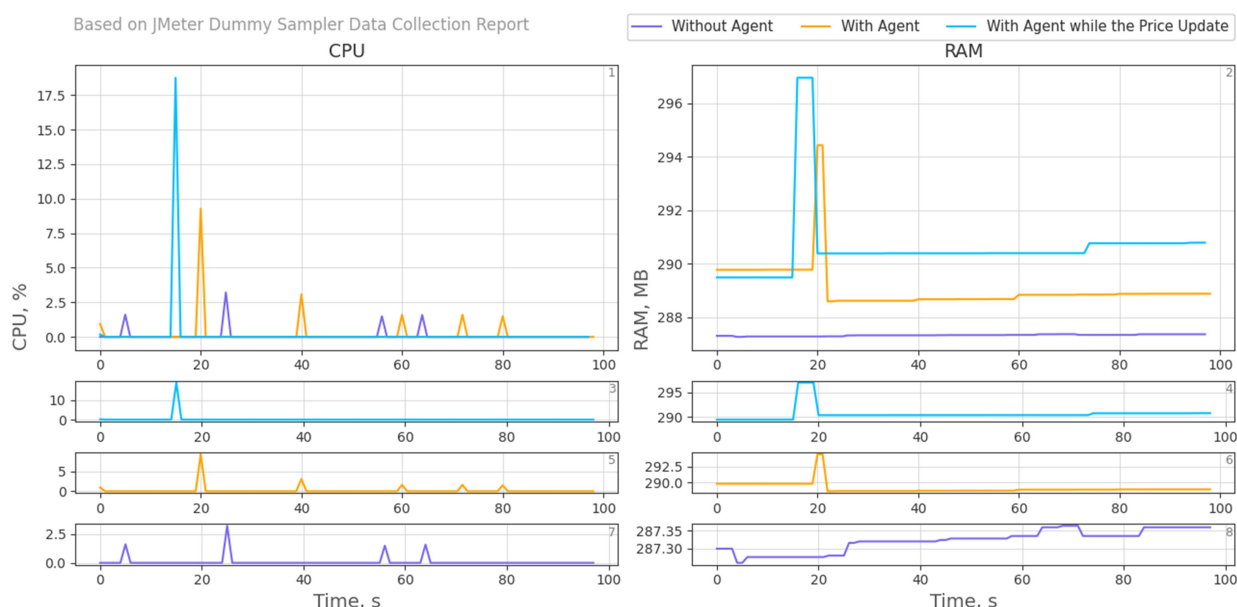


Figure 8. Metrics of hardware resource usage by the XMPP server process using JMeter Dummy Sampler

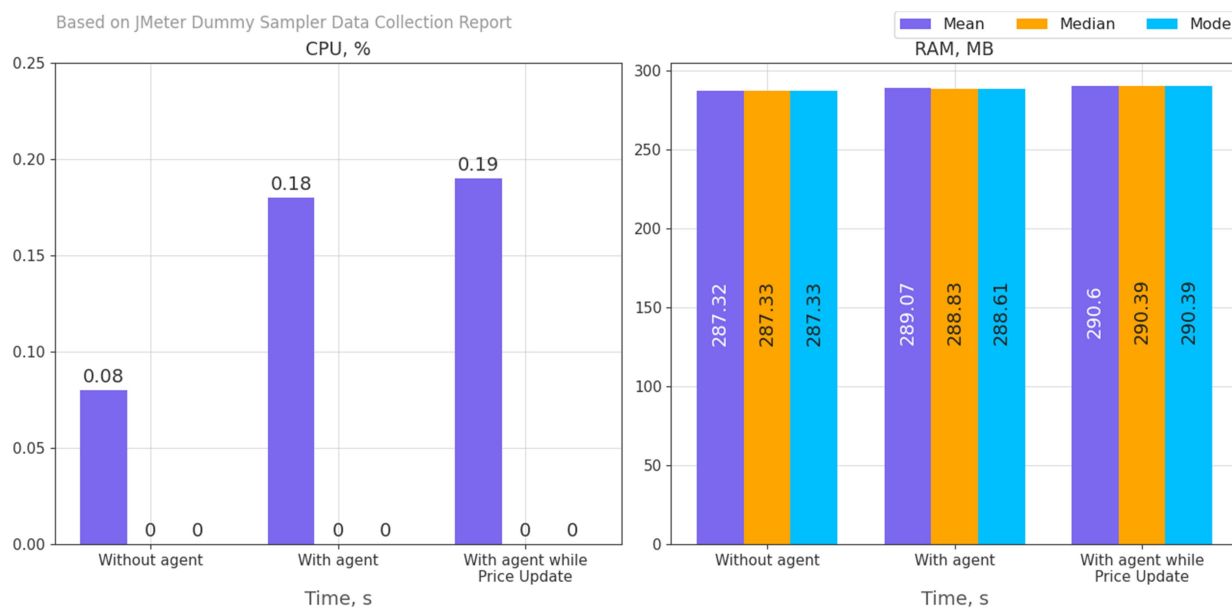


Figure 9. Mean, Median, Mode for the collected data shown in Figure 8

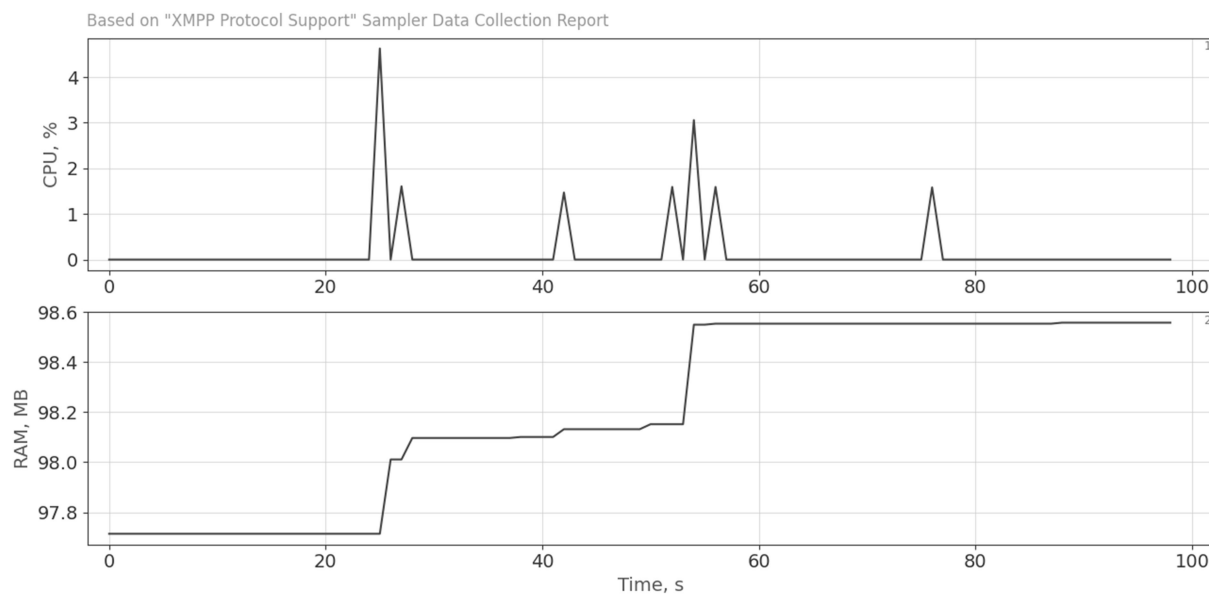


Figure 10. CPU and RAM usage measurements for the PID 10756 (browser tab that hosts the SPADE web GUI)

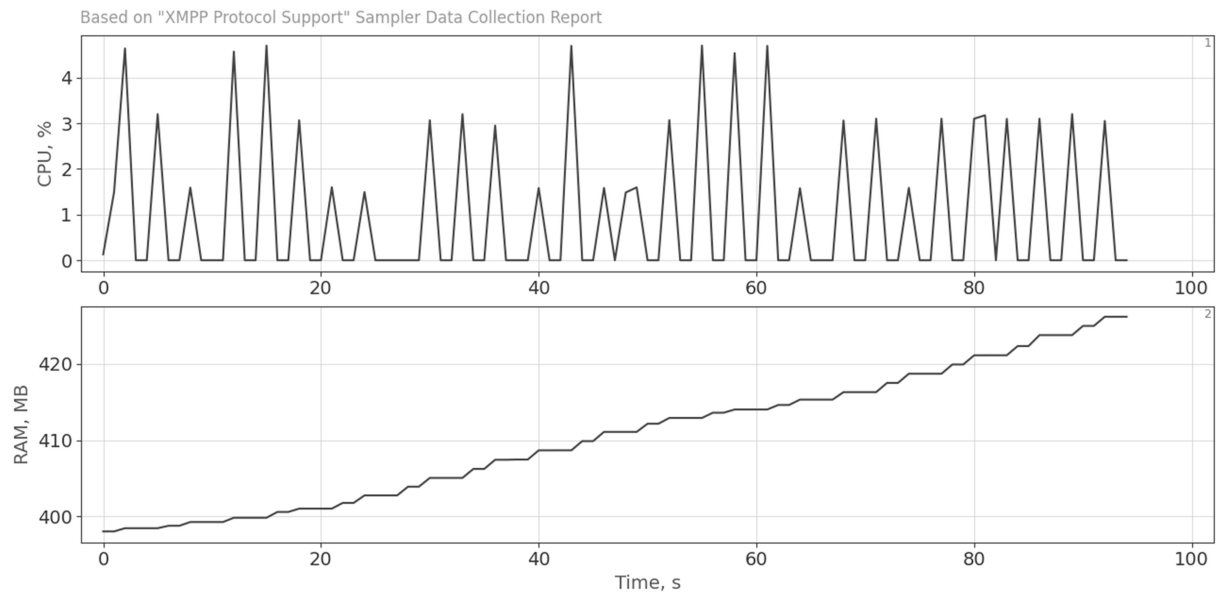


Figure 11. CPU/RAM performance metric for 32 agents as a line graph (each 3.2 s) with a steady upward trend in RAM consumption as the number of SPADE agents connected to the XMPP server increases

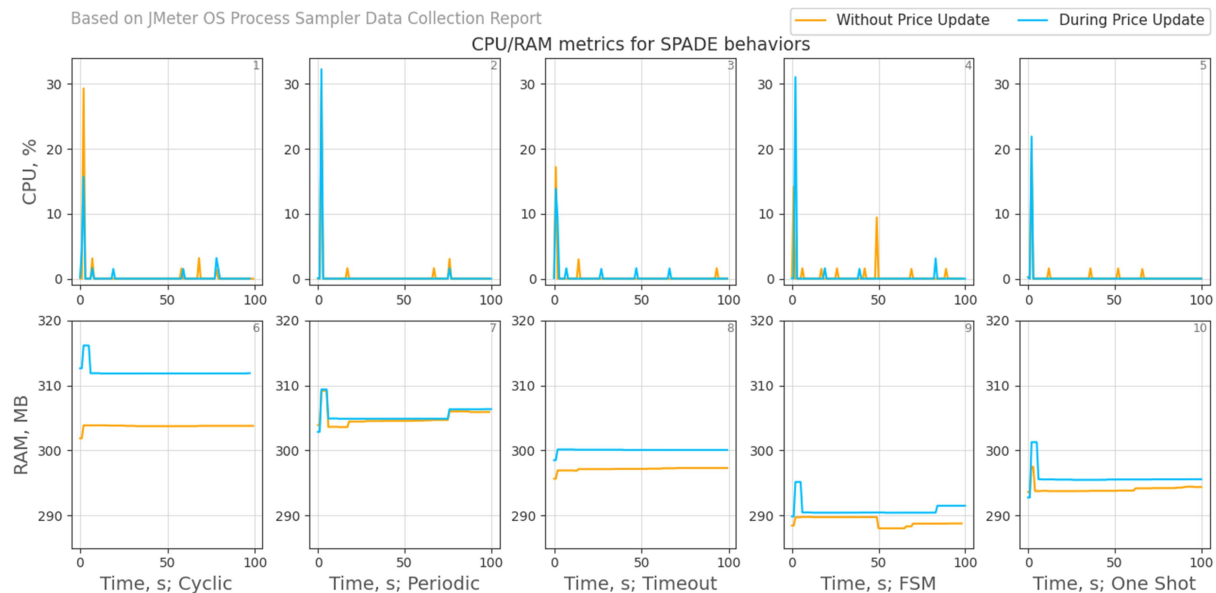


Figure 12. Line graphs for Comparison of HRU amount (CPU, RAM) during the price update process and outside it with different SPADE agent behaviors (FSM, One Shot, Timeout, Cyclic, Periodic)

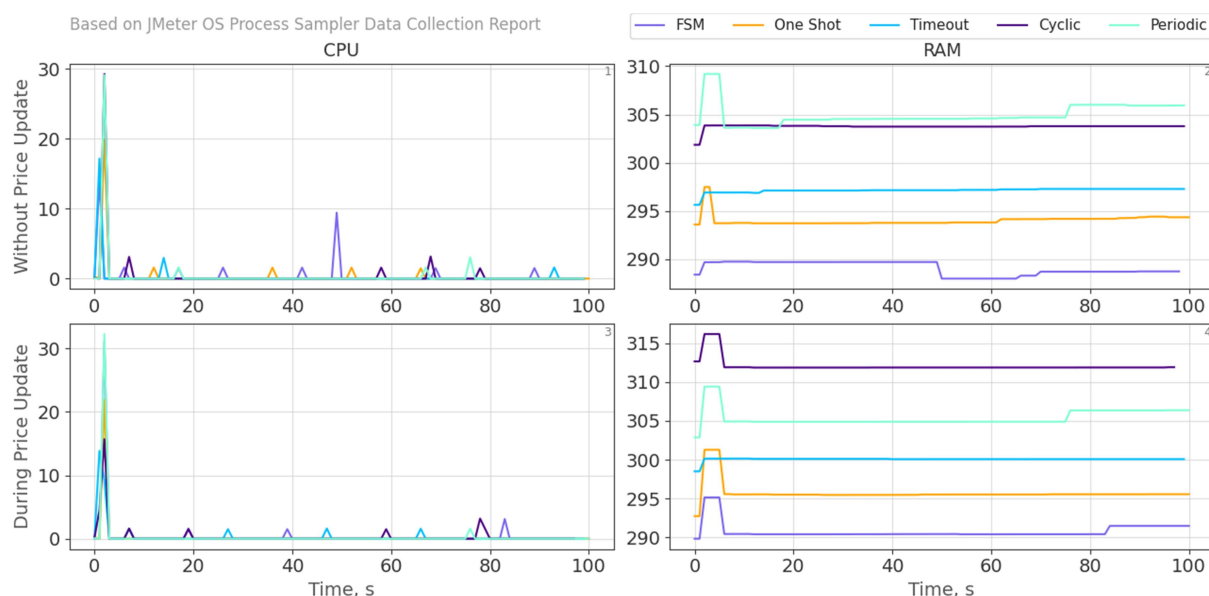


Figure 13. Line graphs for comparing the amount of consumption of hardware resources (CPU, RAM) for different SPADE agent behaviors (FSM, One Shot, Timeout, Cyclic, Periodic) during and outside the price update process

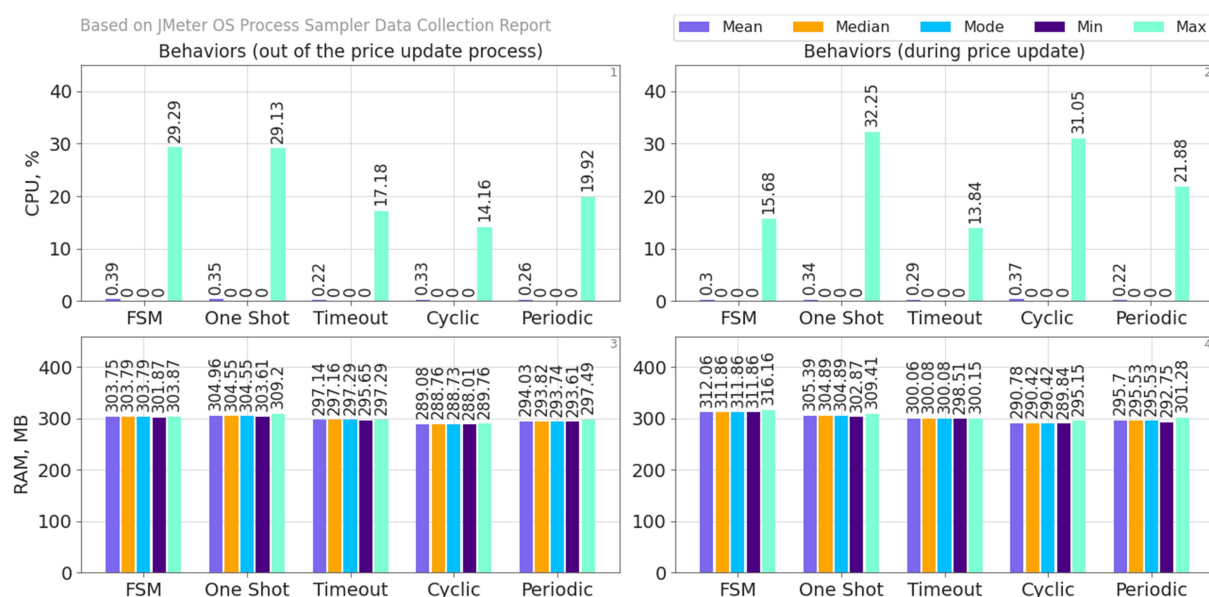


Figure 14. Bar graph: Mean, Median, Mode for different SPADE agent behavior (FSM, One Shot, Timeout, Cyclic, Periodic) metrics during and outside the price update process

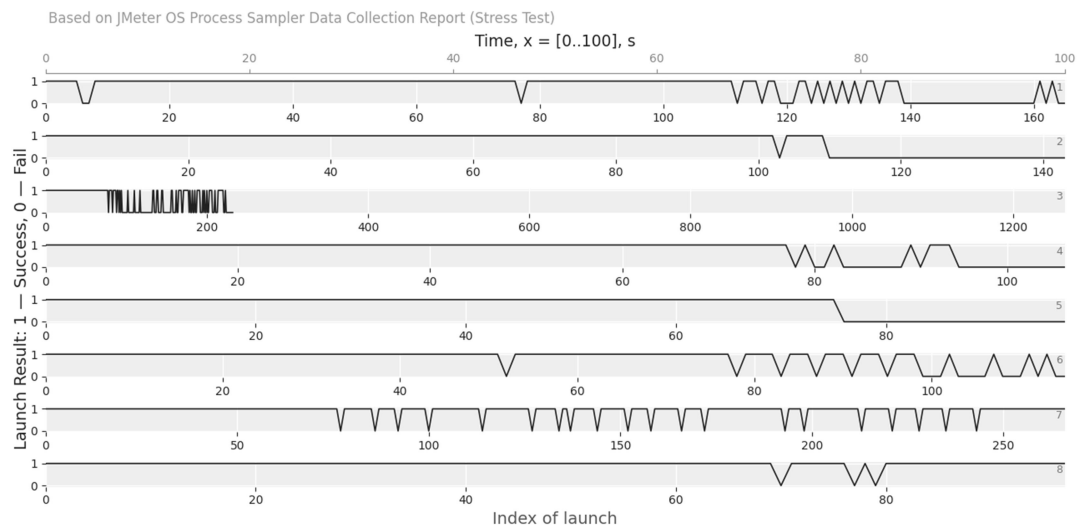


Figure 15. Eight tests for launch errors

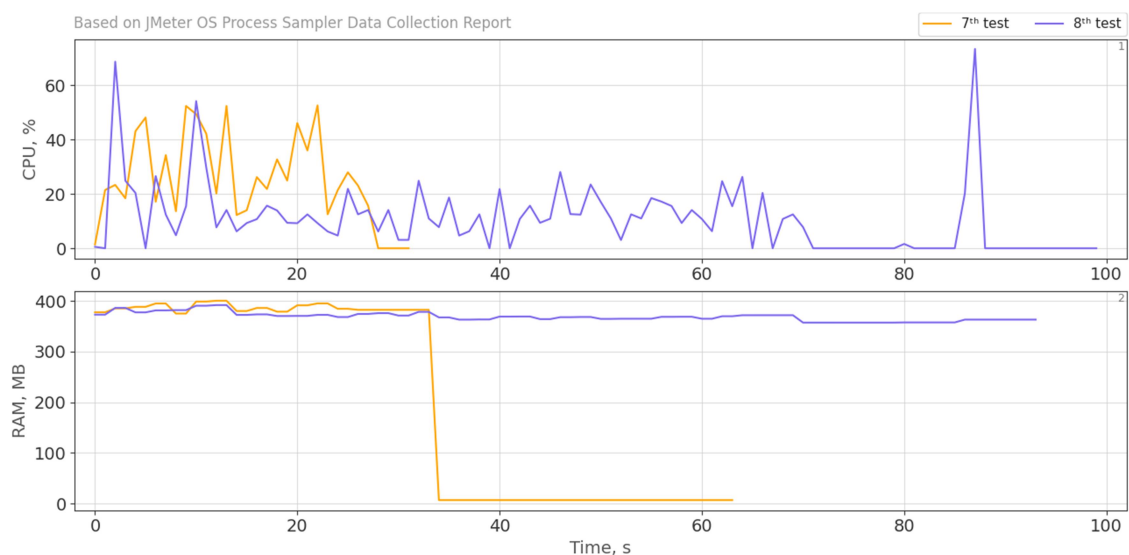


Figure 16. CPU and RAM metrics for 7th and 8th tests

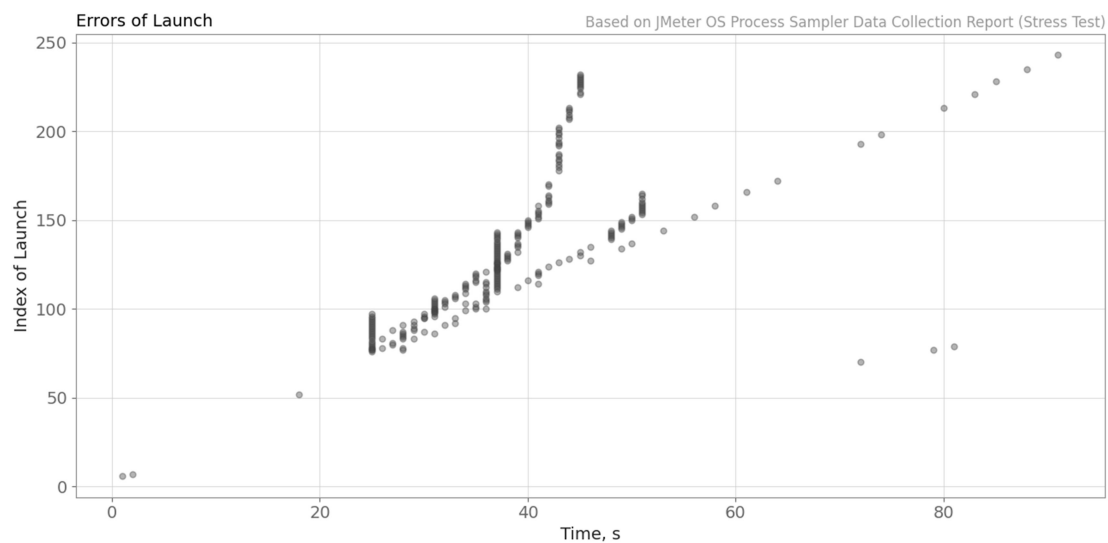


Figure 17. Scatter plot of launch errors

Conclusions

During this study, performance testing of SPADE software agents was carried out (including load and stress testing). As a result of the analysis of the collected data, the performance gain (in terms of hardware resource consumption) was determined for different types of behavior and different interfaces (command line interface (CLI) and agent web user interface (AWUI)). The efficiency in the speed of execution of the price update algorithm for SPADE technologies was also determined (compared to the web).

For the first time introduced the utilization of the Smart Python Agent Development Environment (SPADE) in combination with a cost-based method (CBM) for retail price actualization in the absence of data. To the best of our knowledge, this is the first instance where SPADE agents and CBM are integrated to address pricing challenges like that.

The integration of SPADE and CBM agents into the pricing process is of practical importance for retailers, opening up opportunities for the study and development of new tools with a view to their subsequent application in solving specific problems.

Further development was found by the approach of combining SPADE agents and CBM in dropshipping. This approach can be modified to explore other pricing methods (e.g., customer value-based method, competitive-based method), respond to market dynamics (e.g., adjusting prices depending on market conditions), include additional factors (such as market demand, production costs, and competitor prices) to make intelligent decisions and adapt to changing market conditions in real time.

Acknowledgements

None.

Conflict of Interest

None.

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ПРОГРАМНІ АГЕНТИ SPADE ТА ЇХ ВПЛИВ НА АПАРАТНІ РЕСУРСИ

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Анотація. Усуваючи недоліки оновлення цін при великій кількості товарів в інтернет-магазині, нами було знайдено рішення в застосуванні Smart Python Agent Development Environment (SPADE). У статті представлено процес збору даних про показники продуктивності SPADE та Openfire Server з метою визначення та аналізу споживання системних ресурсів при підключенні програмних агентів з різними типами поведінки, у різній кількості, а також під час взаємодії з веб-додатком.

У цій роботі як інструмент для збору даних та тестування продуктивності (зокрема навантажувального та стресового тестування) використано JMeter. Використано кількісні та якісні методи аналізу даних. При обробці зібраних значень показників використано апаратних ресурсів, виявлення зв'язків і закономірностей між показниками використано методи математичної статистики. Для порівняння поведінки програмного агента SPADE, визначення ефективності одного над іншим, а також з метою визначення ефективності використання інтерфейсу агента в режимі командного рядка порівняно з веб-аналогом у вигляді графічного інтерфейсу користувача (в аспекті продуктивності) використано формули для розрахунку темпу приросту.

Під час дослідження визначено: перевагу SPADE у швидкості виконання програмного коду; різницю в продуктивності між поведінкою агента, а також між режимом веб-інтерфейсу користувача агента (AWUI) і режимом інтерфейсу командного рядка (CLI); особливості використання режиму CLI агента для інтерактивної взаємодії користувача з додатком з метою швидкого виправлення помилок, що виникають під час взаємодії агента з веб-додатком.

Інтеграція агентів SPADE у процес ціноутворення має практичне значення для компаній у роздрібній торгівлі, відкриваючи можливості для вивчення та розробки нових інструментів для подальшого застосування у вирішенні специфічних проблем.

Ключові слова: XMPP, Python, behavior, web, JMeter, CPU, RAM.

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COMBUSTION MODELS FOR BURNING MULTICOMPONENT PYROTECHNIC NITRATE-METALLIZED MIXTURES

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Abstract. The combustion mechanism of compacted mixtures of metallized fuel powders (Mg, Al, etc.), nitrate-containing oxidizers (NaNO_3 , KNO_3 , etc.), organic additives (paraffin, stearin, etc.) and inorganic substances (metal fluorides, metal oxides, etc.) has been established under conditions of external thermal influences, according to which the process of transformation of the initial mixture into combustion products is, on average, stationary and proceeds in three spatially separated zones: condensed phase, where decomposition and high-temperature oxidation of components take place; the interface of phases (burning surface), on which the complete decomposition of components and the ignition of metal particles, which then pass into the flame zone, take place; gas phase (zone of heat release in the flame), in which metal particles burn in a diffusion mode, forming combustion products.

Models of combustion of mixtures that take into account kinetic characteristics of thermal decomposition of the oxidizer, additives of organic and inorganic substances and high-temperature oxidation, ignition and combustion of metal particles in decomposition products, as well as the results of thermodynamic calculations of the temperature of the combustion products of the mixtures and the content of high-temperature condensate (non-oxidized metal) in them have been developed, which allows with a relative error of 8...10% to determine critical ranges of the change in the burning rate of mixtures under conditions of external thermal effects, exceeding which can lead both to the acceleration of the burning process of mixtures and fire-explosive destruction of pyrotechnic products, and to a sharp attenuation of their burning process and failure of products.

Keywords: fire safety, pyrotechnic mixtures, nitrate-containing oxidizers, metal fuels, additives of organic and inorganic substances, thermal influences, combustion processes, combustion models of metallized condensed systems.

Introduction

The purpose of the work: to establish the combustion mechanism of multicomponent compacted mixtures of metal fuel powders and nitrate-containing oxidants with additives of organic and inorganic substances and to develop their combustion models to determine the critical ranges of changes in the burning rate of mixtures, taking into account different values of technological parameters and the influence of external thermal actions.

Research objectives are: analysis of experimental data on the behavior of mixture components under conditions of elevated heating temperatures and external pressures in order to establish the physical and chemical processes occurring in different combustion zones of mixtures; obtaining a system of equations for calculating the dependence of the combustion rate of mixtures on technological parameters (ratio and dispersion of components) and external conditions (elevated heating temperatures and external pressures); determination of critical ranges of changes in technological parameters for a wide range of heating temperatures (up to 800 K) and external pressures (up to 10^7 Pa), exceeding which can lead to a sharp acceleration of the combustion process of mixtures, which leads to the fire-hazardous destruction of products, and to its rapid attenuation and subsequent failure of products under the conditions of their regular use.

Literature review

Currently, compacted mixtures of metal fuel powders (Mg, Al, Ti, Zr etc.), nitrate-containing oxidizers (NaNO_3 , KNO_3 , $\text{Ba(NO}_3)_2$, $\text{Sr(NO}_3)_2$ etc.) with organic (paraffin, thiocol, urotropin, stearin, etc.) and inorganic additives (fluorides (NaF , BaF_2 , SiF_2 , AlF_3 etc.), metal oxides (CuO , Cu_2O , NiO , Sb_2O_3 etc.)) substances are widely used in pyrotechnic products of various purposes (firecrackers and stars, lighting and signal cartridges and projectiles, tracers, IR means of thermal protection of various objects, as well as elements of rocket and space technology, etc.) (Akkerman & Penner, 2020; Fang *et al.*, 2019; Marich *et al.*, 2018). The investigated pyrotechnic products in the process of circulation (during storage, transportation and use) may be exposed to extreme external thermal effects (for example, in the event of a fire in warehouses, in the conditions of their transportation, in the event of thermal shock effects, in the conditions of firing and shelling during their launches, in combat zones, etc. (Jia *et al.*, 2021; Mader, 2019; Xu *et al.*, 2018). Systematization and analysis of various cases of fire-explosive activation of products under the specified conditions show that the main reason for this is premature ignition and explosive development of combustion of mixtures in conditions of a sharp increase in heating temperatures and external pressure under their metal shells, which lead to the fire-hazardous destruction of products for surrounding objects (flying sparks, high-temperature combustion products (with a temperature of more than 2000...3000 K), residues unburned mixtures, parts of destructible metal bodies, etc.). Therefore, the prevention of forced fire-hazardous destruction of products in the event of external thermal effects becomes of significant practical importance.

To date, the mechanism and combustion models of two-component pyrotechnic mixtures have been studied in sufficient detail (compacted mixtures of metal fuel powders (Mg, Al, Ti, Zr etc.) and oxygen-containing oxidizers (nitrates of alkaline and alkaline earth metals (NaNO_3 , KNO_3 , $\text{Ba(NO}_3)_2$, $\text{Sr(NO}_3)_2$ etc.), metal oxides (CuO , Cu_2O , NiO , Sb_2O_3 etc.)) (Bai & Yang, 2019; Fateev *et al.*, 2017; Niu & Wang, 2019).

As for three-component mixtures of metallic fuel + nitrate-containing oxidizer + inorganic substance additive and, even more so, four-component mixtures of the above components, currently the above-mentioned studies are not available for them.

Conducted studies of the behavior of the components of mixtures of powders Mg, Al etc., nitrate-containing oxidizers (NaNO_3 , $\text{Ba(NO}_3)_2$ etc.), organic (paraffin, stearin) and inorganic additives (NaF , BaF_2 etc.) substances in the conditions of elevated heating temperatures inherent in the process of burning pyrotechnic mixtures based on metal fuels and oxygen-containing oxidizers (Kovalyshyn *et al.*, 2018; Dibrova *et al.*, Improving, 2020), made it possible to establish that the combustion process of the charges of the investigated mixtures is stationary on average and proceeds in the same way as in the case of mixed powders (Kovalyshyn *et al.*, 2018), in the following spatially separated zones: condensed phase; on the burning surface; gas phase (flame zone).

Materials and methods

We will analyze the physical and chemical processes occurring in the specified zones using the following mixtures widely used in pyrotechnic products (Dibrova *et al.*, Fire safety, 2020): $\text{Mg} + \text{NaNO}_3 + \text{paraffin} + \text{NaF}$ and $\text{Mg} + \text{NaNO}_3 + \text{stearin} + \text{BaF}_2$.

Condensed phase. The considered inorganic substances begin to melt only at temperatures of 1268...1553 K, and decompose – at temperatures higher than 1700...1800 K. Therefore, these additives within the c-phase can be considered inert, and their contribution to the combustion process of the mixture is carried out already in the flame zone. The change in temperature in the so-called warm-up area of the c-phase of the mixture, which is characterized by a change in temperature from T_0 (the initial temperature of the mixture) to T_m (melting point NaNO_3), is described by the heat conduction equation (Fateev *et al.*, 2017):

$$\lambda_c \frac{\partial^2 T}{\partial \xi^2} - \rho_c u c_c \frac{\partial T}{\partial \xi} = 0, \quad (1)$$

wherein ξ – the direction that coincides with the direction of the coordinate x , opposite to which the combustion front propagates through the mixture sample with speed u , m/s. At the same time, the first term in equation (1) corresponds to the conductive heat flow (λ_c – thermal conductivity coefficient of the mixture, $\text{Wt/m}\cdot\text{K}$), and the second (ρ_c and c_c – density (kg/m^3) and specific heat capacity ($\text{J/kg}\cdot\text{K}$) mixture) – convective heat flow. Integration of this equation leads to the determination of the thickness of the heating layer of the c-phase of the mixture δ_1 :

$$\delta_1 = \frac{a_c^2}{u}, \quad (2)$$

wherein $a_c^2 = \frac{\lambda_c}{\rho_c c_c}$ – coefficient of thermal conductivity of the mixture, m^2/s .

It was established that for the considered mixtures the value of the parameter δ_1 (at $\alpha = 0,5...3,0$) vary from 100 to 200 μm to 3000 to 4000 μm . It is also shown that the decomposition NaNO_3 , paraffin and stearin begins immediately after their melting and noticeably intensifies as the temperature rises. At higher temperatures ($T = 1100...1200$ K), corresponding to the temperature values of the combustion surface T_n , complete decomposition of the oxidizing agent is already taking place (to O_2 , N_2 , etc.) and the indicated additives of organic substances (to CO , CO_2 , H_2 , etc.) according to the following kinetic equations (Kirichenko *et al.*, 2020):

$$\frac{d\varphi_1}{dt} = k_1 e^{-E_1/RT}, \quad (3)$$

$$\frac{d\varphi_2}{dt} = k_2 e^{-E_2/RT}, \quad (4)$$

wherein φ_1, φ_2 – relative degrees of decomposition of the oxidant and organic matter; k_1, k_2, E_1, E_2 – kinetic constants ($E_1, E_2 \gg RT$). The thickness of the reaction layer is much smaller than the thickness of the heated c-phase layer, and in order of magnitude it has the form

$$\delta_2 \cong \frac{2RT_n a_c^2}{uE_1}. \quad (5)$$

In accordance with formula (5) and taking into account the above values δ_1 , we get that the value of the parameter δ_2 (at $\alpha = 0,5 \dots 3,0$) vary from 10 to 15 μm to 350 to 450 μm , i.e. $\delta_2 < \delta_1$ about an order of magnitude. Thus, for the used metal fuel powders, the thickness of the heating layer of the c-phase is much larger than the average size of their particles (d_m), and the thickness of the reaction layer of the c-phase is already commensurate with the size of the particles, i.e. the following conditions are met

$$\delta_2 \ll \delta_1, \delta_1 \gg d_m, \delta_2 \cong d_m. \quad (6)$$

According to experimental data (Kyrychenko *et al.*, 2018), the process of oxidation of metal particles begins in the gasified NaNO_3 melt, together with additives of organic substances, at temperatures $T > 673$ K. The speed of this process is described by the following equation (Kyrychenko, 2022):

$$\frac{d\varphi_3}{dt} = k_3 C_{O_2}^m \bar{\rho}_g^n e^{-E_3/RT} \text{ at } E_3 \gg RT, \quad (7)$$

wherein φ_3 – degree of metal oxidation; k_3 – pre-exponential multiplier (c^{-1}); E_3 – activation energy (kJ/mol); $C_{O_2}, \bar{\rho}_g$ – relative mass content of O_2 in gaseous products, relative density of the gas medium (relative to normal conditions), respectively; m, n – empirical constants. At the same time with the condition $E_3 \gg RT$ it follows that the intense pre-flame oxidation of metal fuel particles in the gaseous products of decomposition of the oxidant and additives of organic substances also occurs in a narrow reaction layer of the c-phase, where complete gasification of the oxidant and additives of organic substances occurs, i.e., the degree of their decomposition $\varphi_1 = \varphi_{1n} \cong 1, \varphi_2 = \varphi_{2n} \cong 1$.

In experimental studies (Kyrychenko *et al.*, Investigation, 2019), it was also established that during the existence of the reaction layer of the c-phase (within $10^{-1} \dots 10^{-3}$ s) according to the kinetic equation (9), the degree of oxidation of the metallic fuel in the c-phase is $\varphi_3 = \varphi_{3n} = 0,2 \dots 0,3$.

Burning surface. Microcine imaging of the combustion surface of mixtures shows that the ignition of metallic fuel particles occurs immediately after they reach the combustion surface (Kyrychenko *et al.*, Study, 2019). At the same time, the interface between the condensed and gas phases is characterized by significant heterogeneity depending on the ratio of components in the mixture: at $0,5 < \alpha < 3,0$ – the burning process in the first approximation can be considered stable and quasi-stationary (the average burning rate throughout the process is constant); at $\alpha < 0,5$ the combustion process becomes unstable and non-stationary; at $\alpha > 3,0$ there are significant pulsations and emissions of significant masses of oxidizer that did not decompose during the burning process, which quickly subsides. At the same time, the combustion surface of the mixture, as in the case of mixed powders (Kyrychenko, Investigation, 2022), can be characterized by an average temperature T_n . Conducted thermocouple measurements T_n made it possible to establish the nature of its dependence on various factors (Kyrychenko *et al.*, Patterns, 2021). When increasing α from 0,5 to 2,0 T_n monotonically decreases from 1200 K to 1080 K ($T_0 = 293$ K; $P = 10^5$ Pa). At the same time, for a stoichiometric mixture in the region of pressure change from 10^5 Pa to 10^7 Pa, T_n increases monotonically from 1100 K to 1350 K ($T_0 = 293$ K).

Gas phase (flame zone). Metal fuel particles dispersed from the combustion surface in the g-phase burn in gaseous products of thermal decomposition of the oxidizer and

additives of organic and inorganic substances (Motrichuk *et al.*, 2020) (in the O₂ flow – the initial stage of the decomposition of the oxidant; in the O₂ + N₂ flow with the addition of CO + CO₂ and water vapor – the decomposition of the oxidant at the temperatures of the combustion surface, taking into account the decomposition of the additives).

From the data presented in (Kyrychenko *et al.*, 2022), it follows that dispersing metal particles burn in the flow of gaseous decomposition products by the diffusion mechanism with the formation of almost spherical glowing zones, where exothermic reactions of the interaction of the diffusing metal vapors with the oxidant of the surrounding gaseous environment take place. At the same time, for large metal particles ($d_m > 200...300 \mu\text{m}$) the combustion process becomes asymmetric and its quasi-stationarity is violated, and for small particles ($d_m < 50...70 \mu\text{m}$) their disintegration (fragmentation) into smaller burning particles is observed in some cases.

The conductive heat flux can be estimated, as in the case of mixed powders (Kyrychenko *et al.*, Study, 2021), using the following approximate formula:

$$q_c \cong \bar{\lambda}_g \frac{T_{max} - T_n}{\delta_3}, \quad (8)$$

wherein T_{max} – the maximum value of the gas temperature in the zone of heat release of the flame, K; δ_3 – thickness of the heat release zone, m; $\bar{\lambda}_g$ – coefficient of thermal conductivity of gas at temperature $\bar{T} = (T_{max} + T_n)/2$. For stoichiometric mixtures of $d_m < 150...200 \mu\text{m}$ according to experimental data ($T_{max} = 2500 \text{ K}$; $T_n = 1100 \text{ K}$; $\delta_3 = 0,5 \cdot 10^{-2} \text{ m}$; $\bar{\lambda}_g = 0,54 \text{ J/m}\cdot\text{K}$ (Dibrova *et al.*, Regularities, 2020), we have $q_c = 3,8 \cdot 10^6 \text{ J/m}^2$.

We will estimate the radiation heat flow under the assumption that the particles of emitting metal oxides have the same temperature T_{max} ; radiation occurs according to the law of an absolutely black body; the degree of blackness of the flame is equal to one; the influence of the dustiness of the outflowing gas flow and the roughness of the combustion surface, as well as the mutual influence of the emitting particles are absent. With the specified assumptions, the radiation heat flux can be estimated using the well-known formula (Fateev *et al.*, 2017):

$$q_R = \sigma(T_{max}^4 - T_n^4), \quad (9)$$

wherein σ – Stefan-Boltzmann constant.

For stoichiometric mixtures and the obtained experimental data (Kyrychenko, 2021), in accordance with formula (9), we obtain that $q_R \ll q_c$ (more than 4...5 times). In fact, the radiation heat flow from the flame zone during the combustion of mixtures is much smaller, since formula (9) gives an overestimated value q_c (assessment from above).

Results and discussion

The mechanism and mathematical model of the combustion process of mixtures of metallic fuel + nitrate-containing oxidizer + addition of organic and inorganic substances under conditions of external thermal influences (elevated heating temperatures and external pressures). The analysis of experimental data on the physic-chemical processes occurring during the combustion of the considered mixtures was carried out (mixtures with $0,5 < \alpha < 3,0$) allows establishing the mechanism of their combustion according to which the process of transformation of the initial mixture into combustion products is stationary, one-dimensional and proceeds in the following three most characteristic zones in the first approximation: condensed phase (c-phase) of the initial mixture, consisting of a heated layer, where chemical transformations can be neglected, and a reaction layer, in which the solid mixture turns into a gas containing metal particles; the combustion surface of the mixture, on which complete decomposition of the oxidizer and organic substance additives occurs, as well as the ignition of metal particles; gas phase (g-phase – zone of heat release in the flame), in which dispersed metal particles burn in the diffusion mode in the flow of decomposition

products of the oxidant and additives of organic substances, forming combustion products with temperature T_c .

With the above-mentioned basic assumptions about the combustion mechanism of the considered mixtures, as well as the assumption of the absence of heat losses to the environment and external forces, the radiation heat flow from the flame zone of the propagation front, the combustion reaction in the c-phase of the initial mixture can be described by the following system of equations known in the theory of the combustion of condensed metallized mixtures (Kirichenko *et al.*, 2020)

$$\frac{d}{dx} \left(\lambda_c \frac{dT}{dx} \right) - \rho_c c_c \frac{dT}{dx} - \frac{H_o \rho_c \alpha}{1+l_c \alpha} u \frac{d\varphi_1}{dx} - H_n \rho_c u \varepsilon_n \frac{d\varphi_2}{dx} + \frac{H_m \rho_c \alpha}{1+l_c \alpha} u \frac{d\varphi_3}{dx} = 0; \quad (10)$$

$$u \frac{d\varphi_1}{dx} = k_1 e^{-E_1/RT}; \quad (11)$$

$$u \frac{d\varphi_2}{dx} = k_2 e^{-E_2/RT}; \quad (12)$$

$$u \frac{d\varphi_3}{dx} = \frac{k_3 C_{O_2}^m}{\bar{\rho}_c^n} e^{-E_3/RT} \quad (13)$$

with boundary conditions:

$$T = T_0, \varphi_1 = \varphi_2 = \varphi_3 = 0 \text{ при } x \rightarrow -\infty; \quad (14)$$

$$T = T_n, \varphi_1 = \varphi_{1n}, \varphi_2 = \varphi_{2n}, \varphi_3 = \varphi_{3n}, \\ \lambda_c \left(\frac{dT}{dx} \right) = q_c \text{ при } x = 0. \quad (15)$$

Here ρ_c , c_c , λ_c – density (kg/m³), specific heat capacity (J/kg·K) and coefficient of thermal conductivity (Wt/m·K) of the mixture; H_o , H_n , H_m – thermal effects of decomposition reactions of oxidant and organic matter, oxidation of metal fuel particles (J/kg); φ_i , k_i and E_i ($i = \overline{1,3}$) – relative degrees of decomposition of oxidant and organic matter, oxidation of metal fuel (by mass) and their kinetic constants (s⁻¹, kJ/mol), respectively; l_c – stoichiometric coefficient of the mixture.

To obtain expressions for determining the burning rate, it is convenient to reduce the system of equations (10) – (13) to one equation:

$$(\rho_c c_c u (T_n - T_0) - q_c) q_c = \frac{\rho_c k_3 \lambda_c H_m C_{O_2}^m R T_n^2}{E_3 \bar{\rho}_c^n (1+l_c \alpha)} e^{-E_3/RT_n} \left[1 - e^{-\frac{E_3(T_n-T_0)}{RT_n^2}} \right] - \\ - \frac{\rho_c k_2 \lambda_c H_o l_c \alpha R T_n^2}{E_2 (1+l_c \alpha)} e^{-E_2/RT_n} \left[1 - e^{-\frac{E_2(T_n-T_0)}{RT_n^2}} \right] - \frac{\rho_c k_1 \lambda_c H_n \varepsilon_n R T_n^2}{E_1} e^{-E_1/RT_n} \left[1 - e^{-\frac{E_1(T_n-T_0)}{RT_n^2}} \right]. \quad (16)$$

Definition T_n . Experimental determination of T_n by existing methods is difficult and sufficiently approximate (Kyrychenko *et al.*, Patterns, 2021), and studies devoted to the analytical determination of T_n are currently limited. Therefore, using systematic data on the kinetics of thermal decomposition of the oxidant and additives of organic substances (Kyrychenko *et al.*, Study, 2021) at temperatures characteristic of the reaction zone of the c-phase of the mixture, the value of T_n can be determined based on the assumption that at $T = T_n$ complete decomposition of the oxidant and organic substances occurs, and the degree of oxidation of metallic fuels φ_3 during the existence of the reaction layer of the c-phase during the combustion of the considered mixtures (Kyrychenko *et al.*, 2022) lies within 0,2...0,3. At $\varphi_{1n} = \varphi_{2n} \cong 1$ and $\varphi_{3n} = \varphi^*$ (example, $\varphi^* \cong 0,25$) to determine T_n , we get the following equation:

$$\frac{u^2}{\lambda_c R T_n^2} \left[\rho_c c_c (T_n - T_0) \left[\varphi_3^* - \frac{H_o l_c \alpha + H_n \varepsilon_n (1+l_c \alpha)}{H_m} \right] - \frac{H_m \rho_c}{2(1+l_c \alpha)} \left[\varphi_3^* - \frac{H_o l_c \alpha + H_n \varepsilon_n (1+l_c \alpha)}{H_m} \right]^2 \right] = \\ = \frac{k_3 C_{O_2}^m}{E_3 \bar{\rho}_c^n} e^{-E_3/RT_n} \left[1 - e^{-\frac{E_3(T_n-T_0)}{RT_n^2}} \right] - \frac{k_2 H_o l_c \alpha}{E_2 H_m} e^{-E_2/RT_n} \left[1 - e^{-\frac{E_2(T_n-T_0)}{RT_n^2}} \right] - \\ - \frac{k_1 H_n \varepsilon_n R T_n^2 (1+l_c \alpha)}{E_1 H_m} e^{-E_1/RT_n} \left[1 - e^{-\frac{E_1(T_n-T_0)}{RT_n^2}} \right]. \quad (17)$$

Definition q_c . For an approximate analytical definition q_c we will use the well-known “heat flow method” (Dibrova *et al.*, Fire safety, 2020), namely: replace the true value of the heat flow from the heat release zone of the g-phase with the average value for this zone:

$$q_c = \bar{\lambda}_g \left. \frac{dT}{dx} \right|_{x=0} = \bar{\lambda}_g \frac{T_c - T_n}{\Delta x}, \quad (18)$$

wherein $\bar{\lambda}_g$ – coefficient of thermal conductivity of gas at temperature $\bar{T} = (T_c + T_n)/2$; Δx – the distance from the combustion surface to the plane on which the temperature is reached T_c (temperature T_c and the corresponding composition of combustion products are the result of thermodynamic calculations (Motrichuk *et al.*, 2020)). At the same time, the value Δx is found from the equation of motion of a spherical metal particle with a radius r :

$$\frac{d^2x}{dt^2} = 0,15 \frac{\bar{\rho}_g V_n^2}{\rho_m r} + 7,52 \frac{\bar{\rho}_g \bar{\nu}_g V_n}{\rho_m r^2}. \quad (19)$$

wherein $\bar{\rho}_g$ – gas flow density at temperature $\bar{T}$; Experimental data on the outflow rate of gaseous decomposition products show that the rate of their relative movement within the heat release zone of the g-phase is $V_n = 1 \dots 10$ м/с. $\bar{\nu}_g$ – coefficient of kinematic viscosity of gas at temperature $\bar{T}$.

Having integrated equation (19) taking into account the initial conditions on the combustion surface (at $t = 0$; $x = 0$, $\dot{x} = u$), we will find the dependence of the displacement of the particle on time:

$$\Delta x = u\tau_c + 0,15 \frac{\bar{\rho}_g V_n^2}{\rho_m} \int_0^{\tau_c} \left[\int_0^t \frac{dt}{r(t)} \right] dt + 7,52 \frac{\bar{\rho}_g \bar{\nu}_g V_n}{\rho_m} \int_0^{\tau_c} \left[\int_0^t \frac{dt}{r^2(t)} \right] dt, \quad (20)$$

wherein τ_c – the burning time of a metal particle when its radius changes from $r_0 = \frac{d_m}{2}$ to $r_k = \frac{d_k}{2}$ (r_k (d_k) – the radius (diameter) of the metal particle at the end of the flame heat generation zone).

Using the well-known equation (Dibrova *et al.*, Regularities, 2020) we find τ_c :

$$\tau_c = \frac{3}{4ab^2} \left[2 \left(\frac{d_m}{2} \right)^{\frac{2}{3}} \left[1 - (1 + l_c \alpha)^{\frac{2}{9}} (g_{me}^c)^{\frac{2}{9}} \right] + b \left(\frac{d_m}{2} \right)^{\frac{4}{3}} \left[1 - (1 + l_c \alpha)^{\frac{4}{9}} (g_{me}^c)^{\frac{4}{9}} \right] - \frac{2}{b} \ln \left[\frac{1 - b \left(\frac{d_m}{2} \right)^{\frac{2}{3}}}{1 - b \left(\frac{d_m}{2} \right)^{\frac{2}{3}} (1 + l_c \alpha)^{\frac{2}{9}} (g_{me}^c)^{\frac{2}{9}}} \right] \right]. \quad (21)$$

Calculations based on formulas (18), (20) and (21) with the involvement of all necessary data on mixtures and their components (Kovalishyn *et al.*, 2018) show that the heat flow q_c depends most strongly on the coefficient of excess oxidizer and dispersity of the metallic fuel: when increasing α from 0,5 to 3,0 values q_c decrease from $5,83 \cdot 10^6$ Вт/м² to $1,34 \cdot 10^6$ Вт/м² (for a mixture of Mg + NaNO₃ + paraffin + NaF) and from $4,12 \cdot 10^6$ Вт/м² to $0,75 \cdot 10^6$ Вт/м² (for a mixture of Mg + NaNO₃ + stearin + BaF₂); when increasing d_m from 74,5 μm to 182 μm values q_c decreases from $4,1 \cdot 10^6$ Вт/м² to $2,3 \cdot 10^6$ Вт/м² (for a mixture of Mg + NaNO₃ + paraffin + NaF) and from $2,9 \cdot 10^6$ Вт/м² to $1,7 \cdot 10^6$ Вт/м² (for a mixture of Mg + NaNO₃ + stearin + BaF₂).

The above equations (16) – (18), (20), (21) allow you to calculate the burning rate of the mixtures under consideration u , the temperature of their burning surface T_n , as well as the burning rate of dispersed metal fuel particles in the decomposition products of these mixtures, their burning times in the zone of heat release of the flame τ_c , degree of their burnout in this zone $\frac{d_k}{d_m}$, the length of this zone Δx and heat flow from the flame heat release zone q_c . Using the necessary values of the physic-chemical parameters of the mixtures and their components (Kovalyshyn *et al.*, 2018) on a PC with the use of standard software (Kyrychenko *et al.*, Study, 2021), calculations were made of the dependences of the burning rate on the technological parameters (the coefficient of excess oxidant and the relative content of additives of organic and inorganic substances), as well as the main parameters of external thermodynamics (heating

temperature, external pressure) according to the equations indicated above (Fig. 1 – 4). From the results of comparing the calculated dependencies with the obtained experimental data, it follows that there is a complete qualitative match between them, which corresponds to the combustion mechanism of the mixtures proposed above. As for the quantitative differences between the calculation and the experiment, they do not exceed 8...12%.

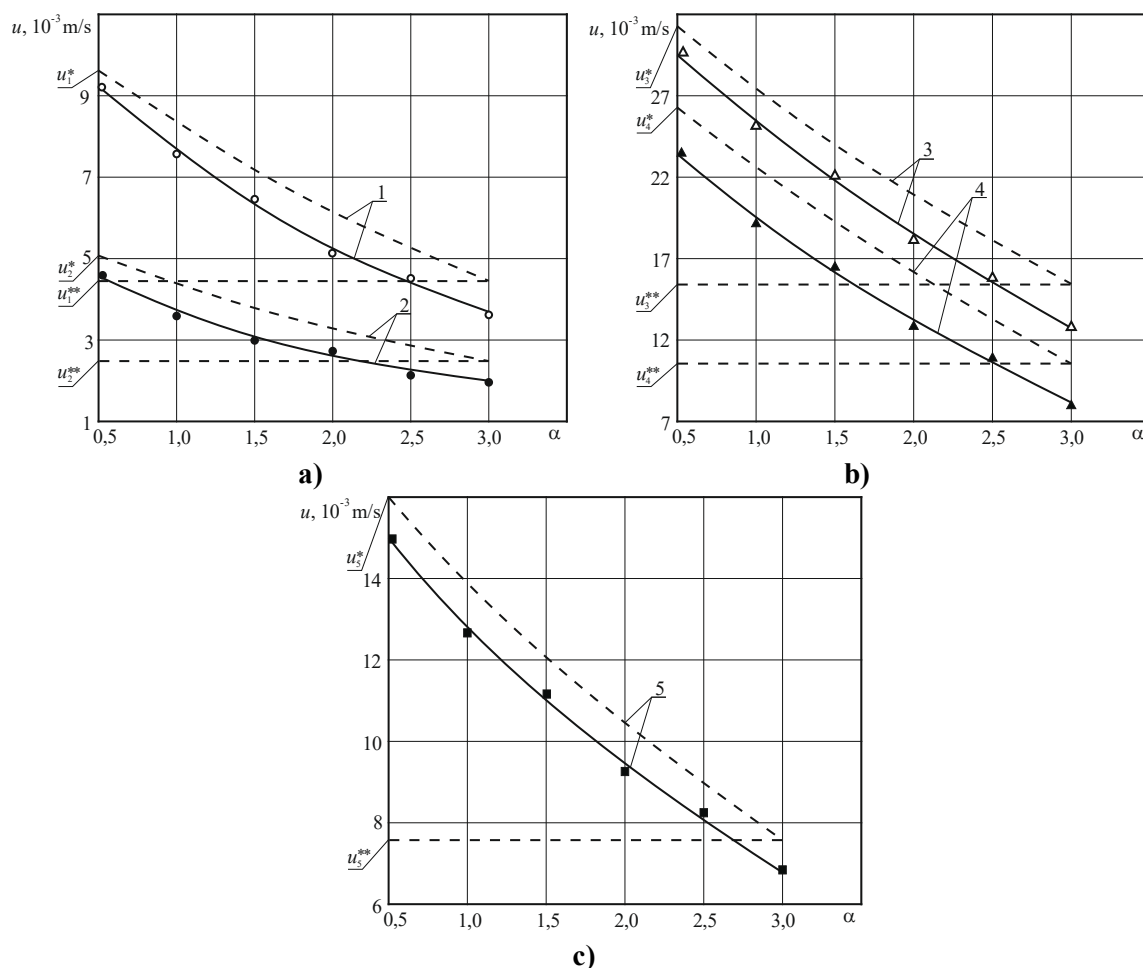


Figure 1. Dependences of the burning rate of mixtures of Mg + NaNO₃ + paraffin + NaF on the coefficient of excess oxidant for different values of the amounts of additives under normal external conditions ($d_m = 74,5 \mu\text{m}$; $d_o = 106 \mu\text{m}$; $C_c = 0,95 \dots 0,96$; $T_0 = 293 \text{ K}$; $P = 10^5 \text{ Pa}$):

- a) – $\varepsilon_f = 0$; 1 – $\varepsilon_n = 0,05$; 2 – $\varepsilon_n = 0,2$; b) – $\varepsilon_n = 0$; 3 – $\varepsilon_f = 0,1$; 4 – $\varepsilon_n = 0,05$;
c) – $\varepsilon_f \neq 0$ and $\varepsilon_n \neq 0$; 5 – $\varepsilon_n = 0,2$; $\varepsilon_f = 0,1$; – – – calculation curve; u_i^* and u_i^{**} ($i = \overline{1,5}$) – critical values of the burning rate of mixtures; $\circ, \bullet, \Delta, \blacktriangle, \blacksquare$ – experimental data

In addition, as a result of the calculations, the following critical ranges of changes in the burning rate of mixtures and technological parameters were established (as an example, finely dispersed Mg powders with $d_m = 74,5 \mu\text{m}$ were considered as the most reactive in active gaseous decomposition products (Marich *et al.*, 2018); at the same time, as the results of the calculations showed, in the case of coarsely dispersed Mg powders (with $d_m = 182 \dots 306 \mu\text{m}$), the considered mixtures become less sensitive to external thermal effects), the excess of which leads to the unstable explosive development of their combustion process under the conditions of external thermodynamics (Tables 1, 2):

$$\varepsilon_{ni}^{**} \leq \varepsilon_n \leq \varepsilon_{ni}^*, \quad \varepsilon_{fi}^{**} \leq \varepsilon_f \leq \varepsilon_{fi}^*, \quad u_i^{**} \leq u_i \leq u_i^*, \quad (22)$$

$$i = 1, 2, 3, \dots$$

Table 1. Ranges of change of critical parameters u_i^* and u_i^{**} (10^{-3} m/s), ε_{ni}^* , ε_{ni}^{**} , ε_{fi}^* and ε_{fi}^{**} for mixtures Mg + NaNO₃ + paraffin + NaF and Mg + NaNO₃ + stearin + BaF₂ under normal external conditions ($\alpha = 0,5 \dots 3,0$; $d_m = 74,5 \mu\text{m}$; $d_o = 106 \mu\text{m}$; $C_c = 0,95 \dots 0,96$; $T_0 = 293 \text{ K}$; $P = 10^5 \text{ Pa}$), $i = \overline{1,10}$

Mixture Mg + NaNO ₃ + paraffin + NaF	Mixture Mg + NaNO ₃ + stearin + BaF ₂
$u_1^* > 9,6$ and $u_1^{**} < 4,7$ at $\varepsilon_{f1}^* = 0$; $\varepsilon_{n1}^* < 0,05$ and $\varepsilon_{n1}^{**} > 0,05$	$u_6^* > 3,7$ and $u_6^{**} < 1,6$ at $\varepsilon_{f6}^* = 0$; $\varepsilon_{n6}^* < 0,05$ and $\varepsilon_{n6}^{**} > 0,05$
$u_2^* > 5,1$ and $u_2^{**} < 2,5$ at $\varepsilon_{f2}^* = 0$; $\varepsilon_{n2}^* < 0,2$ and $\varepsilon_{n2}^{**} > 0,2$	$u_7^* > 2,1$ and $u_7^{**} < 1,2$ at $\varepsilon_{f7}^* = 0$; $\varepsilon_{n7}^* < 0,05$ and $\varepsilon_{n7}^{**} > 0,05$
$u_3^* > 31,4$ and $u_3^{**} < 16,3$ at $\varepsilon_{n3}^* = 0$; $\varepsilon_{f3}^* > 0,1$ and $\varepsilon_{f3}^{**} < 0,1$	$u_8^* > 25,4$ and $u_8^{**} < 11,9$ at $\varepsilon_{f8}^* = 0$; $\varepsilon_{n8}^* < 0,05$ and $\varepsilon_{n8}^{**} > 0,05$
$u_4^* > 26,1$ and $u_4^{**} < 11,5$ at $\varepsilon_{n4}^* = 0$; $\varepsilon_{f4}^* > 0,05$ and $\varepsilon_{f4}^{**} < 0,05$	$u_9^* > 21,1$ and $u_9^{**} < 8,8$ at $\varepsilon_{f9}^* = 0$; $\varepsilon_{n9}^* < 0,05$ and $\varepsilon_{n9}^{**} > 0,05$
$u_5^* > 16,1$ at $\varepsilon_{n5}^* < 0,2$ and $\varepsilon_{f5}^* > 0,1$; $u_5^{**} < 7,7$ at $\varepsilon_{n5}^{**} > 0,2$ and $\varepsilon_{f5}^{**} < 0,1$	$u_{10}^* > 15,3$ at $\varepsilon_{n10}^* < 0,2$ and $\varepsilon_{f10}^* > 0,1$; $u_{10}^{**} < 5,9$ at $\varepsilon_{n10}^{**} > 0,2$ and $\varepsilon_{f10}^{**} < 0,1$

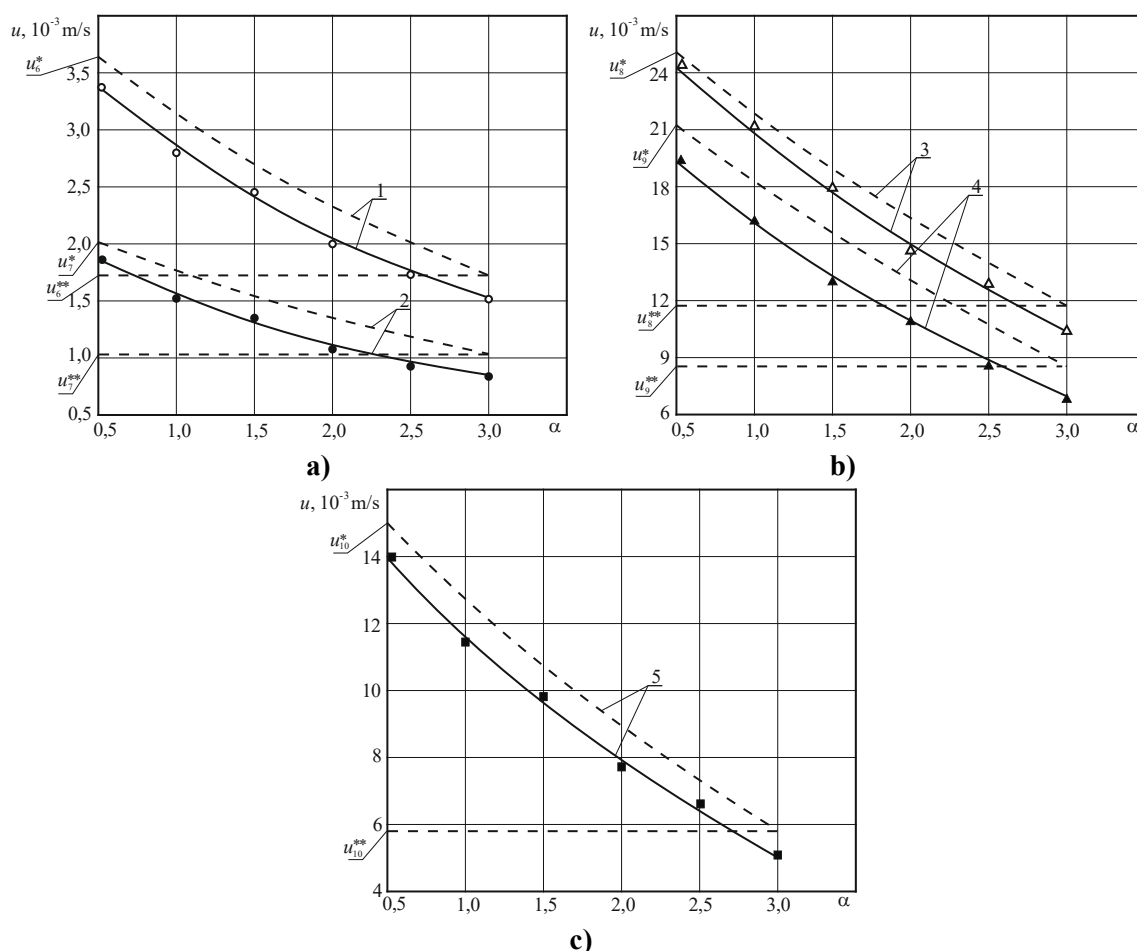


Figure 2. Dependencies of the burning rate of mixtures of Mg + NaNO₃ + stearin + BaF₂ on the coefficient of excess oxidant for different values of the amounts of additives under normal external conditions ($d_m = 74,5 \mu\text{m}$; $d_o = 106 \mu\text{m}$; $C_c = 0,95 \dots 0,96$; $T_0 = 293 \text{ K}$; $P = 10^5 \text{ Pa}$):

- a) – $\varepsilon_f = 0$; 1 – $\varepsilon_n = 0,05$; 2 – $\varepsilon_n = 0,2$; b) – $\varepsilon_n = 0$; 3 – $\varepsilon_f = 0,1$; 4 – $\varepsilon_n = 0,05$;
c) – $\varepsilon_f \neq 0$ and $\varepsilon_n \neq 0$; 5 – $\varepsilon_n = 0,2$; $\varepsilon_f = 0,1$; – – – calculation curve; u_i^* and u_i^{**} ($i = \overline{6,10}$) – critical values of the burning rate of mixtures; $\circ$, $\bullet$, Δ , $\blacktriangle$, $\blacksquare$ – experimental data

Table 2. Ranges of change of critical parameters u_i^* and u_i^{**} (10^{-3} m/s), ε_{ni}^* , ε_{ni}^{**} , ε_{fi}^* and ε_{fi}^{**} for Mg + NaNO₃ + paraffin + NaF and Mg + NaNO₃ + stearin + BaF₂ mixtures under conditions of external thermal influences ($\alpha = 0,5 \dots 3,0$; $d_m = 74,5 \mu\text{m}$; $d_o = 106 \mu\text{m}$; $C_c = 0,95 \dots 0,96$), $i = \overline{11,15}$

Mixture of Mg + NaNO ₃ + paraffin + NaF	Mixture of Mg + NaNO ₃ + stearin + BaF ₂
At $T_0 = 800 \text{ K}$, $P = 10^5 \text{ Pa}$	
$u_{11}^* > 22,3$ and $u_{11}^{**} < 8,4$ at $\varepsilon_{f11}^* = 0$; $\varepsilon_{n11}^* < 0,05$ and $\varepsilon_{n11}^{**} > 0,05$	$u_{16}^* > 8,4$ and $u_{16}^{**} < 3,7$ at $\varepsilon_{f16}^* = 0$; $\varepsilon_{n16}^* < 0,05$ and $\varepsilon_{n16}^{**} > 0,05$
$u_{12}^* > 12,1$ and $u_{12}^{**} < 4,5$ at $\varepsilon_{f12}^* = 0$; $\varepsilon_{n12}^* < 0,2$ and $\varepsilon_{n12}^{**} > 0,2$	$u_{17}^* > 4,1$ and $u_{17}^{**} < 2,2$ at $\varepsilon_{f17}^* = 0$; $\varepsilon_{n17}^* < 0,05$ and $\varepsilon_{n17}^{**} > 0,05$
$u_{13}^* > 70,2$ and $u_{13}^{**} < 33,5$ at $\varepsilon_{f13}^* = 0$; $\varepsilon_{f13}^* > 0,1$ and $\varepsilon_{f13}^{**} < 0,1$	$u_{18}^* > 62,0$ and $u_{18}^{**} < 11,9$ at $\varepsilon_{f18}^* = 0$; $\varepsilon_{n18}^* < 0,05$ and $\varepsilon_{n18}^{**} > 0,05$
$u_{14}^* > 54,1$ and $u_{14}^{**} < 22,3$ at $\varepsilon_{n14}^* = 0$; $\varepsilon_{f14}^* > 0,05$ and $\varepsilon_{f14}^{**} < 0,05$	$u_{19}^* > 48,1$ and $u_{19}^{**} < 19,2$ at $\varepsilon_{f19}^* = 0$; $\varepsilon_{n19}^* < 0,05$ and $\varepsilon_{n19}^{**} > 0,05$
$u_{15}^* > 52,6$ at $\varepsilon_{n15}^* < 0,2$ and $\varepsilon_{f15}^* > 0,1$; $u_{15}^{**} < 14,7$ at $\varepsilon_{n15}^{**} > 0,2$ and $\varepsilon_{f15}^{**} < 0,1$	$u_{20}^* > 29,3$ at $\varepsilon_{n20}^* < 0,2$ and $\varepsilon_{f20}^* > 0,1$; $u_{20}^{**} < 10,1$ at $\varepsilon_{n20}^{**} > 0,2$ and $\varepsilon_{f20}^{**} < 0,1$

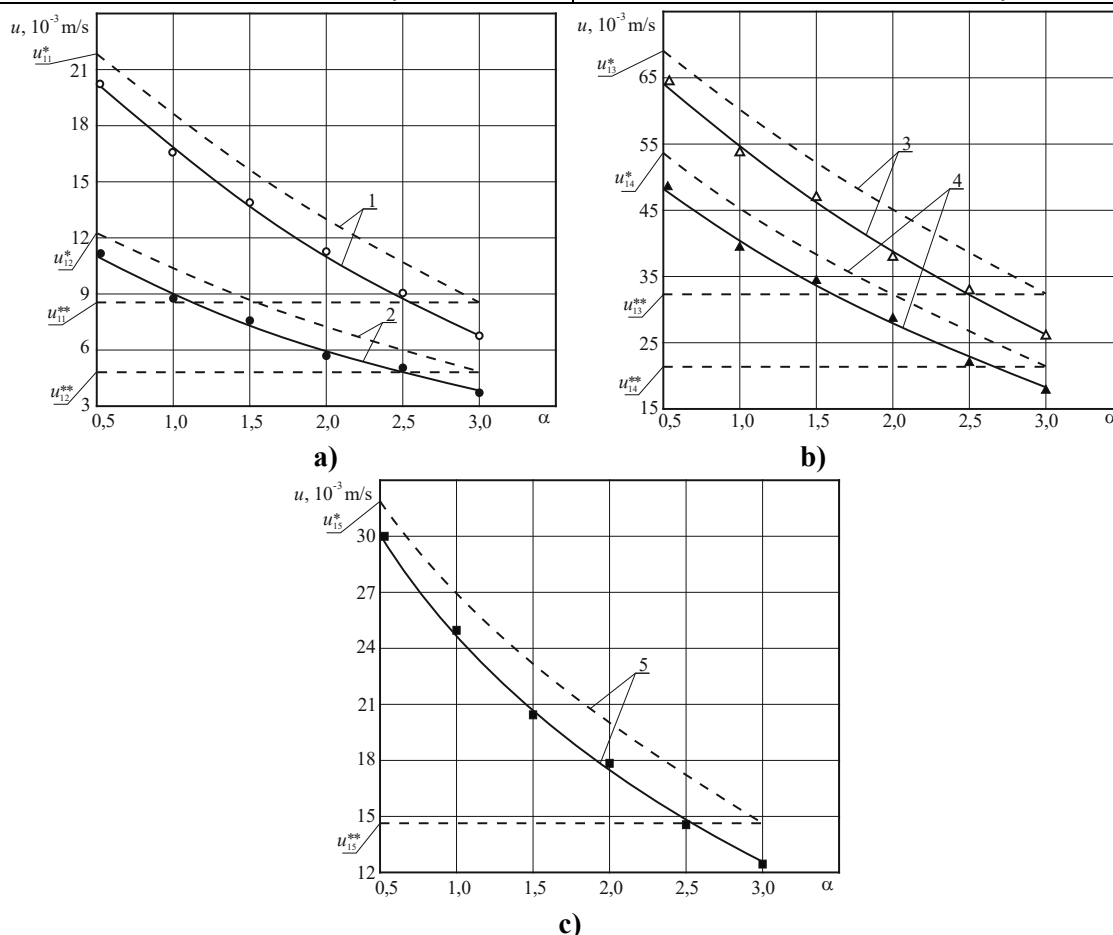


Figure 3. Dependencies of the burning rate of mixtures of Mg + NaNO₃ + paraffin + NaF on the coefficient of excess oxidant for different values of the amounts of additives under conditions of elevated heating temperatures ($d_m = 74,5 \mu\text{m}$; $d_o = 106 \mu\text{m}$; $C_c = 0,95 \dots 0,96$; $T_0 = 800 \text{ K}$; $P = 10^5 \text{ Pa}$): a) – $\varepsilon_f = 0$; 1 – $\varepsilon_n = 0,05$; 2 – $\varepsilon_n = 0,2$; b) – $\varepsilon_n = 0$; 3 – $\varepsilon_f = 0,1$; 4 – $\varepsilon_n = 0,05$; c) – $\varepsilon_f \neq 0$ and $\varepsilon_n \neq 0$; 5 – $\varepsilon_n = 0,2$; $\varepsilon_f = 0,1$; – – – calculation curve; u_i^* and u_i^{**} ($i = \overline{11,15}$) – critical values of the mixture burning rate; $\circ$, $\bullet$, Δ , $\blacksquare$ – experimental data

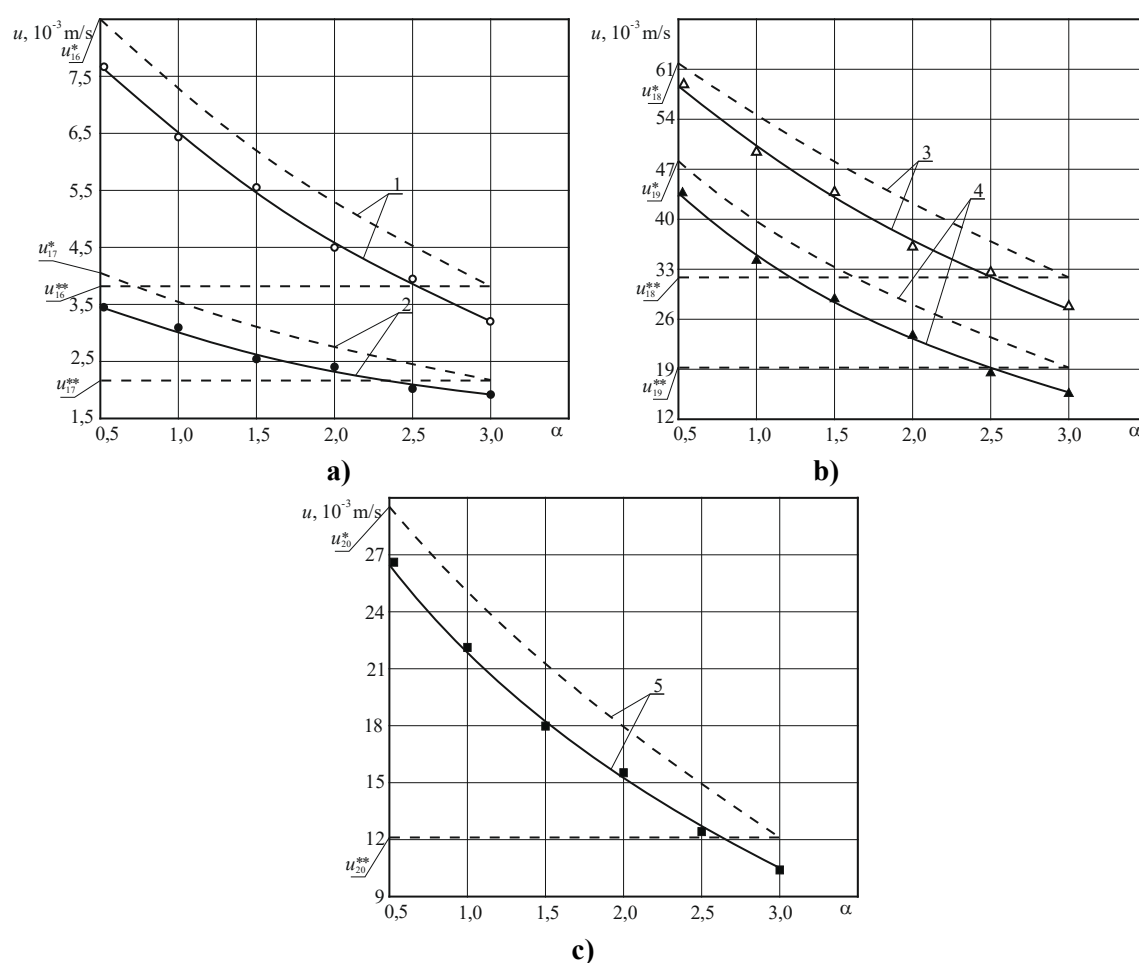


Figure 4. Dependences of the burning rate of mixtures of $\text{Mg} + \text{NaNO}_3 + \text{stearin} + \text{BaF}_2$ on the coefficient of excess oxidant for different values of the amounts of additives under conditions of elevated heating temperatures ($d_m = 74,5 \mu\text{m}$; $d_o = 106 \mu\text{m}$; $C_c = 0,95 \dots 0,96$; $T_0 = 800 \text{ K}$; $P = 10^5 \text{ Pa}$):

- a) – $\varepsilon_f = 0$; 1 – $\varepsilon_n = 0,05$; 2 – $\varepsilon_n = 0,2$; b) – $\varepsilon_n = 0$; 3 – $\varepsilon_f = 0,1$; 4 – $\varepsilon_n = 0,05$;
c) – $\varepsilon_f \neq 0$ and $\varepsilon_n \neq 0$; 5 – $\varepsilon_n = 0,2$; $\varepsilon_f = 0,1$; – – – calculation curve;
 u_i^* and u_i^{**} ($i = \overline{16,20}$) – critical values of the burning rate of mixtures;
 $\circ, \bullet, \Delta, \blacktriangle, \blacksquare$ – experimental data

Thus, mathematical models of the combustion of mixtures of metal + nitrate-containing oxidizer + additives of organic and inorganic substances were developed using standard software provision allows at the design stage and subsequent bench tests of products to predict with an accuracy of 8...12 % the effect of elevated heating temperatures and external pressures (for a wide range of changes in the ratios of components and their dispersion) on the burning rate of mixtures (the duration of action of products equipped with sample mixtures), and as well as critical regimes of sustained combustion propagation under conditions of thermal exposure. This makes it possible to predict various fire-dangerous situations that arise under the conditions of various external thermal effects on the surface of metal casings of products.

Conclusions

The following new results were obtained on the basis of theoretical and experimental studies of the combustion process of multicomponent pyrotechnic nitrate-metallized mixtures under conditions of external thermal effects.

The combustion mechanism of compacted mixtures of metal fuel powders, nitrate-containing oxidizers and additives of organic and inorganic substances under conditions of elevated heating temperatures and external pressures has been established, according to which the processes of transformation of the initial solid mixture into combustion products are stationary and proceed in the following zones: condensed phase (c-phase), where the initial mixture is heated, thermal decomposition of oxidizers and additives, high-temperature oxidation of particles occurs metal fuels in active decomposition products; the phase interface (combustion surface), on which the mixture loses the properties of a condensed medium, while metal particles ignite on it, which are then carried by the flow of gaseous decomposition products into the flame zone; gas phase (g-phase, zone of heat release in the flame), in which transferred metal particles burn in the diffusion mode in gaseous decomposition products, forming combustion plumes.

Mathematical models of the combustion process of four-component mixtures of metal + oxidizer + organic additive + inorganic additive under conditions of external thermal influences were developed, which use the kinetic characteristics of the thermal decomposition of the oxidizer and substance additives, high-temperature oxidation, ignition and combustion of metal fuel particles in different zones, as well as the results of thermodynamic calculations of the temperature of the combustion products of mixtures and the amount of high-temperature condensate (non-oxidized metal) in them, which allows with a relative error of 8...10% to calculate the dependence of the combustion rate of mixtures on technological parameters (the nature and ratio of components, their dispersion) and external conditions (elevated heating temperatures, external pressures). These models make it possible to determine, for a wide range of changes in the heating temperature (up to 800 K) and external pressure (up to 10^7 Pa), the critical ranges of changes in technological parameters, exceeding which can lead to a sharp increase in the rate of combustion of mixtures (with an excess of metallic fuel), which leads to fire-explosive destruction of pyrotechnic products, as well as to a sharp decrease in the burning rate (with an excess of oxidizer) and subsequent failure of the products during their normal use.

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None.

Conflict of Interest

Authors declare no conflict of interest.

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МОДЕЛІ ГОРІННЯ БАГАТОКОМПОНЕНТНИХ ПІРОТЕХНІЧНИХ НІТРАТНО-МЕТАЛІЗОВАНИХ СУМІШЕЙ

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Анотація. Встановлено механізм горіння ущільнених сумішей з порошків металізованих палих (Mg, Al та ін.), нітратовмісних окиснювачів (NaNO_3 , KNO_3 та ін.), добавок органічних (парафіну, стеарину та ін.) та неорганічних речовин (фторидів металів, оксидів металів та ін.) в умовах зовнішніх термічних впливів, згідно з яким процес перетворення вихідної суміші на продукти згоряння, у середньому, є стаціонарним та здійснюється у трьох просторово розділених зонах: конденсована фаза, де відбувається розкладання та високотемпературне

окиснення компонентів; поверхня розділу фаз (поверхня горіння), на якій відбувається повне розкладання компонентів та займання частинок металу, які потім переходять у зону полум'я; газова фаза (зона тепловиділення у полум'ї), в якій частинки металу згоряють у дифузійному режимі, утворюючи продукти згоряння. Розроблено моделі горіння сумішей, які враховують кінетичні характеристики термічного розкладання окиснювача, добавок органічних та неорганічних речовин і високотемпературного окиснення, займання та горіння частинок металу у продуктах розкладання, а також результати термодинамічних розрахунків температури продуктів згоряння сумішей та вмісту у них високотемпературного конденсату (неокисненого металу), що дозволяє з відносною похибкою 8...10 % визначати критичні діапазони зміни швидкості горіння сумішей в умовах зовнішніх термічних дій, перевищення яких може призводити як до прискорення процесу горіння сумішей та пожежовибухонебезпечного руйнування піротехнічних виробів, так і до різкого згасання їх процесу горіння та відмови виробів.

Ключові слова: пожежна безпека, піротехнічні суміші, нітратовмісні окиснювачі, металеві паливі, добавки органічних та неорганічних речовин, термічні дії, процеси горіння, моделі горіння металізованих конденсованих систем.

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METHOD FOR CALCULATION OF LIGHTNING RISK ASSESSMENT USING MS EXCEL

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Abstract. This work considers the method of building a model for calculating the risk of a lightning strike in a building and its implementation in accordance with current regulatory documents using the MS EXCEL computer program.

This technique will be useful for designers who perform a part of lightning protection and during the execution of their projects must calculate the risk of lightning strike. The risk of a lightning strike according to current regulations may consist of the sum of one to four risks: the risk of loss of human life; the risk of losing the ability to provide public services; the risk of loss of cultural heritage and the risk of loss of economic value. This technique is used to calculate the risk of loss of human life as the most important value that can be lost. It provides for the calculation of the risk of lightning strike for public, administrative, industrial or residential buildings, that is, the buildings that the designer most often has to deal with during his work.

This technique is not intended to be used to build risk models for buildings or structures of the following purpose: public communications and objects of cultural purpose, because these buildings involve the calculation of the risk of loss of the ability to provide public services or the risk of loss of cultural heritage, respectively. Also, it does not apply to the calculation of buildings with explosive zones, since the risk calculation for them will be specific. In addition, this technique does not provide for calculations of the risk of loss of economic value, since it is not mandatory according to regulatory documents and is carried out additionally at the request of the customer. At the same time, it can be used as a basis for building more complex models suitable for these types of buildings.

The work considers the methods of solving the main problems faced by the designer during the calculation of the risk assessment: automation of the calculation of similar formulas, and reduction of most of them to several basic types; obtaining a formula that returns a value or a reference to a value from a table or range, and also performs a search for the specified element in the range and returns the relative position of this element; formulation of the risk assessment procedure in accordance with the regulatory document and determination of how certain input data affect the final result.

Keywords: computer simulation, lightning protection, functions in MS EXCEL, formulas in MS EXCEL, designing.

Introduction

As a future member of the European Union, Ukraine has taken on the responsibility of gradually harmonizing its regulatory and technical base with the normative acts of the European community. This became the reason for the adoption of a number of standards (Protection 1-4, 2010, 2011), which replaced the domestic one (Engineering equipment, 2008) in the field of lightning protection. Domestic standards are a translation into the national language of standards developed by the Institute of Electrical and Electronics Engineers (IEEE), which is the largest technical organization in the world and unites specialists in this field from more than 190 countries. These standards (Protection 1-4, 2010, 2011) were published in 2010 and are improved standards published in 2006, based on which the previously active national standard of Ukraine (Engineering equipment, 2008) was developed and associated with it (Rules for arranging, 2017; Rules for the construction, 2001).

Immediately after the publication of the standards (Protection 1-4, 2010, 2011) its innovations began to be discussed at international conferences (Surtees, 2011) and meetings in the participating countries. During the discussions, special attention was paid to the probability of lightning damage and its probability of occurrence. As a result, various protective measures against lightning damage were proposed and their influence on the final result of building and construction protection was investigated (Elliams, 2017; Bao *et al.*, 2021; Araújo *et al.*, 2015) which was discussed in the articles (Souto *et al.*, 2023; Gao *et al.*, 2020; Goh *et al.*, 2017) and in the book (Fernando *et al.*, 2019).

According to the new regulatory documents, in order to assess whether the protection of the building is required, it is necessary to carry out a risk calculation in accordance with the regulatory document (Protection 2, 2010). The calculation algorithm and examples of calculations for the main types of buildings are given in the same document. But due to the large number of such formulas, there is a natural need to automate this process.

After the adoption of European regulatory documents in the field of lightning protection (Protection 1-4, 2010, 2011), software products that facilitate the work of the designer began to appear on the domestic market, allowing to automatically assessing the risk of damage to the building by lightning. You can also find software products in foreign languages that allow you to make online payments. But the disadvantages of all these software products are that they are all paid and do not allow you to issue the results in the form of a document that meets the requirements of the national normative document (Basic requirements, 2009). This, in turn, creates problems during the examination of project documentation and causes comments from experts. A solution option may be to create a model using the MS Excel computer program, followed by exporting the results to a pre-created template in accordance with the regulatory document (Basic requirements, 2009) based on an MS Word document. In addition, one of the advantages of creating a model in MS Excel is the absence of the necessary programming skills, since most designers do not have them.

The use of the MS Excel software complex is widespread in the scientific environment and is used to solve various scientific problems, such as modeling the process of mechanical movement of the body (Horda, & Flehantov, 2015), biological modulation (Tack *et al.*, 1995) and even when teaching science subjects (Ibrahim, 2009). Therefore, the use of MS Excel to create a calculation model for assessing the risk of damage to a building by lightning is fully justified.

The purpose of the work is to build a model for assessing the risk of a lightning strike in a building using MS Excel, which will significantly speed up the work of designers who perform a part of lightning protection and during the implementation of their projects carry out a calculation of the risk assessment of a lightning strike for public, administrative, industrial or residential buildings.

Materials and methods

To obtain a working model in the MS Excel computer program, the following tasks must be solved:

- solve the formulas used to calculate the risk assessment, which are reduced to several main types or have a specific form:

$$R_Y = N_Y \cdot P_Y \cdot L_Y, \quad (1)$$

where R_Y is risk component;

N_Y is number of threatening events;

P_Y is probability;

L_Y is loss.

$$N_Y = N_X \cdot A_X \cdot C_X \cdot 10^{-6}, \quad (2)$$

where N_Y is number of threatening events;

N_X is density of underground lightning flashes;

A_X is area of collection of lightning flashes;

C_X is coefficient.

$$A_X = L \cdot W + 2 \cdot (3 \cdot H) \cdot (L + W) + \pi \cdot (3 \cdot H)^2, \quad (3)$$

where A_X is area of collection of lightning flashes;

L is length of the building;

W is width of the building;

H is building height.

$$A_X = 2 \cdot 500 \cdot (L + W) + \pi \cdot (500)^2, \quad (4)$$

where A_X is area of collection of lightning flashes;

L is length of the building;

W is width of the building.

$$R_I = \sum_{i=1}^N R_{Yi}, \quad (5)$$

where R_I is risk of loss of human life in the building;

R_Y is risk component.

- build a typical formula that returns a value or a reference to a value from a table or range and also performs a search for the specified element in the range and returns the relative position of this element;

- formulate a risk assessment procedure in accordance with the regulatory document (Protection 2, 2010) presented in Fig. 1 and be able to correctly select protective measures to reduce risk (internationally accepted abbreviations in the figure LPS - lightning protection system, SPM - lightning electromagnetic impulse protection measures protection against the electromagnetic pulse of lightning)).

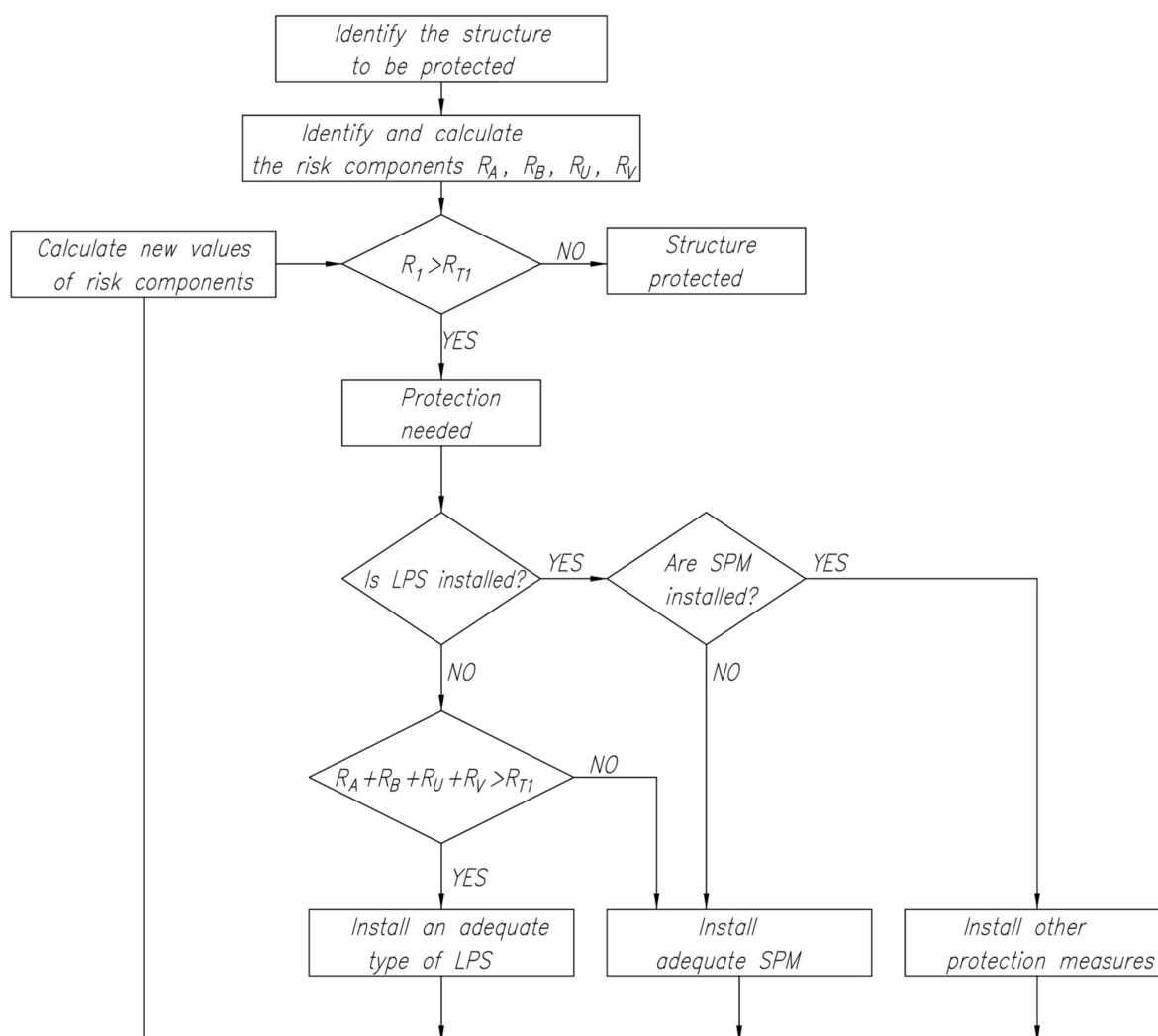


Figure 1. Procedure for determining the need for protection and selection of protection measures

Findings and discussion

To solve the formulas, you first need to get input from the customer of the lightning protection project or the owner of the building for which the lightning strike risk assessment is being performed.

For the optimal distribution of the received data and for convenient use of them in MS Excel, we create two sheets:

- in the first, there will be input data that will have the form of lists, where each block is a separate list – Fig. 2 (1st column - the name of the parameter from the list; 2-nd column - the value of the parameter from the list)

	1	2
1	Structure surrounded by higher objects	0,25
2	Structure surrounded by objects of the same height or smaller	0,5
3	Isolated structure: no other objects in the vicinity	1
4	Isolated structure on a hilltop or a knoll	2
5		
6	Aerial	1
7	Buried	0,5
8		
9	Rural	1
10	Suburban	0,5
11	Urban	0,1
12	Urban with tall buildings	0,01
13		
14	Industrial use equipment	4
15	Equipment: electrical appliances, etc	2,5
16	Equipment: computers, devices with electronic programming	1,5
17		
18	Agricultural, concrete	0,01
19	Marble, ceramic	0,001
20	Gravel, moquette, carpets	0,0001
21	Asphalt, linoleum, wood	0,00001
22		
23	High	0,1
24	Ordinary	0,01
25	Low	0,001
26		
27	No provisions	1
28	One of the following provisions: extinguishers; fixed manually operated extinguishing installations; manual alarm installations; hydrants; fire compartments; escape routes	0,5
29	One of the following provisions: fixed automatically operated extinguishing installations; automatic alarm installations	0,2
30		
31	No special hazard	1
32	Low level of panic	2
33	Average level of panic	5
34	High level of panic	10
35		
36	Hospital, hotel, school, civic building	0,1
37	Public entertainment, church, museum	0,05
38	Industrial, commercial	0,02
39	Others	0,01

Figure 2. Input data that will be in the form of lists

- in the second sheet, the data will be built on the basis of lists, other input data, intermediate and final calculations - Figs. 3-6 (1st and 2nd columns – the name of the parameter and the value of the parameter from the sides, the number of lightning strikes, the size of the building and the number of people and the time of presence; 4th column – the name of other parameters; 5th – the data is built on the basis lists and formulas; 6th – designation of parameters; 7th – intermediate and final calculations; 8th – references to formulas or tables according to the regulatory document (Protection 2, 2010)).

	1	2
1	<i>Number of lightning strikes</i>	
2	<i>TD</i>	26,00
3	<i>NG</i>	2,60
4		
5		
6		
7	<i>Dimensions of the structure</i>	
8	<i>L – length</i>	94
9	<i>W – width</i>	86
10	<i>H - height</i>	15
11		
12	<i>Number of people and time of</i>	
13	<i>nz</i>	1860
14	<i>nt</i>	1860
15	<i>tz</i>	8760

Figure 3. Number of lightning strikes, building dimensions and number of people and presence time

	4	5
1	<i>Table of characteristics of the structure and the surrounding environment</i>	
2	Location factor	Structure surrounded by objects of the same height or smaller
3	Probability of physical damage to a structure (flashes to a structure)	Structure not protected by LPS
4	Probability reducing P_U and P_V depending on line characteristics and withstand voltage of equipment when EB is installed	No SPD
5	Factor relevant to the screening effectiveness of the structure	The maximum value (according to NOTE 3)
6		
7	<i>Table for power lines</i>	
8	Length of line section	Up to
9	Installation factor of the line	Buried
10	Line type factor for a HV/LV transformer on the line	LV power, telecommunication or data line
11	Environmental factor	Urban
12	Factor depending on shielding, grounding and isolation conditions of the line for flashes to a line	Aerial line unshielded
13	Factor depending on shielding, grounding and isolation conditions of the line for flashes near a line	Aerial line unshielded
14	Rated impulse withstand voltage of a system	Industrial use equipment
15	Factor relevant to the impulse withstand voltage of a system	according to NOTE 4 $K_{S4} = 1/U_W$
16	Probability reducing P_U , P_V and P_W depending on line characteristics and withstand voltage of equipment (flashes to connected line)	Aerial or buried line, unshielded or shielded whose shield is not bonded to the same bonding bar as equipment
17		
18	<i>Table of reduction factor</i>	
19	Reduction factor associated with the type of surface	Asphalt, linoleum, wood
20	Probability reducing P_A depending on protection measures against touch and step voltages	No protection measures
21	Probability of injury to living beings by electric shock (flashes to a connected line)	No protection measures
22	Factor reducing loss depending on risk of fire	Ordinary
23	Factor reducing the loss due to provisions against fire	One of the following provisions: extinguishers; fixed manually operated extinguishing installations; manual alarm installations; hydrants; fire compartments; escape routes
24	Factor relevant to the screening effectiveness of shields internal to the structure	The maximum value (according to NOTE 3)
25	Number of possible endangered persons (victims or users not served)	High level of panic
26	Loss due to injury by electric shock	All types
27	Loss in a structure due to physical damage	Hospital, hotel, school, civic building
28	Loss in a structure due to failure of internal systems	It is not standardized

Figure 4. Parameter names, input data and data built on the basis of lists

	4	5
29		
30	Table of loss	
31	Loss due to injury to living beings by electric shock (flashes to structure)	$L_A = r_t \cdot L_T \cdot (n_z / n_t) \cdot (t_z / 8760)$
32	Loss due to injury of living beings by electric shock (flashes to line)	$L_U = r_t \cdot L_T \cdot (n_z / n_t) \cdot (t_z / 8760)$
33	Loss in a structure related to physical damage (flashes to structure)	$L_{B1} = r_p \cdot r_f \cdot h_z \cdot L_{F1} \cdot (n_z / n_t) \cdot (t_z / 8760)$
34	Loss in a structure due to physical damage (flashes to line)	$L_{V1} = r_p \cdot r_f \cdot h_z \cdot L_{F1} \cdot (n_z / n_t) \cdot (t_z / 8760)$
35		
36	Structure protection area table and communication lines	
37	Collection area for flashes to an isolated structure	$A_D = L \cdot W + 2 \cdot (3 \cdot H) \cdot (L + W) + \pi \cdot (3 \cdot H)^2$
38	Collection area for flashes striking near the structure	$A_M = 2 \cdot 500 \cdot (L + W) + \pi \cdot (500)^2$
39	Collection area for flashes to a line	$A_{LP} = 40 \cdot L_{LP}$
40	Collection area for flashes near a line	$A_{LP} = 4000 \cdot L_{LP}$
41		
42	Table of the expected number of dangerous events due to flashes	
43	Number of dangerous events due to flashes to structure	$N_D = N_G \cdot A_D \cdot C_D \cdot 10^{-6}$
44	Number of dangerous events due to flashes near a structure	$N_M = N_G \cdot A_M \cdot 10^{-6}$
45	Number of dangerous events due to flashes to a line	$N_{LP} = N_G \cdot A_{LP} \cdot C_{LP} \cdot C_E \cdot C_{TP} \cdot 10^{-6}$
46	Number of dangerous events due to flashes near a line	$N_{LP} = N_G \cdot A_{LP} \cdot C_{LP} \cdot C_E \cdot C_{TP} \cdot 10^{-6}$
47		
48	Calculation R1	
49	Table of risk components	
50	Probability of injury to living beings by electric shock (flashes to a structure)	$P_A = P_{TA} \cdot P_B$
51	Risk component (injury to living beings – flashes to structure)	$R_A = N_D \cdot P_A \cdot L_A$
52	Risk component (physical damage to a structure – flashes to a structure)	$R_B = N_D \cdot P_B \cdot L_{B1}$
53	Probability of injury to living beings by electric shock (flashes to a connected line)	$P_{U/P} = P_{TU} \cdot P_{EB} \cdot P_{LD/P} \cdot C_{LD/P}$
54	Risk component (injury to living being – flashes to connected line)	$R_{U/P} = N_{LP} \cdot P_{U/P} \cdot L_U$
55	Probability of physical damage to a structure (flashes to a connected line)	$P_{V/P} = P_{EB} \cdot P_{LD/P} \cdot C_{LD/P}$
56	Risk component (physical damage to structure – flashes to connected line)	$R_{V/P} = N_{LP} \cdot P_{V/P} \cdot L_{V1}$

Figure 5. Parameter names and formulas

To facilitate the perception of information, the information is divided into separate blocks, and the cells with numerical values and data built on the basis of lists are marked with the appropriate colors:

- input data is built on the basis of lists from the 1st sheet;
- input data received from the customer;
- intermediate calculations;
- final calculations.

6	7	8
Table of characteristics of the structure and the surrounding environment		
C_D	0,5	Table A.1
P_B	1	Table B.2
P_{EB}	1	Table B.7
K_{S1}	1	Section B.5
Table for power lines		
L_{LP}	50	Section A.4
C_{LP}	0,5	Table A.2
C_{TP}	1	Table A.3
C_E	0,1	Table A.4
C_{LDP}	1	Table B.4
C_{LIP}	1	
U_{WP}	4	ПУЕ Table 2.1.17
$K_{S4/P}$	0,25	Section B.5
P_{LDP}	1	Table B.8
Table of reduction factor		
r_t	0,00001	Table C.3
P_{TA}	1	Table B.1
P_{TU}	1	Table B.6
r_f	0,010	Table C.5
r_p	0,5	Table C.4
K_{S2}	1	Section B.5
h_z	10	Table C.6
L_T	0,01000	Table C.2
L_{F1}	0,10000	
L_{O1}		

6	7	8
Table of loss		
L_A	0,0000001	Formula (C.1)
L_U	0,0000001	Formula (C.2)
L_{B1}	0,0050000	Formula (C.3)
L_{V1}	0,0050000	Formula (C.3)
Structure protection area table and communication lines		
A_D	30643	Formula (A.2)
A_M	965000	Formula (A.7)
A_{LP}	2000	Formula (A.9)
A_{IP}	200000	Formula (A.11)
Table of the expected number of dangerous events due to flashes		
N_D	0,040	Formula (A.4)
N_M	2,509	Formula (A.6)
N_{LP}	0,000	Formula (A.8)
N_{IP}	0,026	Formula (A.10)
Calculation R1		
Table of risk components		
P_A	1,00	Formula (B.1)
R_A	0,0000000	Formula (6)
R_B	0,0001992	Formula (7)
P_{UP}	1,00	Formula (B.8)
R_{UP}	0,0000000	Formula (10)
P_{VP}	1,00	Formula (B.9)
R_{VP}	0,0000013	Formula (11)
$R1$	0,0002005	

Figure 6. Defining parameters, intermediate and final calculations and references to formulas or tables

In cells marked with color as intermediate and final calculations, the following basic typical or specific formulas are used:

- the solution of the typical formula (1) using MS Excel is used for cell R51C7, R52C7, R54C7, R56C7.
- the solution of the typical formula (2) using MS Excel is used for cell R43C7, R44C7, R45C7, R46C7.
- solving formula (3) using MS Excel is used for cell R37C7
- solving formula (4) using MS Excel is used for cell R37C7
- solving formula (5) using MS Excel is used for cell R58C7

To build a typical formula that returns a value or a reference to a value from a table or range, and also performs a search for the specified element in the range and returns the relative position of this element, you need:

- for cells R2C5, R9C5, R11C5, R14C5, R19C5, R22C5, R23C5, R25C5, R27C5, build the data according to the list of relevant blocks from the 1st sheet;
- for cells R2C7, R9C7, R11C7, R14C7, R19C7, R22C7, R23C7, R25C7, R27C7, you need to use the "INDEX" and "LOOKUP" functions.

According to the risk assessment procedure presented in Fig. 1 if R_1 (value in cell R58C7) $> R_{T1}$, measures must be taken to reduce the value of R_1 . According to Fig. 1, these measures are the installation of the appropriate type of LPS, that is, the lightning protection system (change in the value of the R3C7 cell) and the corresponding SPM, that is, the surge protection devices (change in the value of the R4C7 cell). These changes will result in an automatic recalculation of R_1 , again favoring the use of a computer program for calculations. In the case of the necessary further reduction of R_1 according to Fig. 1, it is necessary to take other protective measures, i.e. changing other input parameters and the corresponding automatic recalculation of R_1 .

The obtained model will be especially useful for designers who perform or are going to perform a part of lightning protection and during the execution of their projects perform the calculation of the risk assessment of lightning strikes for public, administrative, industrial or residential buildings.

Results

The proposed technique allows building an effective model for assessing the risk of a lightning strike in a building using MS Excel, as well as:

- solve the basic and private formulas used to calculate the risk assessment;
- build a typical formula that returns a value or a reference to a value from a table or range, and also searches for the specified element in the range and returns the relative position of this element;
- use it for the procedure of studying the effect of protection measures on the final calculations.

In the future, this technique may form the basis for constructing other models for determining the risk of a lightning strike in buildings related to public communications, cultural facilities and explosive zones, while taking into account the recommendations proposed in the article (Uman, 1994).

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Conflict of interest

None.

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МЕТОДИКА РОЗРАХУНКУ ОЦІНКИ РИЗИКУ УДАРУ БЛИСКАВКИ ЗАСОБАМИ MS EXCEL

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Анотація. У роботі розглядається методика побудови моделі розрахунку оцінки ризику удару блискавки в будівлю та її реалізація відповідно до чинних нормативних документів комп'ютерною програмою MS EXCEL. Ця методика буде корисна для проєктувальників, які виконують частину блискавкозахисту і під час виконання своїх проєктів повинні проводити розрахунок оцінки ризику удару блискавки. Ризик удару блискавки згідно з чинними нормативними документами може складатися з суми від одного до чотирьох ризиків: ризик втрати людського життя; ризик втрати можливості надання громадських послуг; ризик втрати культурної спадщини та ризик втрати економічної цінності. Пропонована методика поширюється на розрахунок ризику втрати людського життя як найбільш важливої цінності, яку можна втратити. Методика передбачає розрахунок ризику удару блискавки для громадських, адміністративних, виробничих або житлових будівель – тобто будівель, з якими найчастіше доводиться стикатися проєктувальнику під час своєї роботи. Пропонована методика не розрахована на використання для побудови ризикових моделей для будівель чи споруд такого призначення: громадські комунікації й об'єкти культурного призначення, бо зазначені будівлі передбачають розрахунок ризику втрати можливості надання громадських послуг або ризику втрати культурної спадщини відповідно. Також пропонована методика не поширюється на будівлі, що мають вибухонебезпечні зони, оскільки розрахунок ризику для них буде специфічним; а ще ця методика не передбачає розрахунків ризику втрати економічної цінності, оскільки він не є обов'язковим відповідно до нормативних документів та проводиться додатково за бажанням замовника. В той же час вона може бути використана як основа для побудови більш складних моделей, що підходять для таких типів будівель. У роботі розглянуто методи вирішення основних проблем, з якими стикається проєктувальник під час розрахунку оцінки ризику: автоматизація розрахунку схожих формул та зведення більшості з них до кількох основних типів; отримання формули, що повертає значення або посилання на значення з таблиці чи діапазону, а також виконує пошук зазначеного елемента в діапазоні та повертає відносну позицію цього елемента; формулювання процедури оцінки ризиків відповідно до нормативного документа та визначення того, як саме ті чи інші вхідні дані впливають на підсумковий результат.

Ключові слова: комп'ютерне моделювання, блискавкозахист, функції в MS EXCEL, формули в MS EXCEL, проєктування.

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MODELS OF DYNAMIC OBJECTS WITH SIGNIFICANT NONLINEARITY BASED ON TIME-DELAY NEURAL NETWORKS

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Abstract. The paper is devoted to the problem of nonlinear modeling of objects based on dynamic neural networks. The aim of the work is to improve the accuracy of modeling dynamic objects with significant nonlinearities using neural network models and to determine the scope of effective application of these models. This aim is achieved using time-delay neural networks. To assess the applicability of the proposed neural network models, the study considers simulation objects with two types of nonlinearities: smooth and piecewise linear (saturation). The investigation of suggested models accuracy in nonlinear dynamic object modeling involves two experiments: the study of the models' scalability with different input signals; the study of their extrapolation capabilities. The results of both experiments are compared with the modeling results using the compensatory method of deterministic identification based on functional series. The results of the experiments reveal that the suggested neural network models are not invariant concerning the input signal. However, when trained on a sufficient amount of data generated from input signals of the same type as in the test data set, these models can effectively represent the properties of nonlinear dynamic objects. The extrapolation properties of time-delayed neural networks deteriorate as the input signal amplitudes exceed the range covered by the used training set. The scientific novelty consists in determining a clear relationship between the types of input signals, their amplitudes, and the accuracy of the proposed models. The practical significance of investigation delineates the areas in which time-delay neural networks can be used to address the real-world challenges associated with significantly non-linear objects; demonstrates the increase in accuracy of identifying nonlinear objects compared to functional series models.

Keywords: identification, nonlinear objects, substantial nonlinearities, dynamic neural networks, simulation modeling.

Introduction

The development of technology and science makes it possible to ensure a qualitative increase in the characteristics of modern objects and processes in various fields of activity. On the other hand, this continuous process leads to the complexity of control objects, and tightening of requirements for their functioning (Agresti, 2017; Schoukens, & Ljung, 2019).

Today, in practical applications, dynamic control objects, which are characterized by significantly nonlinear properties are increasingly considered. Due to these characteristics, objects can function in more complex modes that cannot be realized using linear or weak nonlinear characteristics (Schoukens, & Ljung, 2019).

The most important from the point of view of practical use is the class of nonlinear dynamic objects with unknown operational laws and an unknown structure of the "black box" type (Rudin, & Radin, 2019). Such objects, as a rule, are characterized by a complete lack of a priori information about both the operational laws of the object, which can be estimated by methods of parametric identification, and its structure. For an external observer to study the object, only the reaction of the object $y(t)$ (output signal) to the test impact $x(t)$ (input signal) obtained as a result of the so-called "input-output" experiment is available (Rudin, & Radin, 2019; Todorovic, & Klan, 2006).

For successful interaction with such objects (solving control, management, and diagnostic tasks), it is first of all necessary to provide their adequate mathematical support and effective modeling tools. This leads to the use of nonparametric identification methods to build integral nonparametric dynamic models of the control objects. Such models are able to simultaneously take into account the nonlinear and dynamic properties of the object, which ensures high accuracy of model identification (Pavlenko, & Pavlenko, 2023).

It is also known that for a wide class of nonlinear dynamic objects, the relationship between the input $x(t)$ and the output signal $y(t)$ can be explicitly represented by the integral-power series (Volterra series) (Pavlenko, & Pavlenko, 2023). However, Volterra series also have a number of disadvantages that are significant for the above requirements for modern mathematical software and modeling tools. Thus, Volterra series are more suitable for modeling objects with weak smooth unambiguous nonlinearity. The presence of ambiguous or piecewise continuous nonlinear characteristics makes the use of integral-power series ineffective. In addition, the existing restrictions on the amplitudes of the input test signals also prevent the use of such models in the identification of control objects.

An alternative approach to modeling nonlinear dynamic objects is the use of artificial neural networks (NN) (Rao, & Reimherr, 2021; Liu *et al.*, A review, 2016). For a long time, their spread was significantly constrained by the lack of effective algorithmic and instrumental support, and the complexity of their interpretation (Fomin *et al.*, 2023). However, as a result of the progress of intelligent data processing technologies, today we can observe a noticeable increase in interest in NN in the direction of structural and functional identification of complex control object. At the same time, the models are mainly in the form of nonlinear static dependencies ((Rao, & Reimherr, 2021; Liu *et al.*, A review, 2016; Fomin *et al.*, 2023). Such models do not reflect all the properties of a real object, so they cannot provide high identification accuracy.

The literature also describes neural network structures capable of modeling a class of dynamic objects with nonlinear characteristics. However, their capabilities and areas of effective application are not sufficiently studied. This class of objects is inherent in many fields of activity (medicine, engineering, transportation, etc.) that is considered in this paper.

The aim of this paper is to improve the accuracy of modeling dynamic objects with significant nonlinearities using neural network models and to determine the scope of effective application of these models.

This goal is achieved by using dynamic nonlinear models in the form of time delay neural networks.

To study the area of effective application of the proposed models, the following tasks have been set.

1. Investigation of the accuracy of modeling nonlinear objects with smooth nonlinearity.
2. Investigation of the accuracy of modeling nonlinear objects with piecewise linear nonlinearity (saturation).

Literature review

Today, several methods are known for modeling nonlinear dynamic objects using NN (Wang *et al.*, 2009; Liu *et al.*, 2021): Dynamic Neuro-SM (Zhu *et al.*, 2016; Liu *et al.*, An overview, 2016), Wiener-type DNN (Liu *et al.*, 2022; Liu *et al.*, A Wiener-type, 2020; Liu *et al.*, 2017), and time-delay neural networks (TDNN) (Sugiyama *et al.*, 1991; Liu *et al.*, A time delay, 2020; Stegmayer *et al.*, 2004).

Dynamic Neuro-SM models are improved compared to the well-known static neuro-spatial mapping models (Zhu *et al.*, 2016; Liu *et al.*, An overview, 2016), which aim to map a given coarse model of an object to an accurate model. In Dynamic Neuro-SM models, neural networks are used to automatically match and change an existing coarse model into an accurate model through a learning process (Liu *et al.*, An overview, 2016; Sen, 2021). Such models provide an increase in accuracy compared to static neurospatial mapping models, but require some a priori information about the laws of functioning of the object of study (Liu *et al.*, An overview, 2016).

Wiener-type DNNs are based on the principle of constructing a nonlinear Wiener dynamic system, which consists of a simplified linear dynamic model followed by a nonlinear static model (Liu *et al.*, A Wiener-type, 2020; Liu *et al.*, A Wiener-type, 2017). The dynamic characteristics are mostly associated with the linear subsystem, while the nonlinear properties are contained only in the static nonlinear subsystem, which is implemented as an NN (Liu *et al.*, 2022; Liu *et al.*, A Wiener-type, 2020; Liu *et al.*, A Wiener-type, 2017). Such a structure can significantly increase the reliability of a dynamic neural model, but it has a complex (hybrid) structure, which imposes additional requirements on network training algorithms and narrows the scope of the model.

Among these model variants, TDNN are the most common structure consisting of several layers with direct signal propagation (Liu *et al.*, A time delay, 2020; Stegmayer *et al.*, 2004). Such models are capable of learning from the input-output data of nonlinear dynamic objects and have excellent convergence properties (Sen, 2021; Khandani and Mikhael, 2020), which are advantages over the aforementioned Dynamic Neuro-SM and Wiener-type DNN methods.

Due to their simplicity and versatility in modeling nonlinear dynamic objects, TDNN models are the most widely used.

The literature is quite full of studies of TDNN models for dynamic objects with weak nonlinearity ((Liu *et al.*, A time delay, 2020; Stegmayer *et al.*, 2004; Khandani and Mikhael, 2020). It is worth noting a number of publications devoted to the interpretation of TDNN, in particular, the establishment of an information link between these models and Volterra series (Fomin *et al.*, 2023; Stegmayer *et al.*, 2004). However, studies of models of dynamic objects with significant nonlinearity based on TDNN are not sufficiently reflected, which is a problem for the use of such models in applied problems.

This work is aimed at filling the identified gap and focuses on the study of NN for modeling dynamic objects with nonlinear characteristics, identifying the scope of their effective application in solving applied problems of identifying objects with significantly nonlinear characteristics.

Dynamic models based on neural networks with time delay

TDNN models are an effective tool for modeling nonlinear dynamic objects with continuous characteristics. The most commonly used TDNN structure consists of three layers: input, hidden, and output.

There are many structures of neural networks: with several hidden layers, different activation functions, and topologies. However, the use of these structures results in a more complex expression for the output of the NN. This is a significant disadvantage compared to three-layer TDNN for modeling nonlinear dynamic objects.

In the above structure, the input layer of a TDNN includes M neurons, where M is the memory length of the object model. The number of neurons M is chosen to best reflect the dynamic properties of the object. The input layer receives the data $\mathbf{x}(t_n)=[x(t_n), x(t_{n-1}), \dots, x(t_{n-M+1})]$, $t_n=n\Delta t$, $n=1, 2, \dots$

The hidden layer includes K neurons with a nonlinear activation function. The number of neurons K is chosen to best reflect the nonlinear properties of the object.

The TDNN output layer includes 1 neuron with a linear activation function. The signal $y(t_n)$ at the output layer at time t_n depends on the values of the input signal $\mathbf{x}(t_n)$ and is determined by the expression (Giannini *et al.*, 2007):

$$y(t_n) = b_0 + S_0 \sum_{i=1}^K w_i S_i \left(b_i + \sum_{j=1}^M w_{i,j} x(t_{n-j}) \right) \quad (1)$$

where b_0 , b_i are the biases of the neurons of the output and hidden layers, respectively; S_0 , S_i are the activation functions of the neurons of the output and hidden layers, respectively; w_i , $w_{i,j}$ are the weighting coefficients of the neurons of the output and hidden layers, respectively.

Fig. 1 shows the TDNN architecture as a three-layer feedforward network with M inputs, a hidden layer with K neurons, and one output neuron. Such a model can be trained to dynamic behavior with nonlinear characteristics based on input-output data.

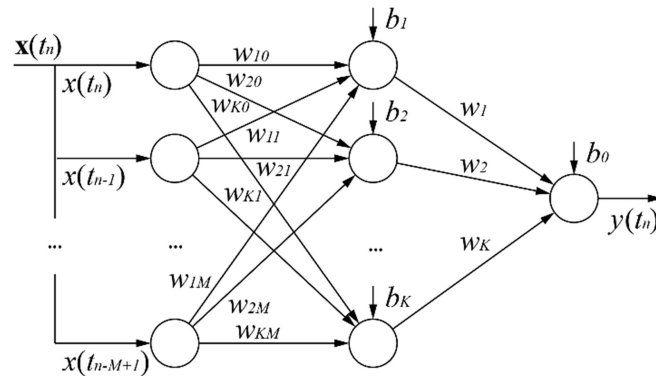


Figure 1. TDNN architecture as a three-layer network with direct signal propagation

Source: developed by the author on the basis of researches (Stegmayer *et al.*, 2004; Giannini *et al.*, 2007)

Setting up the experiment

A simulation model of a test object

The accuracy of TDNN models is studied using the example of a test object. The simulation model of the test object with a first-order dynamic block and a nonlinear feedback block (Fomin *et al.*, 2023) is shown in Fig. 2.

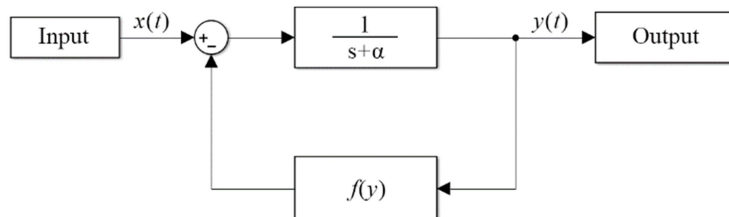


Figure 2. Simulation model of the test nonlinear dynamic object

Source: developed by the author on the basis of research (Fomin *et al.*, 2023)

The feedback block uses a nonlinear function as $f(y)$. In this case, 2 types of nonlinearity are considered.

1. For the case of smooth nonlinearity, it is polynomial: $f_1(y) = \beta y^2$, where β is a parameter (constant).

2. For the case of significant nonlinearity, a function with saturation:

$$f_2(y) = \begin{cases} s, & y > p \\ k \cdot y, & |y| \leq p \\ -s, & y < -p \end{cases} \quad (2)$$

where s is the saturation level, p is the saturation start point, and $k = s/p$ is the gain.

In order to study the accuracy of TDNN models of a test object with different types of nonlinearity $f_i(y)$ ($i=1,2$), training $\mathbf{x}_i^{train}(t_n)$ and test $\mathbf{x}_i^{test}(t_n)$ data sets are generated based on an input/output experiment. To generate these data, test signals $x(t)$ in the form of pulse, step, linear, and harmonic functions with different amplitudes a are fed to the input of the simulation model.

When performing the input/output experiment with different types of nonlinearity, the following parameters of the simulation model were adopted: $\alpha=2.64$; for the case of smooth nonlinearity, $\beta=1.45$; for the case of significant nonlinearity, $s=0.7$, $p=0.7$, $k=1$.

Modeling tools

The Keras library (keras.io) is used for the programmatic implementation of the neural network. This is one of the most popular Python libraries for building small networks with a sequential structure, where layers follow each other, with one input and one output layer.

To build a direct propagation network with Keras, you can use any number of consecutive layers of predefined types: Input, Dense, and Activation. The library has a ready-made set of loss functions and optimization algorithms that allow you to quickly train models and avoid local minima.

A three-layer neural network was created using the Keras library. The input layer consists of M neurons that are fed with the data $\mathbf{x}(t_n)$. The hidden layer consists of K neurons. The output layer consists of one neuron. The block diagram of the TDNN model created using the Keras library is shown in Fig. 3.

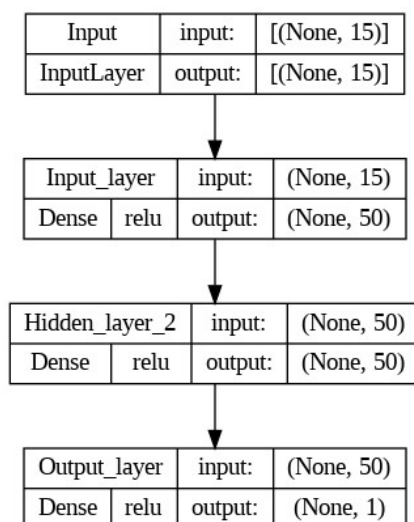


Figure 3. Block diagram of TDNN as a three-layer network with direct signal propagation

Notes: *None* in the dimension vectors of the input and output data of each layer means a variable number of rows in the data.

Source: developed by the author on the basis of Keras library

Defining TDNN parameters

To determine the best values of M and K in a given TDNN structure, a number of neural networks with different numbers of neurons in the input and hidden layers are built.

The result of the experiment as a function of the number of neurons in the input and hidden layers is shown in Fig. 4. The root mean square error function mse from the Keras library is used as a loss.

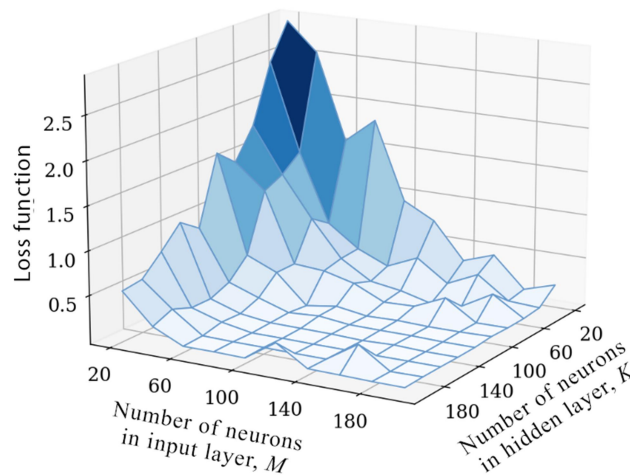


Figure 4. Dependence of losses on the number of neurons in the input and hidden layers

Source: developed by the author

The result of the experiment as a function of the learning time (epoch) and the number of neurons in the input and hidden layers is shown in Fig. 5.

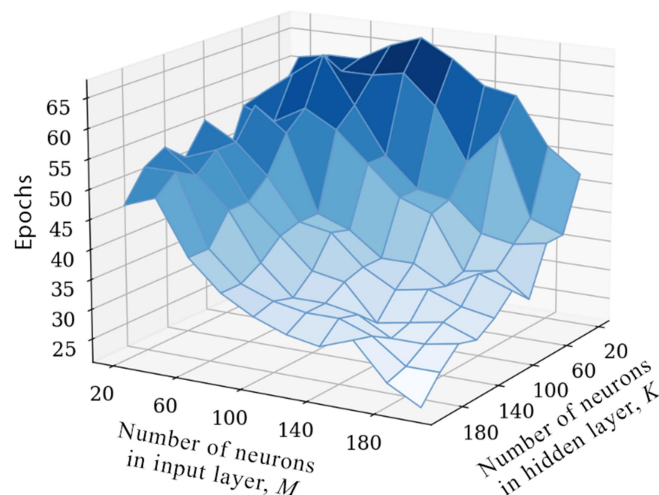


Figure 5. Dependence of training time on the number of neurons in the input and hidden layers

Source: developed by the author

As a result of comparing Figures 4 and 5, the values of the number of neurons in the input and hidden layers of the TDNN $M=15$ and $K=50$, respectively, were chosen to ensure the level of losses ($loss < 1.0$) set by the experimental conditions with an acceptable training time ($epochs < 40$). The obtained TDNN was used to study the accuracy of models of dynamic objects with smooth and significant nonlinearities.

Study of models of dynamic objects with smooth and significant nonlinearities

To study the accuracy of modeling dynamic objects with smooth and significant nonlinearities using TDNN models and determine the scope of their effective application, two experiments were organized and conducted:

1. Study of the scalability of TDNN models to different input signals $x(t)$.
2. Study of extrapolation properties of TDNN models.

The results of both experiments are compared with the results of modeling using deterministic identification methods, namely, integral-power series based on multivariate weight functions.

The models $y_v(t)$ in the form of integral-power series based on multidimensional weight functions are constructed for the test objects by the compensation method (Pavlenko, & Pavlenko, 2023). Fig. 6 shows the $y_v(t)$ models obtained for test dynamic objects with smooth $f_1(y)$ (Fig. 6a) and significant $f_2(y)$ (Fig. 6b) nonlinearities. The 1st-order multivariate weight function $w_1(t)$ and the diagonal cross section of the 2nd-order multivariate weight function $w_2(t, t)$ are also shown here, as well as the object responses $y_1(t)$ and $y_2(t)$ to the input signals $x_1(t) = a\delta(t)$ and $x_2(t) = 2a\delta(t)$ ($a = 0.5$), which are used to identify the multivariate weight functions.

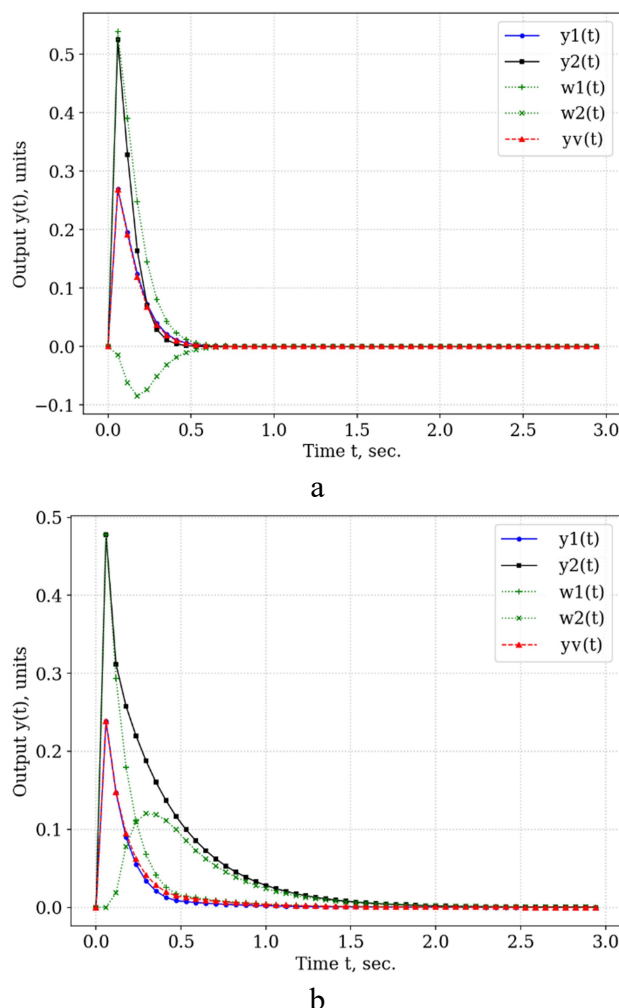


Figure 6. Models of $y_v(t)$ in the form of integral-power series based on multidimensional weight functions obtained for test dynamic objects

Notes: a – smooth $f_1(y)$ nonlinearity, b – significant $f_2(y)$ nonlinearity.

Source: developed by the author

Study of the scalability of TDNN models to different input signals.

The training dataset $\mathbf{x}_i^{train}(t_n)$ is formed on the basis of pulse signals $x(t) = a\delta(t)$ of different amplitudes ($a \in (0, 1]$) at the input of the object and responses $y(t)$ at its output.

The test dataset $\mathbf{x}_i^{test}(t_n)$ includes step $x(t)=a\Theta(t)$, linear $x(t)=at$, and harmonic $x(t)=asin(t)$ signals of different amplitudes ($a \in (0, 1]$) at the input of the object and responses $y(t)$ at its output.

The experiment is performed for objects with nonlinearities in the feedback block in the form of a polynomial function $f_1(y)$, as well as a saturated function $f_2(y)$.

The TDNN model is built on the data of the training set $\mathbf{x}_i^{train}(t_n)$. The scalability of the obtained TDNN model to different input signals is studied on the data of the test set $\mathbf{x}_i^{test}(t_n)$.

The output of the TDNN model $y_{nn}(t)$ is compared with the output of the simulation model $y(t)$ and the result of identifying $y_v(t)$ as an integral-power series based on multidimensional weight functions (Pavlenko, & Pavlenko, 2023; Antipina *et al.*, 2023).

Experiment 1. We investigated the accuracy of modeling using TDNN and integral-power models under the influence of input signals $x(t) = a\delta(t)$ of different amplitudes ($a \in (0, 1]$). Fig. 7 shows a comparison of the output signals $y_{nn}(t)$, $y_v(t)$, and $y(t)$ obtained as a result of the action of the signal $x(t)=a\delta(t)$ ($a=0.65$) at the inputs of the TDNN model, the integral-power series, and the simulation model of a nonlinear dynamic object, respectively.

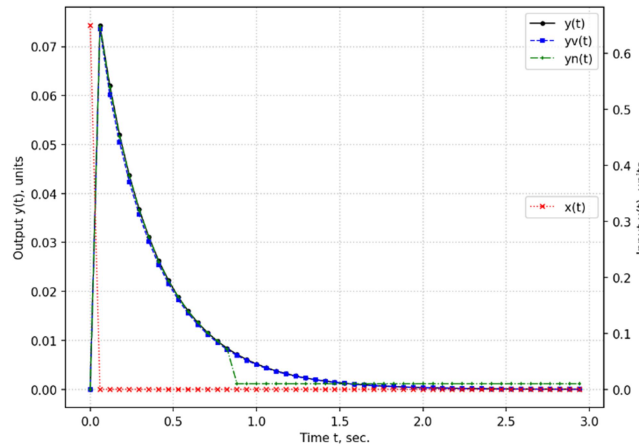


Figure 7. Comparison of the output signals $y_{nn}(t)$, $y_v(t)$ and $y(t)$ obtained as a result of the action of the signal $x(t)=a\delta(t)$ ($a=0.65$) at the inputs of the TDNN model, integral power series and simulation model of a nonlinear dynamic object, respectively
Source: developed by the author

Experiment 1 demonstrates the comparable accuracy of modeling using TDNN and integral-power models under the input signals $x(t)=a\delta(t)$.

Experiment 2. We investigated the accuracy of modeling using TDNN and integral-power models under the influence of input signals $x(t)=a\Theta(t)$, $x(t)=at$ and $x(t)=asin(t)$ of different amplitudes ($a \in (0, 1]$). In Fig. 8 shows a comparison of the output signals $y_{nn}(t)$, $y_v(t)$, and $y(t)$ obtained as a result of the action of the signals $x(t)=a\Theta(t)$ (Fig. 8a), $x(t)=at$ (Fig. 8b), and $x(t)=asin(t)$ (Fig. 8c), $a=0.65$, at the inputs of the TDNN model, the integral-power series, and the simulation model of a nonlinear dynamic object, respectively.

The experiment demonstrates that the TDNN model is significantly inferior in accuracy to the integral-power model under the influence of the input signals $x(t)=a\Theta(t)$, $x(t)=at$, and $x(t)=asin(t)$, which were not included in the training dataset $\mathbf{x}_i^{train}(t_n)$.

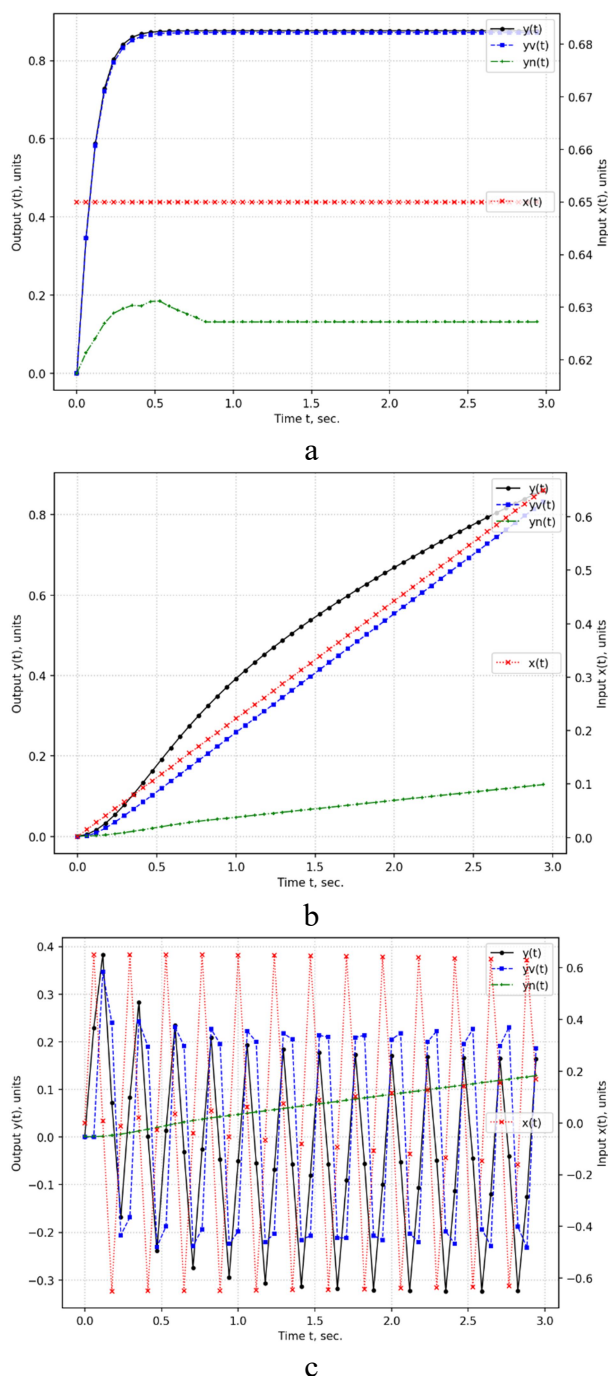


Figure 8. Comparison of the output signals $y_{nn}(t)$, $y_v(t)$, and $y(t)$ obtained as a result of the action of signals at the inputs of the TDNN model, the integral-power series, and the simulation model of a nonlinear dynamic object, respectively

Notes: a – $x(t)=a\Theta(t)$; b – $x(t)=at$, c – $x(t)=a\sin(t)$, $a=0.65$

Source: developed by the author

The experiment shows that TDNN models are not invariant to the shape of the input signal. A TDNN model can adequately reflect the properties of a dynamic object when trained on a sufficient amount of data. The training dataset $\mathbf{x}_i^{train}(t_n)$ should be formed on the basis of input signals of different amplitudes of the same type as in the test dataset $\mathbf{x}_i^{test}(t_n)$. This is a disadvantage of neural network models in comparison with models based on integral-power

series based on multidimensional weight functions (Pavlenko, & Pavlenko, 2023; Antipina *et al.*, 2023; Mitrea *et al.*, 2009; Meruelo *et al.*, 2016).

Study of interpolation and extrapolation properties of TDNN models.

The training dataset $\mathbf{x}_i^{train}(t_n)$ is formed on the basis of pulse $x(t) = a\delta(t)$, step $x(t) = a\Theta(t)$, linear $x(t) = at$, and harmonic $x(t) = asin(t)$ signals of different amplitudes ($a \in (0, 1]$) at the input of the object and responses $y(t)$ at its output.

The test dataset $\mathbf{x}_i^{test}(t_n)$ includes the same signals $x(t)$ with different amplitudes ($a \in (1, 2]$) at the input of the object and responses $y(t)$ at its output.

The experiment is performed for objects with nonlinearities in the feedback block in the form of a polynomial function $f_1(y)$, as well as a saturated function $f_2(y)$.

The TDNN model is built on the data of the training set $\mathbf{x}_i^{train}(t_n)$. The study of the extrapolation properties of the obtained TDNN model is performed on the data of the test set $\mathbf{x}_i^{test}(t_n)$.

The output of the TDNN model $y_{nn}(t)$ is compared with the output of the simulation model $y(t)$ and the result of identifying $y_v(t)$ as an integral-power series based on multidimensional weight functions (Pavlenko, & Pavlenko, 2023; Antipina *et al.*, 2023).

Experiment 3. We investigated the accuracy of modeling using TDNN and integral-power models under the influence of pulsed, stepped, linear, and harmonic input signals of different amplitudes ($a \in [0.1, 0.2, \dots, 1.0]$). Fig. 9 shows a comparison of the output signals $y_{nn}(t)$, $y_v(t)$, and $y(t)$ obtained as a result of the action of the signal $x(t)=a\Theta(t)$ ($a=0.7$) at the inputs of the TDNN model, the integral-power series, and the simulation model of a nonlinear dynamic object, respectively.

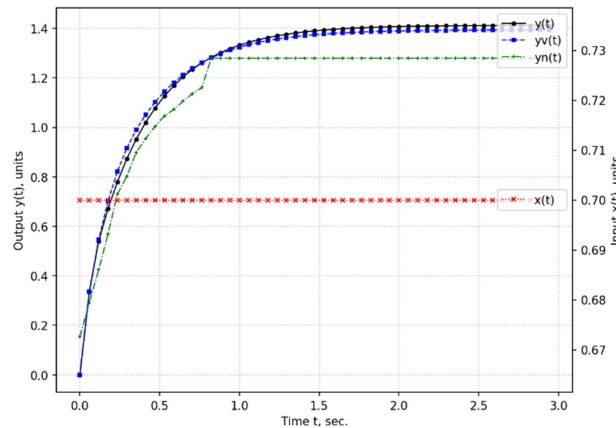


Figure 9. Comparison of the output signals $y_{nn}(t)$, $y_v(t)$ and $y(t)$ obtained as a result of the action of the signal $x(t)=a\Theta(t)$ ($a=0.7$) at the inputs of the TDNN model, integral power series and simulation model of a nonlinear dynamic object, respectively

Source: developed by the author

As a result of Experiment 3, we obtained the mean square error values for TDNN models compared to integral-power series based on multivariate weighting functions for the nonlinear functions $f_1(y)$ and $f_2(y)$, which are shown in Table 1.

Experiment 3 demonstrates the comparable accuracy of modeling using TDNN and integral-power models of the test object with smooth nonlinearity $f_1(y)$. However, when identifying a test object with a significant nonlinearity $f_2(y)$, TDNN models significantly outperform the integral-power models in terms of accuracy.

Table 1. Mean square error of the test object modeling ($a=0.7$)

Type of nonlinearity	Input signal $x(t)$							
	impulse $a\delta(t)$		step $a\Theta(t)$		linear at		harmonic $asin(t)$	
	$y_v(t)$	$y_{nn}(t)$	$y_v(t)$	$y_{nn}(t)$	$y_v(t)$	$y_{nn}(t)$	$y_v(t)$	$y_{nn}(t)$
Polynomial	0,074	0,080	0,082	0,087	0,088	0,096	0,103	0,127
With saturation	0,152	0,121	0,167	0,133	0,209	0,139	0,264	0,184

Source: developed by the author

Experiment 4. We investigated the interpolation and extrapolation properties of models using TDNN and integral-power models under the influence of pulsed, stepped, linear, and harmonic input signals of different amplitudes:

- for the case of studying the interpolation properties of models $a \in [0.05, 0.15, \dots, 0.95]$;
- for the case of studying the extrapolation properties of models $a \in [1.05, 1.15, \dots, 1.95]$.

In Fig. 10 shows a comparison of the output signals $y_{nn}(t)$, $y_v(t)$, and $y(t)$ obtained as a result of the action of the signal $x(t)=a\Theta(t)$ at the inputs of the TDNN model, the integral-power series, and the simulation model of a nonlinear dynamic object, respectively, for the interpolation task at $a = 0.65$ (Fig. 10a) and the extrapolation task at $a = 1.65$ (Fig. 10b).

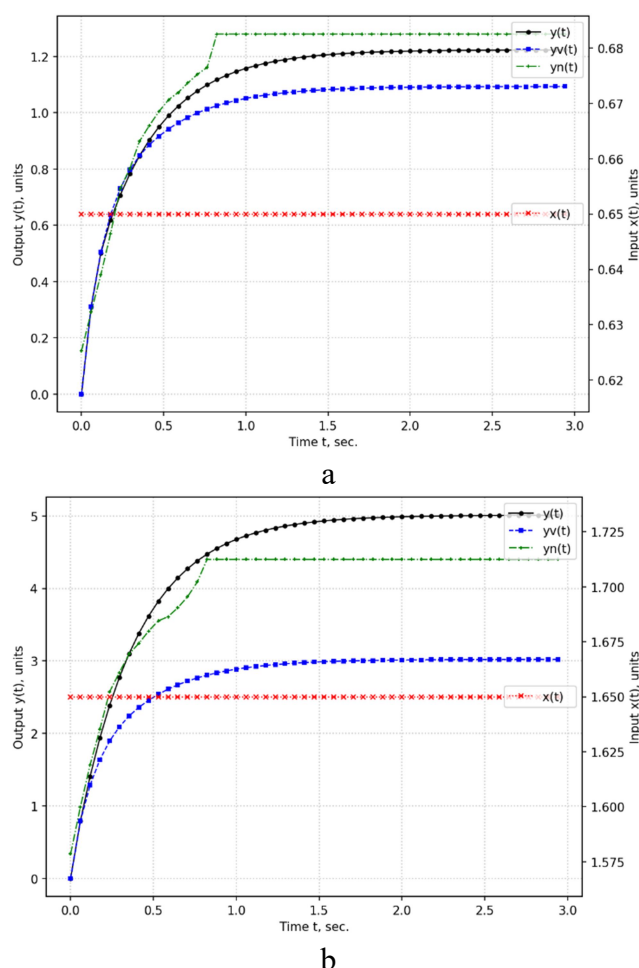


Figure 10. Comparison of the output signals $y_{nn}(t)$, $y_v(t)$, and $y(t)$ obtained as a result of the action of the signal $x(t)=a\Theta(t)$ at the inputs of the TDNN model, the integral-power series, and the simulation model of a nonlinear dynamic object, respectively

Notes: a – interpolation problem ($a=0.65$); b – extrapolation problem ($a=1.65$)

Source: developed by the author

Experiment 4 demonstrates comparable modeling accuracy in the case of studying the interpolation properties of TDNN and integral-power models.

The extrapolation properties of TDNN models deteriorated with increasing input signal amplitudes beyond the range of input signal amplitudes of the training set $\mathbf{x}_i^{train}(t_n)$. Thus, using the input signal $x(t)=1.65\Theta(t)$, the accuracy of the TDNN model decreases by 25%.

At the same time, the accuracy of the model in the form of an integral-power series based on multidimensional weight functions in the case of using a significantly nonlinear function $f_2(y)$ is 30% lower than the TDNN model.

Thus, the area of effective application of TDNN models is the identification of objects with significantly nonlinear characteristics.

Results and discussion

The obtained modeling results show that TDNN models are not invariant to the signal received at the input of the object, which is a disadvantage of these models. However, TDNN models can adequately reflect the properties of nonlinear dynamic objects when trained on a sufficient amount of data generated from input signals of the same type as in the test data set.

The extrapolation properties of TDNN models will deteriorate with increasing input signal amplitudes that go beyond the range of input signal amplitudes of the training set.

When identifying objects with significantly nonlinear properties, such as a saturation function, TDNN models are 10-25% more accurate than integral-power series based on multivariate weight functions.

Thus, the area of effective application of TDNN is the identification of objects with significantly nonlinear properties.

Conclusions

The paper considers the approach to modeling of dynamic objects with essential nonlinearities on the basis of time-delay neural networks. Experiments are organized and researches are carried out to determine the accuracy of the proposed models and the area of effective application of these models.

It is experimentally confirmed that the use of the proposed models for identification of dynamic objects with essentially nonlinear characteristics allows to increase the accuracy of the modeling process by 10-25% in comparison with the models based on deterministic methods of identification, such as integral-power series. based on multidimensional weight functions.

Thus, the area of effective application of models in the form of time-delay neural networks has been established. It is modeling of dynamic objects with significant nonlinearities, where traditional identification methods don't provide sufficient modeling accuracy.

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Conflict of Interest

The authors have no conflict of interest.

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МОДЕЛІ ДИНАМІЧНИХ ОБ'ЄКТІВ ЗІ ЗНАЧНОЮ НЕЛІНІЙНІСТЮ НА ОСНОВІ НЕЙРОННИХ МЕРЕЖ ІЗ ЧАСОВИМИ ЗАТРИМКАМИ

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Анотація. Робота присвячена проблемі нелінійного моделювання об'єктів на основі динамічних нейронних мереж. Метою роботи є підвищення точності моделювання динамічних об'єктів зі значними нелінійностями за допомогою нейромережових моделей та визначення області ефективного застосування цих моделей. Ця мета досягається шляхом застосування нелінійних динамічних моделей у вигляді нейронних мереж із часовою затримкою. Для дослідження області ефективного застосування запропонованих нейромережових моделей розглядаються тестові об'єкти з нелінійностями двох типів: гладкою та кусково-лінійною (насиченням). Для дослідження точності нейронних мереж із часовою затримкою при моделюванні нелінійних динамічних об'єктів проведено два експерименти: дослідження масштабованості моделей до різних вхідних сигналів; дослідження екстраполяційних властивостей моделей. Результати обох експериментів порівнюються з результатами моделювання за допомогою компенсаційного методу детермінованої ідентифікації у вигляді функціональних рядів на основі багатовимірних вагових функцій. Отримані результати моделювання свідчать, що запропоновані нейромережові моделі не є інваріантними щодо вхідного сигналу. Однак ці моделі можуть адекватно відображати властивості нелінійних динамічних об'єктів в разі навчання на достатньому обсязі даних, що формується на основі вхідних сигналів того ж типу, що й у тестовому наборі даних. Екстраполяційні властивості

нейронних мереж із часовою затримкою погіршуються зі збільшенням амплітуд вхідних сигналів, що виходять за межі діапазону амплітуд вхідних сигналів навчальної вибірки. Наукова новизна роботи полягає у визначенні залежності між типами сигналів та їх амплітудами, що діють на вході моделі, і точністю запропонованих моделей. Практична користь роботи полягає у визначенні області ефективного застосування нейронних мереж із часовою затримкою під час розв'язування прикладних задач ідентифікації об'єктів зі значно нелінійними характеристиками; підвищенні точності ідентифікації нелінійних об'єктів порівняно з моделями у вигляді функціональних рядів на основі багатовимірних вагових функцій.

Ключові слова: ідентифікація, нелінійні об'єкти, суттєві нелінійності, динамічні нейронні мережі, імітаційне моделювання.

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MATHEMATICAL MODELS OF ROAD CONSTRUCTION, RECONSTRUCTION AND REPAIR UNDER CONDITIONS OF UNCERTAINTY

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Abstract. The article highlights the importance of mathematical modeling in road construction, reconstruction, and repair in Ukraine. We can outline the importance of this research by taking into account such factors as financial instability and financial uncertainty, as well as the importance to comply with safety standards during any road-related maintenance work. We would also like to point out that there is an increasing need for new tools for optimization and improvement of construction operations. This need exists both due to factors of uncertainty, such as climatic anomalies, dynamics of road traffic, and technological progress in construction, as well as due to numerous social challenges that result in an increase in traffic load, for instance, an ongoing military conflict.

The main goal of our research is to implement mathematical modeling into different phases of any road-related maintenance work, from planning to executing, under conditions of limited finances. Achieving the aforementioned goal will allow to improve assessing and repairing the critical areas and will also improve the choice of optimal nondestructive inspection methods for identifying any damage in road coating and infrastructure. To achieve this goal, we use methods of statistical and system analysis, multi-criteria optimization, and decision-making theory. The main emphasis is on the development of strategic management decisions and their effectiveness.

We have managed to prove that the use of mathematical modeling during the planning phase of any road works allows us to effectively distribute the available financial resources even if they are limited. This practice also makes it possible to dynamically alter the volumes of funding depending on expert analysis of the importance or project completion status.

Upon completion of the initial planning stage, which includes repairing all critical areas of the road in order to minimize the risk of road traffic accidents and using methods of increased safety, we have managed to develop a plan with concrete steps. Following the aforementioned steps allows us to reduce a total number of road traffic accidents occurring in critical areas by 1.4-1.6 times. These results are possible to achieve without going over the established financial restrictions.

We have also developed criteria for assessing the quality of damage identification on the road coating. These criteria are based on the defect detection rate. We have provided a detailed explanation of how this rate can increase from 0,891 to 0,967.

Further scientific research conducted by the author of this paper will focus on a detailed analysis of the results of the implementation of illustrated mathematical models, especially as mathematical support of the analytical and information system for monitoring the state of road infrastructure.

Keywords: mathematical model, motor transport, roadway, critical area, nondestructive inspection method, condition of uncertainty.

Introduction

Modern world is in a state of constant development, which results in an expansion of roadways between cities, countries, and continents (Global Trends 2030, 2012). Apart from planning new road networks, it is also very important to reconstruct and repair the existing ones (Disclaimer: The Ukraine Rapid Damage and Needs Assessment, 2022). However, development and maintenance of road infrastructure demand not only considerable financial

investments but also creation and improvement of project management methods, as well as methods for planning and forecasting such projects (Muhammad *et al.*, 2021; Willar *et al.*, 2023; Browning, 2018).

In Ukraine, mathematical modeling is very important in road construction, reconstruction, and repair, especially under conditions of unstable and uncertain funding, as well as under conditions of following special safety procedures. Climatic anomalies, dynamics of road traffic, technological progress in construction, as well as numerous social challenges causing an increase in traffic load due to the ongoing military conflict, make it necessary to develop new methods and tools for optimization of road construction (Zolotukhin *et al.*, 2021).

However, a rapid development of mathematical modeling in road construction has become very noticeable in the motor transport industry throughout the years (Belyaev, 2020). Scientists work on improving methods of mathematic forecasting of the demand for transport services, create models to analyze the influence of uncertainty on the cost and duration of construction, and utilize artificial intelligence to analyze data to improve resource distribution and project management (Kazeem *et al.*, 2023; Adesola *et al.*, 2023).

The main purpose of this paper is to analyze mathematical modeling during the planning phase of construction, reconstruction, and repair of roads and their support structures under conditions of uncertainty and reduced funding. This analysis can improve the procedure of dealing with critical areas and help choose optimal methods of nondestructive testing to hasten the identification of damage to road coating and analyze the quality of road infrastructure components.

We have identified the following tasks required to reach the aforementioned goal:

- improvement of mathematical model for planning of construction, reconstruction, and repair of roads and related infrastructure under conditions of uncertainty and reduced funding;
- development of a plan for dealing with critical areas on roads;
- optimization of methods of nondestructive testing to hasten the identification of damage to road coating and analyzing the quality of road infrastructure components;

The scientific novelty of our study is as follows:

- we have improved mathematical models designed for establishing an effective functioning of modern road construction industry. These models are based on the models of expert analysis factoring in the uncertainty related to the volumes of funding. Using such models allows for improvement of the existing funding mechanism of construction objects by arranging them according to their cost and priority;
- we have improved the mechanisms for solving applied problems related to optimization of planning of road construction, reconstruction, and repair based on algorithmic diagrams of genetic algorithms and method of time series analysis. The mechanisms themselves are illustrated by the models of discrete optimization and can hasten the identification of damage. They are also used as criteria for choosing methods of nondestructive testing of road coating.

Analysis of literature

Below, we will analyze the results of the latest research and their practical application in road construction. Additionally, we will highlight the opportunities for further research related to the topic in question. This analysis is important to support the development and improve the quality of traffic infrastructure of Ukraine, both of which are important for social and economic development of Ukraine.

Mathematical models and methods used to solve problems of decision theory are not only the foundation of problems analyzed in this paper but a powerful mathematical tool. The

development of modern computing devices and information technologies allows us to use them as programs for support and maintenance.

A group of scientists led by S. S. Kyzyma (Scientific work of Department, 2023) from the National University of Transport has made a noticeable contribution by developing a method for planning of reconstruction and repair of road coating based on technical and economic analysis. Renowned scientists, such as N. Sokolova (Kanin *et al.*, 2022) and I. Sokolova (Markelova *et al.*, 2022), have dedicated their research to mathematical methods used for planning and optimizing the operational use of roads under conditions of uncertainty. Among the scientists who have worked with the mathematical maintenance models are V. Babakov and A. Kravchenko (Kharchenko *et al.*, 2023).

The following Ukrainian scientists also conduct their research in the field of road construction: professor of Dnipro State Technical University Borys Sereda, who studies mathematical modeling of transport and production systems (Sereda *et al.*, 2023); professor of the National University of Transport Artur Onyshchenko, who analyzes mathematical models and methods for optimization of planning and managing road construction projects (Onyshchenko *et al.*, 2019); professor of Vinnytsia National Technical University Serhii Pavlov, who researches methods to optimize the quality and speed of road construction (Wójcik *et al.*, 2021). The following foreign scientists have dedicated their research to the problem in question, including Dr. Carlos Daganzo (Spain), who investigates the optimization of transport systems, including road networks, and is also a creator of several mathematical models for optimizing road traffic and infrastructure (Itani *et al.*, 2021); professor of McGill University, Dr. Michael Florian, who describes methods of optimization of road networks and transport systems (Babazadeh *et al.*, 2021); Henrik Fredriksson (2021) from Blekinge Institute of Technology, who studies mathematical modeling of transport systems for improving the decision-making and analysis of transporting-related issues.

Methods and materials

Creation of a mathematical model for planning of construction, reconstruction, and repair of roads and infrastructure under conditions of uncertainty and reduced financing

In general, planning construction, reconstruction, and repair of roads used for different purposes, as well as the whole related infrastructure, can be characterized by the necessity to define the tasks required to be completed during the given period and the calculation of required financial resources. The primary obstacle capable of influencing efficiency is the uncertainty of volumes of funding for construction programs. For instance, according to (On the report on the implementation of the Law of Ukraine), the volume of underfunding for intermediate-level maintenance and overhaul maintenance of public roads, as well as building new road infrastructure and provision of new gear, materials, etc., was 71.3% of the demand in 2022. According to (Markuts *et al.*, 2023), general financing of roadbuilding will decrease by 14,9 billion UAH in 2023 as compared to the previous year. The main focus of this financing has also shifted from building new roads to repairing the ones destroyed as a result of the ongoing military conflict (Markuts *et al.*, 2023).

One of the most common methods of addressing an issue of uncertainty related to funding is putting on hold all construction work on certain planned objects. Defining such objects is done by factoring in different criteria, for example, importance, current state, remaining cost of construction work, etc. Effective solution to this task requires a clear definition and a reasonable algorithm approach since there are a lot of different types of objects, as well as criteria for their evaluation and restriction.

Expert analysis can be used to evaluate the importance of each object based on different criteria. For example, social and economic importance of an object can be evaluated based on

the following definitions: "high-priority, important, with average priority, low-priority". These definitions are then transformed into normalized scores from 0 to 1.

We can illustrate all criteria used to make decisions regarding the possible reduction of funding of road construction, reconstruction, and repair projects under conditions of underfunding as a hierarchical structure as shown in Fig. 1.

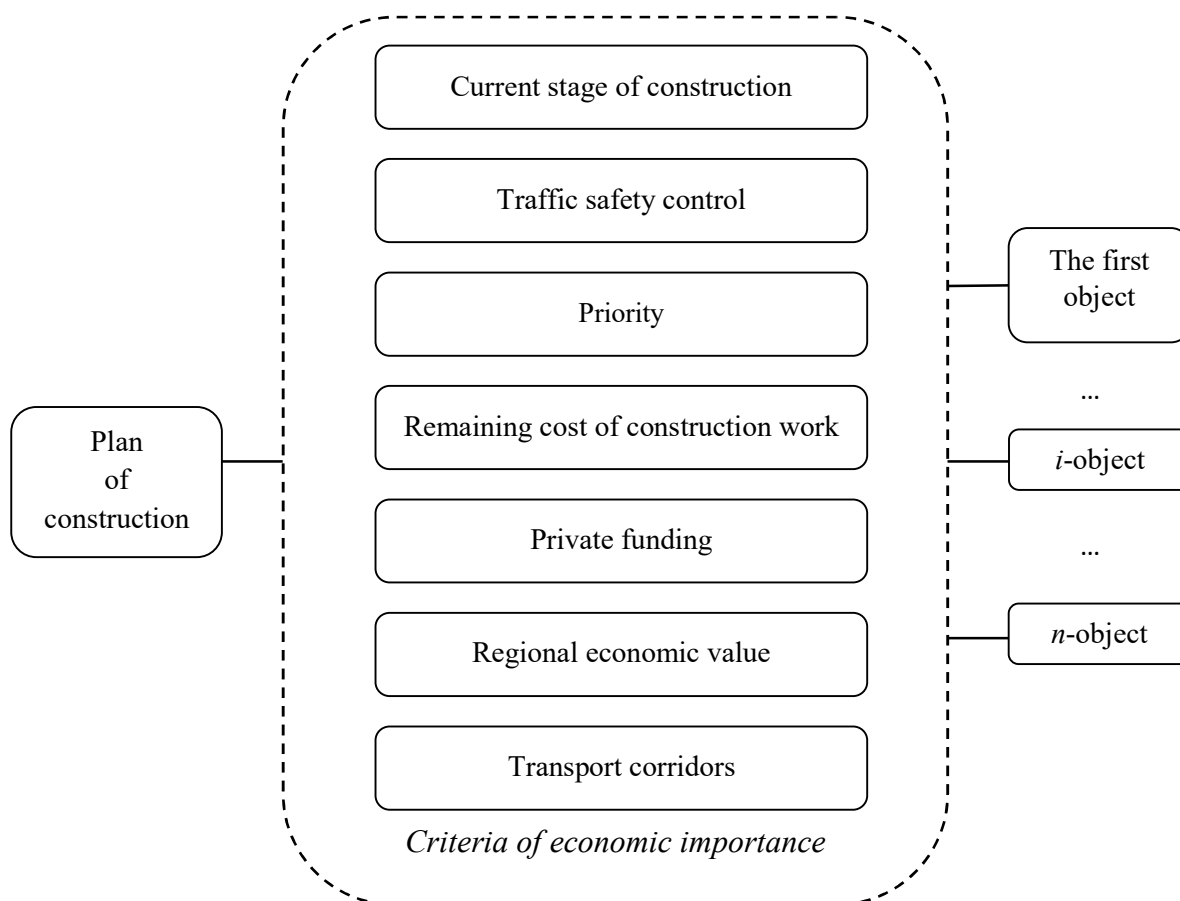


Figure 1. Simplified scheme of criteria of economic importance

According to data from Fig. 1, decision-making is affected by different criteria, such as criteria of economic importance. These criteria include:

- current stage of construction;
- traffic safety and dealing with critical areas;
- priority of construction, which is defined by the government;
- remaining cost of construction work;
- funding received from other sources (except the State Budget of Ukraine);
- evaluation of economic influence on the region;
- contribution to the development of international transport corridors and influence on traffic flow in general.

The aforementioned scheme from Fig. 1 indicates the types of work required to be completed on the roads of different types, including their support structures. In addition, it shows what types of work require funding.

Next, we use paired-comparison method to define the weight numbers of these criteria. We use the same method to analyze hierarchical structures (Mi *et al.*, 2022).

Formulation of the problem. We will now analyze linear convolution for the previously chosen criteria according to the defined weight numbers $\rho_1, \rho_2, \dots, \rho_m$:

$$\sum_{i \in I} \sum_{k=1}^m \rho_k v_{ik} z_i,$$

where v_{ik} is defined as the value of i -object according to k -criterium, z_i is defined as the current stage of constructing i -object.

Correspondingly, the current stage of construction of each object depends on how the program is implemented:

$$z_i = f_i(x_{i1}, x_{i2}, \dots, x_{ih^*}).$$

In this case, boolean value x_{ih} equals 1 if the h -stage of construction of the i -object is properly funded. If not, then $x_{ih} = 0$.

Function f_i has the following attributes:

- $f_i \in [0, 1]$;

The following condition $f_i(x_{i1}^1, x_{i2}^1, \dots, x_{ih^*}^1) \geq f_i(x_{i1}^2, x_{i2}^2, \dots, x_{ih^*}^2)$ is valid for any boolean vector $(x_{i1}^1, x_{i2}^1, \dots, x_{ih^*}^1)$ greater than $(x_{i1}^2, x_{i2}^2, \dots, x_{ih^*}^2)$.

Solution algorithm. Statement of the problem where each stage is completed sequentially (the next stage cannot be completed unless all the previous ones are completed as well) can be illustrated in the following way:

$$x_{ih} \geq x_{ih+1}, h = 1, 2, \dots, (h^* - 1), i = 1, 2, \dots, n.$$

Below we provide a detailed illustration

$$X = \begin{pmatrix} x_{11} & x_{12} & \dots & x_{1h^*} \\ x_{21} & x_{22} & \dots & x_{2h^*} \\ \dots & \dots & \dots & \dots \\ x_{n1} & x_{n2} & \dots & x_{nh^*} \end{pmatrix}.$$

Cost of all planned construction works:

$$B(X) = \sum_{i \in I} \sum_{h=1}^{h^*} b_{ih} x_{ih},$$

where b_{ih} is defined as the cost of all planned construction works on the h -stage.

If the real funding can be described as the value $B_0 < B$ (1), then the following matrix $X = (x_{ih})_{i \in I, h = 1, 2, \dots, h^*}$ is used, whereas:

$$X^* = \arg \max_{X \in X} \sum_{i \in I} \sum_{k=1}^m \rho_k v_{ik} f_i(x_{i1}, x_{i2}, \dots, x_{ih^*}) \quad (1)$$

under conditions:

$$x_{ih} \geq x_{ih+1}, h = 1, 2, \dots, (h^* - 1), \quad (2)$$

$$B(X) = \sum_{i \in I} \sum_{h=1}^{h^*} b_{ih} x_{ih} \geq B_0. \quad (3)$$

Under conditions of uncertainty related to volumes of funding, the following problem can appear: find optimal matrixes $X_1^*, X_2^*, \dots, X_d^*$ for the defined $B_1^0, B_2^0, \dots, B_d^0$ ($B_1^0 < B_2^0 < \dots < B_d^0$) values. The matrixes are required to meet the additional condition of a «build-up»:

$$X_1^* < X_2^* < \dots < X_d^*.$$

Meeting the aforementioned condition allows us to slowly «build up» the plans for funding.

Formulation of the inverse problem. Now, we rewrite the previous problem (1) – (3) in the following way:

$$\sum_{i=1}^n \sum_{k=1}^m \rho_k v_{ik} f_i(x_{i1}, x_{i2}, \dots, x_{ih^*}) \rightarrow \max \quad (4)$$

$$\sum_{i=1}^n \sum_{h=1}^{h^*} b_{ih} x_{ih} \leq B_0, \quad (5)$$

$$x_{ih} \geq x_{ih+1}, h = 1, 2, \dots, (h^* - 1), i = 1, 2, \dots, n, \quad (6)$$

$$x_{ih} \in \{0, 1\}, h = 1, 2, \dots, h^*, i = 1, 2, \dots, n. \quad (7)$$

Here we also introduce new boolean values y_{ih} . These values are related to the previous x_{ih} values in the following way: $y_{ih} = 1$, if $x_{ih} = 1$ for $\forall k \leq h$. In other cases, $y_{ih} = 0$, if $x_{ik} = 0$ for $\forall k > h$. We will use function $q(\cdot)$ to connect the values $x_{ih} = q(h, y_{i1}, y_{i2}, \dots, y_{ih^*})$, $i = 1, 2, \dots, n, h = 1, 2, \dots, h^*$.

In this scenario, we can use a maximization problem equivalent to (4) – (7):

$$\sum_{i=1}^n \sum_{k=1}^m \rho_k v_{ik} z_i(y_{i1}, y_{i2}, \dots, y_{ih^*}); \quad (8)$$

under conditions:

$$\sum_{h=1}^{h^*} y_{ih} = 1, i = 1, 2, \dots, n, \quad (9)$$

$$\sum_{i=1}^n \sum_{h=1}^{h^*} \tilde{b}_{ih} y_{ih} \leq B_0, \quad (10)$$

where $z_i(y_{i1}, y_{i2}, \dots, y_{ih^*}) = f_i(q(1, y_{i1}, y_{i2}, \dots, y_{ih^*}), \dots, q(h^*, y_{i1}, y_{i2}, \dots, y_{ih^*}))$, $i = 1, 2, \dots, n$,

$$\tilde{b}_{ip} = \sum_{h=1}^p b_{ih}, p = 1, \dots, h^*.$$

Problems (8) – (10) are problems of linear programming with boolean values. A solution to this problem can be acquired by building a minorant in nondecreasing order. This minorant will correspond with objective function (8), as well as with rows of h^* -value boolean vectors, which correspond with condition (9) (Chen *et al.*, 2008).

Development of a plan for dealing with critical areas on roads

Formulation of the problem. Suppose the traffic flow consists of vehicles, which are divided into categories $k \in K = \{1, 2, \dots, k^*\}$. They include light motor vehicles of different types and sizes, cargo vehicles of different types, sizes and capacities, buses, two-wheeled vehicles, etc. Then we divide the road into sectors $g_i, i \in I = \{1, 2, \dots, n\}$. In this case, $p_{ik}(x_i)$ is defined as probability of traffic accident in sector g_i for k -category of vehicles under the condition of using measure $x_i \in X_i = \{x_{i1}, x_{i2}, \dots, x_{is}\}$ to reduce the probability of traffic accidents in sector g_i , whereas s is defined as several such measures. Every measure $x_i \in X_i$ is defined by economic, technical, social, and other values. Values $p_{ik}(x_i)$ can be calculated based on a model, for example, a non-linear model introduced in (Saaty *et al.*, 1985).

The problem itself requires creating a plan of measures for reducing the number of traffic accidents in every g_i -sector under conditions of limited resources. These measures revolve around not only reducing the amount of traffic accidents but also reducing the amount of human casualties, financial and material losses as a result of such accidents. Formally, we can present this problem of planning how to deal with critical areas and minimizing the risk of traffic accidents in the following way:

$$R(x) = \sum_{i \in I} \sum_{k \in K} a_k p_{ik}(x_i) \rightarrow \min, \quad (11)$$

under conditions:

$$b_m(x) = \sum_{i \in I} b_{im}(x_i) \leq b_m^*, m \in M, \quad (12)$$

$$x = (x_{i_1}, \dots, x_{i_s}, \dots, x_{i_n}) \in X = \prod_{i \in I} X_i, i \in I, \quad (13)$$

where $m \in M = \{1, 2, \dots, m^*\}$ is defined as an index of expenditure for different resources required to implement measures to reduce the accident rate, b_m^* , $m \in M$ is defined as the given value of constraints of m -resource, a_k is defined as the value of losses as a result of a traffic accident involving transport category $k \in K$.

To solve problems (11) – (13), we can use algorithms described in (Shvartsman, 2023), since these problems are additive problems of discrete programming with multiple restrictions.

Solution algorithm. Definition of losses a_k , $k \in K$ caused by traffic accidents is a completely separate problem, which requires calculation of value of human lives lost during such accidents, as well as losses related to treatment of relevant traumas and repair of damaged vehicles, road objects, etc.

In order to effectively develop measures for reducing the number of traffic accidents, we must consider the human factor, which greatly affects the rate of accidents and deaths. All traffic fatalities have different causes, which can be identified by analyzing statistical data of the Ukrainian Ministry of Internal Affairs (Vedmedenko, 2023) (Table 1). Among the 28 possible causes described in (Vedmedenko, 2023), the major ones are speeding and non-compliance with regulations related to maneuvering on the road with a total of 60% of all cases.

Table 1. Traffic accidents involving human casualties divided by causes, number, and rate in 2022

Cause	Number	Rate, %
Speeding	7561	40,25
Non-compliance with regulations related to maneuvering on the road	3846	20,47
Non-compliance with regulations related to driving through crossings	1467	7,81
Not keeping a safe distance	843	4,49
Crossing the contraflow lane	418	2,23
Drunk driving	790	4,21
Crossing the road in undesignated areas (applied to pedestrians)	593	3,16
Speeding on turn	469	2,49
Non-compliance with regulations related to driving through crosswalks	1443	7,68
Non-compliance with traffic signals of a traffic policeman	236	1,25
Other (rate below 1% for each)	1118	5,96

We define the problem of reducing the number of traffic accidents resulting in fatalities or traumas as a problem with high priority and analyze the mathematical presentation of this problem.

We define equation $D = \{1, 2, \dots, d^*\}$ as a multitude of reasons for traffic accidents with casualties occurring on the road in question. Equation D_i , $i \in I$, $D_i \subseteq D$ on the other hand is defined as a multitude of reasons for traffic accidents for the g_i -sector of the road. For every reason $d \in D_i$ in sector g_i , $i \in I$ we calculate coefficient ρ_{di} , which is defined as the frequency

of traffic accidents with casualties occurring in this sector. We perform these calculations based on statistical data, for example, data from Table 1.

To evaluate the effectiveness of measures x_i , $i \in I$ to reduce the rate of traffic accidents in each sector g_i , $i \in I$ we use the utility function $f_{di}(x_i) \in [0; 1]$, which can be described as a function to reduce the rate of traffic accidents for every cause $d \in D_i$. Implementing this function yields the following results depending on conditions:

- $f_{di}(x_i) = 0$, if measures x_i were not able to reduce the rate of traffic accidents with casualties due to the cause $d \in D_i$;
- $f_{di}(x_i) \in (0; 1)$, if measures x_i were able to reduce the rate of traffic accidents with casualties due to the cause $d \in D_i$;
- $f_{di}(x_i) = 1$, if no traffic accidents with casualties due to the cause $d \in D_i$ were registered in sector g_i .

In this scenario, we can formulate the problem regarding minimization of fatalities and casualties in the following way:

$$R(x) = \sum_{d \in D} \sum_{i \in I} \sum_{k \in K} \rho_{di} h_k N_{ik} (1 - f_{di}(x_i)) \rightarrow \min, \quad (14)$$

under conditions that:

$$b_m(x) = \sum_{i \in I} b_{im}(x_i) \leq b_m^*, m \times M, \quad (15)$$

$$x = (x_{1_s}, \dots, x_{i_s}, \dots, x_{n_s}) \in X = \prod_{i \in I} X_i, i \times I \quad (16)$$

where N_{ik} is defined as the average number of traffic accidents with casualties in sector $i \in I$ for vehicle category $k \in K$; h_k is defined as the average number of individuals in vehicles of category $k \in K$.

Problem (14) – (16) is a modified version of problem (11) – (13). We can define this problem as a problem of discrete programming with multiple limitations. To solve this problem we can use sequential analysis of variants or digital methods (Shvartsman, 2023). Since every transport network is a crucial part of critical infrastructure, we deem modeling processes capable of increasing traffic safety and minimizing traffic accidents an important task.

Optimization of methods of nondestructive testing for identification of damage to roads and other components of road infrastructure

Any defects in public roads and other elements of road infrastructure, such as bridges, tunnels, and overhead roads, adversely affect normal operating conditions. Among such defects are wear and tear of road coating and water isolation, cracks and a large number of holes, plastic deformation, trembling of flexible elements, damaged protective layer and cracks in reinforced concrete structures and fences, damaged expansion dams, destabilization of construction elements, etc. (Shaikh *et al.*, 2022).

The aforementioned defects often appear as a result of natural occurrences capable of affecting the condition of the road. Alternatively, they can be caused by violation of normal operating conditions, for example overloading the road or lack of proper maintenance.

Methods of nondestructive testing effectively identify these defects. Apart from advantages, there are certain disadvantages, since the results of implementing such methods do not always reflect the real state of the object due to the inability to identify all kinds of present defects (Wang *et al.*, 2022).

For instance, using methods of visual control to analyze the condition of the road coating allows to quickly identify visible surface damage, but prevents from identifying any

damage or deformation of deeper layers. As such, analysis of any given road sector may not be objective, thus the efforts directed to cope with the identified defects become less effective, outright ineffective, or even worsen the situation.

This issue can be addressed by using different types of methods of nondestructive testing. This is common practice during research of complex systems which allows us to greatly speed up and increase the probability of defect identification. In addition, it helps to reduce the risk of partial identification (Sidliarenko, 2014). Thus, it is possible to obtain exhaustive information regarding the present damage, as well as compliance with regulations of road safety. The methods of nondestructive testing also allow us to analyze the state of road infrastructure without decommissioning any of its elements. Finally, accumulated statistical data can be used during maintenance and repair, while also helping to avoid possible mistakes during future follow-up inspections (Prokopenko *et al.*, 2019).

Formulation and analysis of the problem. Assume that $L = \{l_i, i \in I = \{1, 2, \dots, i^*\}\}$ is a finite set of defect types in road sectors and other types of road infrastructure, whereas I is defined as a set of damage type indexes. Defects $l_i \in L$ are described according to different criteria, such as geometry (including length and depth of a crack, evenness of road coating, etc.), complexity, probability of causing a traffic accident, etc.

To evaluate the defects $l_i \in L$, we use different methods of nondestructive testing. These methods differ by probability of identifying the defect, cost, or the necessity to utilize additional resources. For example, the effectiveness of visual control depends on qualification of experts responsible for evaluation of damage and unevenness of upper road layers, quality of asphalt, and other attributes. The aforementioned method is both the fastest and the cheapest compared to many others, which require not only specialized tools but also long-term laboratory analysis.

An alternative method revolves around utilizing space monitoring to analyze the state of road coating and road infrastructure, yet it requires additional equipment and trained personnel.

We can present a set of j -methods of nondestructive testing as the equation $M_j = \{m_{jk}\}$, where $j \in J$ is a set of indexes of methods of nondestructive testing, and $k \in K_j \subseteq K$ is a set of indexes of implementation mediums related to methods of nondestructive testing.

Equation $p(m_{jk})$ will serve as an a priori assessment of probability of damage identification by method m_{jk} . The value of the probability of damage identification $p(m_{jk})$ may be specified beforehand in technological documents, defined by experiment, or simply taken from the same research. R_i is defined as a set of alternative means of damage identification $l_i \in L$. Equation $i \in I$ can then be transformed in the following way:

$$R_i = \{r_i^1, r_i^2, \dots, r_i^{t_i}\},$$

where elements of set R_i are fixed technologies of damage identification r_i . On their own, they are a combination of indexes $j \in J$ of sets of different types of methods of nondestructive testing. They are written as $r_i = \{j_1, \dots, j_s\}$, $j_1, \dots, j_s \in J_i \subseteq J$. In this scenario, R_i can be described in the following way:

$$R_i = \begin{pmatrix} j_1^1 & j_2^1 & \dots & j_{s_1}^1 \\ j_1^2 & j_2^2 & \dots & j_{s_2}^2 \\ \dots & \dots & \dots & \dots \\ j_1^{t_i} & j_2^{t_i} & \dots & j_{s_{t_i}}^{t_i} \end{pmatrix}, j_i^1, j_{si}^1, \dots, j_1^{t_i}, \dots, j_{sti}^{t_i} \in J_i. \quad (17)$$

Thus, a combination $r_i = \{j_1, \dots, j_s\} \in R_i$ is defined as a fixed technology of damage identification $l_i \in L$, which utilizes certain nondestructive testing methods. This technology is

the most effective when used after factoring in specifics of the analyzed road sector, as well as technical parameters and operating specifications of tools used for nondestructive testing, including whether or not they can be used in conjunction with each other.

Any technology $r_i \in R_i$ can be represented as possible combinations of types (complex) of methods of nondestructive testing $v_{ri} = (m_{j1k}^i, \dots, m_{jsk}^i) \equiv (m_{jk}^i)_{j \times k}$. They are used to identify damage $l_i \in L$.

Assuming that $V_{r_i} = \prod_{j \in r_i} M_j$ is a set of possible options of implementing technology $r_i \in R_i$, $V_i = \bigcup_{r_i \in R_i} V_{r_i}$ will be defined as a set of all alternative methods of nondestructive testing used to identify partial damage $l_i \in L$, while $V = \prod_{i \in I} V_i$ is a set of alternative methods of nondestructive testing used to identify all possible damage $l_i \in L$, whereas $v = (v_{r1}, \dots, v_{ri}, \dots, v_{ri*}) \equiv (v_{ri})_{i \times I}$, $v_{ri} \in V_i$, $i \in I$, $v \in V$.

We define $P_i(p(v_{ri}))$ as probability of avoiding an emergency situation assuming that damage $l_i \in L$ was identified and dealt with (Donchenko, 2022). In this scenario, $P_i(p(v_{ri})) = 1 - p(v_{ri})$, where $p(v_{ri}) = 1 - \prod_{j \in J_i} (1 - p(m_{jk}^i))$ is defined as probability of identifying damage $l_i \in L$ while using complex v_{ri} for technology r_i .

Here, we analyze the problem related to identifying all defects at once from the available set L . First, we assume that $l_i \in L$ are already known, and different complexes $v_{ri} \in V_i$ are used for their identification. In this scenario, the probability of avoiding an emergency situation can be presented in the following way:

$$P_L(v) = \prod_{i \in I} p(v_{ri}). \quad (18)$$

Value $P_L(v)$ is a lower estimate of probability to identify a set of defects L . This value can be used as a criterion to choose methods of nondestructive testing used to identify all defects $l_i \in L$ at once.

Assume that C_0 budget is provided to implement methods of nondestructive testing (including purchase and/or usage of tools, development of methods, personnel training, etc.). Thus, a problem related to developing the complex of methods of nondestructive testing can be presented in the following way:

$$P_L(v) = \prod_{i \in I} p(v_{ri}) \rightarrow \max \quad (19)$$

$$C(v) = \sum_{i \in I} \sum_{j \in J} c_{ji}(v_{ri}) \leq C_0, \quad (20)$$

$$v \equiv (v_{ri})_{i \times I}, v_{ri} = (m_{j1k}^i, \dots, m_{jsk}^i) \in V_i, k \in K_j \subseteq K, v \in V = \prod_{i \in I} V_i, \quad (21)$$

where c_{ji} is defined as the volume of funding required to implement option v_{ri} .

We can define problems (19) – (21) as problems of discrete programming with multiple limitations. To solve this problem we can use algorithms of sequential analysis of variants or digital methods (Zhang *et al.*, [2020]). Solving this problem results in development of complex of different types of methods of nondestructive testing $v^* = (v_{r1}^*, \dots, v_{ri}^*, \dots, v_{ri*}^*)$, where $v_{r1}^* = (m_{j1i}^*, \dots, m_{jsi}^*)$, $C(v^*)$ is defined as resources and $Pl(v^*)_L(v^*)$ is defined as probability.

We can improve the aforementioned mathematical model by conducting additional evaluation of severity of defects or the state of structure targeted by methods of

nondestructive testing. In addition, we can simplify the choice of methods of nondestructive testing for cases, which do not require complex solutions.

Results and discussion

To prove the effectiveness of analyzed mathematical models used for planning road construction, reconstruction, and repair, including all relevant infrastructure, under conditions of uncertainty and reduced funding, we have conducted multiple calculations. Acquired results allow us to conclude that improving road safety and reducing the rate of traffic accidents require implementation of special measures, aimed at reducing the number of such accidents by 40-60%. The price of these measures should remain within the established limits.

We have analyzed a bridge structure as an example of planning the measures aimed at dealing with critical areas on roads, in combination with further optimization of methods of nondestructive testing used to identify damage in road coating and components of road infrastructure. As primary targets of methods of nondestructive testing, we can name asphalt-concrete roads, reinforced concrete structures, welds, and other parts. To identify set of defects L in bridge structure, we can use radio-wave methods of nondestructive testing ($M_1 = \{m_{1k}\}, k \in K_1$), acoustic methods of nondestructive testing ($M_2 = \{m_{2k}\}, k \in K_2$), radioscopy methods ($M_3 = \{m_{3k}\}, k \in K_3$), methods of visual control ($M_4 = \{m_{4k}\}, k \in K_4$). The probability of identifying defects by applying the aforementioned methods in the classic sense was the following: $P_{L1} = 0,913$; $P_{L2} = 0,908$; $P_{L3} = 0,963$; $P_{L4} = 0,891$.

Optimization of these methods results in the alteration of every complex. These complexes v_{ri}^* will transform into $v_{r1}^* = (m_{1k1}, m_{2k2}, m_{3k3}, m_{4k4})$, where $k_1 \in K_1 \subseteq K$, $k_2 \in K_2 \subseteq K$, $k_3 \in K_3 \subseteq K$, $k_4 \in K_4 \subseteq K$ are defined as chosen k -modifications of relevant methods of nondestructive testing used to identify i -defect. In this case, the low value of P_H -probability rate used to identify such defects equals 0,967.

By comparing our results with those described in (Somy *et al.*, 2022), we have deemed them congruent, and thus we can conclude that our models are not only correct but also applicable for quick calculations. Among other similar models, they can also be integrated into the programs used for planning and organization of road work.

Conclusions

In this research, we have highlighted that reduction of funding for road construction, reconstruction and repair is one of the main reasons for alteration or reallocation of funds for the ongoing projects, as well as for the projects yet to be started. Thus, mathematical modelling of such road construction projects allows to develop a plan of acquiring enough funds under conditions of reduced funding and allows to alter volumes of such funding by analyzing the object state, whereas an expert analysis of importance or project completion status are taken into account.

Reducing the amount of accident clusters can be achieved by minimizing the amount of traffic accidents in general, as well as minimizing the amount of deaths as a result of such traffic accidents. To solve mathematical problems related to reduction of accident clusters and minimizing the risk of traffic accidents, as well as to model the scenarios of increased safety, it is necessary to use a plan for implementing the measures to reduce the number of such traffic accidents by 40-60%. The aggregate cost of implementing the aforementioned means must not go beyond the defined limits.

The analyzed problem of nondestructive testing is based on the optimal choice of methods of nondestructive testing whenever it is needed to identify an entire set of defects L . Probability detection rate P_L , which has increased from 0,891 до 0,967, allows evaluation of the process of identification of defects.

The upcoming research conducted within the scientific field analyzed in this paper will focus on the results of an implementation of analyzed mathematical models as a mathematical supplement for analytical and information systems for monitoring the state of roads. These systems will focus on supporting decision-making regarding the development of construction and maintenance plans, road repair and maintenance of current public roads, and improvement of operational facilities and structures. The aforementioned systems are important to support general road infrastructure according to established development strategy, as well as to improve road networks and implement state, social or purpose-oriented programs related to the road industry.

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МАТЕМАТИЧНІ МОДЕЛІ БУДІВНИЦТВА, РЕКОНСТРУКЦІЇ ТА РЕМОНТУ ДОРІГ ЗА УМОВ НЕВИЗНАЧЕНОСТІ

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Анотація. У статті наголошується на важливості математичного моделювання в сучасних умовах будівництва, реконструкції та ремонту автомобільних доріг в Україні. Основні аспекти, які роблять це актуальним, включають фінансову нестабільність, невизначеність фінансування, а також необхідність дотримання високих стандартів безпеки на дорогах під час проведення робіт. Зазначається, що змінні фактори, такі як кліматичні аномалії, динаміка транспортного руху, технологічний прогрес у будівельній галузі та соціальні виклики, пов'язані зі збільшенням навантаженням на дороги через військовий конфлікт, вимагають нових підходів та інструментів для оптимізації будівельних процесів.

Головною метою дослідження є застосування математичного моделювання для планування та виконання робіт на автомобільних дорогах і спорудах, зокрема в умовах обмеженого фінансування. Це допоможе покращити процес усунення аварійно-небезпечних ділянок та вибрати оптимальні методи неруйнівного контролю для виявлення пошкоджень у дорожньому покритті та інфраструктурі. Для досягнення цієї мети використовуються методи статистичного та системного аналізу, багатокритеріальної оптимізації та теорії прийняття рішень. Основний акцент робиться на розробленні стратегічних управлінських рішень та їх ефективності.

Показано, що використання математичного моделювання в процесі планування автомобільних дорожніх робіт дозволяє ефективно розподілити фінансові ресурси, навіть при їх обмеженому обсязі. Ця практика також дає змогу динамічно змінювати рівень фінансування, враховуючи при цьому експертні оцінки важливості та ступеня завершеності робіт на об'єкті.

В результаті проведеного планування робіт із виправлення аварійно-небезпечних ділянок доріг з акцентом на мінімізацію ризику дорожньо-транспортних пригод та застосування методів підвищеної безпеки був розроблений план впровадження конкретних заходів та засобів. Використання цих заходів передбачає зниження кількості дорожньо-транспортних пригод на аварійно-небезпечних ділянках в 1,4–1,6 разу, і це досягається без перевищення визначених фінансових обмежень.

Встановлена оцінка якості виявлення пошкоджень на дорожньому покритті, використовуючи показник імовірності виявлення різноманітних дефектів. Детально показано, які оптимізаційні заходи дозволили підвищити цей показник з 0,891 до 0,967.

У подальших наукових дослідженнях автора передбачається ретельно дослідити результати впровадження обговорюваних математичних моделей, особливо як математичної підтримки аналітично-інформаційної системи для моніторингу стану дорожньої інфраструктури.

Ключові слова: математична модель, автомобільний транспорт, автошлях, аварійно-небезпечна ділянка, метод неруйнівного контролю, умова невизначеності.

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A BASIC QUANTUM KEY DISTRIBUTION PROTOCOL

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Abstract. Over time, the complexity of threats that can be perpetrated against critical infrastructure is increasing, including cyberattacks, large-scale failures, terrorist attacks, etc. The confidentiality of data processed and transmitted within critical infrastructure is a key aspect of its security. Traditional cryptography methods, although reliable, are becoming vulnerable to advanced computing and quantum capabilities of attackers. For this reason, the relevance of studying and applying quantum cryptography in critical infrastructure is becoming increasingly important. They are highly resistant to attacks related to computational aspects and provide untraceability of keys and data due to the principles of uncertainty. However, they also require complex technical implementation and further research for widespread implementation. Quantum cryptography can provide reliable protection against current and future attacks while maintaining data confidentiality and user identification. However, it is important to choose the right methods and tools to ensure the maximum level of data confidentiality, taking into account the characteristics of the network.

The article describes in detail the processes of improving the quantum key distribution protocol using quantum identification and quantum channel multiplexing methods, describes the mathematical apparatus of the improved method, and defines the stages of forming the key distribution protocol stack. The proposed improved method of quantum key distribution creates the possibility of its universal application under conditions of uncertainty, providing fast operation speed and a higher level of data security.

Keywords: Twin Field protocol, quantum channel multiplexing, quantum identification, quantum channels, quantum cryptography, key distribution protocol stack.

Introduction

Today, one of the newest quantum key distribution protocols is the Twin Field QKD protocol (Sun *et al.*, 2022; Meda *et al.*, 2022; Chan *et al.*, 2021). It uses the concept of two polarized quantum channels and quantum interference between two polarized photon states to ensure secure key exchange between two parties. Due to its characteristics, it is considered the most promising of all known protocols, if the type of attack is not taken into account. However, it can also be improved. In particular, it is possible to improve the efficiency of the protocol by reducing the number of errors and increasing the data transfer rate. New technologies can be used for this purpose, for example, the use of quantum channel multiplexing, which allows more information to be transmitted simultaneously, as well as the use of new methods of data processing and verification. It is also possible to use more sophisticated encryption techniques that allow for a higher level of security for the transmission of quantum information. In particular, there is the "quantum identification" technique, where information is transmitted between the parties using a quantum system that provides mutual authentication of the parties. Twin Field QKD (TF-QKD) (Park & Heo, 2021) is a quantum key distribution protocol that uses

two synchronized emitting circuits that generate pairs of photons in a spin state. Thus, quantum channels in TF-QKD are channels that transmit quantum bits based on photon emission.

The purpose of the article is to reveal the principles of quantum key distribution, to identify its role in ensuring the security of communications and information exchange, and to consider the possibilities of applying this protocol in various fields, including cryptography and network security.

The main objectives of the research are:

1. Consider the principles and functionality of the Twin Field QKD protocol, including its main components and stages of operation.
2. Analyze the multiplexing methods used to simultaneously transmit multiple quantum channels and determine their efficiency and advantages.
3. Present specific improvements to the Twin Field protocol, including multiplexing techniques and quantization, and justify their importance.
4. Consider the practical aspects of implementing the Twin Field QKD protocol and new methods of multiplexing and quantization.
5. Identify opportunities for further research in the field of quantum key distribution and development of the Twin Field protocol.

Development of a basic QKD protocol. Quantum channel multiplexing can be applied to TF-QKD in order to increase the bandwidth and efficiency of quantum key distribution. Quantum channel multiplexing (Woo et al., 2020; Wengerowsky *et al.*, 2019) allows more information to be transmitted over a quantum channel at one time by dividing it into multiple physical channels. However, when applying quantum channel multiplexing to TF-QKD, some technical difficulties must be taken into account due to the increasing number of photons to be transmitted through quantum channels. As the number of photons increases, the noise in the channel increases and can degrade the transmission quality.

To avoid the deterioration in transmission quality associated with the increase in the number of photons to be transmitted through quantum channels when multiplexing quantum channels in the Twin Field QKD protocol, additional techniques can be used to reduce channel noise. One such technique is to reduce the impact of channel noise by filtering the signal. Filtering can reduce channel noise by eliminating some of the noise that affects signal transmission.

Materials and methods

Multiplexing of quantum channels (Lin *et al.*, 2020) in the Twin Field QKD protocol can lead to an increase in the number of transmitted photons and the time required for data transmission. The quantitative indicators that may increase with quantum channel multiplexing may include:

1. The number of photons required to transmit data may increase depending on how many channels are to be multiplexed.
2. The data transmission time may increase due to the need to transmit more photons and depending on the photon transmission rate through the quantum channels.
3. Energy consumption for data transmission may increase due to the need to use additional equipment to multiplex the channels and signal amplifiers to transmit the photons.
4. The complexity of the system may increase due to the need to use additional equipment and software for multiplexing quantum channels.
5. The cost of the system may increase due to the need to use additional hardware and software for quantum channel multiplexing.

Wavelength Division Multiplexing (Haigh *et al.*, 2020; Wang *et al.*, 2022; Yousefi, & Yangzhang, 2020) is a technology used in fiber optic communications where multiple signals of different wavelengths are combined in the same medium (i.e., optical fiber) through superposition. Thanks to multiplexing, the sending and receiving parties can transmit large amounts of information to each other over a single channel, thus making more efficient use of the available optical fiber bandwidth. When integrating a QKD system with an existing fiber infrastructure, multiplexing allows quantum and classical signals used for key generation, synchronization, error correction, and privacy enhancement to coexist with data signals carrying other information for bidirectional communication between parties over the same fiber line. Consequently, multiplexing makes the QKD process less resource-intensive, as a single fiber can be used to transmit all the information between the transmitter and receiver, instead of using separate fibers for each of the quantum and classical signals.

The process of quantum channel multiplexing for the TF-QKD protocol can be described as follows:

1. Preparation of quantum groups: Quantum groups are prepared at the transmitter (Alice) and receiver (Bob). Each quantum group is composed of light pulses that correspond to quantum bits (qubits) using, for example, photon polarization. The formula for preparing quantum groups during quantum channel multiplexing for the Twin Field QKD protocol can be given as follows:

Suppose we have N quantum channels, then each channel must use M quantum states to transmit data. At the same time, according to the Twin Field QKD protocol, each of the channels must use L quantum states to measure in the correct basis. Therefore, the total number of quantum states required to prepare quantum groups for N channels can be calculated by the formula:

$$N_g = N(M+L), \quad (1)$$

where N_g is the total number of quantum states required to prepare quantum groups for all N channels.

2. Multiplexing of quantum channels: The quantum groups are transmitted over a single channel that multiplexes the quantum channels using, for example, frequency division multiplexing. The formula for multiplexing quantum channels for the Twin Field QKD protocol can be given as follows:

Suppose we have N quantum channels that we want to multiplex, and for each of them we use two phase-shifted light modulators to transmit two quantum states. Each channel transmits M quantum states for data transmission and L quantum states for measurement in the correct basis. The total number of quantum states required to multiplex N channels can be calculated by the formula:

$$N_t = 2N(M + L), \quad (2)$$

where N_t is the total number of quantum states required to multiplex all N channels.

3. Transmission of quantum groups: Quantum groups are transmitted from the transmitter to the receiver. The quantum groups passing through the channel can be labeled with indices, allowing them to be separated at the receiver. The quantum group transmission formula for quantum channel multiplexing in the Twin Field QKD protocol can be written as follows:

Suppose we have N quantum channels that we want to multiplex, and for each of them we use two phase-shifted light modulators to transmit two quantum states. To multiplex the quantum states from different channels, two different quantum channels are used - channel Z and channel X - which transmit information using vertical and horizontal polarization, respectively.

When multiplexing quantum states from N channels, the total quantum state is transmitted to channel Z :

$$|\varphi_Z\rangle = \bigotimes_{j=1}^N |\varphi_j^{(Z)}\rangle, \quad (3)$$

where $\varphi_j^{(Z)}$ is the quantum state transmitted in the j -th quantum channel using channel Z . Similarly, the total quantum state is transmitted for channel X :

$$|\varphi_X\rangle = \bigotimes_{j=1}^N |\varphi_j^{(X)}\rangle, \quad (4)$$

where $\varphi_j^{(X)}$ is the quantum state transmitted in the j -th quantum channel via channel X .

In both cases, we multiply quantum states from different channels because they are transmitted through different quantum channels (channel Z and channel X).

4. Measurement of quantum groups: At the receiver, each quantum group is measured separately to obtain quantum bit values. The results are then used to calculate the key.

After the total quantum states have been transmitted over the Z and X channels, respectively, they arrive at the receiver. To measure each quantum state from each channel, the receiver uses two phase-shifted light modulators that measure the vertical and horizontal polarization. After measuring the quantum state in the j -th channel using the Z channel, the measurement operator for the vertical polarization is as follows:

$$M_j^{(Z,0)} = |0\rangle\langle 0|, \quad (5)$$

and for horizontal polarization:

$$M_j^{(Z,1)} = |1\rangle\langle 1|. \quad (6)$$

Similarly, after measuring the quantum state in the j -th channel using channel X , the measurement operator for the vertical polarization is as follows:

$$M_j^{(X,0)} = \frac{1}{2}(|0\rangle\langle 0| + |1\rangle\langle 1|), \quad (7)$$

and for horizontal polarization:

$$M_j^{(X,1)} = \frac{1}{2}(|0\rangle\langle 0| - |1\rangle\langle 1|). \quad (8)$$

As a result of measuring the vertical and horizontal polarization for each channel, the receiver receives two-bit sequences: $bj(Z)$ and $bj(X)$, which correspond to the results of measuring the quantum state in the j -th channel using channel Z and channel X , respectively.

In the process of measurement, a projection onto the corresponding basis occurs. Thus, the output state will be equal to the projection of the input state onto the corresponding basis:

$$|\varphi_{Z,out}\rangle = \frac{1}{\sqrt{2}}(|0\rangle\langle 0| + |1\rangle\langle 1|)|\varphi_Z\rangle, \quad (9)$$

$$|\varphi_{X,out}\rangle = \frac{1}{\sqrt{2}}(|+\rangle\langle +| + |-\rangle\langle -|)|\varphi_X\rangle, \quad (10)$$

$$|\varphi_{Y,out}\rangle = \frac{1}{\sqrt{2}}(|+i\rangle\langle +i| + |-i\rangle\langle -i|)|\varphi_Y\rangle, \quad (11)$$

where $|\varphi_{Z,out}\rangle$, $|\varphi_{X,out}\rangle$, $|\varphi_{Y,out}\rangle$ are the input quantum states, and $|\varphi_Z\rangle$, $|\varphi_X\rangle$, $|\varphi_Y\rangle$ are the output quantum states after projection to the corresponding basis. These output states are transmitted through the appropriate channels on the receiver side, which decompresses them and performs measurements as in the opposite direction, which allows to obtain a bit sequence in which information is stored according to the basis in which the states were measured.

5. Error correction: If errors occur during the measurement process, a feedback channel can be used to correct the errors, as is commonly done in quantum key distribution protocols. The feedback channel allows you to eliminate erroneous bits and improve the quality of information transmission.

The error correction formula in the quantum channel multiplexing protocol for TF-QKD uses the least squares principle and consists in finding the optimal error vector e for each channel by means of measurements in the Z-base and using the inverse propagation matrix:

$$e = S^{-1}(X - Y), \quad (12)$$

where X is Alice's measurement, Y is Bob's measurement, and S is the propagation matrix representing the relationship between the number of transmitted and received quantum bits.

The resulting error vector e is then used to correct the output keys received from each channel by eliminating the bits that cause errors.

In the TF-QKD protocol, quantum channel multiplexing allows to increase the number of transmitted quantum bits per unit time. This improves the efficiency of the protocol and reduces the time it takes to transmit keys between Alice and Bob. However, multiplexing quantum channels can lead to some problems, such as increased channel noise and the need to use more complex error correction methods. In general, quantum channel multiplexing is an important element in quantum key distribution protocols, which allows to increase the efficiency and speed of information transmission. However, when using this technology, it is necessary to take into account some technical difficulties and problems that may affect the quality of data transmission.

The Twin Field protocol is one of the quantum key distribution protocols to which quantum identification (QID) can be applied to identify trusted devices and ensure the security of the key distribution process.

The process of applying quantum identification in TF-QKD includes the following steps:

1. Physical channel verification: Before starting the identification process, each device verifies the physical channel to ensure that it is not subject to interception or data modification. The process of verifying physical communication channels with quantum identification includes the following steps:

- Quantum state generation: The sender and receiver generate quantum states to be used during verification.
- Sending and receiving quantum states: the sender sends quantum states to the receiver through a physical communication channel. The receiver receives the quantum states and stores them for further processing.
- Measurement of states: the receiver measures the quantum states that have come to it. The measurement is performed in a random base, which is determined randomly for each state.
- Sending the measurement results: the receiver sends the measurement results to the sender via an unsecured communication channel.
- Comparison of results: the sender compares the receiver's measurement results with its own results. If the results match, the communication channel is considered secure. If the results do not match, it may indicate that the communication channel has been compromised.
- Repeat the procedure: If the results do not match, the process is repeated several times. If the results still do not match, the channel is secure.

2. Sending test signals: During the identification process, each device sends test quantum signals to the other device.

3. Measuring the received signals: after receiving the quantum signals, each device measures them to obtain information about the states in which they were sent.

4. Comparing the results: each device compares the measurement results to make sure that the test signals were received correctly.

5. Reliable identification: If the comparison results match expectations, the devices can identify each other as trusted. If the results do not match, the process is repeated until the devices are reliably identified.

6. Transition to the key distribution phase: after successful identification, the devices move to the key distribution phase, in which they perform quantum signals to create a shared encryption key that will be used to securely exchange information between the trusted devices.

In the key distribution process, quantum signals are sent by the sender and then received by the receiver. The sender and receiver compare the results of their measurements to determine whether the data was transmitted without interference. If the results match, then they can use a shared key to securely encrypt and decrypt messages. If the results do not match, it indicates an interception attempt, and the process repeats.

Formation of a key distribution protocol stack. The quantum protocol stack (Zhao, & Qiao, 2023) is a set of different stages and procedures used in quantum protocols to ensure the security of information transmission. Building a stack is an important component of a quantum protocol and helps ensure its security and reliability. The stack is used to store intermediate results during the execution of a quantum protocol. When two parties to the protocol interact, each of them saves its own parts of the stack. Saving this data allows you to preserve the order of interaction between the parties to the protocol and ensure the correct execution of its steps. The Twin Field QKD protocol is one of the quantum protocols used to securely exchange keys between two parties. The following stack can be created for it:

1. Quantum source – generates pairs of quantum bits (qubits) that are transmitted through different channels.

2. Quantum multiplexer – combines quantum bits from different channels into one quantum stream.

3. Quantum channel – transmits quantum bits between remote parties to the protocol.

4. Quantum demultiplexer – breaks the quantum stream into separate quantum bits, which are then sent to the receivers.

5. Quantum receiver – receives the quantum bits and performs measurements of the corresponding states to obtain keys.

6. Classical channel – transmits classical bits (e.g., to preserve the parameters of quantum bit transmission) between remote parties to the protocol.

7. Quantum identifier – used to verify that the receivers are the true receivers of the corresponding quantum bits. This is achieved by sending additional quantum bits that are used to measure identical states between remote parties.

8. Classical identifier – used to transmit information about the confirmation of successful quantum identification and other classical messages used to control the protocol.

The Twin Field QKD protocol uses two quantum channels to transmit quantum bits, and quantum sources are used to generate pairs of quantum bits per channel. To multiplex the quantum channels, different frequencies of light are used for each channel, which can be separated by using appropriate filters. For example, you can use filters with an opaque band for one channel at one light frequency, and filters with an opaque band for another channel at

another light frequency. In this case, quantum sources generate pairs of quantum bits on each channel at the corresponding light frequency.

In addition, the Twin Field QKD protocol uses quantum identification to provide an additional level of security for the transmission of quantum bits. Quantum identification is based on the fact that the detector can measure the parameters of the photon's quantum state without changing this state. Quantum identification is used to verify that the correct quantum bits have been transmitted and to detect possible attempts to intercept quantum bits.

Quantum sources for the Twin Field QKD protocol generate pairs of quantum bits with the appropriate light frequencies for each channel, which are then transmitted through quantum channels. Quantum identification is used to verify the correctness of the transmission and provide an additional level of security for the transmission of quantum bits.

To realize this process, we obtain the following mathematical model:

1. Measurement of the energy state of an electron in an atom:

$$H_{at} |\psi_i\rangle = E_i |\psi_i\rangle. \quad (13)$$

2. Sending the generated photon to the generated detector:

$$|\psi_i\rangle \rightarrow |\psi_f\rangle. \quad (14)$$

3. Registering the generated photon:

$$|\psi_f\rangle \rightarrow |1\rangle \text{ with probability } P_1 \text{ or } |0\rangle \text{ with probability } P_0. \quad (15)$$

4. Mixing of generated photons using quantum channel multiplexing:

$$|\psi\rangle = \sum_{i=1}^n \alpha_i |1_i\rangle. \quad (16)$$

5. Using quantum identification to check the state of photons:

$$|\psi\rangle = \sum_{i=1}^n \alpha_i |1_i\rangle \rightarrow |\psi'\rangle = \sum_{i=1}^n \alpha_i |1_i\rangle a \delta o |\psi'\rangle = |0\rangle. \quad (17)$$

6. Transmission of a mixed signal to the receiver and the beginning of the process of quantum key exchange using the Twin Field QKD protocol:

$$\rho_{mix} = p_1 \rho_1 + p_2 \rho_2 + \dots + p_n \rho_n, \quad (18)$$

where n is the number of channels through which quantum states are transmitted, p_i is the probability of sending a quantum state through channel i , and ρ_{mix} is the mixed quantum state received at the receiver after mixing signals from different channels.

A quantum multiplexer (Lu, & Qiu, 2020; Khan *et al.*, 2016) for Twin Field QKD protocol is a device that allows multiplexing multiple quantum channels in a single fiber optic link. Using a quantum multiplexer, several independent quantum channels can be transmitted over a single fiber while maintaining their independence.

The quantum multiplexer in the Twin Field protocol also provides quantum identification (QID), which allows detection of any intermediate controlled cross-path emitters (CPEs) that can be used to study or steal quantum information. The QID is used to determine the individual state of each qubit that is transmitted through the quantum channel. This allows us to confirm that the qubits have not been tampered with during transmission and that the channel has not been compromised.

The following formulas are used for the quantum multiplexer in the Twin Field QKD protocol:

1. Formula for preparing quantum groups:

$$|\psi\rangle_{AB} = \frac{1}{\sqrt{2}} (|0\rangle_A |\psi_0\rangle_B + |1\rangle_A |\psi_1\rangle_B), \quad (19)$$

where $|\psi_0\rangle_B$ and $|\psi_1\rangle_B$ are quantum states corresponding to different communication channels.

2. The formula for multiplexing quantum channels:

$$|\psi\rangle_{ABCD} = \frac{1}{\sqrt{2}} (|0\rangle_A |\psi_0\rangle_B |\psi_0\rangle_C + |1\rangle_A |\psi_1\rangle_B |\psi_1\rangle_C), \quad (20)$$

where $|\psi_0\rangle_C$ and $|\psi_1\rangle_C$ are quantum states corresponding to different user IDs.

3. The formula for the transmission of quantum groups:

$$|\psi\rangle_{AB} \rightarrow \frac{1}{\sqrt{2}} (|0\rangle_A |\psi_0\rangle_B + |1\rangle_A |\psi_1\rangle_B). \quad (21)$$

4. Formula for measuring quantum groups:

$$M_B^Z (M_A^X \otimes I_{BC}) |\psi\rangle_{ABC} = \frac{1}{\sqrt{2}} (|0\rangle_A |\psi_0\rangle_B |\psi_0\rangle_C - |1\rangle_A |\psi_1\rangle_B |\psi_1\rangle_C), \quad (22)$$

where M_A^X and M_B^Z are the measurement operators corresponding to the X and Z bases, respectively.

5. Error correction formula:

$$|\psi_{corr}\rangle = \frac{1}{\sqrt{2}} (|0\rangle^A |0\rangle^B + e^{i\phi} |1\rangle^A |1\rangle^B) \otimes |\varphi\rangle_{AB}, \quad (23)$$

where $|\varphi\rangle_{AB}$ is the shared quantum state used for quantum identification.

A quantum channel for the Twin Field QKD protocol is a communication channel between two trusted parties (for example, Alice and Bob) that allows the transmission of quantum states using quantum channel multiplexing and quantum identification technologies. Such a channel ensures the security of information transmission through the use of the laws of quantum mechanics and quantum cryptography, which makes it reliable for protecting confidential information.

A quantum channel is formed according to the following scenario:

1. Encoding quantum bits of the transmitted message into quantum states:

$$|\psi_0\rangle = |0\rangle, |\psi_1\rangle = |1\rangle, |\psi_2\rangle = |+\rangle, |\psi_3\rangle = |-\rangle. \quad (24)$$

2. Base transformation operations on the side of Alice and Bob:

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \quad (\text{Adamar operation}), \quad (25)$$

$$Z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \quad (\text{PaulSinger operation}). \quad (26)$$

3. Multiplexing of two quantum channels transmitting quantum bits $|\psi_0\rangle$ and $|\psi_1\rangle$:

$$|\psi_0\rangle = \frac{1}{\sqrt{2}} (|\psi_0\rangle_A |\psi_0\rangle_B + |\psi_1\rangle_A |\psi_1\rangle_B).$$

4. Multiplexing of two quantum channels transmitting quantum bits $|\psi_2\rangle$ and $|\psi_3\rangle$:

$$|\psi_1\rangle = \frac{1}{\sqrt{2}} (|\psi_2\rangle_A |\psi_2\rangle_B + |\psi_3\rangle_A |\psi_3\rangle_B). \quad (27)$$

5. Transmission of quantum channels from Alice to Bob.

6. Measurement of quantum channels using projectors on the ground states.

7. Error correction.

A quantum demultiplexer for the Twin Field QKD protocol is a device that separates a mixture of quantum signals that have been transmitted over a quantum channel using quantum channel multiplexing. The device distributes quantum signals to different receivers that receive these signals using quantum identification. The quantum demultiplexer is an important component of the Twin Field QKD protocol, as it allows for a continuous flow of quantum data between the parties involved in the quantum key exchange. The multiplexed quantum signals are separated in the following sequence:

1. Time slot division.

$$U^{\wedge(t)}_{dmux} = \sum_{i=1}^n P^{\wedge(t)}_i \otimes U^{\wedge}_{swap} \otimes P^{\wedge(t)}_i, \quad (28)$$

where $P^{\wedge(t)}_i$ is a projector to a quantum state in time slot t , $U^{\wedge}_{swap}$ is a SWAP gate that exchanges states of two qubits.

2. Separation of frequency channels:

$$U^{\wedge(f)}_{dmux} = \sum_{i=1}^n P^{\wedge(f)}_i \otimes U^{\wedge}_{swap} \otimes P^{\wedge(f)}_i. \quad (29)$$

3. Separation of spins:

$$U^{\wedge(s)}_{dmux} = \sum_{i=1}^N P^{\wedge(s)}_i \otimes U^{\wedge}_{swap} \otimes P^{\wedge(s)}_i. \quad (30)$$

A quantum receiver for the Twin Field QKD protocol is a device that is designed to receive quantum signals that have been transmitted over multiplexed channels within this protocol. The quantum receiver allows quantum identification and reading of the data transmitted by the sender.

In the Twin Field QKD protocol, the quantum receiver receives quantum signals containing photons that have been emitted by random polarizations from different channels. The receiver can measure the polarization of each photon and determine which channel it belongs to by means of multiplexing. In addition, the quantum receiver performs quantum identification, which allows you to verify that the data was transmitted without interception.

The formulas for the quantum receiver for the Twin Field QKD protocol are complex and depend on the specific implementation of the device. However, the general approach is to measure the quantum states containing photons from different channels and process this data to recover the transmitted information.

1. First, a measurement operation is performed in the basis corresponding to the transmitted bit:

$$M^{\wedge}_j = \int_{B_j} d\omega |\omega\rangle\langle\omega|, \quad (31)$$

where $j \in \{0, 1\}$ is the transmitted bit, B_j is the basis corresponding to the transmitted bit, $|\omega\rangle$ is the state of the input quantum signal.

2. Probability of receiving the transmitted bit:

$$p_j = \text{Tr}\{\rho_j M^{\wedge}_j\}, \quad (32)$$

where ρ_j is the state density of the transmitted quantum signal.

3. The probability of error in the quantum channel:

$$e = \frac{1}{\sqrt{2}} (\sqrt{p_0} - \sqrt{p_1})^2. \quad (33)$$

4. Error correction:

$$E^{\wedge} = \frac{1}{\sqrt{p_0}} |0\rangle\langle 0| - \frac{1}{\sqrt{p_1}} |1\rangle\langle 1|. \quad (34)$$

5. The final state obtained after error correction:

$$\rho' = E^{\wedge}_{\rho_j} E^{\wedge\dagger}. \quad (35)$$

The quantum identifier is one of the elements of the Twin Field QKD protocol and is used to determine the identity of quantum channels between two interlocutors. Its main purpose is to prevent eavesdropping on quantum channels and message tampering. It can be implemented using quantum systems, such as photons or qubits, which are sent between the two parties to the protocol. In this case, the interaction between quantum systems allows the interlocutors to determine whether the channels are identical, i.e. whether they have not been altered or tampered with.

The quantum identifier in the Twin Field QKD protocol can be described by the following formulas:

1. Suppose Alice has a prepared state ρ_A and sends it over the channel to Bob. Bob can retrieve this state using the decomposition operator:

$$|\psi'_B\rangle = E(\rho_A)|\psi_A\rangle. \quad (36)$$

2. Bob can then verify that the state was sent by Alice using quantum identification:

$$P_{accept} = Tr(M\rho_A), \quad (37)$$

where M is the projection operator for recognizing the state, and Tr is the trace operator. If P_{accept} is high enough, Bob confirms that the state was sent from Alice.

The classic identifier for the Twin Field QKD protocol is an information exchange between the parties to the protocol used to confirm mutual authenticity and establish the secret key. It includes identification information about each user, such as name, device number, public key, etc., as well as information about the protocol parameters used to generate quantum keys. In addition, the classical identifier may also include information about the state of the communication channel, such as the noise level, which may affect the quality of quantum data transmission.

The formula for the classical identifier in the Twin Field QKD protocol can be written as:

$$c = H(x), \quad (38)$$

where H is a hashing function that converts a random vector x into a random number c of fixed length. The value of c is sent to the sender and receiver so that they can compare their identities and make sure they are using the correct quantum channels and quantum bits to exchange keys.

Also, to make the protocol more secure, a hash function with a key k can be used, which is added to the formula:

$$c = Hk(x). \quad (39)$$

Results and discussion

The principles and main components of the Twin Field QKD protocol were considered in detail during the study. The results presented on quantum channel multiplexing methods that can be used to simultaneously transmit more than one quantum stream. It was shown how these methods can improve the performance and efficiency of the Twin Field QKD protocol. This paper explores the possibilities and advantages of quantum identification in the context of quantum key distribution and shows how this aspect can improve the security and robustness of the protocol. It follows from the research that the use of quantum channel multiplexing and quantum identification methods can significantly improve the efficiency of the Twin Field QKD protocol. This opens up new opportunities for secure and efficient quantum key distribution.

Conclusions

This paper presents the development of a quantum key distribution protocol based on the improved Twin Field QKD protocol. One of the key achievements is the use of quantum signal multiplexing methods, which made it possible to bring the protocol to a new level of efficiency and speed of quantum key transmission. This opens up a wide range of opportunities for the development of quantum communications and ensuring their operation in real-world conditions. Additionally, the article discusses the introduction of quantum identification methods that provide a high level of security in the distribution of quantum keys. This is becoming an important factor, especially in the context of modern cybersecurity threats. In addition, the article demonstrates the developed concept of a key distribution protocol stack that allows choosing the optimal protocol depending on specific scenarios and communication requirements. This makes the system flexible and adaptive to different conditions. In summary, this paper opens up new application perspectives for quantum communication by enhancing the security and efficiency of the key distribution process. This helps to create a solid foundation for the development of quantum networks and expands the possibilities of applying quantum technology in the modern world, including the areas of cybersecurity, communications, and computing.

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Conflict of Interest

There is no conflict of interest.

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БАЗОВИЙ ПРОТОКОЛ РОЗПОДІЛУ КВАНТОВОГО КЛЮЧА

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Анотація. З плином часу зростає комплексність загроз, які можуть здійснюватись проти критичної інфраструктури, включаючи кібератаки, великомасштабні відмови, терористичні акти тощо. Конфіденційність даних, які обробляються і передаються в межах критичної інфраструктури, є основним аспектом її безпеки. Традиційні методи криптографії, хоча й надійні, стають уразливими перед сучасними обчислювальними та квантовими здатностями атакуючих. Через це актуальність вивчення та застосування квантової криптографії в критичній інфраструктурі набуває все більшого значення. Вони мають високу стійкість до атак, пов'язаних з обчислювальними аспектами, і забезпечують невідслідковуваність ключів і даних завдяки принципам невизначеності. Однак вони також вимагають складної технічної реалізації та подальшого дослідження для широкого впровадження. Квантова криптографія може забезпечити надійний захист від сучасних та майбутніх атак, зберігаючи конфіденційність даних та ідентифікацію користувачів. Проте важливо правильно підібрати методи та засоби для забезпечення максимального рівня конфіденційності даних, зважаючи на особливості мережі. У статті детально описано процеси вдосконалення протоколу квантового розподілу ключів за допомогою методів квантової ідентифікації та мультиплексування квантових каналів, описано математичний апарат вдосконаленого методу та визначено етапи формування стеку протоколу розподілу ключів. Запропонований вдосконалений метод квантового розподілу ключів формує можливість універсального його застосування в умовах невизначеності, забезпечуючи швидкодію виконання операцій та більший рівень захищеності даних.

Ключові слова: протокол Twin Field, мультиплексування квантового каналу, квантова ідентифікація, квантові канали, квантова криптографія, стек протоколу розподілу ключів.

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A SYSTEMATIC APPROACH TO THE AUTOMATION OF THE PROCESSES OF ENSURING PERSONNEL COMPETENCE AT CRITICAL INFRASTRUCTURE FACILITIES OF THE DEFENSE FORCES OF UKRAINE

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Abstract. The publication is devoted to the problems of automation of the system of selection and assessment of personnel compliance, which should ensure the safety of critical infrastructure facilities of the Defense Forces of Ukraine. The article examines the main regulatory documents, requirements for personnel, and ways of assessing the appropriateness of their knowledge, skills, and competencies. The requirements of professional standards developed for the sphere of critical infrastructure of the Defense Forces of Ukraine and information protection are taken into account. This work aims to identify the basic problems associated with the selection of qualified personnel, assessment of their compliance and determination of the quality of work in activity processes. The materials of the article refer specifically to the objects of the critical infrastructure of the Defense Forces of Ukraine and consider the features related to the processes of ensuring the security of the critical infrastructure. The results obtained as a result of the analysis of personnel problems in the field of ensuring the security of critical infrastructure facilities should help the heads of institutions, organizations, enterprises, as well as HR units in the formation and staffing of units, training and placement of personnel. When preparing the publication, the main normative acts regulating the processes of critical infrastructure protection, the experience of developed countries, primarily the USA and the European Union, security standards (DSTU ISO/EN 27001, NIST Special Publication 800-181) and recommended practices were considered.

The conclusions contain recommendations regarding the automation of the system of selection, training and advanced training of personnel in the field of protection of critical infrastructure objects, as well as its information and cybersecurity. Recommendations are given for improving the automation of personnel selection and placement procedures, planning professional development, and creating a professional training system based on the knowledge management system.

Keywords: automation, management systems, critical infrastructure protection, personnel competence, information security standards, knowledge, skills, competencies, knowledge management.

Formulation of the problem

In the conditions of Russian military aggression, one of the primary tasks of the state is to ensure the protection of the critical infrastructure (CI) of the Defense Forces of Ukraine. The basic principles and principles of CI protection are determined by the Law of Ukraine "On Critical Infrastructure" (2021). In the context of the practical organization of protection, the

Law provides for the introduction of an automated security system of the CI of the Defense Forces of Ukraine. Its construction and provision of an adequate level of protection face problems that have a direct impact on both the state of system security and the resource needs, including financial ones, required for their solution. One of the most urgent and key in this sense is the problem of personnel competence, which ensures the protection and restoration of infrastructure facilities. It is on the level of competence and qualification of personnel that both the amount of resources and the response time to security incidents depend, which directly affects both the defense capability of the country and the quality of life of the population.

Protection of CI objects is a vital task in the conditions of military aggression for the Defense Forces of Ukraine (DF). The exceptional need to organize the protection of critical infrastructure is reflected in legislation (On Critical Infrastructure, 2021; On the Basic Principles, 2019; On Approval of General Requirements, 2019). At the moment, the characteristics of critical infrastructure objects (CICs), the procedure for their identification, accounting, unification into management sectors, and the procedure for managing each sector, including in the context of organizing the protection of the identified objects, have been determined.

Taking into account the legally established organizational uniting of the SOU OKI into a complex hierarchical structure, which has a state-appointed authority in the field of critical infrastructure protection (On Critical Infrastructure, 2021), we will consider the actual aspects of automating the system of training and improving the competence of personnel involved in ensuring the protection of both individual OKI and of the entire CIS as a whole.

Analysis of recent research and publications

Personnel management system, according to the classics of this field of research, activity and use (Armstrong, Barnard, Drucker, Karloff, Maslow, Mescon, Taylor, Follet, Fayol, etc.), consists of the following closely related and interdependent elements of technologies (Figure 1):

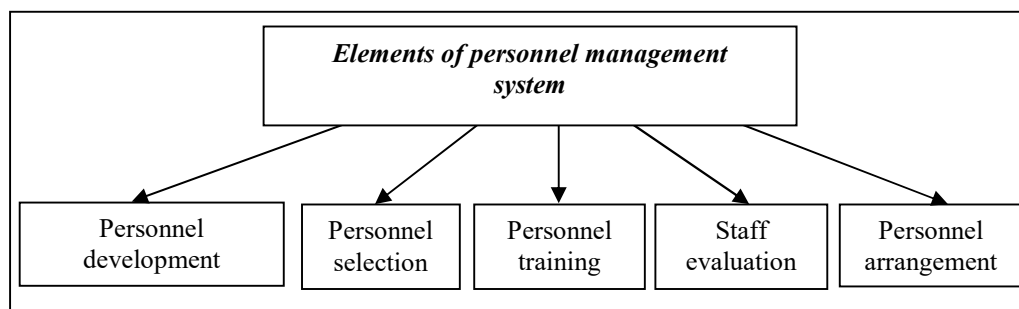


Figure 1. Component systems of personnel management

With, it is impossible to categorically separate the elements of the personnel management system from each other. They form a single whole, since it is impossible to carry out the selection, training and placement of personnel without personnel evaluation; personnel training without selection and evaluation; staffing without personnel selection, evaluation and training. Therefore, the main technology of personnel management is the assessment of personnel, which determines their quality, their suitability for the performance of relevant duties and tasks for the protection of KI SOU.

The concept of "human-centeredness" was first reflected in philosophical science, and later, with the development of the human resources management system, it was also spread in personnel management.

As noted by the President of the Academy of Pedagogical Sciences of Ukraine, Academician V.G. Kremen, "...the philosophy of human-centrism is not just another philosophical and anthropological teaching, but the transformation of philosophizing from humanistic considerations as such into a new type of metaphilosophy and worldviews directly related to the higher meanings of being, which act through life and living thinking. Turning to the problems of spirituality, morality and the unity of the inner world of a person, anthropocentrism, as a principle of holistic understanding of the person, corresponds to the search of modern socio-philosophical thought.

People-centeredness meets the requirements and demands of modern post-industrial civilization, which is looking for an experienced, creative, proactive and at the same time innovative thinking person" (Kremen, & Ilin, 2022).

For many years, the principle of people-centeredness has been at the center of the activities of personnel management bodies, personnel services, and personnel bodies of the armies of the leading countries of the world.

Qualitative selection of the personnel of SKI SOU should be decided with the help of methods that make it possible to determine the degree of suitability of this or that citizen to perform the duties of professional activity or the degree of his suitability for a new position for him. Determining the degree of suitability (conditional suitability, unsuitability) of a person (person) to perform military professional duties is possible only when using technologies of professional psychological selection for military service, for a new position (Vetrov, & Vraneshych, 2020).

The analysis of professional activity is carried out within the framework of professionography, on the basis of professional studies, the study of the content of each individual position (specialty) (Andreeva, 2005).

Strategic approaches to the use of personnel management technologies in the areas of personnel management and career management in the military organizations of NATO member states have been used since the beginning of the 20th century.

The system of promotion in the NATO armies has been developed over many years of application and the corresponding legal framework: in the USA (1947, 1981), Germany (1971), France (1976), Spain (1999), Hungary (2002) (The Army Strategic Planning Guidance, 2023; On Adopting the Regulations, 2001; Official bulletin of the French Armed Forces, 2009; On the Organization of Personnel, 1999).

The entire system of promotion of officers of the Armed Forces (AF) of the United States is built on the cultivation of the spirit of competition according to the principle: the higher the military rank and position, the stricter the selection criteria should be (Study of the problems, 2018). It mainly ensures fair selection in the officer corps. Terms of service in each military rank are strictly observed. It is believed that an officer cannot "sit" without advancing through the official ladder, and if the established terms are exceeded, he must be dismissed as unpromising. This is how, for example, they will do with a captain who has more than 16 years of service (4+two captain's terms of 6 years each), or a colonel with 30 years of service (25+5 years of the maximum colonel's term), who have no prospects for further promotion. Uniform minimum terms of military service (service) have been established for officers in all branches of the US Armed Forces to receive the next military rank: to receive the rank of 1st lieutenant - 2 years, captain - 4, major - 10 years, lieutenant colonel - 15 years, colonel - 22 years.

Many works of domestic scientists are devoted to the formation of a high-quality and professional management staff: G. Atamanchuk, N. Nyzhnyk, A. Obolonskyi, V. Oluyko, E. Okhotskyi, I. Surai, O. Turchynov, and others (Study of the problems, 2018). The first impetus and the greatest influence on the development of the direction of creation and ensuring the level of professionalism of the management units of the SKI contributed to the

works of the classics of management in general and personnel management in particular. The classics of this direction are M. Armstrong, M. Weber, A. Maslow, S. Taylor, E. Meskon, P. Drucker, and others.

During research in this direction, the first standards of professional service were created, which were based on the "system of merits and merits", which, in turn, required the determination and approval of accounting for the necessary business and personal qualities when appointing and promoting to managerial positions of any level of SKI, regardless of race, skin color, religion, gender, marital status, age. The main criteria were the greatest competence, high moral and ethical standards.

The personnel services of the NATO member states determine that the selection of a candidate for the position of SKI SOU should be:

- objective and based on the evaluation of the merits (achievements) of each candidate;
- competitive, but to be carried out according to processes and indicators that should be understandable to any serviceman - soldier, sergeant or officer;
- evaluation of the candidate is a key part of the selection both for the members of the selection commissions and for the officers who carry out the initial selection of candidates in units (compounds);

- the selection must take into account issues related to the individual, personal preferences of the candidate for the nature of the type of activity of the appointment, assignment of a military rank, referral to training and training (On Approval of the List of Works, 1994; Andreeva, 2005; Obolonsky, 2001; Krill, 2018).

The purpose of the article is a scientific justification for the use of modern information technologies for the automation of the personnel training system for the protection of the OSI, as an integral organic addition to the basic toolkit of the automated security management system of the OSI.

Presenting main material

The requirements for the organizational support of OKI are determined, including, by Resolution of the CMU dated June 19, 2019 No. 518 "On approval of General requirements for cyber protection of critical infrastructure objects" (p. 2). The requirements provide for both the creation of appropriate units and the inclusion of specialists in them, who must perform actions to ensure the safety of OKI SOU. At the same time, at the level of the object itself, it is quite difficult to find both the necessary personnel and to determine the degree of their compliance and readiness to perform the relevant job duties.

When carrying out work on the selection and training of personnel, it is important to clearly understand what knowledge, skills and competencies a specialist should possess. The content of such training stems from the concept of CI protection, which is largely borrowed from the experience of developed countries that have gone a long way in creating a CI protection system and have stable experience. The general approach in the organization of the protection of CSI is that the protection of CSI is based on the management system, and, accordingly, on the information infrastructure, as the basis of the functioning of any management system. Therefore, the main practice of protection is based on the DSTU standard ISO/EN 27001 (Information Security, 2022), which defines the requirements for the information security management system. This standard is based, in turn, on DSTU ISO/EN 9001, and is essentially a quality system, the implementation of which allows to ensure the protection of information in the organization. According to the concept of the standard, information that is determined by the organization as valuable, as well as information that needs to be protected by the law, is subject to protection. Thus, the requirements of the standard regarding information affect all business processes and aspects of the organization's

activities, organization management, internal and external interactions, technologies and personnel. Personnel requirements are defined in section 7 of the standard, and define the organization's responsibility for ensuring that personnel are competent, have the appropriate education, training or experience.

In (Information Security, 2022), a comparative analysis with standards and methods in working with personnel in the field of CI security of other countries is given, and best practices are considered. The requirements of the standards are taken into account, including DSTU ISO/EN 27001 "Information Security, Cyber Security and Privacy Protection - Information Security Management Systems - Requirements" (2022), NIST Special Publication 800-181 "Workforce Framework for Cybersecurity (NICE Framework)" (n.d.).

In particular, it is possible to highlight some important competencies, knowledge and skills:

- personnel must be competent in identifying potential CI threats and be able to prevent them. This may include studying methods of cyber protection, physical security and other aspects of the security of OKI SOU;
- personnel must be trained to respond to a variety of incidents, such as natural disasters, man-made accidents, or cyber attacks. It is important to be able to quickly and effectively respond to danger and ensure the safety of personnel and OKI SOU;
- competent personnel must know how to ensure the uninterrupted operation of the OKI SOU in the event of a crisis or incident. This may include working with backup power sources, water supply, security systems, information technology, etc.;
- staff must understand and comply with the laws and regulations related to the safety of OKI SOU. Failure to comply with legal requirements may result in serious legal consequences;
- threats and technologies are constantly changing, so personnel must be ready to learn and constantly update their knowledge and skills, both in the field of security and in the field of other functionality.

All these aspects, requirements, areas of competence are aimed at forming the ability of personnel to ensure the reliable and safe work of OKI SOU and protect them from possible threats.

Proper training of personnel, which must ensure the protection of critical infrastructure, requires the creation of an appropriate concept. Such a concept should provide a certain unification, in particular, in terms of the subject area - ensuring the safety of the OKI SOU, in terms of the requirements for a specialist - the application of professional standards, in terms of the procedure - to apply typical methods and procedures at the level of the corporation - SKI.

In order to apply the best practices in the field of SCI protection, it is necessary to take into account the complexity of the problem, requirements for applicability, flexibility and level of generalization of methods, limitations in resources, especially in time. To the greatest extent, when forming a system of working with personnel, the task of organizing CI protection is met by the concept of knowledge management (Malikhin, & Yarmolchuk, 2020, pp. 1-3), since it has the ability to compensate for resource limitations by more active application of the intellectual component. This concept is based on the definition of knowledge as a value and an asset, as well as taking into account in this asset the practical skills, abilities, etc., that individual specialists of OKI SOU have. According to the concept, knowledge is an important element of SKI resources, and the management of these resources will provide additional opportunities when organizing actions in extreme conditions of accidents, aggressor terrorism, attacks and liquidation of the consequences of SOU OKI.

Application of the concept does not require the creation of new functions or changes in business processes. It is seen that this concept operates at the level of understanding by the

heads (managers) of the organization of the main principles of the concept and the application of these principles in the conduct of usual activities. These include:

1. Creating a knowledge base. The procedure of creating knowledge is largely based on the identification of knowledge, the selection of useful knowledge, the creation of a knowledge base and the delivery of this knowledge to the members of the team to whom this knowledge applies. For this, the search and implementation of processes that contribute to the creation of new knowledge can be carried out. This may include stimulating working groups to share ideas, holding briefings and trainings to build a knowledge base.

2. Identification and documentation of knowledge. In order to ensure the possibility of taking knowledge into account, applying and managing it, it is necessary to define knowledge, if possible document it - describe it, add it to the knowledge base and connect it with processes and specialists. It is advisable to involve the entire team of OKI SOU in this process. To ensure motivation on the part of specialists, it is advisable to introduce incentives for employees to share their knowledge and experience. Documenting knowledge is an important element of the concept, as knowledge that is not documented is easily lost. Various tools, instructions, knowledge base procedures can be used for the purpose of documentation. In the existing version, it can be maintaining a database or an internal portal for storing and distributing information for OKI SOU.

3. Dissemination and transfer of knowledge. The organization must develop an automated training system that takes into account and applies the principles of the concept of knowledge management. Such a system can include the creation of a training and development program that helps employees acquire new knowledge and skills, foresee the use of effective training methods, such as trainings, webinars, online courses and mentoring.

4. Knowledge, as a valuable asset, should be available to those members of the OKI SOU team who can use it. This requires shared access to information. This access can be organized by creating centralized information systems for accessing and sharing information between employees, using secure networks or special software for sharing access to resources.

5. The key element of implementing the concept of knowledge management is providing motivation for joint learning. The motive can be both material and moral encouragement, a correctly built career model, participation in the results of the SKI activity. Creation of motivational systems and rewards for those who actively share knowledge and teach others, encouragement of collective learning and exchange of experience should be ensured.

6. Knowledge, as a valuable asset, must be protected. Knowledge protection can be ensured by implementing confidentiality and protection of valuable information, developing policies to restrict access to certain types of knowledge, introducing relations in the organization that include the element of knowledge protection in the corporate culture of OKI.

7. Knowledge management, as a process, requires control and analysis. For this purpose, it is possible to introduce monitoring and evaluation of the results of knowledge base management, including measuring the impact of the implemented measures on the productivity and results of OKI SOU.

8. The culture of relationships in the team of OKI SOU (corporate culture) is an element of the automated management system (including knowledge base management) and is largely the result of the implementation of the knowledge management concept. Corporate culture will strengthen the organization's potential if it is based on openness and cooperation. The management of OKI SOU should encourage the spread of a culture in which employees feel that their opinions and ideas are important and their contributions are valued. This creates a favorable environment for the exchange of ideas and free communication.

Knowledge management in the field of information security and AI protection can face a number of problems and challenges. These include the rapid change in technologies and threats, as the security field is constantly evolving, and new technologies and threats to OSI

are emerging very quickly. This makes it difficult to constantly update the knowledge of the staff and train them in new methods of information protection, but at the same time it increases the importance of the very task of security of OKI SOU. Some staff members may not fully understand security threats or consider them to be serious. Such a situation may lead to insufficient compliance with security policies and rules for the use of information.

Insufficient funding for training and development of personnel in the field of security of OKI SOU leads to a systematic limitation of access to resources and training programs. Insufficient communication, insufficient exchange of information and knowledge between different parts of the organization can cause underestimation of threats and loss of opportunities for timely response to incidents of OKI SOU. Lack of clear and efficient automated knowledge management processes can lead to confusion and wasted time. Different SOU OKIs have different corporate cultures and structures, in organizations with a higher level of hierarchy, it is usually more difficult to implement knowledge base management initiatives that require an open exchange of information. Table 1 shows examples of the application of the concept of knowledge management at the level of the organization's development strategy.

Table 1. Application of the knowledge management system in the organization

Company	Implemented knowledge management system (KMS)	Implementation results
Microsoft	Own knowledge management solutions such as SharePoint and Microsoft Teams	These tools help teams work together on projects, share knowledge and documents, which increases work productivity
Siemens	A knowledge management system has been implemented, which covers knowledge sharing, employee training and collaboration between different departments	The organization increased innovativeness and ensured the efficiency of new product development. The system facilitates quick search and exchange of knowledge, improves communication and cooperation between departments and various business units of the company
IBM	IBM uses an advanced KM strategy to support its global teams, including forums, virtual communities and e-learning systems	This allows the company to quickly adapt to market changes, effectively manage projects and improve the qualifications of employees
Daimler AG	Developed a specialized platform for sharing knowledge and best practices between in-house engineers and third-party developers	More effective use of innovative technologies and solutions in various projects and company products is ensured
Novo Nordisk (Denmark)	Novo Nordisk actively invests in training and development programs for its employees, including internal academies and training centers	Professional development and development of employees' skills takes place, which has a positive effect on the company's productivity and innovation
Santander Bank (Spain)	The bank uses analytics and intelligent data analysis tools to better collect and process information about customers, products and market trends	Increasing efficiency in decision-making, improving the quality of customer service and optimizing the bank's internal processes
ABB (Switzerland)	ABB implements knowledge management solutions to integrate different databases, design systems and engineering tools to facilitate collaboration between specialists	More effective coordination of projects, reduction of time for development of new products and improvement of the quality of solutions

Leading international companies are actively implementing knowledge management strategies to increase efficiency, promote innovation, strengthen communications and improve decision-making processes. In each case, the strategies are adapted to specific business processes and the company's corporate culture, which ensures the maximum benefit from their implementation.

From the analysis of the materials in Table 1, it follows that knowledge management is the process of creating, distributing, using and storing knowledge in the organization in order to increase its capacity in all aspects of activity. The analysis shows that modern knowledge management systems are usually based on the use of automated information systems that are integrated into the organization's business processes. Successful implementation of the knowledge management strategy in the organization requires a systematic approach, management support and active participation of all employees. A correctly chosen and implemented knowledge management strategy is a powerful tool for increasing efficiency and achieving the strategic goal of OKI SOU.

Compliance monitoring and assessment systems should be implemented for all CAIs in the system. Methodical and educational materials should also be developed, as well as support measures should be implemented, under which a training system will emerge and be able to function, which will ensure the training of various specialists in a single paradigm of SKI.

The totality of these measures forms a system of personnel training in general for the CI protection system. At the moment, the system that is successfully operating in the USA belongs to the most developed systems for the protection of critical infrastructure. Its detailed description can be found in the document "National Infrastructure Protection Plan (NIPP)" (2013) on the website of the specialized government organization CISA (an agency within the structure of the US Department of Homeland Security responsible for the protection of critical infrastructure). The NIPP is a document that defines strategic goals, priorities and approaches to protect critical infrastructure such as energy systems, transport, communications and other critical sectors from various threats, including cyber attacks, natural disasters and acts of terrorism. The plan includes a description of the structure of governance and cooperation between the public and private sectors, as well as defines methods of risk analysis and measures to reduce them. It is regularly updated to take into account current threats and technological changes. It also defines the basic requirements for personnel involved in the performance of critical infrastructure protection tasks.

The advantage of the US critical infrastructure protection model is also that a series of national standards and frameworks (NIST, FISMA and others) have been developed for it, which contain a sufficient set of requirements and practices to cover most elements of CI protection.

It is possible to highlight the following features of this system:

1. The requirements for qualifications, knowledge and skills of specialists are based on the NIST standard 800-181 "Workforce Framework for Cybersecurity (NICE Framework)" (n.d.).
2. The specialties for which professional standards are developed in accordance with the general requirements of the standard are defined.
3. Separate functions are allocated for specialties, for which specialized training courses can be created, training and knowledge testing for which are implemented on automated training and testing systems.
4. Assessment centers are used to assess the suitability of specialists, and assessments of both the state and some non-state training centers (such as Cisco, Microsoft and some others) are valid.

Ukraine is currently implementing approximately the same model. NIST standards are recommended for use by the authorized body. Based on the NICE Framework standard, six professional standards have been developed and another fifteen professional standards are being prepared. A specialized Qualification Center was created and accredited, the task of which is to determine the compliance of qualifications with the requirements of professional standards in the field of information security. Measures are being taken to implement other important elements of the personnel training and evaluation system for the field of CI protection. It is possible to use automation tools in the training system itself. There are many training and testing systems for face-to-face and distance learning. Such systems function in most educational institutions, so there is no need to provide a detailed description of the example.

The main component of such an automated system is the training courses that they offer to the staff of OKI SOU. Such training courses should provide knowledge and skills that meet the qualification requirements of professional standards. The division of the profession into modules, each of which corresponds to a certain production function, will allow the formation of a flexible system of professional development, which can consist of 1-2 annual plans, according to which specialists will have the opportunity to obtain the necessary knowledge in full without a significant break from production.

Such centers can have a centralized knowledge base on methodical materials, accumulate exam materials, be connected to a network, contain monitoring elements and process training statistics, forming objective data on the state of professional readiness of the personnel of the entire segment of SKI.

Software can ensure the implementation of modern approaches to learning, include practice on simulation simulators, provide elements of the knowledge management system.

To improve productivity and automate personnel processes, primarily related to monitoring and selection, selection and promotion of OKI SOU personnel, hundreds of software and analytical platforms have been created on them.

Structurally, a typical training and testing center consists of the following blocks: a training and testing system and a training and testing class. The training and testing system is connected to an external network with network protection through a router. The central element of the training and testing system includes: a network management system, a software and technical system of training and testing, a video surveillance system for the testing process. The training and testing class has separate workplaces for methodologists and examiners, as well as for persons undergoing testing under video surveillance.

The basis of such software is business intelligence (BI) analytical systems, which are defined as computer methods and tools for organizations that provide the translation of transactional business information into a form accessible to users, suitable for business analysis, as well as tools for mass work with such processed information (Prokopenko *et al.*, 2020).

Leading positions in software development in this field belong to well-known leading companies: SAP, ORACLE, ADP, IBM. Also recently, a large number of new companies have been involved in this process.

The latest trends in the development of special analytical software for Business intelligence are the use of advanced information technologies based on cloud computing, which provides advantages in their use on various types of workstations and mobile devices.

In addition to the main list of functions for processing a large array of data (Big Data), some software and analytical applications may include the following opportunities for innovation:

1. Testing and assessment of personnel competence - intended for preliminary assessment of knowledge, abilities, skills, acquired qualifications of applicants for the position in order to select the best of them. The most popular software, which is in demand among many global companies in this field, is software and analytical platforms and services:

HackerRank - a platform for evaluating the competencies of labor resources by recruiting organizations for the selection and hiring of employees with the necessary qualities;

Pymetrics - a service that uses unbiased algorithms to find suitable candidates using gamified neurobiological tests. The service is on the market relatively recently, but has already proven itself well;

Self Management Group - human resource management software and analytics with integrated diagnostics and assessments to attract, manage and evaluate candidates.

2. Use of artificial intelligence. Use of artificial intelligence (AI) technologies in automated business analytical processes. The best services include:

Ideal - uses AI technologies to select candidates, analyzing complex information about them: resumes, evaluations and data on their performance;

Textio - a global system for the unification according to a single standard of the text data of published resumes of candidates, written according to different presentation and structure, and automatic correction of possible grammatical and syntactic errors in the text. The main feature offered by the system is the ability to detect patterns in language, helping personnel agencies to better select candidates.

3. Use of Applicant Tracking Systems (ATS) - candidate tracking system:

Bullhorn - a specialized analytical application designed for searching and selecting candidates;

SAP SuccessFactors - special software and information and analytical support for human resources management. The system uses technologies based on talent management methodology;

iCIMS - a complex of software for optimizing the work of personnel managers involved in the processes of personnel recruitment, promotion and career management;

Oracle Taleo Cloud Service - special software and information and analytical support for searching, recruiting, promotion and retention of qualified specialists with the help of a multifunctional software package;

Workday - a software system that combines accounting, personnel management and planning in a single cloud ERP system to improve business efficiency;

SmartRecruiters - special software and information and analytical support, which, due to the use of AI and social networks, allows personnel managers to effectively search for candidates and select qualified specialists in any part of the world.

In addition to BI-systems narrowly directed in the field of personnel management, there are universal systems, the capabilities of which allow conducting Big Data analysis in any field of activity. The most powerful business intelligence tools, according to the Gartner publication for 2020 and previous years, include the software products of Tableau, Qlik and Power BI companies.

Their main difference from ready-made BI solutions is slightly different approaches to the order of data processing, as well as their adaptability to any organizational requirements regarding the construction and implementation of dashboards at automated workplaces.

Information panels is an integral part of a BI system designed to visualize a large array of information that is analyzed in the form of graphs, charts and other forms of displaying quantitative information, which, in turn, simplifies awareness and helps management assess the real state of affairs and make an informed decision.

The use of in-memory processing technology (conducting analysis and calculations in RAM) and Business Discovery (business research module) in Qlik software products is quite functional, which allows analyzing business information at any level, avoiding time-consuming and expensive work from the construction of repositories and multidimensional OLAP cubes. Any calculations of the Qlik BI system are performed instantly even with very large volumes of information when a large number of users work simultaneously, which significantly increases work efficiency. Algorithms for building analytical models, their advantages and disadvantages are shown in Figure 2.

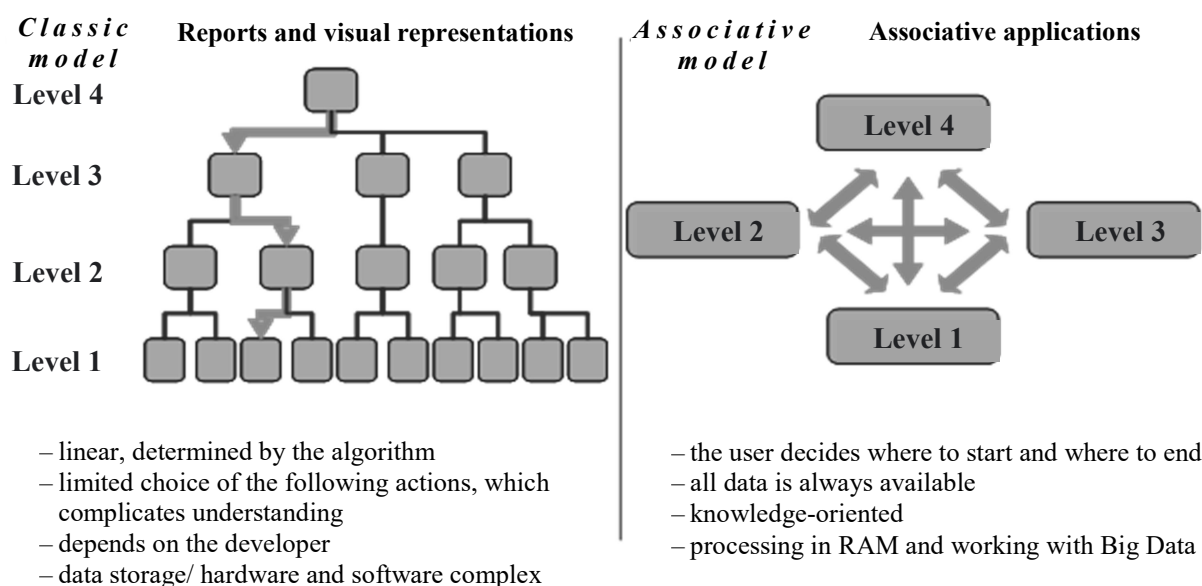


Figure 2. Algorithms for building analytical models

The associative architecture of the model will allow managing the relationships between data not at the application level, but at the level of the platform's internal mechanisms. The software in which this is implemented stores separate data tables and associative relationships between them in RAM, where each value of each field is related to all other values of the associative model. When creating new samples, the user sees: how the data is related to his request, data that is not included in the sample. This allows the user to work as comfortably as possible, answering new questions independently without the help of information technology specialists (Study of the problems, 2018).

The Qlik Business Discovery service allows you to analyze information in different information sections (by update time) and regardless of the automated personnel management systems in which this information is stored, to quickly deploy and scale even when using a large number of data sources, it includes joint analytics tools in real time.

Special attention during the construction of BI-systems is paid to their implementation. The main idea of this stage is that the implementation of the system should not take place at the final stage of its creation, but should be carried out in parallel from the very beginning of the creation of the system. The world's leading software developers are recommended to start development with a simple version, quickly put it into practice, and gradually improve and expand the automated system based on the experience gained from the interaction between the user, the system and the one who designs it.

So, for many organizations in the world of use BI-systems for processing large data sets (Big Data), designed for effective personnel management, especially aimed at finding, selecting and retaining qualified specialists, are increasingly becoming the norm every year, without which it is impossible to run an effective business to obtain maximum profits.

The use of special software and analytical support in the activities of personnel services of the OKI Secondary School at all levels of management of the organizational hierarchy will allow solving a number of problematic issues related to the acceleration of the pace of professionalization of the Defense Forces of Ukraine, improving the quality of staffing, transparency, objectivity and justification of personnel decisions of the OKI Secondary School, qualitative selection and promotion of the best candidates for key positions.

Based on the results of the assessment and determination of the required number of candidates for the Reserve for the respective positions, a rating is compiled (by majors, specializations, positions, ranks). Rating - a list of candidates compiled based on the results of the competitive selection based on the quantitative indicator of the points scored by them according to the principle of higher score to lower.

When compiling the rating, it is necessary to take into account:

- N-th number of parameters (indicators, evaluation criteria);
- the weight of each parameter and its possible influence on the overall result;
- the number of members (number of votes) participating in the compilation of the rating;
- the weight of each vote depending on the status of the member of the commission (chairman, expert in a given field, specialist of the highest category in the field of activity, boss, colleague, subordinate).

In theory, the rating is the lower bound of the Wilson confidence interval for the Bernoulli parameter, which can be determined by the formula:

$$\left(\hat{p} + \frac{z_{\alpha/2}^2}{2n} \pm z_{\alpha/2} \sqrt{\left[\hat{p}(1 - \hat{p}) + \frac{z_{\alpha/2}^2}{4n} \right] / n} \right) / (1 + z_{\alpha/2}^2 / n)$$

where: p is the share of positive evaluations; z – quantile of the standard normal distribution (an indicator characterizing the distribution of a random variable relative to the median); n is the total number of assessments.

According to this formula, the lower limit of the share of positive evaluations is estimated under the conditions of taking into account only positive and negative evaluations (that is, without taking into account the 5-point evaluation system).

At the same time, another mathematical apparatus known as Bayesian estimation (named after the author Thomas Bayes) can be used to determine the rating when applying statistical dependencies. This evaluation involves taking into account not only the average arithmetic value of the evaluations provided by the members of the commissions, but also their number:

$$\frac{\text{the number of votes}}{\text{the number of votes} + n} \times \text{GPA} \times \frac{n}{\text{the number of votes} + n} \times 7.2453$$

where 7.2453 is some average value that is taken as the basis of the method.

Compiling a rating of candidates is the main task of the commissions regarding the results of the evaluation in the selection process (Krill, 2018; Workforce Framework, n.d.; Prokopenko *et al.*, 2020).

Thus, the existing automated system makes it possible to ensure staffing at the necessary level to perform the tasks of OKI SOU as assigned.

Conclusions

Thus, for the successful management of the knowledge base in the field of critical infrastructure protection, when implementing knowledge management as a system for improving the qualifications of SOU personnel, it is important to implement strategies based, on the one hand, on the requirements of standards (Information security, 2022; Workforce Framework, n.d.), on the other - on implementation of knowledge base management principles as a process to which process management rules are applied. This may include ongoing training, building a safety culture, collaboration with other organizations and internal communication, and improving knowledge base management processes.

Implementation and compliance with the rules must be ensured and participated by the management of OKI SOU, all possible technologies and technical means must be applied, the knowledge base management process itself must be deeply integrated into the organization's business processes.

The staff should be motivated, have a desire for knowledge due to the possibility of obtaining career prospects and material remuneration. The listed conditions, combined into an automated system, will allow to increase the efficiency of the organization's activities and ensure the protection of OKI SOU under the condition of limited resources.

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Conflict of interest

None.

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СИСТЕМНИЙ ПІДХІД ДО АВТОМАТИЗАЦІЇ ПРОЦЕСІВ ЗАБЕЗПЕЧЕННЯ КОМПЕТЕНТНОСТІ ПЕРСОНАЛУ НА ОБ'ЄКТАХ КРИТИЧНОЇ ІНФРАСТРУКТУРИ СИЛ ОБОРОНИ УКРАЇНИ

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Анотація. Публікація присвячена проблемам автоматизації системи підбору та оцінки відповідності персоналу, що має забезпечувати безпеку об'єктів критичної інфраструктури Сил оборони України. В статті розглянуто основні нормативні документи, вимоги до персоналу та шляхи оцінки відповідності його знань, умінь і компетенцій. Враховані вимоги професійних стандартів, розроблених для сфери критичної інфраструктури Сил оборони України та захисту інформації. Ця робота має на меті визначити базові проблеми, пов'язані з добором кваліфікованого персоналу, оцінкою його відповідності та визначенням якості роботи в процесах діяльності. Матеріали статті стосуються саме об'єктів критичної інфраструктури Сил оборони України і розглядають особливості, пов'язані з процесами забезпечення безпеки критичної інфраструктури. Результати, отримані внаслідок проведеного аналізу проблем персоналу в сфері забезпечення безпеки об'єктів критичної інфраструктури, мають допомогти керівникам установ, організацій, підприємств, а також службам HR при формуванні та комплектуванні підрозділів, підготовці та розстановці кадрів. Розглянуто основні нормативні акти, що регулюють процеси захисту критичної інфраструктури, досвід розвинених країн, в першу чергу США та Європейського Союзу, стандарти безпеки (ДСТУ ISO/EN 27001, NIST Special Publication 800-181) та рекомендовані практики. Висновки містять рекомендації щодо автоматизації системи добору, підготовки та підвищення кваліфікації персоналу в сфері захисту об'єктів критичної інфраструктури, а також її інформаційної та кібербезпеки. Наведено рекомендації щодо удосконалення автоматизації процедур добору та розстановки кадрів, планування підвищення кваліфікації та створення системи професійної підготовки, що базується на системі управління знаннями.

Ключові слова: автоматизація, системи управління, захист критичної інфраструктури, компетентність персоналу, стандарти інформаційної безпеки, знання, навички, компетенції, управління знаннями.

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THE INFLUENCE PATTERNS OF NOZZLE DESIGN AND TECHNOLOGICAL PARAMETERS OF GAS-ASSISTED LASER CUTTING ON THE STAGNANT PRESSURE OF ASSISTING GAS

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Abstract. The paper proposes and implements a methodology for experimental measuring of the dimensions of the action zone and the amount of pressure, which ensures the removal of the liquid phase during gas laser cutting and is created by the flow of the assist gas on the surface of the part. During the research, based on a serial LTS-PRO-6000-1530-LD machine of Aramis company, serial one-channel and two-channel nozzles of Thermacut company with an outlet diameter of 1.5 mm were installed in the optical head of the machine. In the experiments, air with the gauge pressure at the nozzle inlet of 0.5 MPa and 1 MPa was used as the assist gas. The regularities of the influence of the nozzle design, the gap between the nozzle and the part, and the gauge pressure at the nozzle inlet on changes in the diameter of the supersonic jet of the assist gas and the amount of pressure it creates exerting the surface of the part under technological conditions of gas laser cutting have been established. The obtained array of experimental data has shown that the traditional approach to the use of the existing range of serial nozzles makes it problematic to effectively design gas laser cutting processes with maximum productivity and reproducibility of the cut quality. This is related to complex phenomena in the supersonic jet, which determine the high sensitivity of the pressure value on the part's surface to changes in the nozzle geometry and process technological parameters. As a result, there is no understanding of what kind of pressure is created by the jet of the assist gas in the cutting zone under certain technological parameters of the process. The methodology proposed in this paper makes it relatively easy to create "passports" for the nozzles that each machine is equipped with. Thus, it becomes possible to take into account the real value of the assisting pressure field in the cutting zone when designing a specific technological process. As a result, productive high-quality cutting is more

reliably ensured on a given technological installation and the level of process reproducibility is improved. Experimental verification has demonstrated a fairly good correlation between the local stagnant pressure of the assist gas jet and the maximum laser cutting speed and the cut quality.

Keywords: gas laser cutting, assist gas, nozzle, supersonic jet, fiber optic laser.

Introduction

In modern technological installations for gas-assisted laser cutting of metals, air of various pressures (0.2-2 MPa) and a wide range of nozzles, both in terms of design and geometric dimensions (Riveiro *et al.*, 2019), are widely used as an assist gas. The assist gas plays an important role in metal laser cutting technologies. In (Olsen, 2006) the maximum possible cutting speed for different workpiece thicknesses is determined as a function of the laser power and the assist gas jet pressure. That is, the pressure of the assist gas jet on the surface of the workpiece has a significant impact on the productivity and quality of the cutting process. This is because this pressure determines the parameters of melt removal from the cutting zone. Obviously, as the laser power increases, the material melting rate cannot exceed the rate of its removal (Halm *et al.*, 2021). Because of this, there are many works devoted to the various roles of the assist gas in gas-assisted laser cutting technologies. Some of them study the aerodynamics of supersonic assist jets (Darwish *et al.*, 2019), others focus on the parameters of jet interaction with the workpiece (Zhang & Gogos, 2004; Chen *et al.*, 2001). T. Qin *et al.* (2022) consider the role of gas jet pressure in laser cutting of carbon fiber reinforced plastics. In (Ullah *et al.*, 2022), during laser cutting of aluminum alloys, the assisting gas pressure is taken as the basic parameter for process optimization along with the radiation power and cutting speed.

Other scientists study the influence of the composition and purity of the gas. In the paper (Zhou *et al.*, 2016), authors study the role of supersonic nozzle in fiber laser cutting of stainless steel using Ar gas as an assist gas. It has been shown that the internal shape of the supersonic nozzle produces a stable jet at the outlet and may be better than a conventional nozzle if we plan to eliminate streaks on the workpiece area during fiber laser cutting. P. Wen *et al.* (2016) propose a method for designing a supersonic nozzle based on a two-dimensional isentropic calculation of the dynamic gas pressure. The use of oxygen as an assist gas should take place at full utilization of the combustion heat from the Fe-O reaction. The dynamic behavior of the oxygen and gas flow, determined by the nozzle structure and cutting parameters, is a key factor affecting productivity and cutting quality.

The role of the nozzle design in shaping the parameters of the assist gas jets is studied in (Fieret *et al.*, 1987). However, most researchers note that the potential of modern high-power (2-12 kW) fiber lasers is not always fully utilized due to the inefficient removal of molten material by the assist gas jet (Riveiro *et al.*, 2019). Therefore, many researchers conduct numerical experiments to model the process of removing molten material from a laser cut kerf (Yagi *et al.*, 2021). The results presented in this paper J. Pocorni *et al.* (2017) suggest that the cut front produced when cutting stainless steel with a fiber laser and a nitrogen assist gas is covered in slow moving humps which themselves are covered by a thin layer of faster moving liquid. M. Borkmann & A. Mahrle, (2021) showed that in cutting metals with solid-state lasers, a characteristic cutting edge structure is generated whose formation mechanisms still elude a consistent explanation. Several studies suggest a major contribution of the pressurized gas flow. Particular emphasis must be devoted to the gas boundary layer and its developing flow characteristics, since they determine the heat and momentum exchange between the cutting gas and the highly heated melt surface and thus the expulsion of the molten material from the kerf.

Hence, it is clear how important information about the pressure parameters in the cutting zone is when designing technological processes for a particular technological installation. Based on the above, the authors had a goal to develop a methodology and appropriate equipment and to conduct a set of studies that would allow determining for each nozzle design the change in pressure value under certain technological parameters of gas-assisted laser cutting.

This makes it clear how important information about the pressure parameters in the cutting zone is when designing efficient technological processes. Based on the above, the authors set goal to create a framework for more reliable provision of conditions for productive high-quality gas laser cutting using a specific technological installation and increase the level of process reproducibility. The goal is achieved by developing a methodology, appropriate equipment, and conducting a set of experimental studies to establish numerical regularities of the dynamics of changes in the diameter of the supersonic assisted gas jet and the pressure created by it in the cutting zone, depending on the nozzle design and specific process parameters.

Literature review

It is well known from the theory of gas dynamics that conical nozzles can provide a maximum jet velocity at the nozzle outlet equal to the speed of sound in the surrounding medium (Mach number = 1). For air, the condition for the assisting jet to reach the speed of sound at the nozzle tip is met if the ratio of the pressure inside the nozzle P_0 to the pressure of the surrounding atmospheric air P_a exceeds 1.89 ($P_0/P_a > 1.89$), i.e., in almost all possible cutting regimes. However, since under such conditions the static pressure in the jet always exceeds the atmospheric P_a , an additional expansion of the jet occurs immediately after the nozzle tip and, accordingly, its velocity becomes supersonic (Laval nozzle effect). At supersonic jet velocity, a shock wave is formed as a result of its reflection from the atmospheric air. Subsequently, the shock wave propagates in the form of a "barrel", in the lower part of which a gas compression zone is formed, which is commonly referred to as the Mach disk. Due to the reflection of the lateral shock wave from the surrounding air, a second "barrel" similar in shape to the first is formed behind the first Mach's disk. In a free-flowing jet, this structure can be repeated several times. Immediately after the Mach disk, the flow velocity of the assist gas becomes less than the speed of sound. Thus, the structure of the jet has a complex axisymmetric structure with significant fluctuations in diameter and flow rate (Fig. 1).

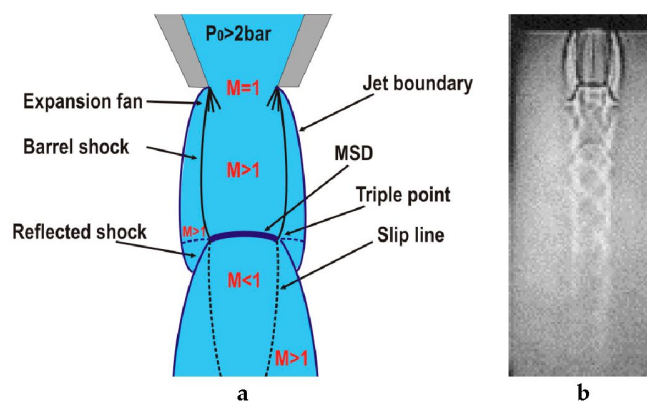


Figure 1. Scheme (a) and shadowgraph image (b) of the free jet emerging from a conical nozzle commonly used in laser fusion cutting for an operating parameter range $P_0/P_a > 1.89$ (Riveiro *et al.*, 2019)

The pressure of the assist gas (cutting pressure) on the surface of the workpiece is directly determined by the jet stagnant pressure. Uneven flow velocity and diameter along the length of the jet due to the formation of shock waves leads to fluctuations in the assist pressure on the surface of the workpiece in the cutting zone. This, in turn, affects the rate of molten material removal and, accordingly, the productivity and quality of cutting and definitely impairs the reproducibility of the process.

In the paper (Miller, 1988), the author proposes to determine the distance from the nozzle tip to the first Mach disk using the following empirical equation:

$$\frac{x_M}{d} = 0.67 \sqrt{\frac{P_0}{P_a}} \quad (1)$$

where x_M – distance from the nozzle tip to the first Mach disk;

d – outlet diameter of the nozzle;

P_0 – full pressure inside the nozzle;

P_a – atmospheric pressure.

The accuracy of this equation raises some doubts because it does not take into account the thermophysical parameters of the gas and the fact that the jet is not free in gas-assisted laser cutting. However, it is clear from the above that changes in the P_0/P_a ratio, the design and outlet diameter of the nozzle, and the stand-off between the nozzle and the surface of the workpiece lead to significant changes in the jet structure and, accordingly, uncertainty in the actual value of the cutting pressure of the assist gas. This uncertainty complicates the design of high-performance modes and worsens the level of process reproducibility even with minor changes in these parameters.

Materials and methods

Based on the above, the task was set to create an installation and an appropriate methodology that would allow obtaining sufficiently accurate experimental data on the patterns of change in the jet diameter and the value of the assisting pressure on the surface of the part when using a specific type of nozzle, model of technological installation, and parameters of the gas-assisted laser cutting process.

The general layout and 3D model of the research installation are shown in Fig. 2.

The proposed method of measuring the jet diameter and the pressure of the assist gas on the surface of the part is based on the use of a specially designed installation (Fig. 2, b). The installation is fixed on the working table of the machine (Fig. 2, a). The operator, using a tuning laser and feed drives, sets the nozzle of the optical head 1 so that the central axes of the nozzle and the force transmission cylinder 3 (structurally placed steplessly with respect to the top plate 2) coincide. Then the stand-off tracking unit determines the coordinate of the Z-axis when the nozzle's end face touches the surface of the cylinder 3, taking it as the zero reference point. A highly sensitive 0.01 mm thick copying film is fixed on the surface of the plate 2 by magnetic posts 5. The gauge pressure is set by the machine's pneumatic system and is additionally controlled by an external manometer. Sensor 7 measures the force from the jet 6 with an error not exceeding ± 0.00981 N. The prints from the jet pressure on the copying film were photographed and processed using CAD system. As a result, the error in determining the diameter of the assist gas jet on the surface of the part did not exceed ± 0.01 mm. Fig. 3 shows a sample of the results of measuring the jet diameters after one of the experiments. An optical fiber with a diameter of 0.5 mm was used as a reference for determining the spot diameters. The passport deviation of the optical fiber dimensions from the nominal value does not exceed 1 μm . The average stagnant pressure of the assisted jet was calculated by dividing the measured force by the spot area.

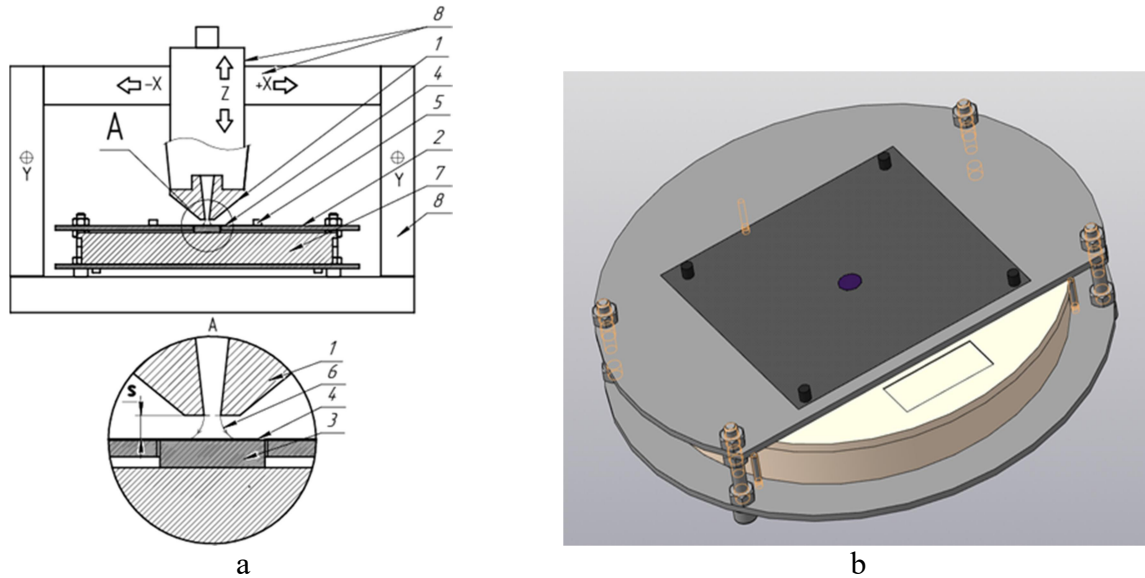


Figure 2. General scheme for measuring the jet diameter and assist gas pressure (a), 3D model of the installation for recording the jet diameter and assist gas pressure (b):

- 1 – single-channel and two-channel nozzles from Thermacut with an outlet diameter of 1.5 mm;
- 2 – top plate of the installation for recording the force of the assist gas pressure;
- 3 – cylinder for transferring the force from the action of the assist gas jet to the meter;
- 4 – copying film for recording the jet diameter; 5 – magnetic film fixation racks;
- 6 – a jet of assisting gas; 7 – force sensor;
- 8 – coordinate motion drives of the serial machine LTS-PRO-6000-1530-LD by LTD Aramis;
- s – controlled stand-off between the nozzle and cylinder 3

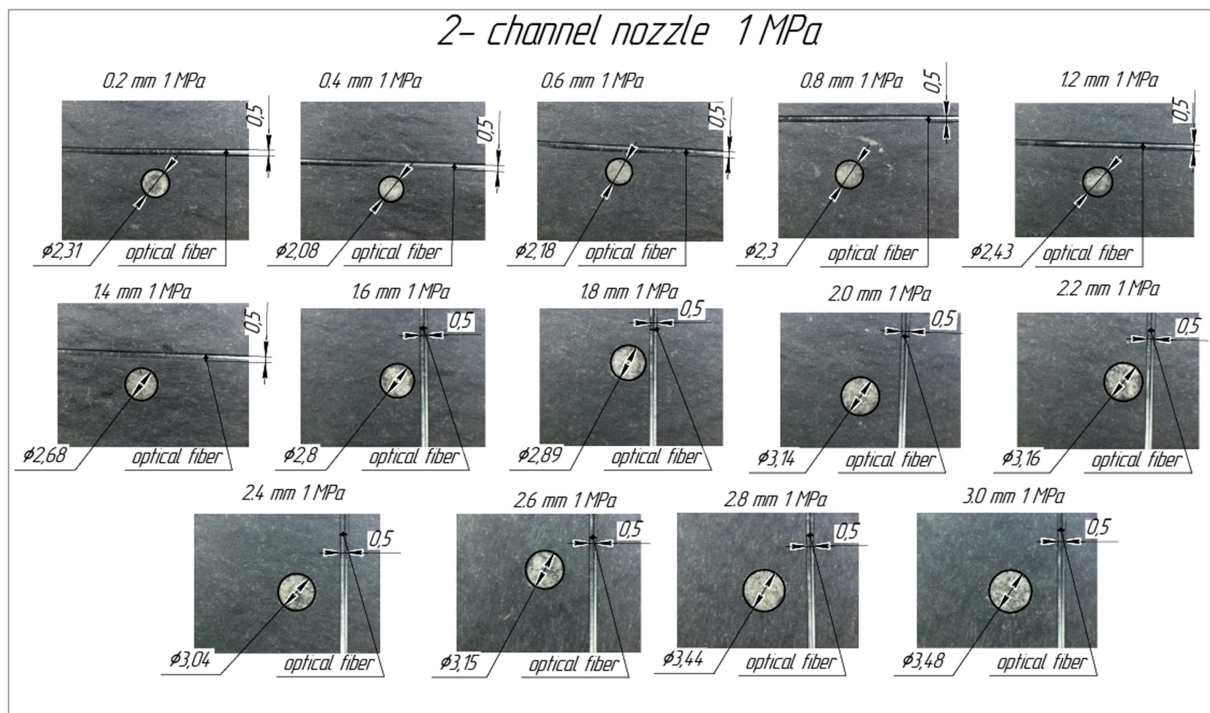


Figure 3. Results of determining the diameter of the assisting gas jet using CAD system

The studies were carried out using the serial machine LTS-PRO-6000-1530-LD from Aramis. The optical head of the machine was equipped with serial single-channel and dual-channel nozzles from Thermacut with an outlet diameter of 1.5 mm (Fig. 4). In the experiments, air with a gauge pressure at the nozzle inlet of 0.5 MPa and 1 MPa was used as an assisting gas.

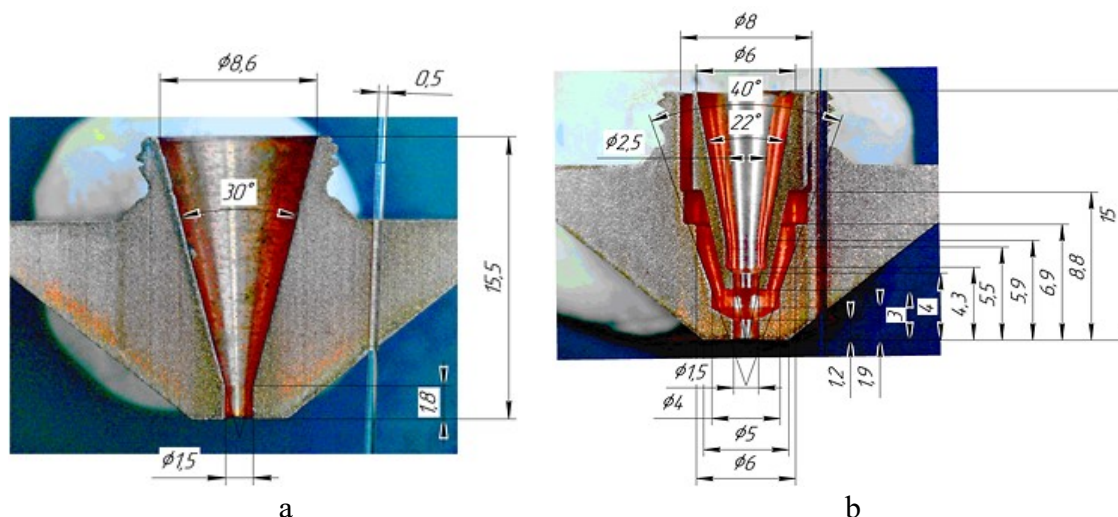


Figure 4. Configuration and geometric dimensions of Thermacut's standard single-channel (a) and dual-channel (b) nozzles with a center bore diameter of 1.5 mm

The value of the stand-off s between the nozzle section and the force transmission cylinder 4 of the recording system (Fig. 2) was set and controlled by the stand-off tracking system of the LTS-PRO-6000-1530-LD serial machine with an error of ± 0.01 mm.

Results and discussion

A series of experiments was conducted to determine the regularity of the influence of the nozzle design, the stand-off between the nozzle and the workpiece, and the gauge pressure at the nozzle inlet on the size and nature of the change in the diameter of the assist gas jet and the amount of cutting pressure created by it on the surface of the workpiece. The main results are shown in Figs. 5-7. All experiments were repeated three times. The maximum variation of the obtained values did not exceed 3 %.

A detailed analysis of the obtained results showed the following. At $P_n = 0.5$ MPa (Fig. 5, curve 3), when the stand-off between the nozzle and the workpiece changes from 0.2 mm to 3 mm with a step of 0.2 mm when using a dual-channel nozzle, the diameter of the assist gas jet remains relatively stable. The changes are oscillatory with a slight downward trend. The slope coefficient of the approximating line (as a general estimate of the trend) is $\gamma = -0.062$ (Fig. 6, a). An increase in the overpressure in the nozzle to $P_n = 1$ MPa (Fig. 5, curve 4) already significantly affects the change in the diameter of the assist gas jet. An increase in diameter is observed compared to $P_n = 0.5$ MPa in the entire range of stand-offs. While maintaining the oscillatory nature of the changes, there is a clear tendency to increase the diameter with an increase in the stand-off s . The slope of the approximating line is $\gamma = 0.5$ (Fig. 6, b).

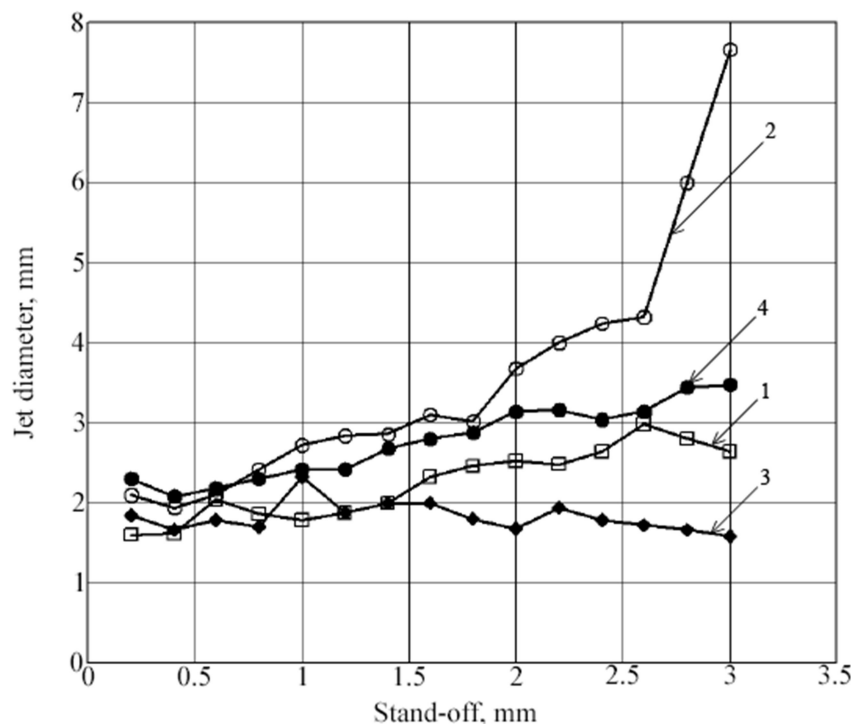


Figure 5. Change of the jet diameter in the contact area with the workpiece surface depending on the stand-off between the nozzle and the workpiece:

- 1 – single-channel nozzle, gauge pressure $P_n = 0.5$ MPa; 2 – single-channel nozzle, gauge pressure $P_n = 1$ MPa; 3 – dual-channel nozzle, gauge pressure $P_n = 0.5$ MPa; 4 – dual-channel nozzle, gauge pressure $P_n = 1$ MPa

As expected, the results obtained in the study of a single-channel nozzle under the same conditions differ from the dual-channel nozzle. At $P_n = 0.5$ MPa with stand-offs from 0.2 mm to 1.4 mm, the parameters of the jet diameter change are close to the results of the dual-channel nozzle. Subsequently, when the stand-offs increase from 1.4 mm to 3 mm, the single-channel nozzle forms significantly larger jet diameters (Fig. 5, curve 3). The slope of the approximating line is $\gamma = 0.464$ (Fig. 6, c).

When using a gauge pressure of $P_n = 1$ MPa in the range of stand-offs of 0.2 mm to 0.8 mm, the parameters of the change in jet diameter are close to the results of the dual-channel nozzle (Fig. 5, curve 4). When the stand-off changes from 0.8 mm to 1.8 mm, a relatively slight increase in the jet diameter is observed compared to the dual-channel nozzle. With an increase in the stand-off from 1.8 mm to 2.6, the excess already increases significantly, and the oscillatory nature of the change in the jet diameter disappears. From 2.6 mm to 3 mm, there is an abrupt linear increase in diameter (from 4.32 mm to 7.65 mm).

It can be stated that the flow practically "scatters". The slope coefficient of the approximating line is $\gamma = 1.556$ (Fig. 6, d). It is worth noting that the results obtained generally confirm the known solution to the problem of jet narrowing. The essence of the solution is to surround the central jet with a gas flow flowing from a slotted annular contour whose diameter is several millimeters larger than the diameter of the central jet. This led to the development of dual-channel nozzles. The component of the flow velocity from the annular contour is directed radially with respect to the nozzle axis and thus limits the expansion of the central jet.

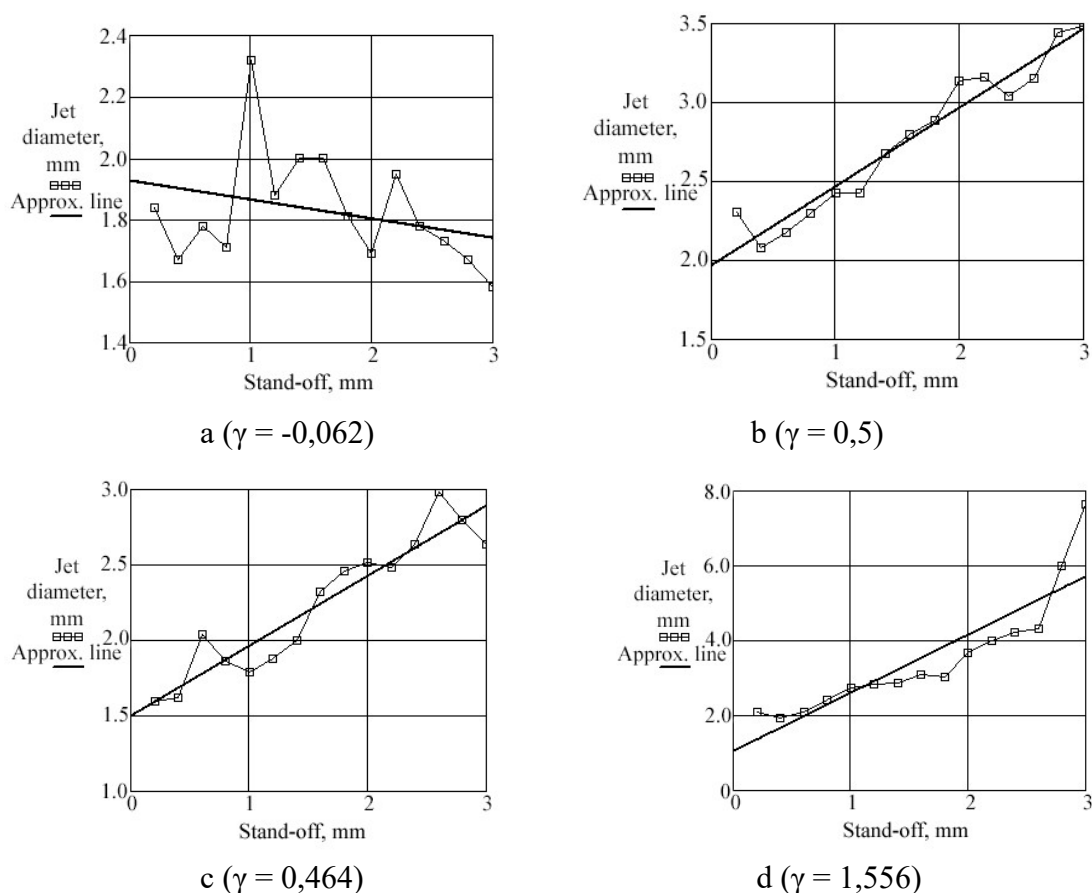


Figure 6. Approximating lines of graphs of changes of the jet diameter in the processing surface contact area depending on the gap between the nozzle and the part. Obtained using the Mathcad:

a – (dual-channel nozzle, $P_n = 0.5$ MPa); b – (dual-channel nozzle, $P_n = 1$ MPa);
c – (single-channel nozzle, $P_n = 0.5$ MPa); d – (single-channel nozzle, $P_n = 1$ MPa)

The obtained graphs of the assist gas pressure change are shown in Fig. 7. When using a single-channel nozzle and $P_n = 0.5$ MPa (Fig. 7, curve 1), when the stand-off changes from 0.2 mm to 1 mm, the cutting pressure of the assist gas increases oscillatingly and reaches a maximum at a stand-off of 1 mm (444 kPa). After that, it drops rather smoothly and oscillatingly. Thus, for a given nozzle with $P_n = 0.5$ MPa, a 1 mm stand-off is optimal in terms of maximum process productivity. There is a zone of relatively stable pressure at stand-offs of 0.8 mm – 1.2 mm (411 kPa – 444 kPa).

An increase in the overpressure in the nozzle to $P_n = 1$ MPa (Fig. 7, curve 2) leads to a local maximum of cutting pressure at a stand-off of 0.4 mm (686 kPa) with a sharp drop to 443 kPa at a stand-off of 0.6 mm. The second local extreme of the cutting pressure is observed at a stand-off of 0.8 mm (502 kPa). With a further increase of the stand-off, the cutting pressure drops oscillatingly. Moreover, at some stand-offs, the cutting pressure at $P_n = 1$ MPa is lower than at $P_n = 0.5$ MPa ($s = 1$ mm, $P_n = 1$ MPa – 409 kPa, $P_n = 0.5$ MPa – 444 kPa). Thus, when using this type of nozzle, increasing the gauge pressure from $P_n = 0.5$ MPa to $P_n = 1$ MPa will give a significant increase in cutting pressure only at stand-

offs as close as possible to 0.4 mm (+320 kPa). But at such stand-offs, there is a risk of rapid clogging of the nozzle or damage to the protective glass of the optical head. In the range of 0.6 mm – 0.8 mm, an increase in the pressure at the nozzle inlet gives a significantly lower increase in cutting pressure (+105.5 kPa ... +91 kPa). From the point of view of achieving maximum cutting performance, the use of this type of nozzle for stand-offs larger than 1 mm makes no sense.

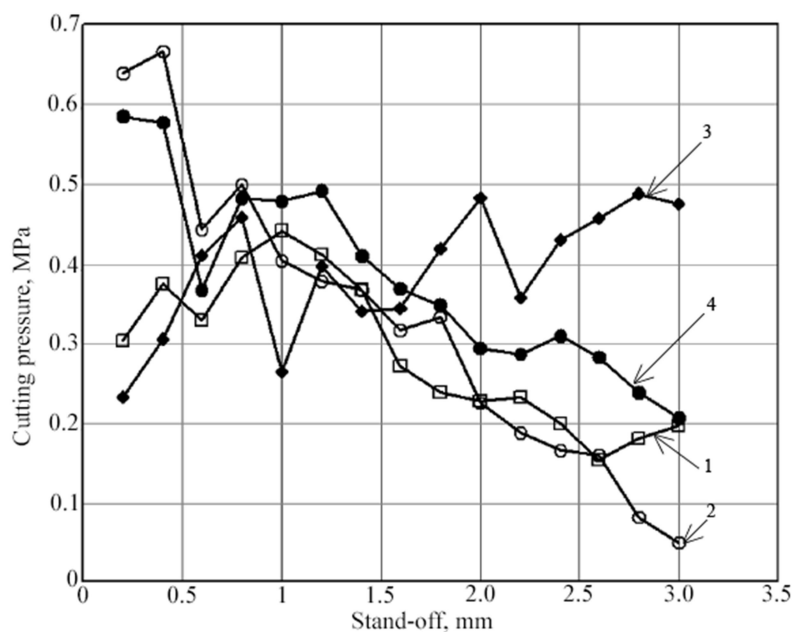


Figure 7. Change of cutting pressure on the surface of the workpiece depending on the stand-off between the nozzle and the workpiece:

- 1 – single-channel nozzle, gauge pressure $P_n = 0.5$ MPa; 2 – single-channel nozzle, gauge pressure $P_n = 1$ MPa; 3 – dual-channel nozzle, gauge pressure $P_n = 0.5$ MPa; 4 – dual-channel nozzle, gauge pressure $P_n = 1$ MPa

When using a dual-channel nozzle and $P_n = 0.5$ MPa (Fig. 7, curve 3), a close to linear increase in cutting pressure is observed when the stand-off changes from 0.2 mm to 0.8 mm with a local extremum at a stand-off of 0.8 mm (477 kPa). After that, at a stand-off of 1 mm, the cutting pressure drops sharply (267 kPa). With a further increase in the stand-off, the changes in cutting pressure are oscillatory in nature with an extreme at a stand-off of 2 mm (491 kPa). This is followed by a characteristic sharp drop in pressure at a stand-off of 2.2 mm (369 kPa), followed by a smooth increase to a maximum value at a stand-off of 2.8 mm (510 kPa). Moreover, a certain stability of the cutting pressure (465 kPa – 510 kPa) is observed over a relatively wide range of stand-offs from 2.6 mm to 3 mm. Based on the above, it is easy to conclude that when using this nozzle and an overpressure of $P_n = 0.5$ MPa, the condition for ensuring maximum process performance is cutting at stand-offs of 2 or 2.8 mm.

An increase in the overpressure in the dual-channel nozzle to $P_n = 1$ MPa (Fig. 7, curve 4), as in the case of a single-channel nozzle, gives a local maximum cutting pressure at stand-offs of 0.2 mm ... 0.4 mm (598 kPa ... 594 kPa), which is, however, lower than that for a single-channel nozzle. Then there is a pressure drop at the stand-off of 0.6 mm to 370 kPa.

The achieved pressure value is lower than the corresponding value for a single-channel nozzle. At the stand-offs of 0.8 mm to 1.2 mm, a zone of sufficiently high, stable cutting pressure (483 kPa to 496 kPa) is observed. In the range of 1.2 mm – 3 mm stand-offs, there is a smooth oscillating decrease in cutting pressure without sharp extremes. Thus, when using this type of nozzle, doubling the overpressure at the nozzle inlet, as in the case of a single-channel nozzle, results in a significant increase in cutting pressure only at stand-offs of 0.2 mm - 0.4 mm, which are quite risky in terms of a high probability of damage to the nozzle or the protective glass of the optical head. The extremes of the cutting pressure at the stand-offs acceptable for trouble-free cutting at the excessive nozzle inlet pressures of $P_n = 0.5$ MPa and $P_n = 1$ MPa are practically the same.

To experimentally verify the results obtained, test samples of carbon steel with a thickness of 1 mm were cut on a serial LTS-PRO-6000-1530-LD machine from Aramis using a dual-channel nozzle with a diameter of 1.5 mm. The experiments determined the maximum straight cut speed with acceptable side surface quality (Fig. 8).



Figure 8. Photographs of the side surface of test specimens made of carbon steel with a thickness of 1 mm:

a – radiation power $N = 3$ kW, cutting speed $F = 28000$ mm/min, overpressure $P_n = 1$ MPa, monitored stand-off $s = 1.2$ mm; b – radiation power $N = 3$ kW, cutting speed $F = 24000$ mm/min, overpressure $P_n = 1$ MPa, monitored stand-off $s = 2$ mm;

The data shown in Fig. 8 demonstrate a fairly good correlation between the cutting pressure of the stagnant gas jet (Fig. 7) and the maximum laser cutting speed. The absence of dross and obvious damage to the side of the cut surface was considered acceptable quality. A drop in the cutting pressure from 496 KPa ($s = 1.2$ mm) to 296 KPa ($s = 2$ mm) leads to a decrease in the maximum cutting speed from 28000 mm/min to 24000 mm/min. Visual analysis also shows a clear deterioration in the side surface roughness of the test samples. Thus, the data shown in Fig. 8 demonstrate a fairly good correlation between the cutting pressure of the stagnant gas jet (Fig. 7) and the maximum laser cutting speed and quality.

Conclusions

1. The developed methodology and a series of experimental studies made it possible for the first time to establish quantitative dependences of the diameter of the supersonic jet of the assisted gas (air) and the cutting pressure in the machining zone created by its stagnation on the surface of the part on the design of the nozzle, the stand-off between the nozzle and the part, and the pressure at the nozzle inlet.

2. The established numerical regularities of the dynamics of changes in the diameter of the supersonic assisting gas jet under conditions of gas-assisted laser cutting have shown that a dual-channel nozzle, compared to a single-channel one, significantly reduces the jet

expansion over the entire range of changes in the studied parameters. These results are consistent with the data known in the literature.

3. The obtained array of experimental data showed a complex oscillatory nature of the change in cutting pressure depending on the stand-off size, individual for each nozzle design and the overpressure value at its inlet. In the range of stand-offs from 0.2 mm to 3 mm selected for the study, the differences in maximum and minimum cutting pressures exceeded 100 %. That is, with the traditional use of the existing range of serial nozzles, without the results obtained in the experiments, it is impossible to predict at the design stage of the technological process what kind of pressure is created by the jet of the assisting gas in the cutting zone under specific technological conditions. In practice, this makes it problematic to effectively design gas-assisted laser cutting processes for maximum productivity and reproducibility of cutting quality.

4. Experimental verification of the obtained results was carried out on a serial machine LTS-PRO-6000-1530-LD by Aramis during gas-assisted laser cutting with maximum process productivity. The verification showed a good correlation between the local stagnant pressure of the assisting gas jet and the maximum laser cutting speed and the quality of the side surface.

5. In the future, the use of the methodology proposed in this paper makes it relatively easy to obtain a set of graphs of changes in cutting pressure for each nozzle that is equipped with the machine. This will give an understanding of what kind of pressure the jet of assisting gas creates in the cutting zone under certain technological parameters of the process. Accordingly, it will be possible to more reliably ensure productive high-quality cutting at a particular technological installation and improve the level of process reproducibility.

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ЗАКОНОМІРНОСТІ ВПЛИВУ КОНСТРУКЦІЇ СОПЛА ТА ТЕХНОЛОГІЧНИХ ПАРАМЕТРІВ ГАЗОЛАЗЕРНОГО РІЗАННЯ НА ТИСК ГАЛЬМУВАННЯ АСИСТУЮЧОГО ГАЗУ

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Анотація. В роботі запропонована та реалізована методика експериментального вимірювання розмірів зони дії та величини тиску, який забезпечує видалення рідкої фази при газолазерному різанні і створюється потоком асистуючого газу на поверхні деталі. При проведенні досліджень на базі серійного верстата LTS-PRO-6000-1530-LD фірми Арамис в оптичній головці верстата встановлювалися серійні сопла (одноканальне та двоканальне) компанії Thermaxcut з вихідним діаметром 1,5 мм. В експериментах як асистуючий газ використовували повітря з манометричним тиском на вході в сопло 0,5 МПа та 1 МПа. Встановлено закономірності впливу конструкції сопла, зазору між соплом і деталлю та манометричного тиску на вході в сопло на зміни діаметра надзвукового струменя асистуючого газу та величину тиску, який він створює при гальмуванні на поверхні деталі, за технологічних умов газолазерного різання. Отриманий масив експериментальних даних показав, що традиційний підхід до використання існуючого спектра серійних сопел робить проблематичним ефективне проектування процесів газолазерного різання максимальної продуктивності та відтворюваності якості різі. Це пов'язано зі складними явищами в надзвуковому струмені, які визначають високу чутливість величини тиску на поверхні деталі до змін геометрії сопла та технологічних параметрів процесу. В результаті немає розуміння, яку саме величину тиску створює струмінь асистуючого газу в зоні різання за тих чи інших технологічних параметрів процесу. Запропонована в роботі методика дозволяє відносно просто створити «паспорти» сопел, якими комплектується кожний верстат. Таким чином стає можливим урахування реальної величини поля асистуючого тиску в зоні різання при проектуванні конкретного технологічного процесу. Відповідно, надійніше забезпечується продуктивне високоякісне різання на цій технологічній установці та покращується рівень відтворюваності процесу. Експериментальна верифікація продемонструвала досить добру кореляцію між локальним тиском гальмування асистуючого газового струменя та максимальною швидкістю лазерного різання і якістю різі.

Ключові слова: газолазерне різання, асистуючий газ, сопло, надзвуковий струмінь, оптоволоконний лазер.