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Зміст / Contents

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Performance optimisation techniques for Conflict-free Replicated Data Types (CRDT)

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Abstract. The research relevance is determined by the need for distributed data handling optimisation that does not cause conflicts during replication, since the introduction of such types of data leads to an increase in the need for their optimisation and performance. The study aims to develop techniques to improve the efficiency of various types of data with conflict-free replication. To achieve this goal, the methods of analysis and experimentation were used. The study results demonstrate that the use of certain optimised methods of conflict-free data types in replication leads to a significant improvement in efficiency and reduction of resource costs. The results show that caching and precomputation, asynchronous synchronisation, and local processing are the most effective methods for improving the efficiency of Conflict-free Replicated Data Types. It is established that the choice of a specific method for improving the performance of Conflict-free Replicated Data Types should be justified and based on a careful analysis of the requirements and characteristics of a particular distributed system. This takes into account user needs, data criticality, edit frequency, etc. The research includes the development and optimisation of synchronisation algorithms that significantly improve the performance of these types of data in distributed systems. The work includes simple software implementations for detailed analysis and study of methods for optimising the performance of data types in conflict-free replications. The introduction of distributed computing has made it possible to optimise the processes of data replication and synchronisation, which helps to reduce overheads and improve system performance. It is concluded that the study is of practical importance since the use of optimised conflict-free data types with replication in real distributed systems can improve their efficiency and reliability. The practical significance of the study lies in the possibility of applying optimised methods of data types with conflict-free replication in real distributed systems, which will increase their performance and ensure efficient operation under conditions of high load and limited resource potential

Keywords: ways to increase performance; data replication; distributed systems; synchronisation efficiency; data synchronisation methods

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INTRODUCTION

Modern information systems require superior performance and reliability for the replication of large data amounts and synchronisation across distributed systems. CRDTs (Conflict-free Replicated Data Types) are known for said reliability, as they combine replication and conflict resolution. They are abstract data structures that can be replicated and synchronised between different nodes in a network without the need for centralised control. However, despite the potential benefits of CRDTs, there are issues related to their performance and scalability in real-world applications. It is these aspects that are of interest to researchers and developers, as improving the performance and efficiency of CRDTs can have a significant impact on distributed systems. In this context, studying ways to improve the performance of CRDTs becomes an urgent problem for researchers and practitioners.

With the rapid growth of data volumes and distributed systems in the modern world, conflict-free data types of research are becoming increasingly relevant. Implementing conflict-free data replication systems requires a constant search for efficient synchronisation and optimisation methods, especially under heavy loads. This topic becomes especially relevant due to the need to ensure performance and reliability in distributed systems, where data access must be ensured even in the absence of stable communication and in the face of conflicts and failures. In addition, innovations in this area can solve the current challenges of the modern Internet of Things, streaming data processing, and improve the reliability and performance of cloud services, making this topic critical for the further development of the information society. In general, the results of the conflict-free CRDT data types of study can improve performance and reduce resource costs when using CRDT in distributed systems, which will be of great practical importance in the modern information environment.

The research problem at this stage is becoming more relevant and complex, as existing CRDT synchronisation and replication methods demonstrate limitations that seriously restrict their performance and scalability. This necessitates the development of more efficient and optimised synchronisation methods to ensure the reliability and stability of distributed systems. In addition, the overheads associated with CRDT replication and synchronisation processes are coming to the fore and are becoming important factors that can affect the performance and speed of distributed applications. Given that even small delays in the synchronisation process can cause conflicts and loss of data compatibility, research in this area is becoming key to ensuring the quality and reliability of distributed systems in the modern information landscape.

Previous research on CRDT determined challenges and limitations, but many aspects remain unexplored. For instance, A. Lutsenko (2020) explored models of conflict-free replicated data types to resolve conflicts between replicas and their use in mobile collaborative offline applications for text documents. The author also developed a software application for creating and editing text documents in a collaborative mode, and analysed experimental data. N. Boliubash and M. Olinyk (2023) investigated certain performance improvement techniques for a progressive web application. To optimise performance, they use analysis and synthesis methods, methods for developing progressive web applications, and methods for optimising their performance. B.O. Biletskyy (2019) discussed the main stages of machine learning, including data collection and storage, training, and evaluation. The study determined that special CRDT data structures are essential in building NoSQL DBMSs (database management systems) to solve the problems of parallel modification of shared resources and always resolve inconsistencies.

Y. Kordiaka and O. Padko (2021) addressed the development of collaborative software for editing text documents in real-time, using conflict-free replicated data types. This study describes in detail the implementation of CRDTs and their application to enable the synchronisation and collaboration of users on shared text documents in a networked environment. V. Ryabushkin (2020) implemented a system for automatic conflict resolution in text using CRDT. The author emphasises that CRDT can be automatically replicated in a parallel application without the need to manually resolve conflicts. V. Shynkarov (2023) reviewed the main optimisation approaches and their applications. The author describes linear programming methods for solving optimisation problems and also considers nonlinear optimisation methods. In contrast to the above studies, which focus on either conflict-free data types or general optimisation methods, this study focuses on methods for improving CRDT and their development.

The aims of the study were to develop approaches to improving the performance of conflict-free replication data to reduce overheads and increase the speed of data replication in a distributed system. Synchronisation efficiency, scalability, and optimisation methods development for various algorithms to improve performance and reduce resource costs in systems using CRDT were addressed.

LITERATURE REVIEW

The issue of distributed data optimisation and replication is relevant in the modern information society. The growth of data volumes and distributed computing has led to an increased demand for efficient methods to ensure the availability, reliability and performance of these systems. Previous studies on this topic point to several key aspects that should be considered. These include the importance of ensuring data integrity during replication, minimising resource consumption when synchronising replicas, and ensuring the high performance of distributed systems.

For instance, B. Portela *et al.* (2023) investigated the use of CRDTs in distributed systems. The authors propose an approach to secure data in CRDTs using secure multi-party computation (MPC). The results include extending formal models of CRDT security, proving the security of such designs using MPC, and developing a language and type system for creating secure CRDTs.

Yu. Mao *et al.* (2022) considered the possibility of using the reversal of operations in CRDTs to achieve strong final consistency (SEC) in distributed systems. The authors defined the concept and design of reversible CRDTs that allow for the reversal of changes made. They also proposed different reversal methods for implementing reversal operations and discussed the impact on system performance. D. Adas and R. Friedman (2021) discussed CRDT sketches for storing statistics about data flows and their application in distributed systems. The authors present CRDT algorithms for implementing such sketches and analyse their performance based on real-world tasks.

G. Zakhour *et al.* (2023) described the concept of CRDTs that ensure the compatibility of replicated data and the absence of conflicts between replicas, and propose a programming language Propel with a special type of system for automatic verification of the algebraic properties of CRDTs. They presented successful verification of CRDT implementations and compared it with other verification tools. N. Saquib *et al.* (2021) presented CRDT employment to ensure strong determination of replicated data in distributed systems. CRDTs allow for resolving conflicts between replicas without additional coordination and provide high data availability. The study also discusses the importance of using CRDTs to achieve strong condemnation and demonstrates their effectiveness in realistic distributed system scenarios.

I. David and E. Syriani (2022) addressed the growing need for real-world collaborative modelling in engineering and proposed a framework for this. The framework is based on conflict-free replicated data types that provide scalable and reliable replication mechanisms. The authors demonstrate the benefits of their framework through a model example and compare it with other state-of-the-art modelling solutions. M. Nicolas *et al.* (2022) investigated the use of CRDT in distributed systems to ensure high availability. They point out the problem of the growing size of identifiers in CRDTs and propose a new CRDT sequence with a renaming mechanism that reduces the overhead and improves system performance over time. Experimental results confirm the effectiveness of this mechanism.

D. Brahneborg *et al.* (2022) addressed distributed CRDT systems with read and update operations without synchronous network requests. However, most CRDTs are based on atomic dispatch, which can be excessive for independent CRDT objects. This study proposes a replication protocol, CReDiT (CRDT enhanced with intelligence), which effectively exploits the switchability of CRDTs and reduces the complexity and network load compared to atomic broadcasting. CReDiT uses fewer communication steps and is less sensitive to server failures, ensuring efficient data replication. A. Tranquillini (2022) proposed a method for structuring the state of mobile applications using Redux and strongly typed languages, which allows the use of CRDT to create a coherent state. This enables replicas to edit their state autonomously and merge conflicts. The study also considers the use of a server as a communication channel and analyses the impact of this architecture on the design and optimisation of CRDTs. The analysis of the listed studies indicates the relevance of the CRDT topic. However, the research also highlights the need for further study of data types with conflict-free replication and the creation of methods to optimise their performance.

MATERIALS AND METHODS

The research was conducted using the analysis and experimentation methods. The analysis method was used to address the theoretical aspects of CRDT employment in distributed systems. This method was used to analyse studies of various authors on this topic, the mathematical properties of CRDT, synchronisation algorithms, and other theoretical foundations that underlie data types with conflict-free replication. The analysis is necessary for a deeper understanding of theoretical concepts related to CRDTs and their possible applications in distributed systems. The analysis of the mathematical properties of conflict-free data types determined in detail the mathematical foundations of CRDT, such as commutativity and associativity of operations. The study of synchronisation algorithms allowed to learn CRDT synchronisation algorithms, including their mechanism for resolving conflicts and ensuring data consistency. The analysis of possible applications in distributed systems helped to identify possible areas of application of CRDT in distributed systems and assess their potential impact on data integrity and performance.

The experimental method conducted as part of this study included the implementation of data type-specific approaches using conflict-free replication methods in distributed systems. During the experiment, actual distributed systems were implemented that used CRDT structures to ensure data integrity and avoid potential conflicts between replicas. The results of the comparative analysis of different CRDT implementations determined the advantages and limitations of each approach. The VS Code development environment and the JavaScript programming language were used to implement software solutions and conduct the experiment. Furthermore, the Cross-Platform File Format Apps platform was used to visualise the structural scheme of the local processing method. An important element of the study was the mathematical formula and task for the caching and precomputation method, as well as a table with the analysis and subsequent comparison of the results for asynchronous synchronisation. This made it

possible to obtain objective information about the performance and efficiency of the considered methods in practical conditions.

Thus, analysis and experimentation methods were used to develop methods of local processing, caching and pre-computation, and asynchronous synchronisation. Their advantages and disadvantages are described. Programme operation containing a local copy of data as an object and data update processing, a method of combining local copies of data from other replicas, identical updates, adding the result to the cache, checking the result, calculating and storing the result in the cache, simulating the calculation of a value by key, obtaining calculated values for users, an asynchronous method of applying an update from another replica, and asynchronous replica merging is described. The task of improving the performance of the online store and the formula for the caching and pre-calculation method are explained. Formula (1) illustrates how reducing data access time affects the speed of query handling:

$$S = k / T\_access, \quad (1)$$

where S – query handling speed; T_access – data access time; k – proportionality constant that determines the amount of influence of access time on handling speed.

The main components of the structural diagram were also shown, namely the internal structure of the replica, the processes of local processing of changes and saving the results, which include a local copy of the data, a change log, making changes, local processing, conflict resolution, and change results.

RESULTS

Conflict-free data types of performance improvement methods in replication. Modern distributed systems require a reliable and efficient mechanism for synchronising data between different replicas. CRDTs, which provide conflict resolution and data integrity, are a powerful solution for achieving these goals. However, improving their performance and optimising them can create new perspectives for distributed systems.

CRDT performance optimisation is relevant in the context of distributed systems, where data consistency and performance are crucial. The performance of data types with conflict-free replication has certain advantages and disadvantages. The advantages include ensuring conflict resolution and data integrity, increasing replication performance and speed, and reducing resource usage. In other words, optimisation techniques can improve the CRDT conflict handling efficiency, which ensures the reliability and integrity of replicated data. They are designed to reduce the overhead of synchronising data between replicas, which leads to improved system performance. Some methods are designed to speed up the data replication process by reducing transmission and processing time for updates. Optimisation techniques can also reduce the memory and computing resources required to store and synchronise data. The disadvantages are the complexity of implementation, the possibility of new problems, context-specific dependencies, and the possibility of losing some CRDT guarantees. Some optimisation methods may be difficult to implement, requiring additional effort from developers. Optimisation may lead to new problems or deteriorate other aspects of the system, which requires careful analysis and testing. The effectiveness of such methods may depend on the specific use case and system characteristics. Optimisation itself may lead to the loss of some guarantees, such as strong final consistency, which requires careful analysis and balance.

The following methods can be used to optimise the efficiency of data types with conflict-free replication: “Local processing”, “Caching and precomputation” and “Asynchronous synchronisation”. The Local Processing method is one of the possible methods for improving CRDT performance. It implies the ability to perform most of the CRDT operations locally on each replica without the need for direct network communication with other replicas. The main idea is that replicas can independently process and update their local copies of data based on changes made by users, as long as these changes do not conflict with other changes in the system. This method reduces the amount of network traffic, as not every operation needs to be sent to other replicas immediately. This is especially helpful when network resources are limited, or a large number of replicas are present.

The Local Processing method involves performing certain actions. First, each replica stores its local copy of the data and keeps a log of changes. Next, users can make changes to their local copies of the data, and the replica tries to apply these changes to its local copy of the data. If there are no conflicts between the changes, they are accepted and stored locally. If a conflict occurs, the replica tries to resolve it locally or queries other replicas for a solution.

The advantages of the Local Processing method are reduced network load, reduced communication costs, and localisation. In other words, the method significantly reduces the amount of network data exchange, which can improve system performance, especially in conditions of limited network resources. Fewer data exchange means less network communication costs, which can lead to savings in system maintenance costs. Replicas can operate on a local copy of the data, which keeps data access times low.

Disadvantages of the Local Processing method are conflicts and, the complexity of algorithms. This means that when conflicts arise between changes on different replicas, additional synchronisation may be required to resolve them. Algorithm development that can resolve conflicts locally can be an important and complex task (Fig. 1). While the program output is shown in Figure 2.

```
class CRDT {
  constructor() {
    this.data = {}; // Local copy of data as an object
  }

  applyLocalUpdate(key, value) {
    // Local data refresh handling
    this.data[key] = value;
  }

  merge(otherCRDT) {
    // Local data copy merge method for other replicas
    for (const key in otherCRDT.data) {
      if (!(key in this.data)) {
        this.data[key] = otherCRDT.data[key];
      }
    }
  }

  getData() {
    return this.data;
  }
}

const replica1 = new CRDT();
const replica2 = new CRDT();

replica1.applyLocalUpdate("user1", "data1");
replica2.applyLocalUpdate("user2", "data2");

// Replica 1 and replica 2 have different updates
console.log("Replica 1 data:", replica1.getData());
console.log("Replica 2 data:", replica2.getData());

// Replica merge
replica1.merge(replica2);
replica2.merge(replica1);

// Now both replicas have both updates
console.log("Replica 1 data after merge:", replica1.getData());
console.log("Replica 2 data after merge:", replica2.getData());
```

Figure 1. An example of a simple application of the Local Processing method
Source: compiled by the authors

```
Replica 1 data: { user1: 'data1' }
Replica 2 data: { user2: 'data2' }
Replica 1 data after merge: { user1: 'data1', user2: 'data2' }
Replica 2 data after merge: { user2: 'data2', user1: 'data1' }
```

Figure 2. Local processing method output
Source: compiled by the authors

This code is an example of a CRDT implementation and demonstrates how two replicas merge their data without conflicts. Both replicas end up with the same data after the merge. A diagram of the internal structure of the replica and the processes for processing changes locally can also be drawn (Fig. 3).

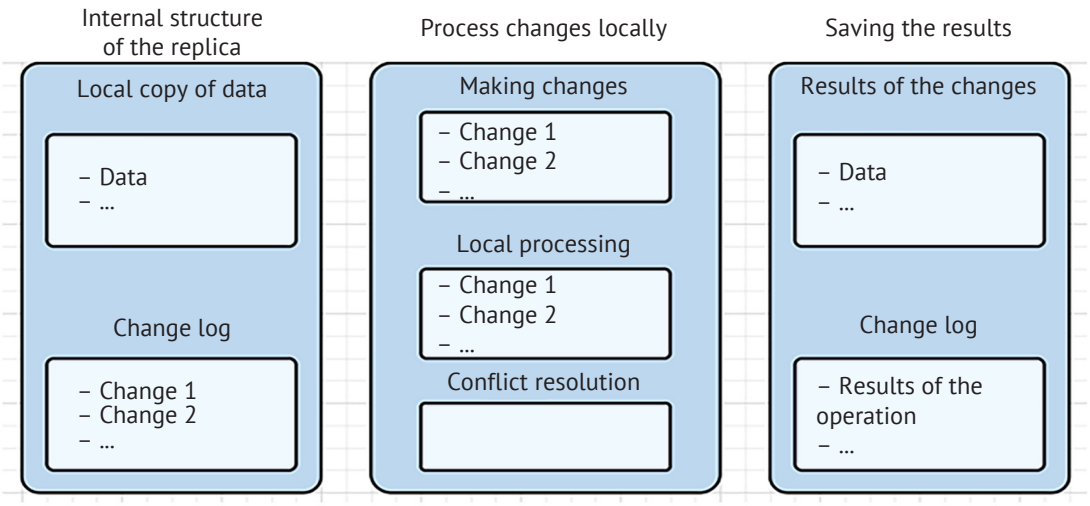

Figure 3. Local processing method diagram

Source: compiled by the authors

The main components of this diagram include the internal structure of the replica, the processes of processing changes locally, and storing the results. With the internal replica structure, each replica has its local copy of the data, and the log records all changes that are made to the local copy of the data. The processes of processing changes locally contain certain stages. When a user makes changes to their local copy of data, these changes are first recorded in the change log. Then the replica tries to apply these changes to its local copy of the data directly. If there are conflicts between changes, the replica tries to resolve them locally using conflict resolution algorithms. Saving the results is done as follows: if the changes are successfully processed and conflicts are resolved, the results are saved locally, and the local copy of the data is updated. Local copies of data can also pre-calculate the results of operations and store them for later use, which helps to improve performance and reduce network data exchange.

The Cache and Precompute method are another key approach to optimising CRDT performance. It involves the use of a mechanism for caching data and results of operations on replicas. This method provides local copy storage of certain data and results of operations on replicas. Local data copies are used for quick access to information without the need for network exchange. It also involves the pre-calculation of some transaction results that can be known in advance and stored on the replicas. The Local Processing method also involves specific procedures. Each replica maintains its local copies of data and operation results. When performing operations where the results can be pre-calculated, the replica cheques whether it already has the result of this operation. If the result is already prepared, the replica uses it without operating again. If the result is not known, the operation is performed, and the result is stored in the cache for later use. The advantages of this method are improved access time, network communication savings, and localisation. This method significantly reduces the time to access data and transaction results, as most requests can be handled locally. The reduction in network communication leads to more efficient use of network resources. Replicas can operate on local data and results, which improves efficiency and reduces network load.

The disadvantages of the Cache and Precomputation method include cache management, data relevance, memory consumption, and precomputation. Data management is required for the effective operation of this method, as a faulty cache of data and results can lead to incorrect results or increased memory consumption. Keeping local copies of data can lead to data out-of-date issues if other replicas have changed the data, requiring additional synchronisation to keep the information up to date. Caching can increase memory consumption on replicas, especially if the data or results of operations are voluminous. Furthermore, not all operations can be pre-computed in advance, and for some operations, this method may not make sense (Fig. 4). While the program output is shown in Figure 5.

```
class CRDTWithCaching {
  constructor() {
    this.data = {}; // Local copy of data as an object
    this.cache = {}; // Cache for storing pre-calculated results
  }

  applyLocalUpdate(key, value) {
    // Local data update processing
    this.data[key] = value;

    // Add the result to the cache
    this.cache[key] = value;
  }

  getFromCache(key) {
    // Check if the result is in the cache
    if (key in this.cache) {
      return this.cache[key];
    } else {
      // If the result is not in the cache, calculate it
      const result = this.computeValue(key);
      // Save the result to the cache
      this.cache[key] = result;
      return result;
    }
  }

  computeValue(key) {
    // Simulate calculating the value by key
    return `Computed value for ${key}`;
  }

  getData() {
    return this.data;
  }
}

const replica1 = new CRDTWithCaching();

replica1.applyLocalUpdate("user1", "data1");
replica1.applyLocalUpdate("user2", "data2");

// Retrieving data from the cache
console.log("Data for user1:", replica1.getFromCache("user1")); // Calculated value for user 1
console.log("Data for user2:", replica1.getFromCache("user2")); // Calculated value for user 2
```

Figure 4. Implementation of a simple programme of the Cache and Precomputation method
Source: compiled by the authors

```
Data for user1: data1
Data for user2: data2
```

Figure 5. The result of the caching and pre-calculation method
Source: compiled by the authors

This Cache and Precomputation implementation is a simple CRDT performance optimisation programme. It provides storage and use of local copies of data to improve access to it. The result of executing the code outputs the merged data from the replicas that contain the data for the users.

Certain formulae and tasks can also be used to show how methods for optimising the efficiency of conflict-free data types in replications work. For example, for the caching and precomputation method, a simple formula that shows how reducing data access time can affect the speed of query service (formula (1)) can be used. Different formulae can be applied to this method: data access time, the ratio of access time reduction, memory consumption, and other performance indicators.

Tasks can also be of different types, for example, the task "Improve the performance of an online store when loading the product page and calculating prices with discounts". First, an online store with many products and various discounts that can be applied to the products, should be assumed. Users visit the product page to view the assortment and prices. This task can be approached from different angles: without caching and with caching. In the first case, every time a user opens the product page, the server must calculate prices for each product, accounting for current discounts. This may require database queries and many calculations. It can take a long time to load the page, especially if with a large assortment of products and many users. In the second case, the first calculated prices for products are stored in the cache on the server. When the product page is loaded, the server cheques whether the cache contains relevant results for a given query (for example, for a given user and their selected region). If the results are in the cache, the server returns them to the client without calculating them. This renders the product page quickly and reduces the load on the server and database.

Task results:

- the time it takes to load the product page from the cache is reduced, no repeated calculations are required;
- the server processes fewer database queries and saves computing resources;
- users get quick access to product prices, which increases their satisfaction and increases conversion.

This approach helps improve the performance of the online store and provides a positive user experience.

The asynchronous synchronisation method is also a strategy for optimising CRDT performance. This method increases concurrency and reduces latency while synchronising data between replicas. It involves allowing replicas to communicate and synchronise data asynchronously, without explicitly waiting for responses from other replicas. This improves system performance in distributed environments and enables faster data exchange.

This method operates as follows. Each replica stores its local copy of data as an object. Replicas can asynchronously merge their data with other replicas. During the merge, replicas access the data of other replicas and apply to their local data what they do not already have. If the data is already local or known from previous merges, the replica ignores it. Since the operation is asynchronous, replicas can continue operating even if the join has not yet been completed.

The advantages of the asynchronous synchronisation method include increased parallelism, reduced latency, and performance. That is, replicas can interact and synchronise data in parallel, which allows for better use of the system's computing resources. The absence of blocking synchronisation reduces waiting time during data exchange and operations. The method allows the system to maintain stable performance even during intensive data exchange and heavy workloads.

"Asynchronous synchronisation" has the following disadvantages: the complexity of implementation, the possibility of conflicts, and task specificity. Developing asynchronous synchronisation can be complex and requires careful management of conflicts and the order in which operations are performed. Asynchronous synchronisation can lead to conflicts that require additional processing and resolution. Moreover, not all types of data and operations can be effectively synchronised asynchronously, and for some tasks, other methods may be more appropriate (Fig. 6). While the program output is shown in Figure 7.

```
class CRDT {
  constructor() {
    this.data = {}; // Local copy of data as an object
  }

  applyLocalUpdate(key, value) {
    // Local data update processing
    this.data[key] = value;
  }

  async mergeAsync(otherCRDT) {
    // Asynchronous method for merging local copies of other replica data
    for (const key in otherCRDT.data) {
      if (!(key in this.data)) {
        await this.applyRemoteUpdate(key, otherCRDT.data[key]);
      }
    }
  }

  async applyRemoteUpdate(key, value) {
    // Asynchronous method for applying updates from another replica
    if (!(key in this.data)) {
      this.data[key] = value;
    }
  }

  getData() {
    return this.data;
  }
}

const replica1 = new CRDT();
const replica2 = new CRDT();

replica1.applyLocalUpdate("user1", "data1");
replica2.applyLocalUpdate("user2", "data2");

// Asynchronous replica merging
(async () => {
  await replica1.mergeAsync(replica2);
  await replica2.mergeAsync(replica1);

  // Both replicas have both updates
  console.log("Replica 1 data after merge:", replica1.getData());
  console.log("Replica 2 data after merge:", replica2.getData());
})();
```

Figure 6. An example of a simple application of the asynchronous synchronisation method
Source: compiled by the authors

```
Replica 1 data after merge: { user1: 'data1', user2: 'data2' }
Replica 2 data after merge: { user2: 'data2', user1: 'data1' }
```

Figure 7. Asynchronous synchronisation method result
Source: compiled by the authors

This code illustrates the principle of asynchronous data synchronisation between CRDT replicas. It shows the process of asynchronous data merging of replicas and outputs the result of this synchronisation. There are two options for different approaches to data synchronisation to compare the main characteristics of the asynchronous synchronisation method (Table 1).

Table 1. Comparison of different data synchronisation approaches

Characteristic	Variant 1	Variant 2
Core idea	Asynchronous exchange without interruptions.	Interrupting change exchange with interruption of other replicas
Approach principle	Replicas maintain local data and a change log. Changes made on one replica are asynchronously sent to other replicas	Replicas maintain local data and a change log. Changes made on one replica are sent to other replicas with interruption
Conflict resolution	Conflicts are resolved asynchronously	Conflicts are resolved by locking
Advantages	Increased concurrency and performance, reduced network load, and localisation	Ensure data is up-to-date, and reduce the risk of conflicts
Disadvantages	Possible conflicts that need to be resolved, the complexity of developing synchronisation mechanisms	Blocked flows and expectations, possible conflicts, less concurrency

Source: compiled by the authors

Thus, the table presents a comparison of the two options for data synchronisation in the asynchronous synchronisation method and highlights their main characteristics, advantages and disadvantages. Using the table helped to visualise the difference between the two approaches to data synchronisation and help to understand their impact on the system. Thus, each of the CRDT types of performance improvement methods has its advantages and disadvantages, and the choice of a particular method will depend on the needs and requirements of a particular distributed system. The study results demonstrate the importance of the context and project requirements when selecting a method to ensure data integrity and improve performance in a distributed system.

DISCUSSION

Y. Zhang *et al.* (2023) discussed the importance and complexity of developing conflict-free replicated data types to ensure the efficient operation of distributed systems. The researchers pointed out the need for formal specification and verification of CRDT design, as well as systematic testing of the implementation. The authors proposed the MET (Model Evaluation Tools) framework, which combines model checking at the design level and exploratory testing at the CRDT implementation level. This approach detects errors and improves the reliability of CRDTs in distributed systems. The common aspects between the present study and the aforementioned one are that both consider the use of conflict-free replicated data types. However, this study uses programmes written in C++ in the VS Code environment for methods to improve CRDT performance. Moreover, Y. Zhang *et al.* (2023) focused on the design and testing of conflict-free data types using the MET framework.

N. Saquib *et al.* (2022) investigated extensions to CRDT data types that enable their use in distributed systems such as the Internet of Things (IoT), even in the face of resource constraints and diversity. The methods are designed to ensure robustness and strong replica consistency and to avoid the limitations of standard CRDTs. The authors studied various conflict-free data types in replicas and found that their methods allow for increased performance of operations compared to conventional CRDTs for the workloads considered. The common aspect of the studies is the investigation of CRDT performance optimisation techniques. However, N. Saquib *et al.* (2022) used IoT to achieve this goal, whereas the study did not have specific distributed systems.

Yu. Ou and J. Zhou (2023) highlighted that CRDTs are a popular approach for group editing in applications, but they have the problem of inefficient data fetching. To solve this problem, the paper proposes a new data fetching algorithm, Relative Distance Skip List (RDSL), which is an efficient and stable solution. RDSL uses a probabilistic structure of identifiers based on the relative distances between CRDT nodes. This algorithm improves the efficiency of CRDT by providing fast access to data. Both studies develop certain approaches to improve the efficiency of CRDT types. However, to implement this improvement, the study proposed methods of local processing, caching and precomputation, and asynchronous synchronisation. Yu. Ou and J. Zhou (2023) proposed an RDSL algorithm.

Sh. Laddad *et al.* (2022a) highlighted the challenges in developing reliable distributed applications and proposed the use of CRDT as a promising approach to achieve coordination in distributed systems. The authors emphasised the limitations of CRDT in providing secure observations of data state. They proposed the extension of conflict-free data types in replications with a query model based on monotonicity from the CALM (Consistency as Logical Monotonicity) theorem to provide more guarantees and secure interaction with the replicated state of applications. This study creates new possibilities for improving the reliability and efficiency of CRDT in distributed systems. Both studies share the idea of using conflict-free data types in replication in distributed systems, considering their advantages and disadvantages, as well as the possibility of making CRDT more efficient. However, Sh. Laddad *et al.* (2022a)

used the CALM theorem, while the present study contains certain tasks and formulae, but no theorems.

F. Guidec *et al.* (2021) considered the use of conflict-free replicated data types in opportunistic networks (OppNets), where information is transmitted through temporary radio contacts between mobile nodes. A delta-state-based algorithm for synchronising CRDT replicas in OppNets is proposed, and experimental results confirm the effectiveness of this algorithm, especially when working with container CRDTs. This approach exploits CRDT functionality to withstand asynchronous communication and can find practical application in distributed networks with unpredictable connections between nodes. This study, similar to the work of F. Guidec *et al.* (2021), focused on conflict-free data types in replications and does some experiments on the effectiveness of CRDT. However, the aforementioned paper used the OppNets network, and this paper considers CRDT in different distributed systems without being tied to a specific network.

S.E. Brynjulfsen (2023) addressed replicated conflict-free data type efficiency optimisation using an SQLite database. CRDTs enable data replication without the need for coordination and provide certain guarantees regarding data consistency. However, there are performance issues due to the use of triggers in SynQLite, which leads to slower performance compared to SQLite. The study proposes various approaches to improve the performance of CRDT types and identifies a solution that significantly improves their performance. The common aspects between the two papers are the optimisation of CRDT performance and the practical implementation of these types. However, this article uses different C++ programmes, while the study by S.E. Brynjulfsen (2023) used an SQLite database.

S. Rostad (2020) investigated distributed CRDTs that guarantee strong end-to-end logic (SEL) and have important properties such as switchability and idempotency. The authors have considered delta CRDTs, which are state-based, and state-based CRDTs, where their instances are synchronised by sending their state to each other. The paper explores existing types of CRDTs and proposes new designs, including the "Causal Length Set" (CLSet), a simple and efficient delta state-based CRDT, and the "Multiple Value Map" (MVMap), a CRDT designed with user-friendliness in mind. Both articles discuss the effectiveness of CRDTs. However, the article by S. Rostad (2020) uses CLSet and MVMap designs for this purpose. The present study did not address the designs but rather used methods for the performance of distributed data types.

G. Litt *et al.* (2022) considered the possibility of applying CRDT to multi-text data with formatting that allows editing and sharing of data without the need for coordination. The authors created a model for preserving user intent in multi-text editing and developed a CRDT algorithm that satisfies this model. The basic idea of the algorithm is to store formatting next to the text and output the final formatted text from these areas in a deterministic way. The algorithm has been prototyped, validated by testing, and integrated into the editor's interface, and its properties of preserving correctness and user intent have been proven. G. Litt *et al.* (2022) focused on conflict-free data types in replications and their testing, as well as on the convenience of CRDT for users. However, this paper developed methods for optimising CRDT types, and another paper developed a CRDT algorithm for preserving user intentions in multi-text editing.

Sh. Laddad *et al.* (2022b) explored the types of CRDTs, which are a powerful tool for creating distributed systems without the need for coordination. However, the researchers emphasised that their proper design is a challenge. This study introduces Katara, a system that automatically generates validated CRDTs from consistent implementations of data types. It provides a simplified and reliable way to create CRDTs that can be useful for developers of distributed systems. Both studies focus on CRDTs, but Sh. Laddad *et al.* (2022) used the Katara system to create CRDTs. This article did not use specific systems but studied CRDTs in general.

J. Bauwens and E. Gonzalez Boix (2020) addressed CRDTs, which are special data types designed for highly available systems and guarantee a certain level of consistency. However, the implementation of CRDTs requires keeping track of additional metadata, which can be inefficient at scale. The authors analysed the metadata problem in CRDT and proposed a new optimisation strategy that helps to reduce the memory overhead. They also proposed a solution to improve the responsiveness of CRDTs built on robust causal language. The results of the study show that this approach can significantly ease metadata management compared to existing methods. Both studies considered approaches to optimise conflict-free replicated data types. However, unlike this article, the study by J. Bauwens and E. Gonzalez Boix (2020) focused on the introduction of metadata in CRDT. This article discusses the use of CRDT with different data types.

This study uses a specific programming language, tables, flowcharts and formulae. However, unlike previous research, it is not limited to specific frameworks, systems, algorithms, theorems, networks, databases, or designs. This makes it more versatile and easier to use. Nevertheless, both this study and all the articles listed above make an important contribution to the development of CRDTs and their application in distributed systems. They provide a variety of approaches to solving problems and improving the functionality of CRDTs, which extends their practical use in modern applications and systems.

CONCLUSIONS

This research aimed to improve conflict-free replicated data types, which are key components in distributed systems. A wide range of aspects related to these data types were covered, and the goal was to develop new methods to ensure their efficiency and applicability.

The study analysed various aspects of CRDTs, including their theoretical basis, synchronisation mechanisms, and potential challenges associated with their application in real-world distributed systems. The possibilities of improving the performance of CRDTs were investigated using analysis and experimentation methods. To implement the study, simple programmes were written and various examples, a table, a formula, and a block diagram were used. The C++ language and VS Code environment were used for the programmes, and the Cross-Platform File Format Apps platform was used for the block diagram.

To optimise the efficiency of CRDT, local processing, caching and pre-computation, as well as asynchronous synchronisation, are deemed most effective. The study results show that the local processing method improves system performance by reducing network load and reducing network communication costs, as well as providing low data access time. By using the caching and precomputation method, it is possible to reduce data access time, reduce network communication, and increase overall network efficiency. The asynchronous synchronisation method makes better use of the system's computing resources, reduces the waiting time during data exchange, and maintains stable performance even under heavy load. The results also confirm that these methods significantly improve performance and reduce resource consumption. However, each of the methods for improving CRDT performance has not only advantages but also limitations, and the choice of a particular method should be determined by the requirements and needs of a particular distributed system. Based on the results of the study, it is possible to conclude that CRDTs have great potential in improving the consistency and performance of distributed systems. However, they also require additional research and optimisation to be used in practise.

Based on this study, several recommendations can be made for further research and development in the field of conflict-free replicated data types. For example, further research could include the development of new applications of CRDTs in different industries. Developers can continue to research methods to improve the performance of these data types. They should also create more powerful tools for implementing CRDTs and testing their performance and reliability. Future research should focus on security and privacy issues when using CRDTs. In summary, the results of this study indicate the importance and prospects of using CRDTs in distributed systems and provide specific methods to improve their performance and efficiency.

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CONFLICT OF INTEREST

None.

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Методи оптимізації продуктивності Conflict-free Replicated Data Types (CRDT)

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Анотація. Актуальність досліджуваної проблеми полягає у необхідності оптимізації роботи з розподіленими даними, що не викликають конфліктів при реплікації, оскільки введення таких типів даних призводить до збільшення потреби у їхній оптимізації та підвищенні продуктивності. Метою дослідження є розробка способів підвищення ефективності різних типів даних з реплікацією без конфліктів. Для досягнення мети були використані методи аналізу та експерименту. Результати дослідження демонструють, що застосування певних оптимізованих способів безконфліктних типів даних у реплікаціях призводить до значного покращення ефективності та зниження ресурсних витрат. За результатами було визначено, що методи кешування і попереднього обчислення, асинхроної синхронізації та локальної обробки є найефективнішими для покращення ефективності Conflict-free Replicated Data Types. Встановлено, що вибір конкретного методу для покращення продуктивності Conflict-free Replicated Data Types має бути обгрунтованим і здійснюватися на основі уважного аналізу вимог та характеристик конкретної розподіленої системи. Це враховує потреби користувачів, ступінь критичності даних, частоту редагування тощо. Дослідження включає розроблення та оптимізацію алгоритмів синхронізації, що значно підвищує продуктивність таких типів даних у розподілених системах. У роботі є прості програмні реалізації для детального аналізу та вивчення методів оптимізації продуктивності типів даних у реплікаціях без конфліктів. Впровадження розподіленого обчислення дозволило оптимізувати процеси реплікації та синхронізації даних, що сприяє зниженню накладних витрат та підвищенню швидкодії систем. Зроблено висновок про практичну важливість дослідження, оскільки використання оптимізованих безконфліктних типів даних з реплікацією у реальних розподілених системах може покращити їхню ефективність та надійність. Практичне значення дослідження полягає в можливості застосування оптимізованих методів типів даних з безконфліктною реплікацією у реальних розподілених системах, що дозволить підвищити їхню продуктивність та забезпечити ефективну роботу в умовах великої навантаженості та обмеженого ресурсного потенціалу

Ключові слова: способи збільшення результативності; реплікація даних; розподілені системи; ефективність синхронізації; методи синхронізації даних

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Future prospects: AI and machine learning in cloud-based SIP trunking

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Abstract. The relevance of the study lies in the consideration of artificial intelligence and machine learning as one of the most important technologies that determine the future of the telecommunications industry. Integration of artificial intelligence and machine learning into cloud-based Session Initiative Protocol trunking solutions can potentially significantly improve the efficiency, performance, and security of these solutions. The purpose of the study was to analyse the possibilities of integrating artificial intelligence and machine learning in cloud-based Session Initiation Protocol trunking solutions. The analysis and the case study methods were applied. The study found that in the modern world, artificial intelligence and machine learning can no longer be considered separately from many aspects of human activity. These technologies are widely used in the telecommunications sector. The integration of artificial intelligence and machine learning in this sector is a key to solving various problems. The findings underline that artificial intelligence and machine learning have the potential to significantly improve the efficiency, performance, and security of cloud-based Session Initiation Protocol trunking solutions. In particular, it was found that these technologies can be successfully used for intelligent call routing, optimising resource allocation, and providing a higher level of security. The results of the study are an important contribution to improving intelligent call routing, optimising resource allocation, and improving the level of security for data and network protection. In addition, the results of the study have the potential to increase the competitiveness of telecommunication companies and ensure the sustainable development of this industry

Keywords: telecommunications; network monitoring; quality of service; routing; dynamic management; integration and capabilities

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INTRODUCTION

The modern stage of development of the telecommunications industry is marked by constant changes and continuous improvement of the infrastructure of communication networks. The integration of artificial intelligence (AI) and machine learning (ML) in cloud-based Session Initiation Protocol (SIP) trunking solutions is recognised as one of the most relevant and technologically advanced paradigms. These advanced technologies have the potential to revolutionise many industries, including telecommunications. In the context of SIP trunking, they open up opportunities for solving important tasks such as management automation, optimising resource allocation, improving security, and intelligent call routing. Integration of AI and ML into SIP trunking is at the early stages, but it has great potential. The future promises even deeper integration of these technologies in cloud-based SIP trunking solutions, which will further improve the efficiency, reliability and security of this industry. This integration will open up new opportunities for the development of the telecommunications industry, ensuring its greater adaptability and ability to meet the growing needs of users.

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Researchers in the field of telecommunications are actively considering the integration of AI and ML in SIP trunking, analysing such aspects of integration as automation of resource allocation, improving security, control automation, intelligent call routing. The analysis of existing publications once again confirms the relevance of the subject matter. The study by N. Kashuba (2023) considered the possibility of using AI to optimise cloud SIP trunking solutions and evaluates the effectiveness of using AI in this area. The results of the study showed that AI can significantly improve the efficiency of cloud-based SIP trunking solutions. Basically, according to the researcher, this applies to automating real-time decision-making based on analysing a large amount of data coming from SIP trunking. For example, an AI system can independently respond to changes in network load and adapt settings to optimise performance. The possibility of using ML for call recognition in cloud-based SIP systems is also discussed by K.S. Rudenko (2021). The researchers suggested using ML to recognise the type of call, speech recognition, and subscriber number. Based on the results of this study, it was concluded that the accuracy of call recognition for various parameters has improved, which significantly affects the quality of services provided.

Much attention is paid to the problems of AI integration in cloud SIP trunking solutions by T.M. Sylka (2021). The researcher proposes a general approach to integrating AI in cloud-based SIP trunking solutions and gives some examples of implementing this approach. In particular, this refers to the use of intelligent analysis methods to identify errors in SIP trunking and automate the process of managing them. I.S. Tyunder (2022) reviewed trends in AI and ML integration in cloud-based SIP trunking solutions. The researcher analysed the potential opportunities and benefits of using these technologies in this area. Consequently, ML algorithms can detect abnormal activity and potential security threats, which improves network security. In addition, according to the researcher, AI-based systems can adapt to changes in network conditions, which makes them more flexible about changes in traffic volumes.

The possibilities of using AI and ML to improve the quality of customer service in cloud-based SIP trunking solutions are also considered in the paper by L. Nikitina *et al*. (2023). They offer a number of AI and ML methods and algorithms that can be used to solve problems such as predicting network load, detecting network anomalies, and providing personalised services to subscribers. Thus, ML algorithms, such as classification or clustering, can group subscribers by common characteristics. However, despite the significant contribution of Ukrainian researchers to the investigation of this issue, there are some aspects that were not considered in these publications. These aspects include the ethical issues of using AI and ML in cloud-based SIP trunking solutions, the resource intensity of the AI infrastructure, and the ability of AI and ML to adapt to changes.

The purpose of this study was to explore the possibilities and potential of integrating AI and ML in cloud-based SIP trunking solutions to improve productivity, and to analyse trends and challenges in the field of SIP trunking and determine the role of AI and ML in solving these problems. The objectives of the study include exploration of the possibilities of using AI and ML to optimise resources and improve SIP trunking performance, identifying specific challenges that arise when integrating AI and ML in the SIP trunking industry, and exploring examples of successful implementation of AI and ML in cloud-based SIP trunking solutions and their impact on performance and security. These goals and objectives are the main benchmarks of this study, aimed at unlocking the potential and prospects of AI and ML in the field of cloud-based SIP trunking solutions. Analysing and answering these questions will help to understand how these technologies can change the face of the telecommunications sector and how their implementation can help improve efficiency and security in this area.

LITERATURE REVIEW

AI has become a key in modern telecommunications industry, where cutting-edge technologies such as 5G make innovation critical. According to research by J. Burg (2023), the global AI market in telecommunications could reach USD 14.99 billion by 2027. AI applications address key challenges such as network management, data analytics, efficiency, and competitiveness. Examples include optimising the network by analysing data from sensors and automating customer service through chatbots.

Companies that already use AI include Vodafone, WCTel, Orange Spain, and Verizon for alleged repairs and fraud prevention. An Accenture study found that AI can increase profitability by 38% and drive the growth of telecommunication companies (Are AI innovations…, 2023). To ensure competitiveness, modern enterprises need programmable networks that adapt to customer requirements. The speed of AI adoption and automation is crucial to avoid the limitations of innovation, as happened with the transition from 4G to 5G. This is exactly what is stated in a study by STL Partners (Progress in telco…, 2023).

A. Castro *et al*. (2018) noted that AI and ML are becoming increasingly important in modern telecommunications. They help optimise networks, improve customer service, and ensure the security of network operations. AI and ML are used to monitor the network in real time, identify potential problems, and predict resource costs. They help to avoid congestion and ensure network reliability. These technologies automate routine processes, including customer service and hardware deployment, which increases efficiency and reduces costs. ML analyses network load data, helps to predict peak loads, and flexibly respond to changes in customer needs. AI and ML are also used to detect scammers and prevent fraud in telecommunications, and to improve customer service by creating virtual assistants and chatbots.

According to T.M. Sylka (2021), the use of AI and ML in telecommunications contributes to network optimisation, improved service, and greater security of network operations. These technologies are already being successfully applied to network optimisation, customer service, marketing, anti-fraud, and cyber security. The study by Ch.X. Wang *et al*. (2023) examined the use of AI to optimise the 5G network and subsequent generations. The researchers consider network monitoring, anomaly detection, load forecasting, resource optimisation, and the benefits and challenges of using AI in telecommunications. It is noted that training AI models requires large data sets, which can complicate their collection and processing by telecommunications operators. AI models can be complex and time-consuming to train, which can slow down their implementation. The research also pointed to the vulnerability of AI models to attacks, so telecommunications operators should take measures to protect them. C. Zhang *et al*. (2019) focused on the use of AI for customer service in telecommunications. The researchers discussed aspects such as creating chatbots, automating customer service tasks, and personalised customer service. This study is the most applied, as it examines specific examples of the use of AI for customer service in telecommunications.

MATERIALS AND METHODS

This study used a comprehensive approach to research, combining theoretical analysis with case studies and practical applications. This allowed the authors to present an in-depth study of AI and ML in cloud-based SIP trunking. The methods of scientific cognition included theoretical analysis of open sources, study of scientific publications, and conducting a case study to evaluate practical applications. The analysis was used to learn the basics of AI and ML, and the structure and principles of cloud SIP trunking solutions, and played a key role in learning the basics of AI and ML integration in the context of SIP trunking and in understanding the functioning of cloud solutions in this area. During the analysis, special attention was paid to the theoretical foundations of automated processing of large amounts of data, given their importance for SIP trunking in cloud computing. The analysis provided the basis for further steps of the study, where AI, ML, and cloud solutions were applied practically to solve specific problems in the field of SIP trunking.

The analysis of open sources and scientific publications helped to collect up-to-date information about modern trends and challenges in the field of SIP trunking and became a key stage of the study, as it helped to systematise and evaluate modern trends and challenges facing the SIP trunking industry. The analysis covered a wide range of sources; including research papers conference materials, technical reports, and documentation from leading industry players. During the analysis, several key topics that are relevant for modern SIP trunking were identified. Firstly, it is a matter of efficiency and optimisation of resources in the context of increasing data volume and quality of service requirements. In the course of the study, various equations for estimating call routes were considered. One of the key formulae is the utility function equation (U), which allows evaluating each possible route for a call in terms of its suitability. Utility function equation (1):

$$U = \alpha - \beta, \quad (1)$$

where α – bandwidth consumed; β – route delay.

General view of the utility function equation (2):

$$(U) = \sum (W_i * X_i), \quad (2)$$

where W_i – weighting factor that reflects the importance of each route selection factor; X_i – value of each factor that is considered when choosing a route.

The second significant topic was data security and confidentiality in SIP trunking networks. Research and scientific publications have revealed the risks associated with potential threats and attacks on the SIP trunking network, and proposed methods for intelligent detection and protection against such threats. The third key topic was the integration of AI and ML in cloud-based SIP trunking solutions. Through open source analysis, successful examples of implementing these technologies to improve productivity and provide real-time intelligent services were identified. In general, the analysis of open sources and scientific publications helped to understand ongoing problems and opportunities in the field of SIP trunking, which forms the basis for further research and implementation of innovative solutions.

However, the main part of research was case studies and real-world implementations. The case study stage included a detailed analysis of specific cases of AI and ML use in cloud-based SIP trunking systems and a study of existing solutions and their impact on the effectiveness of SIP trunking services. The materials used for the study included documentation for various SIP trunking systems, software tools for data analysis, and equipment for creating a test environment. The materials used were selected based on their compliance with the research goals and opportunities for creating realistic scenarios. The results of the study will be useful for industry professionals and researchers who want to use the potential of AI and ML to transform and optimise cloud-based SIP trunking services. In addition, the ethical component will be highlighted to ensure responsible and sustainable implementation of AI in the telecommunications industry.

RESULTS

Artificial intelligence and machine learning techniques to improve productivity. The modern stage of development of the telecommunications industry is characterised by constant changes and continuous improvement of

the infrastructure of communication networks. In this context, the integration of AI and ML in cloud-based SIP trunking solutions is recognised as one of the most relevant and promising technological paradigms. AI benefits not only businesses in the consumer sector, but also affects all sectors of the economy and aspects of public life. Regardless of the type of application or service, AI collects and analyses different types of data, and then uses the corresponding results to perform a specific action or set of actions. AI is primarily used as cloud AI, which means that the underlying network is used to transfer data to the cloud, where the underlying intelligence responsible for data processing and output is located. Standard SBC devices offer a number of advantages, including simplicity, scalability, and low cost. However, they have certain limitations, such as the inability to scale to large networks and the lack of security features. The additional use of AI in SBC addresses these limitations and provides a number of additional benefits (Table 1).

Table 1. Comparison table of network operation using SBC with the addition of AI

Characteristics	SBC	SBC with AI
Operating principle	Network transmits data directly between endpoints.	SBC performs routing, flow management, and security functions. AI is used to improve network efficiency and security.
Advantages	Simplicity, scalability, low cost.	Efficiency, security, and personalisation.
Disadvantages	Inability to scale to large networks.	Cost and complexity of implementation.
Usage	Small and medium-sized enterprises.	Large enterprises and telecommunications companies.

Source: compiled by the author

In the future, the network and AI are expected to merge. The general scheme of the infocommunication network architecture, which provides support for embedded AI functions, is shown in Figure 1.

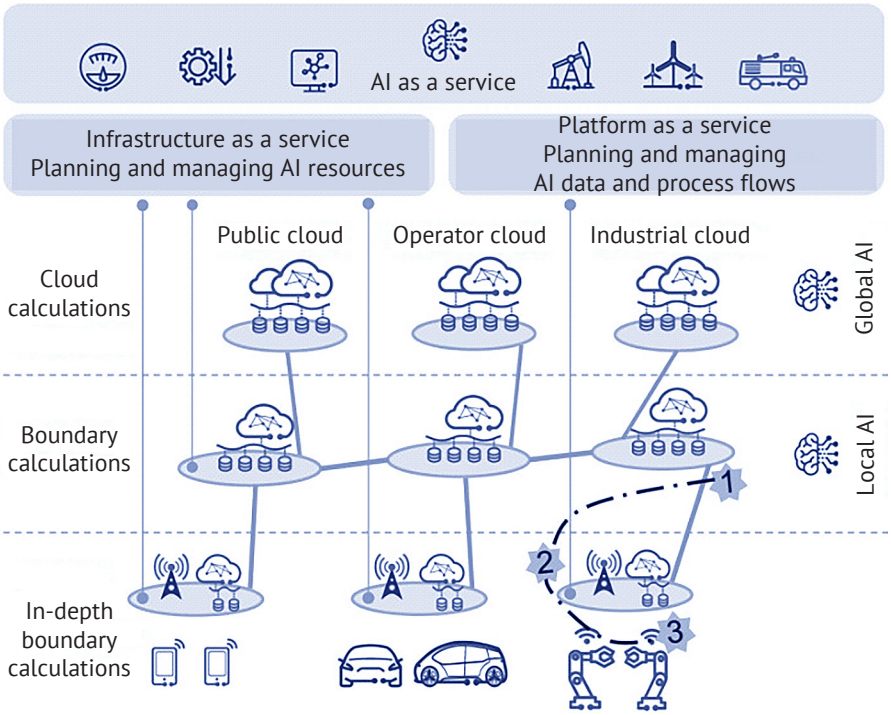

Figure 1. Architecture of the infocommunication network segment with AI support
Source: M. Vasylkivskyi *et al.* (2022a)

In the telecommunications industry, it is important to ensure stable and reliable network operation in real time and detect possible anomalies in time. AI and ML allow creating monitoring systems that analyse data flows and detect congestion, connection problems, and other anomalies that may affect network performance. Much research is aimed at preventing anomalies and detecting network performance degradation, with Software-Defined Networking (SDN) playing a special role in this, which can be modified by software. Researchers classify traffic and prevent possible problems using ML methods. Difficulties arise due to constant changes and scaling of network traffic (Romanchuk, 2022).

AI and ML are powerful tools for automatically detecting anomalies in networks, they analyse and study network parameters (Abbasi *et al.*, 2021). After build-

ing a "healthy" network model, AI and ML constantly monitor network performance in real time and notify administrators of any unusual deviations. This approach ensures network security, reliability, and early detection of problems (Alzahrani & Alenazi, 2021). It is AI and ML that help network operators predict the costs and resources needed to keep the network running. This helps to optimise resource allocation and reduce costs (Network performance monitoring…, 2023). Various AI and ML techniques are used to achieve these goals, including neural networks, time series analysis, and data clustering and classification methods. Such combinations of methods allow creating powerful systems for monitoring and detecting anomalies.

Predictive maintenance and Quality of Service (QoS) optimisation are important for virtualised networks. There has been an increase in research aimed at using ML to solve complex problems in a virtualised Network Virtualisation (NV) environment (Shafin *et al.*, 2020; Vertuam Neto *et al.*, 2021; Vasylkivskyi *et al.*, 2022a). Analysis of key performance indicators (KPI), such as expected latency and alarms, plays an important role in solving virtualised network and service management tasks (Vasylkivskyi *et al.*, 2022b). However, KPI measurement can increase costs by creating the need for adaptive measurement schemes that dynamically adjust the speed of monitoring and determine the volume of controlled parameters.

ML techniques, including regression, improve adaptive monitoring and prediction of telemetry data that would otherwise require measurements. One of the important tasks is to develop mechanisms for measuring the KPIs of virtualised networks with high quality of service requirements, especially for ultra-low latency services. ML-based predictive maintenance ensures smooth operation of virtualised networks (Zhang *et al.*, 2020). It is necessary to identify the causes of performance degradation, such as incorrect configuration or failure, which may affect KPIs. With a large amount of telemetry data and the stochasticity of network events, this task becomes difficult. ML-based research helps to solve these problems.

To ensure network reliability and efficiency, especially in SDN, a load balancing strategy is important to optimise resources and ensure network sustainability, especially in a distributed environment. Analysing the traffic of large SDN networks is difficult due to the distributed nature of the system and the variety of traffic types. Resource optimisation is difficult due to the distributed nature of the network, the large number of nodes and segments, and the variety of traffic types. To achieve optimal network performance, it is necessary to develop algorithms and strategies that take these problems into account and ensure a balance in network management. Scalability is a problem in SDN networks as they become larger and more complex. Developing adaptive algorithms to optimise load distribution is a key requirement in such conditions.

There are various approaches and strategies for solving load balancing problems in large networks. Load balancing algorithms include metric-based algorithms that estimate traffic conditions and dynamically adjust loads to optimise network performance. Additionally, dynamic load balancing algorithms automatically adjust load balancing based on the traffic structure for even load distribution. Configuring the network topology and resource allocation strategy helps to control traffic routing and ensure optimal flow.

The use of virtualisation techniques provides flexibility and resource optimisation in large SDN networks, while cloud computing platforms can be used to handle growing traffic and ensure scalability. Analytics helps to collect and analyse system performance data and develop more efficient algorithms and load balancing strategies. The use of ML and AI methods in this context opens up new opportunities for optimising large SDN networks and solving load balancing problems in rapidly developing networks. The continuous development of these technologies allows creating more accurate and efficient algorithms and strategies for optimal network performance.

Integration of machine learning and artificial intelligence techniques for security and fraud detection. The use of statistical methods and ML in the field of commercial cybersecurity systems has a long history. The trend in this area is that virtually all cybersecurity vendors include ML and AI in their products or services. Even companies of different scales prefer to create specialised data processing teams that are actively working to improve ML and deep learning technologies. However, an important topic is the effectiveness of such investments and the achievement of positive results (Yan *et al.*, 2020).

The use of ML and AI methods in cybersecurity includes detecting and analysing malware, spam, and phishing attacks, and prioritising vulnerabilities for further response to them. They are also used to respond to cyber incidents, including analysing network traffic data and system logs, identifying potential security threats, and automatically responding to detected issues. ML and AI techniques help improve detection, response, and prevention of potential threats, increasing the level of security for networks and systems.

However, there are two key issues. First, it is accuracy due to the lack of large amounts of marked-up data and the dynamic and unstable nature of cyber threats. Second, it is a matter of scaling, because integrating and scaling deep learning systems into real-world cybersecurity systems can be costly and complex. Despite these challenges, the use of ML and AI in cybersecurity is an important step in ensuring Internet security and identifying new threats, and the development of these technologies continues to improve their effectiveness and capabilities in the future. In the telecommunications industry, AI is actively used to detect and prevent fraud (Fig. 2).

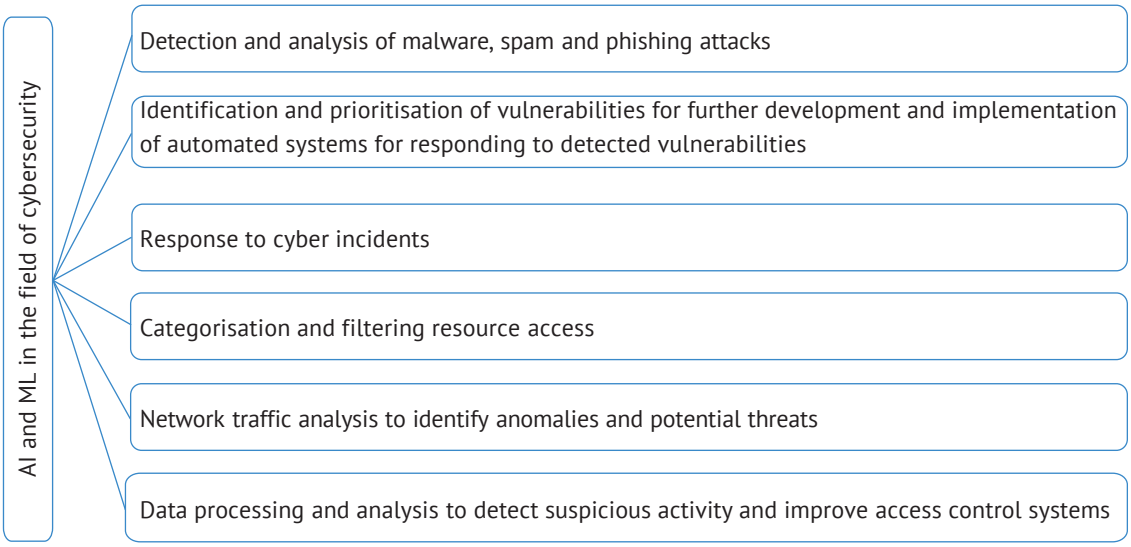

Figure 2. Aspects of using ML and AI methods in the field of cyber security
Source: compiled by the author

AI-based fraud detection systems allow companies to get a more complete and accurate view of customer activity, and respond to suspicious activity faster and more efficiently than ever before. They detect a variety of fraudulent activities, including identity theft, unauthorised access to accounts, and manipulation of financial transactions. These systems identify fraudulent calls, text messages, and emails, and detect anomalies in customer behaviour and changes in habits. Using AI to detect fraud helps companies to reduce false signals and accurately distinguish between legitimate and fraudulent activity, which reduces the number of incorrect signals that require additional investigation and saves companies time and money. The use of AI-based fraud detection systems is strategically important for telecommunications companies and contributes to ensuring the highest level of cybersecurity in the face of ever-growing threats.

One of the key advantages of using AI is the speed of response to potential threats and the ability to adaptive detection of fraudulent activities. The development of AI-based fraud detection technologies continues, which allows creating more effective cybersecurity solutions.

Intelligent call routing and session management. Intelligent call routing and session management in modern telecommunications systems makes it easier to optimise call processing and session management. With the growing volume of data and the development of networks, there is a need for more efficient approaches. One promising area is context-sensitive call routing based on user behaviour, which uses AI and ML techniques to optimise routing based on individual user behaviour. The key to context-oriented call routing is to provide the optimal route for each call based on the user context, which includes parameters such as geolocation, device type, user activity, time of day, previous calls, and other factors. Using this context, the system decides to choose the optimal route to maximise user satisfaction and network efficiency.

Complex call routing problems can be solved by mathematical modelling and calculations, using calculation formulae and algorithms to optimise the use of network resources and meet user needs. One of the key ones is the utility function equation (U), which allows evaluating each possible route for a call in terms of its suitability. The equation for the utility function can look like this (3), for example:

$$U = \alpha * (Consumed\ bandwidth) - \beta * (Route\ delay), \quad (3)$$

where α and β – weighting factors that determine the importance of throughput and latency in calculations; *Consumed bandwidth* – amount of bandwidth that a route consumes to transmit a call; *Route delay* – average delay time on the route.

In addition, the following mathematical equation (4) can be used to calculate the utility function when choosing the optimal route:

$$\text{Utility function } (U) = \sum(W_i * X_i), \quad (4)$$

where U – value of the utility function for this route; $\sum$ – sum for all alternative routes considered; W_i – weighting factor that reflects the importance of each route selection factor; X_i – value of each factor that is considered when choosing a route.

Factors (X_i) may include parameters such as route throughput (measured in bits per second (bps); route latency (measured in milliseconds (ms); route cost (defined in monetary terms); route reliability (can be measured as a percentage), and other factors that may be important for a particular routing. Each of these factors (X_i) is estimated for each possible route, and their weighting factors (W_i) are established based on the

importance of each factor for a particular case. After calculating the values of all factors for each route, the utility function (*U*) helps determine the optimal route for a call that maximises user satisfaction and meets network requirements.

The context-oriented routing system in telecommunications, using AI and ML, adapts to the changing context of users to optimise call routing. It is important to continuously improve ML algorithms and ensure a high level of security and transparency for the future development of this technology, which can become the standard for telecommunications companies, improving the quality of service, and reducing costs. AI and ML play a role in personalisation and adaptive call processing, analysing customer data, creating personalised scenarios, and detecting anomalies in real time. They are also used for traffic forecasting, session routing, troubleshooting, and optimising resource allocation in telecommunications, improving the quality of service and reducing costs in the face of increasing traffic and complexity. The use of these technologies for fraud detection and prevention was considered by V.A. Savchenko and O.D. Shapovalenko (2020).

The use of AI in the context of SIP trunking management has advantages such as optimisation and automation of processes, but creates problems with data privacy and ethical aspects that require careful analysis and consistent approaches. One of the key tasks is to ensure the confidentiality of users' corporate and personal data when analysing large amounts of data, including call traffic and metadata. This can be achieved by recognising and anonymising data, restricting access to data, ensuring transparency of AI algorithms, combating bias, and complying with relevant data protection laws. Effective management of data privacy and ethical aspects requires careful consideration, development of appropriate policies and technologies to ensure data protection and compliance with ethical standards to maintain user trust and comply with legal requirements.

Implementing AI and ML in a SIP trunking network requires overcoming barriers and challenges. The main challenges include data security, the need for scalability, and efficient data processing. Optimised algorithms and specialised hardware contribute to efficient data processing, and the right investment strategy helps to reduce costs and achieve high ROI (return on investment). Retraining of personnel is necessary to work with new technologies. Overcoming these challenges requires the right approach and strategy to optimise telecommunications services and improve their efficiency. Overcoming these barriers and challenges requires the right approach and strategy to help companies implement AI and ML to optimise telecommunications services and improve their efficiency. Implementing AI systems in the telecommunications industry requires significant computing power and can create real-time delays. These limitations can be overcome by using cloud computing to access additional resources and develop specialised hardware. It is also important to develop AI algorithms with minimal latency and place computing resources closer to users. For efficient use of resources, it is advisable to implement dynamic resource management, data caching, and prediction systems. The development of optimised strategies and technologies will help ensure efficient operation of AI systems in telecommunications without significant computing power limitations and real-time delays.

Machine learning and artificial intelligence in the cybersecurity and telecommunications system: application examples, impact on the security and quality of services, and personnel training. In modern conditions, more and more companies are starting to use AI and ML in their activities (Table 2).

Table 2. The use of AI by leading telecommunications companies

Company	Customer care	Marketing&CRM	Networking&IT Ops	Fraud&security
Afiniti	✓			
AlBrain	✓			
Anodot	✓		✓	✓
Arago			✓	
Aria Networks			✓	
Avaamo	✓			
B. Yond			✓	
Cardinality		✓	✓	
Guavus	✓	✓	✓	✓
Intent HQ		✓		
IPsoft	✓			
Nuance	✓			
Skymsnd			✓	✓
Subtonomy	✓		✓	
Tupl	✓		✓	
Wise Athena		✓		✓

Source: compiled by the author

Implementing AI and ML in cloud-based SIP trunking solutions helps to improve efficiency, reduce costs, and ensure network and data security by detecting threats in real time, according to V. Vasilyshyn (2022). Fortinet has developed FortiAI, a highly efficient real-time threat detection system for protecting SIP networks and user data. FortiAI uses AI and ML to analyse traffic, recognise patterns, detect anomalies, and respond immediately to potential threats. This approach provides reliable protection of the network and privacy of user data, and the ability to respond to previously unknown threats. Twilio uses ML to optimise call routing in its cloud-based telecommunications services. AI analyses network parameters, predicts optimal routes, selects the best path to call, and dynamically adapts to network changes. This improves the quality of service and optimises communication costs, making ML an important part of telecommunications systems. Zendesk Talk uses AI and data analysis to create an efficient and personalised call processing system. This allows operators to provide personalised support, reducing response time and increasing customer satisfaction. Verizon uses ML to analyse and predict consumer activity, which allows them to optimise resources, improve the quality of service, and respond to changes in demand.

Real-world examples of the use of AI and ML in SIP trunking highlight their importance for the telecommunications industry. They improve the safety, efficiency, and quality of services. These examples also point to the potential of AI and ML for the future development of telecommunications technologies. The introduction of AI and ML in SIP trunking requires systematic measurement of their business impact and staff training. Employee training should include learning the basics, learning specific topics that cover the use of algorithms, data analytics, and working with appropriate tools. This can be done through lectures, seminars, online courses, practical assignments, trainings, workshops, and mentoring. AI and ML in the telecommunications industry open up opportunities for automating processes, detecting anomalies, and optimising real-time solutions. However, to achieve the best results and maximise the benefits of these technologies, it is necessary that staff have the understanding and skills to use them.

Staff training includes learning the basics of AI and ML, and practical skills and their application in specific work scenarios. This process begins with a carefully designed curriculum that includes both theoretical and practical aspects of using these technologies. Staff training can be conducted internally within the company or involve external experts and trainers. An important part of the process is practical exercises and projects that allow employees to put their acquired knowledge and skills into practise. This approach to training allows companies to maximise the benefits of using AI and ML in the field of SIP trunking, increase operational efficiency and maintain competitiveness in the telecommunications services market.

5G and SIP Trunking: integrating artificial intelligence and machine learning – opportunities and implications for the industry. The introduction of 5G revolutionises SIP trunking networks, providing resource optimisation, improved service quality, and reduced power consumption. For example, Nokia and Ericsson use AI to optimise real-time 5G networks. Data analytics on 5G networks helps to detect anomalies, optimise call routing, and personalise call processing, which is key to improving the quality of service (Fig. 3).

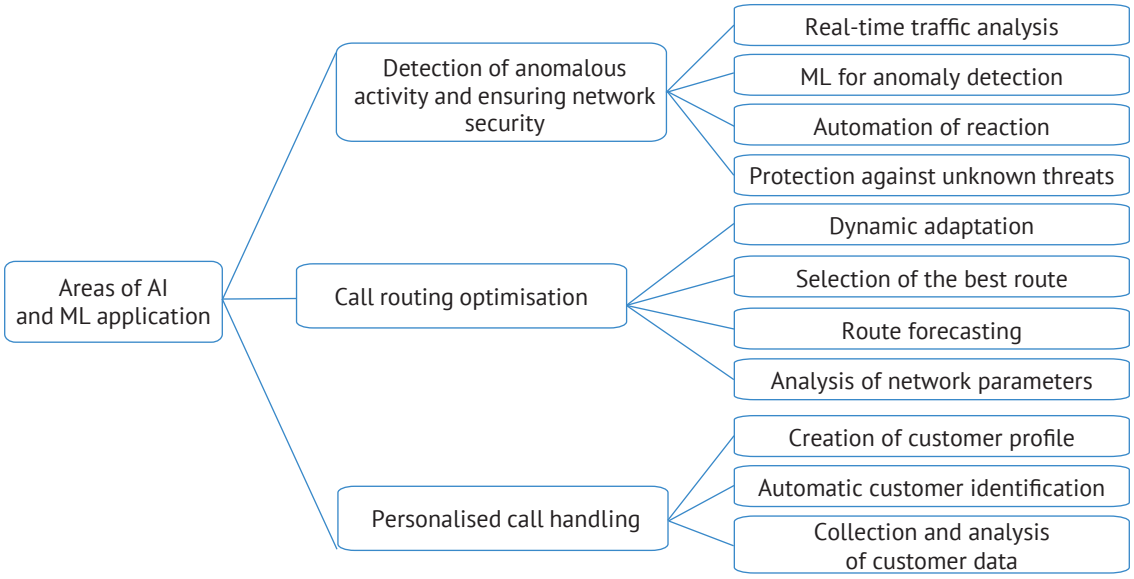

Figure 3. Areas of AI and ML application in cloud-based SIP trunking solutions
Source: compiled by the author

Google Fi uses AI to automatically determine the optimal carrier for each call or message based on the user's location and communication quality, providing a personalised service (Bohn, 2018). Verizon's 5G network (Citizen Verizon) uses ML to analyse consumer activity and user interests, recommending service packages that best suit their needs. T-Mobile (Digital Responsibility) personalises advertising services for its customers by analysing their usage data and sending ads that match their interests. These examples illustrate how AI and ML transform SIP trunking services into customised 5G networks for users. The use of AI and ML on a 5G network improves security and ensures threat detection and prevention. Fortinet Sase Extends Security to Protect Microbranches developed the FortiAI system, which uses ML to detect previously unknown threats in real time on a 5G network, ensuring the security of data and services in SIP trunking. Cisco (latest products and innovations across Cisco) analyses the behaviour of 5G network users to ensure network security and protect user data.

AT&T uses AI to detect attacks on the 5G network, such as DDoS (distributed denial-of-service attack) attacks, and automatically block fake traffic before causing damage. Nokia uses ML to analyse traffic patterns and detect anomalies in 5G networks. Ericsson uses AI to analyse the state of equipment in real time, and Huawei uses ML to optimise network load by reallocating resources to ensure the best possible quality of service. Verizon uses AI to identify problems in 5G coverage, analyse data on communication quality and latency, and provide recommendations for optimising antenna and node performance. Samsung uses ML to predict the load on 5G base stations to ensure stable network operation these examples illustrate how the use of AI and ML in 5G networks leads to significant improvements in monitoring and management processes.

Using edge computing in telecommunications networks where AI and ML optimise SIP services helps to reduce real-time latency, improve service quality, and ensure data security. Cisco uses this approach to handle calls on 5G networks, while Huawei and Nokia use it for various tasks on SIP trunking networks. Edge computing is an important component for the successful implementation of AI and ML in these networks, contributing to reliability and improving the quality of service.

DISCUSSION

The use of AI and ML in modern SIP trunking systems is becoming a key factor for improving the performance and reliability of telecommunications services. This is also confirmed by M. Alauthaman *et al.* (2018), who analysed AI and ML in the context of telecommunications services. The introduction of AI and ML methods in the field of monitoring, optimising the quality of service, security, and intelligent routing can improve the efficiency and quality of service for users. In addition, with the development of 5G networks and the transition to cloud environments, edge computing becomes necessary to ensure low latency and optimise network resources. According to D. Carrillo Melgarejo (2023) the 5th generation mobile network (5G) is not yet able to work with mission-critical applications that require low latency and high reliability, which gives grounds for further research in this area.

The problems of using AI and ML to optimise routing in 5G networks are also considered in the paper by S. Aljawarneh *et al.* (2018). They developed a new routing method that uses ML models to predict the best route. Many studies on the use of AI and ML in telecommunications show that AI and ML have significant potential to improve the efficiency and reliability of telecommunications networks. These technologies will continue to play an increasingly important role in the development of telecommunications networks in the future. N. Ameen *et al.* (2020) investigated methods for optimising resource allocation in 5G networks. The continuous development of these technologies helps to create more accurate and efficient algorithms and strategies that contribute to the optimal functioning of growing networks.

Equally important is the issue of data security and threat detection. Much attention is paid to the issue of security and threat detection in the paper by S. Amuru *et al.* (2016). They developed a new assessment method that uses ML models to identify potential security threats. Through these developments and the introduction of innovative solutions, the telecommunications industry is preparing for the upcoming challenges of 5G and delivering high-quality services to customers. The examples presented above clearly confirm and emphasise the conclusions and results obtained in this paper. The use of AI and ML in telecommunication systems leads to a noticeable improvement in the efficiency and quality of service. However, along with the benefits of using AI and ML in telecommunications, many researchers are concerned about ethics and responsibility. They consider the ethical aspects of using these technologies, in particular, in terms of transparency, privacy protection and possible socio-cultural consequences. This discussion is becoming increasingly relevant and requires careful consideration in the context of the widespread adoption of AI and ML in telecommunications systems.

The ethical aspects and management of AI and ML in the field of SIP trunking are an important aspect that requires serious consideration and attention. Achieving successful results in implementing AI and ML in SIP trunking networks requires high standards of ethics, fairness, accountability, and transparency. The transparency and accessibility of decision-making algorithms using AI and ML allow experts and the public to understand exactly how decisions are made and why. This is important for checking for fairness and identifying possible distortions. It is these issues that are discussed by L. Batra and H. Taneja (2020). The authors of this paper proposed approaches to assessing the fairness and accountability of such algorithms.

Privacy and data protection are key aspects in the context of using AI and ML on a SIP trunking network. Since this network processes large amounts of personal data, such as calls, messages, and other communication information, maintaining high standards of privacy protection is an extremely important task. Ensuring the privacy of users and the confidentiality of their personal data is not only a legal requirement, but also a key aspect from the standpoint of users' trust in the SIP trunking system. In addition, it is important to determine what data can be used to analyse and improve services, and ensure that this analysis is anonymous and impersonal, considering all regulatory requirements for the processing of personal information. Transparency in data collection, storage, and use should come first, and users should be able to control how their data is used and processed on the SIP trunking network. This is stated in the study by P. Bernal (2020). The researcher discussed issues such as privacy, transparency, and bias. He also offers recommendations for managing the ethical risks associated with the use of AI in SIP trunking systems.

Universal ethical standards and regulations can serve as important guidelines for developers and network operators in matters of privacy protection and data processing. According to M.H. Bhuyan *et al.* (2013), this approach will help create an ethical and responsible SIP trunking system that meets the highest standards of AI and ML ethics. Considering possible biases in the use of AI and ML helps to avoid discrimination and negative consequences for certain groups of users. In this context, the term "bias" refers to possible deviations or directivity in AI and ML algorithms, which may occur due to incorrect or insufficient training data or due to incorrect definition of model parameters. This bias can lead to incorrect decisions or distortions in solving problems, and discrimination or negative impact on certain user groups. Thus, ensuring fairness in AI and ML algorithms involves identifying and correcting possible biases to prevent negative consequences.

Accountability and responsibility in the context of the use of AI and ML in the SIP trunking network are essential components for ensuring the ethical and responsible operation of these systems. According to L. Batra and H. Taneja (2020), companies and organisations that use AI and ML in the SIP trunking network should establish clear internal procedures and policies that define the rules for using these technologies. This policy should include principles and norms related to the protection of user privacy, and requirements for the ethical processing of data. Companies should also appoint responsible individuals who are tasked with monitoring and enforcing these policies. This includes not only monitoring data collection and processing, but also identifying and addressing possible ethical issues that may arise when using AI and ML. In addition, an important aspect is the creation of mechanisms for reporting to regulators and the public on the use of AI and ML in the SIP trunking network. This will provide greater transparency and trust in such systems and make companies more accountable for their actions.

Universal ethical norms and regulations serve as important guidelines for defining standards and requirements for the use of AI and ML in the SIP trunking network, ensuring a high level of ethics and responsibility in this area. Ensuring fairness, accountability, and transparency helps maintain user trust and ensures efficient use of AI and ML on the SIP trunking network. Ethical guidelines for AI-driven SIP services play a critical role in ensuring high performance standards and maintaining user trust. Since these technologies can affect various aspects of users' lives and safety, compliance with ethical principles becomes an extremely important task.

CONCLUSIONS

This study examined various aspects of the use of AI and ML in SIP trunking systems and their impact on the telecommunications industry. The introduction of AI and ML in SIP trunking systems opens up wide opportunities for improving telecommunications services, ensuring security and optimising resources. AI and ML allow optimising call routing, identify security threats, improve resource management, reduce latency, ensure privacy and fairness, and combine solutions from different vendors. In general, the use of AI and ML in SIP trunking systems opens up broad prospects for improving telecommunications services, ensuring security, and optimising resources. It is important to adhere to ethical principles and standards when using these technologies in order to maximise the benefits for society and business. The introduction of AI and ML into cloud-based SIP trunking systems promises to be a key factor in the development of the telecommunications industry. This innovation has the potential to transform telecommunications and improve the quality of service.

With the development of 5G networks, the amount of data and processing speed requirements are increasing. AI and ML open up opportunities to solve these problems, ensuring low latency and high quality of service. The expanded use of AI will automate many processes in SIP trunking, including monitoring, management, testing, and data analysis. This will improve efficiency and reduce costs. AI and ML also play an important role in personalising services. They will allow creating services that meet the individual needs of users and predict their requirements, increasing the level of customer satisfaction. By using AI and ML to optimise resources and route calls in the cloud, businesses will be able to use infrastructure more efficiently and reduce costs. AI will become an important part of ensuring security in SIP trunking systems, and ML will help identify new threats and protect user data. Overall, the future of AI and ML in cloud-based SIP trunking promises to be an impressive innovative path to improve telecommunications services and provide more efficient solutions for businesses and users. However, along with

all the benefits, ethical and security issues arise that require careful consideration and compliance with relevant standards and norms. It is necessary to continue research and development of these technologies, considering their ethical and safe use.

Future research in this area should focus on further developing AI and ML techniques and technologies that would allow for even greater levels of automation, optimisation, and security in SIP trunking networks. Understanding the ethical aspects and impact of these technologies on society also remains a relevant topic for further research.

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CONFLICT OF INTEREST

None.

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Майбутні перспективи: ШІ та машинне навчання в хмарному SIP-транкінгу

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Анотація. Актуальність дослідження полягає у розгляді штучного інтелекту та машинного навчання як одних із найважливіших технологій, що визначають майбутнє телекомунікаційної галузі. Інтеграція штучного інтелекту та машинного навчання у хмарних рішеннях Session Initiation Protocol-транкінгу потенційно може значно покращити ефективність, продуктивність та безпеку цих рішень. Метою дослідження було проаналізувати можливості інтеграції штучного інтелекту та машинного навчання в хмарних рішеннях Session Initiation Protocol-транкінгу. Були застосовані метод аналізу та метод кейс-стаді. За результатами дослідження встановлено, що в сучасному світі штучного інтелекту та машинного навчання вже не можуть бути розглянуті окремо від багатьох аспектів людської діяльності. Ці технології широко використовуються в телекомунікаційній сфері. Інтеграція штучного інтелекту та машинного навчання в цей сектор є ключовою для вирішення різноманітних завдань. Отримані результати підкреслюють, що штучного інтелекту та машинного навчання мають потенціал значно підвищити ефективність, продуктивність та безпеку хмарних рішень Session Initiation Protocol-транкінгу. Зокрема, виявлено, що ці технології можуть бути успішно використані для інтелектуальної маршрутизації дзвінків, оптимізації розподілу ресурсів та забезпечення вищого рівня безпеки. Результати дослідження є важливим внеском у покращення інтелектуальної маршрутизації дзвінків, оптимізації розподілу ресурсів, підвищення рівня безпеки для захисту даних та мереж. Окрім того, результати дослідження мають потенціал для підвищення конкурентоспроможності телекомунікаційних компаній і забезпечення сталого розвитку цієї галузі

Ключові слова: телекомунікації; моніторинг мережі; якість обслуговування; маршрутизація; динамічне управління; інтеграція і можливості

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On specifics of adaptive logging method implementation

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Abstract. Relevancy of this work is based on the fact that having an understanding of why given code behaves the way it does, both during normal execution and when encountering erroneous states, is an invaluable part of a good software design. As software systems become more complex, the demand for solutions, that can give deeper insight into code execution, remains high. The goal of this work is to formalize a software tool able to provide better observability of a program. Main methods used are: analysis of common approaches such as monitoring and logging, formalization of main components and modeling of an example implementation based on the Singleton software pattern. As a result, "severity only" based logging was analysed and core parts of "adaptive logging method" were described in a similar manner. There are two distinct features of this method: log tagging and subsequent introduction of a configuration schema that is capable of adapting to changing requirements during software program execution. Systems utilizing such approach gain the ability to extract more precise information about execution flow and also can focus on particular components that might behave incorrectly. As this switch is designed to happen without restarting the observed program, it should be possible to debug and investigate some issues without the need to try and reproduce from scratch the state of an environment where those have occurred. An example of formal description based on the Singleton software pattern is also presented, describing necessary methods and their signatures required to set up a basic variant of an adaptive logging method. This approach could be utilized by a variety of different applications and programming languages as it is developed in general terms and all required abstractions should be present in multiple environments

Keywords: cyber attacks; information security; observability; debugging; adaptive approach; application model

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INTRODUCTION

Software systems are deeply connected with various parts of human lives and every year more and more areas such as education, medicine, commerce, science and others become increasingly computerized. It allows being more productive and makes everyday life easier. In order to satisfy high demands of such systems, software programs grow both in scale and complexity. This also results in growing number of threats, endangering different aspects of human lives. The relevance of this research is based on the fact that it is equally

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important to create efficient, correct, scalable and performant programs and to protect main aspects of information security – integrity, availability, confidentiality – while also providing sufficient level of observability in a software system.

Studies have shown that information technologies, and the Internet in particular, considerably affect the life of an individual. Total number of Internet users in 2023 was a little bit over 5 billion people and that number grew by 98 million new users compared to previous year, with more than 92% of users accessing it using hand held devices like smartphones (Digital…, 2023). It is evident that information security and its importance are widely recognized: spendings on cybersecurity solutions by various companies increased from 34 billion dollars in 2017 to a projected 42 billion dollars in 2020 (Alenezi *et al.*, 2020). Still security issues remain quite challenging, as software threats come in different shapes and forms. Social engineering, for example, is a very powerful way of gaining information about employees and exploiting their weaknesses. Even though these attack vectors were known for years, it is still quite challenging to handle them effectively (Corradini, 2020). Attackers can even target such sensitive parts of life as health care, causing huge monetary losses and endangering individuals (Joyce *et al.*, 2021). Worldwide crises, such as Covid-19 pandemic, are also actively exploited by attackers, who create malicious software, send ransomware, etc, using vulnerable state people found themselves in to their advantage (Yadav, 2021). From February to March 2020 the number of recorded spam emails was 220 times higher than previously. Some of the most common cybersecurity threats were: Distributed Denial of Service (DDOS) attacks, malicious websites and domains, ransomware, mobile threats and spam emails (Khan *et al.*, 2020).

Solutions to some of the problems are widely known, and a common one to avoid compromising privacy of data on the Internet is to use virtual private network (VPN) technology, which allows for information exchange to be protected using assymetric cryptographic encryption algorithm (Zhylin *et al.*, 2020). According to data recorded during initial lockdowns in Poland, the usage of Open VPN compared to pre-lockdown periods almost doubled and that was the first and straightforward consequence of the measure's governments took to prevent spread of the virus (Karpowicz, 2021). Such services aided a lot in mitigating issues that appeared as a lot of employees were forced to work from home (Bispham *et al.*, 2021). They can also help in common scenarios such as accessing sensitive data from public Wi-Fi networks, but even high level of awareness can sometimes be not enough (Sombatruang *et al.*, 2020). Control is another important aspect in programming. This research is focused on one part of control in software systems – observability, which can be achieved using technique called "logging". Application logging can be described as a process of recording events that happen during application's lifecycle (Application logging…, n.d.). In order to fully benefit from any implementation, it is necessary to remember about the costs of logging and avoid exposing unnecessary information (Li *et al.*, 2021).

The main goal of this work was to present a method that should help developers gain a deeper level of observability in their systems, while allowing to be accurate and comprehensive in finding software problems. The main problem of this research is related to the fact that standard "severity only" based approach to logging can sometimes be really hard to leverage in order to fix bugs in a timely manner. The practical novelty of the results is presented as a formal description of a software implementation for the proposed solution.

MATERIALS AND METHODS

There are three main methods used in this research: analysis, formalization and implementation. First of all, analysis of a general "severity only" approach to logging is conducted. Its formal signature is presented and some drawbacks are emphasized. Based on those drawbacks, requirements and signatures for adaptive logging method are created, describing main components of common practical implementations. Usage of the Singleton software pattern is rationalized and example implementation is constructed in general terms using Unified Modeling Language (UML) diagram. Different parts of practical implementation are purposefully designed in a decoupled way, without any bindings to a specific programming language or execution environment, in order to make adaptive logging method as flexible and reusable as possible. Resulting description can be used by developers as a starting point in implementing this method in specific programs and software solutions.

One of the most widely used methods in practice of tracking application state through logging can be described as a "severity only" one. Severity in this case basically means the level of importance of a log message. The RFC 5424 – Syslog Protocol (RFC – Request for Comments) states that severity levels must be in the range of 0 to 7 inclusive (lower values correspond to more dangerous situations) (Gerhards, 2009). Based on those practical implementations, such as Winston logger library (Winston, 2024), define their general "log" method (1) as such that can accept two parameters: severity level literal and log message contents (most commonly a string value).

$$f_{log} = f(Sev, M), \tag{1}$$

where Sev – a severity of current log invocation; M – a message.

Then these reporting messages might end up in standard output stream, on local or even on remote file systems, aggregated in huge log files that require careful processing because of their size. However, there are some solutions, like AMiner – open-source tool

that enables fast log parsing, analysis and alerting (Landauer *et al.*, 2023) or even some techniques that can greatly aid in filtering and processing. For example, H.M. Marin-Castro & E. Tello-Leal (2021) showed that trace-clustering and trace/event level filtering were the most widely used preprocessing techniques as those are easy to implement and can deal with noise and incompleteness in an adequate manner. Sometimes it is much more desirable to filter out unneeded data during generation step rather than during log examination phase. This is also important from performance perspective as naturally being a side effect to the system logging introduces some overhead that can limit effectiveness and impact users of a software system.

In order to allow for generation phase filtering, logging mechanism has to allow access to three main components: ability to mark particular log invocations with descriptive identifiers ("tags"), set up proper reinitialization mechanism that would allow to change configuration of tags and provide a robust and exhaustive configuration method that is used together with reinitialization function when composing next state for the logging software solution.

RESULTS AND DISCUSSION

The starting point of the formalization procedure is to describe adaptive log method (2) signature. Its parameters list starts similarly to the one from "severity based" log method (1), but has an additional parameter.

$$f_{log\ adp} = f(Sev, M, T_{incl}), \quad (2)$$

where Sev – a severity of current log invocation; M – a message; T_{incl} – a set of tags that describe current invocation.

As a result, it is possible to uniquely identify and group messages, while being more declarative compared to some method of project wide convention of prefixing or marking log message strings with some agreed identifiers. By adding the third parameter to log method signature, more consistent behavior can be enforced and this improvement can be taken a step further, making it truly adaptive. Tagging allows to group and identify particular log invocations, adding the ability to run some computations and decision making based on tags. The runtime environment needs access to some form of configuration mechanism in order to specify which invocations to execute and which to skip. This method should combine severity-based mechanism, but also add something that would allow targeting specific log tags (3). Signature for this config initialization method is:

$$f_{init} = f(Sev, C), \quad (3)$$

where Sev – the lowest severity level runtime should report; C – special configuration object that maps tags to their corresponding action, include or exclude.

The contents of the C configuration object (4) should be constructed in such a way that would: allow to have the ability to explicitly exclude specific log tags, which would result in runtime skipping those from output; add means to explicitly include certain tags; provide some way to combine these two in a relation similar to logical "AND", which would mean that only those logging statements that satisfy both operands of this operator, should be included in final output; for complex and multipurpose setups (when it is important to gain insight into different parts of running software during the same execution cycle) there should also be some way to combine tags, joined by "AND", into structure that would be similar to logical "OR" operation.

$$C = T_{11}^{mod}\ \&\&\ T_{12}^{mod}\ \&\&\ldots\|\|\ T_{21}^{mod}\ \&\&\ T_{22}^{mod}\ \&\&\ldots\|\|\ldots, \quad (4)$$

where T_{ij} – a particular tag; mod (modifier) – "include" or "exclude"; && – equivalent of logical "AND" operator; || – equivalent of logical "OR" operator.

By combining the ability to mark logger calls and configuring the desired set of tags to either include or exclude, this mechanism can greatly lower the verbosity of reporting while also reducing load and resource consumption of software. This is essentially what can be called "adaptive logging method" because of its ability to specify the intent more clearly and in a way "adapt" to changed requirements.

As application logging is generally a system wide concern, it's fairly reasonable to expect to be able to utilize corresponding software in different parts of code. It also needs the ability to apply reinitialization method (3) in a portable manner where it can be called once and be altered in all places where it's used. The Singleton programming pattern is one possible solution that is able to cover these requirements. With it, it is possible to have centralized piece of software that can be used in any part of a program and overriding logging configuration in accordance to changed requirements happens in a very natural form. It is worth mentioning that whole idea of adaptive logging serves as a wrapper for general logging mechanisms and as such this research won't focus on any logging related tasks (as modeling and developing those correctly would possibly require solving issues like working with different formats, utilizing different transports and protocols for log transmission, handling synchronous and asynchronous processing, etc., and is out of the scope of this discussion). Instead, it is expected for existing, well tested solutions (like Winston logger) to be leveraged, using a wrapper around those to add adaptive logging functionality.

The instance of a Singleton would first need to have logging library or framework enclosed in one of its member properties (it might even be completely private to enforce correct usage of dedicated methods). The interaction with this framework should happen through a public method which basically implements adaptive

log method signature (2). This is going to be the main reference point in different parts of the program: if it is desired to capture some details about execution process, it gets invoked with corresponding severity level and desired tags are passed to it for identification (with some text-based description). A method that allows overriding current configuration (called, for example, "init") and is basically an implementation of equation (3) should be another part of public Singleton interface.

To better visualize intended structure of an example implementation a common UML class notation is used, where class attribute corresponds to logging library member property and class operations are essentially two public methods required for proper functionality. This example does not limit class attribute by using particular type signatures as different logging frameworks might be presented having different public interfaces, but for public methods signatures are provided for both parameters and return types (note, that "void" in context of function return type just means that function is not expected to return anything after its execution).

It's also worth noting that described class instance is designed to be as general and programming language agnostic as possible and used type signatures should have similar concepts in multiple languages. As such, "List" basically describes some form of an array of items, "Tuple" represents a structure with exactly two elements and for "modifier" it is expected to have exactly one of two possible literal values. This structure presented in Figure 1 should present a good starting point for anyone trying to implement "adaptive logging method" in their own workflow. As mentioned before, this definition is expected to be fairly portable to many existing implementations and workflows based on its general shape and decoupled type signatures.

Adaptive logging Singleton
- logLibrary (e.g. Winston logger)
+ **log**(*severity*: string, *tags*: List< string >, *message*: string): void + **init**(*severity*: string, *config*: C): void, where + *C*: List< OrSegment >; + *OrSegment*: List< AndSegment >; + *AndSegment*: List< TagDef >; + *TagDef*: Tuple< string, modifier >; + *modifier*: "include" or "exclude";

Figure 1. Adaptive logging Singleton structure
Source: compiled by the authors

At this point all main results, such as formal definitions and example formal implementation using Singleton software pattern, are presented. It is worth discussing where these results fit compared to similar or related solutions. Observability based on logging is one of commonly used approaches, monitoring, which can be characterized as the task of assessing the health of a system using predefined metrics that are collected by runtime environment and can then be analysed, is the other one (Observability…, 2022). It deals mainly with predefined metrics, such as memory usage, central processing unit (CPU) utilization, throughput, number of input/output (IO) operations, etc. Monitoring is not limited by those, and, for instance, it is possible to use natural language processing for extracting key data from the software monitoring data in order to predict possible defects (Wang *et al.*, 2021). In combination with, for example, neural network technologies, it is possible to develop complex software monitoring and early warning systems for such sophisticated fields as Internet-of-Things (Ma *et al.*, 2022). In contrast, logging allows to report on multiple different attributes and is not really limited by some common metrics, which is why being able to adapt to changed requirements is a significant capability to have in a software system. As for natural language processing and neural networks usage, adaptive logging method in its current form aims to reduce need for those (as it should produce less unwanted noise and relies more on manual input), but as software systems grow, it should certainly be possible to employ those techniques improving initial ideas and, for example, proactively alter reporting precision using some form of neural network-based solution.

Testing is another common solution for control related issues in programming. It is defined as a "process of assessing the functionality of a software program" and is generally accomplished through writing special test suits and test cases that aim to provide a system, or a part of it, with some inputs and then validate obtained results, although testing might not be entirely sufficient method for preventing software failures (Chioteli *et al.*, 2022). Some terminology still might require refinement to better correspond to the real-life scenarios and requirements instead of using formal approaches that might not always work as expected (Trautsch *et al.*, 2020). It provides a basic development technique that allows the developer to ensure that the code works in a more reliable and controlled manner. In contrast to logging, and adaptive logging in particular, main difference would be that testing relies on predefined and prepared sets of inputs, while logging is more about runtime examination of program's behavior. However, those should not be treated as replacements of one another and instead the best possible results in terms of more reliable software can be achieved having both and improving those synchronously: issues detected using logging might become new test suits and bottlenecks discovered while running different types of testing can tell which parts of the system are error-prone and require more detailed reporting.

Adaptive logging approach is different from, for example, the technique presented in research conducted by H.M. Kabamba *et al.* (2023). While their focus was mainly to introduce a solution that can be applied transparently to a software system, with limited intervention from an application developer, for some

scenarios more suitable solution would be to empower software engineer to be as precise as they need to be and limit not the amount of work needed to setup appropriate reporting, but rather amount of effort needed to process results. On the other hand, approaches like log slicing, presented in study by J.H. Dawes *et al*. (2023), work in a similar way and even solve related problems, for example log identification. Although their way of determining the related context given a particular log invocation looks interesting, adaptive logging emphasizes that it's best to solve those aspects during log generation phase, rather than during processing phase afterwards, as this can help in both limiting the amount of information to process and also in limiting load that runtime machine needs to deal with.

J. Torres Martínez *et al*. (2019) noted that different cybersecurity issues such as intrusion detection, attack classification, etc. can be tackled using machine learning approaches. Possible application domains of such techniques are: filtering spam in email messaging, blogs in social networks, images and videos, intrusion detection in a form of Denial of Service (DOS) attacks, probe attacks, "Remote to Local" and "User to Root" attacks, with very impressive results, such as 97% accuracy of DOS attacks detection using techniques such as Decision Tree or Neural Networks, as was mentioned by K. Shaukat *et al*. (2020). In a way, the use of this technology can reduce the need for logging as an observability tool (as several problem domains can be covered without resorting to manual interaction, for example in DOS detection), and in case of adaptive logging this might significantly reduce the need for a human input, rendering adaptability benefits somewhat redundant. But despite such promising results, broad application of machine learning systems could be problematic based on issues related to expensive training and narrow application fields for particular models, according to F. Liang *et al*. (2019), and so, at least for the time those approaches evolve, it is still very important to have "hands on" control over software systems, which adaptive logging aims to provide.

Adaptive logging formalization involves defining a method with a signature comprising a severity parameter, a message, and tags for unique message identification and grouping. This method combines severity-based logging with tag targeting through a configuration mechanism to specify which log invocations to execute or skip, aiming to enhance logging clarity and adaptability. The approach employs the Singleton programming pattern for portable reinitialization and acts as a wrapper for existing logging mechanisms such as the Winston logger. A Singleton for adaptive logging includes a logging library property, accessible through a public method with an adaptive log signature, and allows configuration overriding through a method like "init". Adaptive logging provides a flexible alternative to traditional monitoring and testing methods, complementing monitoring's focus on predefined metrics and testing's reliance on predefined inputs, thereby improving software reliability when used in conjunction. It enables developers to efficiently manage reporting precision and remains valuable alongside machine learning solutions for addressing cybersecurity issues.

CONCLUSIONS

In this work a deeper look at control issues in a software system is presented (mainly in a form of an observability aspect of information security). The research is focused on an aspect of application logging, and a general "severity only" based approach is analysed. Its main drawback is concluded to be an insufficient degree of flexibility and as a result inability to adapt to changes in reporting requirements. The solution to this problem is presented in a form of "adaptive logging method", that can be provided with the same parameters (severity and a message), but also utilizes a mechanism of tagging, which then allows to set up a specific architecture that should be capable of solving adaptivity issue. All of the necessary parts are formalized and presented as a general function signature (which should allow for cross platform and cross language implementations) and an example implementation based on the Singleton software pattern is presented using a Unified Modeling Language class notation. The resulting solution allows both to group related log calls using tags and to apply filter-like capability at the log generation phase, which makes it more precise than common logging approach and also allows to tone down performance impact of a logging solution by targeting very specific parts of an application.

Among topics for further research, several present a particular interest, for example selecting an appropriate subscription-based change propagation mechanism in order to adapt to changed requirements in a timely manner; improving adaptability in terms of not only "when" to log something, but also "what" to log, adding some layer of control on top of a tag-based mechanism. Another topic that could be covered is exploring possible integration with modern application orchestration mechanisms, that could potentially allow to reroute loads from erroneous services and isolate those for further investigation, as well as utilize machine learning approaches to gather foundational materials that could help in establishing some basic logging scenarios, created using the information extracted from bug reports of the frameworks and libraries used in a project.

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CONFLICT OF INTEREST

None.

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Про особливості впровадження методу адаптивного логування

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Анотація. Актуальність цієї роботи полягає в тому, що розуміння причин чому певний код виконується певним чином, як протягом нормального циклу виконання, так і у випадку помилок, є важливою частиною хорошого дизайну програмного забезпечення. Оскільки комп'ютерні системи стають складнішими, запит на рішення, що дозволяють глибше поглянути в процес виконання коду, лишається на високому рівні. Метою даної роботи є формалізація програмного інструменту, здатного забезпечити кращу спостережність програми. Основними методами роботи є: аналіз поширених підходів, таких як моніторинг та логування, формалізація основних компонентів та моделювання прикладу реалізації на основі патерну програмування Singleton. В результаті було проаналізовано логгінг на основі «тільки критичність» і аналогічним чином описано основні частини «методу адаптивного логування». Є дві відмінні риси цього методу: тегування лог повідомлень і подальше введення схеми конфігурації, яка здатна адаптуватися до мінливих вимог під час виконання програми. Системи, що використовують такий підхід, мають можливість отримувати більш точну інформацію про хід виконання, а також можуть зосередитися на певних компонентах, які можуть поводитися некоректно. Оскільки таке перемикання відбувається без перезапуска програми, за якою спостерігають, має бути можливість налагоджувати та досліджувати деякі проблеми без необхідності намагатися відтворити з нуля стан середовища, в якому вони виникли. Також представлено приклад формального опису на основі патерну програмування Singleton, який описує методи та їхні сигнатури, необхідні для створення базового варіанту адаптивного методу логування. Цей підхід може бути використаний різними програмами та мовами програмування, оскільки він розроблений в загальних рисах і всі необхідні абстракції повинні бути присутніми в різних середовищах

Ключові слова: кібератаки; безпека інформації; спостережність; дебагінг; адаптивний підхід; прикладна модель

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Innovative technologies for tourism development in the Carpathian region

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Abstract. The relevance of the study is due to the sharp increase in interest in the field of travel in the context of the development of modern technologies and the need to create innovative approaches to improve the service and safety of tourists. The purpose of this study is to analyse the concept of a "smart region" and identify strategies for integrating information technology in the travel industry to improve the service and safety of tourists in the region of Zakarpattia. The study used the methods of analysis, synthesis, generalization, deduction, and systematization to assess the needs of tourists and develop optimal solutions. The potential for integrating information technology into tourism in the "smart region" of Zakarpattia was studied. It is established that the creation of a tourist information platform with personalized recommendations and support for different languages and cultures can help increase the attractiveness of the region for tourists. In addition, the use of cross-platform solutions for the development of mobile applications will ensure that the platform is accessible to a diverse audience, regardless of their devices. An important aspect is the storage of information on the user's device and automatic synchronization with the server, which ensures continuous availability of the platform. The use of voice assistants and an inclusive interface will ensure convenient use of the platform for people with disabilities. The results of the study indicate the potential of information technology to improve the tourism industry and improve the quality of tourist services. The study confirms the importance of integrating technology to achieve strategic goals in tourism development and increase the competitiveness of Zakarpattia as a tourist destination. The introduction of innovative technological solutions can be a key factor in creating a "smart tourist space" that will provide convenience, safety, and pleasure for tourists. The practical significance of the study lies in the possibility of using its results to further improve the information and technological infrastructure of the tourism industry in the "smart region", as well as the possibility of improving tourist services and increasing the competitiveness of the "smart region" by introducing an information technology platform

Keywords: recommendation system; pandemic; "smart region"; COVID-19; Zakarpattia

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INTRODUCTION

The rapid development of information technology necessitates the transformation of the tourism industry towards "smart regions". One of the important aspects of this transformation is the creation and implementation of information technology platforms aimed at addressing the challenges and tasks that arise in the context of modern tourism. This issue has become especially relevant in the context of the global COVID-19 pandemic, when the tourism industry has witnessed significant changes in the demand and structure of services. The problem of this study is the insufficient integration of information technology tools in the tourism industry of the "smart region" of Zakarpattia, which hinders the development and efficiency of the tourism sector. In addition, in the context of the COVID-19 pandemic, new challenges arise that require innovative solutions in the field of tourism, such as an effective management system and tourist safety.

The publication by S. Kalinichenko *et al.* (2023) examined the impact of information technology on tourism development. The paper emphasizes the importance of integrating innovations into the tourism sector to ensure the comfort, safety, and speed of tourist services. The relevance of implementing digital solutions in the context of competition and changes in consumer demand in the tourism industry is highlighted. The paper by A.V. Avryata (2023) highlights the key trends in the international tourism market and the impact of changes related to integration and globalization on the tourism industry. The article identifies the importance of information technology, in particular its role in addressing the consequences of the COVID-19 pandemic, and highlights the opportunities to expand the infrastructure of the tourism industry through innovative technologies. This paper calls for the competent use of information technology in tourism to improve the tourism market and economic development of the country.

The article by A. Mokryi (2023) investigated the impact of innovations on marketing technologies in tourism, identifying their main role in the development of the tourism business. The author analysed the latest trends, such as the use of artificial intelligence, bots, social media marketing, and location-based technologies. The study analyses the problem of assessing the relevance of marketing technologies for enterprises and proposes a scoring method for selecting the most relevant technologies in the tourism industry. The authors I. Kulyniak & Yu. Bondarenko (2022) analysed in their work the classification of factors influencing the development of tourism. They identified economic, political, social, technical, cultural, and natural factors, revealing the main elements that determine the strength of influence of each group. The study by T. Lysiuk *et al.* (2021) examined the impact of innovative digital technologies, including contactless payment, face recognition systems, online monitoring, and artificial intelligence, on the functioning of tourism enterprises such as TUI, Coral Travel, Tez Tour, Feyeria Mandriv, and Poikhaly z namy. It is noted that these technological advances improve management and quality of service. Examples of successful use of such technologies by Ukrainian tourism enterprises are provided.

Given the analysis of previous studies, several unresolved problems related to innovations in the tourism industry can be identified. The shortcomings in the integration of information technology tools in the travel sector and the lack of comprehensive solutions to optimize and improve tourist services remain relevant issues. In addition, the impact of the COVID-19 pandemic on the tourism industry and the development of effective solutions to overcome these challenges have not received full scientific coverage. Therefore, the purpose of this study was to consider the concepts of a "smart region" and identify strategies for integrating information technology in the tourism sector to improve tourist services and safety in the Zakarpattia region.

MATERIALS AND METHODS

The deduction method used in this study involves drawing specific conclusions based on general principles and assumptions. It was used to study the main principles and concepts underlying the development of an information technology platform for the tourism industry of a "smart region". The key aspects to be taken into account when developing the platform, such as user interaction, integration with other services, and consideration of data security and confidentiality requirements, were identified. The deductive method allowed to draw logical conclusions and formulate the basic principles of developing an information technology platform to support tourism in a "smart region".

To conduct a study of the latest trends in the field of tourism and information technology, the analysis method was used. This method involved the systematic study, classification, and interpretation of information, which allowed to understand the current state and trends in this industry. The main difficulties and challenges faced by the tourism industry in the context of a "smart region" were identified. The advantages and limitations of different approaches to integrating digital technologies into travel were also analysed, as well as existing practices of using technology in the tourism sector in other regions and countries. In addition, the needs, and requirements of tourists for information technology solutions in the field of tourism were identified, and the impact of the COVID-19 pandemic on the tourism industry and the possibilities of using technology to overcome its consequences were analysed. In addition, the possibilities of using information technology to improve the safety and comfort of tourists in the region were explored.

The synthesis method used in this study was a systematic combination of different ideas, concepts, and requirements to create a new concept. Using this

method, the concept of an information technology platform for the tourism sector of a "smart region" was developed. The requirements for the functionality and efficiency of such a platform included, in particular, the ability to quickly and easily search for and book tourist services, an interactive map of the region with the marking of interesting objects and routes, personalized recommendations on routes and excursions, information resources about tourist sites and cultural events, a mobile application with additional functions such as reminders about planned trips, support for different languages and cultures, organization of transport and events, user feedback and evaluation, and so on. The conceptual architecture and functionalities of the platform were developed taking into account the requirements for its usability and accessibility. In addition, a synthesis of strategies for interacting with other tourism services and systems was carried out. Recommendations for the implementation and support of the platform were synthesized to ensure its successful implementation in practice. Also, a general concept of integrating information technology into the region's tourism infrastructure was developed to achieve the main goals of "smart tourism" development.

The systematization method consisted of organizing and classifying information, which allowed identifying the main aspects and functions and describing them systematically. The systematization method was used to identify the main functionalities that a platform should include to provide a full range of travel services and to describe the requirements for the security and confidentiality of data processed on the platform to ensure a high level of information protection. In addition, the main methods of interaction between the platform and other systems and services to ensure its integration into the tourism market ecosystem were summarized. The requirements for mobility and accessibility of the platform for users on different devices and at different Internet access points are also systematized.

The method of generalization included the analysis of specific data and phenomena to identify general patterns, which allowed to move from individual cases to general conclusions and establish the basic principles of the information technology platform. Using the method of generalization, the main trends were identified and conclusions were drawn based on the research results. The general principles of the functioning of the information technology platform for the tourism industry of a "smart region" were also established, and the key requirements and needs of users regarding the platform's functionality were summarized to ensure their satisfaction and ease of use. The basic principles of the platform's interaction with other systems and services were summarized to ensure its integration into the tourism ecosystem.

RESULTS

A "smart region" is a concept that uses digital technologies, communication tools, and data analytics to create an efficient and effective service environment aimed at improving the living standards of residents and strengthening the resilience of the region (Gracias *et al.*, 2023). A "smart region" is defined not only by the use of modern technologies but also by the integration of these technologies into all areas of economic and socio-cultural development.

There are different methodological approaches to characterizing the components of a "smart city". The most universal synthetic method is to identify six key components, namely: "smart economy", "smart environment", "smart citizens", "smart living", "smart mobility", and "smart governance" (Fig. 1).

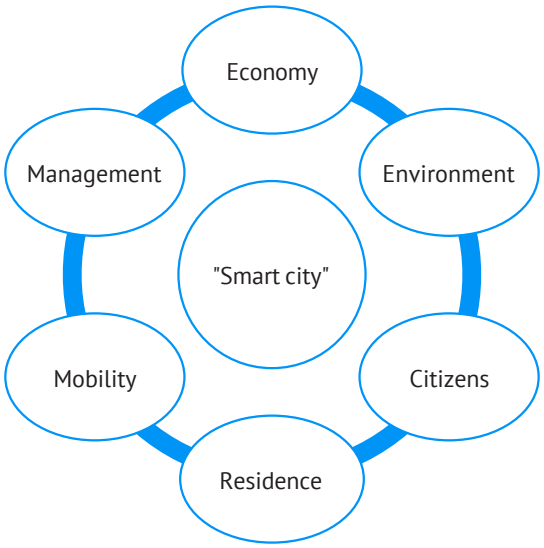

Figure 1. Components of a "smart city"

Source: R. Lozynskyy *et al.* (2021)

To ensure that entrepreneurship thrives and develops, it is key to create an active economy that promotes the efficient use of resources and fosters innovation. An active economy is defined as a key driver of prosperity and attracts entrepreneurship by supporting innovation and a start-up culture. By involving citizens in local governance and decision-making, the basis for "smart civic participation" is created, which is one of the key components of a "smart city". Citizens play an important role in restoring democracy in local governance by actively participating in decision-making and promoting citizen participation. The "smart environment" is aimed at preserving nature and creating a sustainable urban environment. "Smart mobility" uses advanced technologies to improve transport infrastructure and solve parking and traffic congestion problems. "Smart living" improves the quality of life by optimizing infrastructure and facilitating social interaction. "Smart governance" emphasizes a systematic approach to civic participation and access to e-governance, which promotes openness and restores trust in government (Sharma *et al.*, 2023).

The integration of information technology in the tourism sector of Zakarpattia is an important strategic step to improve and optimize the tourism industry in this location. It involves the development and implementation of advanced information systems aimed at improving tourist services. Recommendation systems are becoming an essential element, providing individualized recommendations and information for travellers. An important component is the creation of information models to assist in management and planning. Special attention should be paid to the booking system to ensure an efficient and convenient mechanism for tourists and businesses in the industry. This may include the introduction of online platforms that simplify the booking process and provide access to up-to-date information on hotels, restaurants, tourist routes, etc.

In light of the challenges posed by the COVID-19 pandemic, it is important to integrate information technology to ensure safety and meet health requirements. This may include the development of applications to track the epidemiological situation, e-ticketing systems to avoid physical contact, and other innovations aimed at improving the safety and health of tourists. This integration of technologies aims not only to create an attractive environment for tourists but also to create a "smart tourist space" that responds to the needs and expectations of the modern traveller (Casado-Aranda *et al.*, 2021; Gavurova *et al.*, 2022). According to 2021 data, Ukraine's gross domestic product (GDP) in the tourism sector was 11.82%, highlighting the importance of this industry for the country's economy (Tourist barometer..., 2023). These statistics show that the development and implementation of information technology innovations in tourism can significantly increase the competitiveness and attractiveness of the region for tourists, which, in turn, is important for ensuring sustainable economic development.

The main objectives for the development of the "smart region" of Zakarpattia are focused on increasing the attractiveness of the region, optimizing the tourism business, ensuring the safety and health of tourists, creating "smart infrastructure", increasing competitiveness, and promoting sustainable development. Table 1 provides a specific description of each goal and its relationship to the implementation of "smart tourism" in Zakarpattia.

Table 1. Goals for the development of the "smart region" of Zakarpattia

Objective	Description
Increasing tourist attractiveness	To make the territory of Zakarpattia more attractive to tourists by using information technology to improve services and provide innovative tourist offers.
Optimization of the travel business	Ensure the efficiency of the tourism business through the introduction of information technologies that facilitate booking management, marketing, and customer interaction.
Ensuring the safety and health of tourists	Respond to challenges related to the pandemic and other potential hazards by using technology to monitor the epidemiological situation, contactless services, and compliance with sanitary standards.
Creating a "smart infrastructure"	Development of infrastructure that uses information technology to optimize transport routes, provide access to up-to-date information and improve the overall tourist environment.
Increasing competitiveness	Ensure the region's competitiveness by using information technology to create innovative tourism products and improve marketing strategies.
Promoting sustainable development	Interest in developing tourism that promotes environmental sustainability supports local culture and considers the social aspects of the territory.

Source: created by the authors

To optimize the tourism business, it is necessary to create a travel information platform that should be guided by the principles of "privacy by design" and "privacy by default", which ensures the minimum amount of collection and processing of personal data of travellers by the destination state to fulfil the requirements of entry. "Privacy by design" involves a proactive approach to preventing privacy violations, while "privacy by default" guarantees automatic protection of personal data without the traveller's involvement. It is also important to comply with international standards, such as ISO 29100 for IT system design, ISO 17975 for health information consent and ISO 27799 for health data security. Effective measures should be implemented to

protect and secure data, including encryption protocols, secure data storage and regular security checks. Access to traveller data should be restricted to authorized individuals only, with strict authentication and authorization mechanisms in place to prevent unauthorized access. Compliance with international standards such as ISO 27001 and 27701, which set out requirements for information security management systems, is also recommended (Culot *et al.*, 2021; Taherdoost, 2022).

A tourism information platform that integrates with other systems and services in the tourism industry should provide convenience and efficiency for all stakeholders. This means that the platform should interact with other tourism resources, such as hotel reservations, routing and itinerary planning, online services, and others, to provide a comprehensive service to tourists. Accessibility and mobility are key characteristics of such a platform, as it should be accessible from any device with an Internet connection, as well as mobile applications for smartphones and other devices. This will ensure that tourists can access the information and services they need anywhere and anytime, which will greatly increase user convenience and satisfaction.

The platform should also provide personalized information and recommendations to users based on their individual needs, preferences, and travel history. This will help to make travel more comfortable and enjoyable for each tourist, and increase the likelihood of repeat visits to the region. Additionally, it is necessary to take into account the different languages and cultural backgrounds of users to ensure convenience and accessibility. For example, the platform should be able to translate information into different languages and provide cultural information and advice for tourists from different backgrounds (Sarji *et al.*, 2023; Ivars-Baidal *et al.*, 2023). The tourist information platform for the "smart region" of Zakarpattia should meet the needs of modern tourists. The main functionalities of such a platform are described in Table 2.

Table 2. Main functions of the tourism information platform

Functionality	Description
Search and book services	A system for searching and booking hotels, restaurants, excursions, transport, and other tourist services in the region.
Interactive map of the region	A detailed and interactive map showing tourist attractions, routes and interesting places to visit. Use of GPS to determine the user's location.
Personalized recommendations	A system for analysing users' preferences and travel history to provide personalized recommendations for routes, excursions, and restaurants.
Information resources	Presentation of information about tourist attractions, the history, and culture of the region, national parks, museums, and other objects in the form of text descriptions, photos, videos, and audio guides.
Mobile application	Developing a mobile application for easy access to the platform from mobile devices. Providing additional features such as reminders of planned trips, offline maps and navigation.
Feedback and assessments	Allowing users to leave feedback, ratings, and reviews of tourism services and facilities. Help other users make informed decisions and improve the quality of service in the region.
Support for languages and cultures	The ability to translate information into different languages and provide specific recommendations for different cultural groups.
Organization of transport	Providing information on public transport, taxis, car rental and other transport services. Assist tourists in getting around the region with ease.
Event organization	Possibility to view and register for tourist events, festivals, and excursions taking place in the region.

Source: created by the authors

The development of the platform involves the creation of a responsive design that automatically adapts to screen sizes and is optimized for playback on various gadgets, ensuring optimal visual display and correct functioning of functions on different types of devices. This approach ensures optimal visualization and functionality of the interface on any device, regardless of its type and size. The use of cross-platform solutions such as Flutter or React Native will allow developers to create applications that run on different operating systems (Android and iOS) using a single code. This approach will simplify the development and maintenance of applications, ensuring high efficiency and productivity on different devices (Biørn-Hansen *et al.*, 2020).

To ensure convenient and efficient use of the platform without the need for an Internet connection, it should be possible to save a certain part of information and functions on the user's device. This will allow users to use certain functions of the application offline and ensure the uninterrupted operation of the platform even in the absence of a connection to the server. Data synchronization with the server should occur automatically when there is a connection, which will allow for storing up-to-date information and regularly updating the data. In addition, the platform should have support for special needs, including the development of an inclusive interface with the ability to change font sizes, colour schemes and other parameters for users with disabilities. This will help to improve the accessibility of the platform for different categories of users and ensure their comfortable use of the services. The introduction of text-reading functions with the help

of voice assistants will allow users with disabilities to access information through audio presentation, making the platform more accessible and convenient.

Information technology plays a key role in creating innovative solutions aimed at improving the quality of service and ensuring the safety and comfort of tourists. Firstly, the introduction of a tourist information platform allows tourists to access all the necessary information from a single source. Thanks to the search and booking of services, an interactive map of the region, personalized recommendations and other features, tourists can easily find the information they need and plan their trips. The mobile app makes this process even more convenient, allowing users to access the platform from anywhere and at any time.

Security and data protection is also an important aspect in the development of a travel platform. The use of the principles of "privacy by design" and "privacy by default", as well as compliance with international data protection standards, ensures that users' personal information is safely stored and processed. In addition, information technology contributes to the creation of "smart infrastructure" and optimization of transport routes, which increases accessibility and ease of travel for tourists. They also help to organize tourism events and festivals, ensuring their effective coordination and promotion. Overall, the integration of information technology into tourism in Zakarpattia is an important step towards increasing the region's competitiveness and providing high-quality and convenient services for tourists. This allows to implement the concept of "smart tourism", which contributes to the sustainable development of the region and meets the needs of the modern traveller.

DISCUSSION

A "smart region" is a concept that uses digital technologies, communication tools and data analysis to improve the lives of residents and increase the region's resilience to the negative impacts of external factors such as natural disasters, economic fluctuations, or epidemiological threats. This concept envisages the integration of modern technologies into all areas of economic and socio-cultural development. The most universal approach to characterizing a "smart region" is to define six key components: "smart economy", "smart environment", "smart citizens", "smart residence", "smart mobility", and "smart governance".

The introduction of information technology in the tourism industry in Zakarpattia is a strategic step to improve and optimize the tourism industry in this location. This involves the creation and use of advanced information systems, recommendation systems and information models for better management and planning. The booking system is an important component that provides an efficient and convenient mechanism for tourists and businesses in the industry. This may include the introduction of online platforms to simplify the booking process and provide access to up-to-date information.

In the context of the COVID-19 pandemic, the introduction of information technology has become important to ensure safety and compliance with sanitary standards in tourism. This includes the development of apps to track the epidemiological situation and e-ticketing systems to avoid physical contact. Such innovations are aimed at ensuring the safety and health of tourists and creating a "smart tourist space". The main objectives of the development of the "smart region" of Zakarpattia include increasing the attractiveness of the region, optimizing the tourism business, ensuring the safety and health of tourists, creating "smart infrastructure", increasing competitiveness, and promoting sustainable development. To achieve these goals, it is important to introduce information technology, such as booking systems and recommendation systems, which will simplify the travel service process and improve service. It is also necessary to ensure the security of travellers' data by implementing encryption measures and strict access control.

The Tourism Information Platform for the Zakarpattia Smart Region aims to provide a user-friendly and efficient experience for all stakeholders. Its main functions include search and booking of services, an interactive map of the region, personalized recommendations, information resources, a mobile application, feedback and ratings, support for languages and cultures, transport, and event organization. The platform should be accessible from any device with Internet access and have mobile applications for smartphones and other devices. Providing personalized recommendations and support for different languages and cultures are key aspects of responding to the needs of modern tourists.

Using cross-platform solutions, such as Flutter or React Native, will allow the developing of applications that run on different operating systems using a single code. The platform should also provide users with the ability to use certain functions offline without an Internet connection, while keeping some information and functions on the user's device. This will ensure that the platform continues to operate smoothly even when there is no connection to the server. In addition, the platform should support the special needs of users, such as an inclusive interface for users with disabilities and text reading functions with the help of voice assistants to improve accessibility and comfort of use of the platform.

The research by I.Y. Dir (2021) describes the current level of development of the "smart city" concept around the world, analysing the strategies of different cities and rankings of leading institutions that study this topic. The author examined policies adopted in different regions of the world, including Europe, Asia, North America, Latin America, and the Caribbean, and identified the various goals pursued by these regions in the development of "smart cities". The study also looked at the benefits that "smart cities" can bring to their residents. In comparison, the current study focuses on the concept of a "smart region", in particular, on the

implementation of this concept in the tourism sector in the Zakarpattia region. This study analysed specific goals and strategies for the development of the tourism industry in a particular region, in particular, paying attention to the integration of information technology and ensuring the safety and health of tourists through the implementation of "smart solutions". While the researchers' work is focused on analysing the strategies of cities within the framework of the "smart cities" concept in the world, this study aims to analyse specific measures to increase the attractiveness of a tourist region through the use of information technology and "smart approaches".

The study by N. Chung *et al*. (2021) examines the concept of "smart tourism cities" and highlights the need to integrate innovation and technology into tourism applications and urban infrastructure. They emphasize that "smart tourist cities" open up opportunities for everyday life and travel and are the result of the merging of the tourism business with everyday life. The authors propose to consider the concept of "smart tourist cities" and the role of urban centres in creating value for residents and travellers, in particular, through the development of an index for assessing the competitiveness of cities in the field of tourism. Compared to the current study, which focuses on a specific region of Zakarpattia and the application of "smart solutions" in the tourism sector to increase its attractiveness and safety, the researchers' work has a more general focus on creating competitive "smart tourist cities" as a concept.

A study by J.C. Cepeda-Pacheco & M.C. Domingo (2022) proposes the use of a deep learning-based tourist recommendation system that uses the Internet of Things to enhance the tourist experience in a "smart city". Tourists provide information about their travels and personal preferences through a city's app or website, and a deep learning-based recommendation system analyses this data to provide recommendations for the most appropriate tourist activities. In addition, the system can react in real-time to information about places already visited and contextual information such as location and weather conditions to suggest additional activities. Compared to this study, which focuses on the implementation of "smart technologies" to improve the safety and comfort of tourists in a specific region, the researchers' work aims to develop personalized recommendation systems to improve the overall tourist experience in a "smart city" using deep learning and the Internet of Things.

The study by P. Martinovich (2023) is devoted to the theoretical aspects of the development of the concept of "smart specialization" at the regional level, including the search for strategies and the dissemination of relevant processes to ensure the sustainable development of regions. The author systematized the main postulates of "smart specialization" development, pointing out the importance of technological progress for economic growth and competitiveness of the country. The main stages of the development and spread of "smart specialization" in the market space are highlighted, and its role as an innovative tool that contributes to the progressive development of the regional economy with strategic approaches to the regional environment is identified. Compared to this study, which focuses on the use of "smart technologies" to improve the tourist experience in a particular region, the researcher's work considered the theoretical and strategic aspects of introducing "smart specialization" for the development of the regional economy.

The study by P.P. Fedorka *et al*. (2023) examined the key methods and prerequisites for creating "smart cities" both in Ukraine and abroad, to implement them in the Zakarpattia region using advanced technologies. The study included an analysis of existing theories, practical solutions, and a comparative analysis of approaches to the formation of "smart cities" and "smart regions". The authors have developed criteria for determining the ways of development of Zakarpattia region to turn it into a "smart region". They propose a project of an information technology platform to improve decision-making efficiency and develop scientific models for the development of a "smart living environment" for the region's residents. Both studies are important for the development of the region and propose strategies to improve the quality of life of residents and the region's attractiveness to investors and tourists.

The concept of a "smart region" involves the integration of digital technologies and data analytics to improve the quality of life of residents and ensure the sustainability of the region. In the Zakarpattia region, this is manifested through the development of the tourism industry, including information systems and security measures for tourists. Integrating "smart solutions" into tourism not only improves service but also ensures the safety and health of travellers. Planning, booking, and information are becoming more convenient thanks to the use of information technology, which contributes to the region's competitiveness and attractiveness to tourists from other regions and countries.

CONCLUSIONS

The study found that the integration of information technology into the tourism industry of the "smart region" of Zakarpattia has great potential to increase the attractiveness of the region for tourists and ensure their safety. The development of a tourist information platform with personalized recommendations and support for different languages and cultures can contribute to the growth of the tourism potential of Zakarpattia. Cross-platform solutions for mobile application development can ensure that the platform is accessible to the entire audience of users, regardless of their devices. The use of voice assistants and an inclusive interface can greatly facilitate the use of the platform for people with disabilities. Saving information on the user's device and automatic synchronization with the server

allows for continuous availability of the platform even when there is no Internet connection.

The integration of information technologies into tourism in Zakarpattia will help to improve the level of tourist services, create safer conditions, and promote the development of the tourism industry in the region. The study confirms the importance of technology integration for achieving strategic goals in tourism development and increasing the competitiveness of Zakarpattia as a tourist destination. The results of the study demonstrate the potential of information technology to improve the tourism industry and the quality of tourist services in the region. To summarize, the integration of information technologies into tourism in Zakarpattia has the potential to increase the attractiveness and efficiency of tourist services, contributing to the sustainable development of the region. Recommendations arising from the study include the development of an information technology platform that takes into account the needs of tourists to the maximum extent possible and integrates with other services of the tourism industry, such as booking systems and interactive maps, to ensure convenient and efficient use for all stakeholders. Areas for further research could include analysing the impact of information technology innovations on tourism development, studying the wishes and needs of users regarding the functionality and interface of the platform, and improving security and data protection systems in the context of the tourism industry.

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CONFLICT OF INTEREST

None.

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Інноваційні технології розвитку туризму в Карпатському регіоні

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Анотація. Актуальність дослідження обумовлена різким зростанням зацікавленості у сфері подорожей в умовах розвитку сучасних технологій та необхідністю створення інноваційних підходів для покращення обслуговування та безпеки туристів. Метою даного дослідження є проведення аналізу концепції «розумного регіону» та визначення стратегій інтеграції інформаційних технологій у галузі подорожей для поліпшення обслуговування та безпеки туристів у регіоні Закарпаття. Під час дослідження застосовувалися методи аналізу, синтезу, узагальнення, дедукції та систематизації для оцінки потреб туристів та розробки оптимальних рішень. Було вивчено потенціал інтеграції інформаційних технологій у туризм «розумного регіону» Закарпаття. Встановлено, що створення туристичної інформаційної платформи з персоналізованими рекомендаціями та підтримкою різних мов та культур може допомогти зростанню привабливості регіону для туристів. Крім того, використання крос-платформених рішень для розробки мобільних додатків дозволить забезпечити доступність платформи для різноманітної аудиторії, незалежно від їхніх пристроїв. Важливим аспектом є збереження інформації на пристрої користувача та автоматична синхронізація з сервером, що забезпечує неперервну доступність платформи. Застосування голосових асистентів та інклюзивного інтерфейсу забезпечить зручне використання платформи для осіб з інвалідністю. Результати дослідження вказують на можливості інформаційних технологій у вдосконаленні туристичної індустрії та покращенні якості обслуговування туристів. Дослідження підтверджує важливість інтеграції технологій для досягнення стратегічних цілей у розвитку туризму та підвищенні конкурентоспроможності Закарпаття як туристичного напрямку. Впровадження інноваційних технологічних рішень може стати ключовим чинником у створенні «розумного туристичного простору», який забезпечить зручність, безпеку та задоволення для туристів. Практичне значення дослідження полягає в можливості використання його результатів для подальшого вдосконалення інформаційно-технологічної інфраструктури туристичної галузі в «розумному регіоні», а також в можливості покращення обслуговування туристів та збільшення конкурентоспроможності «розумного регіону» шляхом впровадження інформаційно-технологічної платформи

Ключові слова: рекомендаційна система; пандемія; «розумний регіон»; COVID-19; Закарпаття

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Digital modelling technologies in the mining industry: Effectiveness and prospects of digitalisation of open-pit mining enterprises

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Abstract. Due to the rapid development of the mining industry and the need to increase its competitiveness, digital modelling technologies for open-pit mining enterprises become a relevant and important direction of research. The aim of this study is to analyse integrated digital models for optimising open-pit mining enterprises, aimed at increasing productivity, ensuring safety, and reducing environmental impact. Among the methods used, it is worth mentioning the analytical method, classification method, functional method, statistical method, synthesis method, and others. During the research, an analysis of integrated digital models for optimising the operation of open-pit mining enterprises was conducted. The implementation of integrated digital models in mining enterprises has led to a significant increase in the level of resource extraction productivity, providing a more efficient organisation of work processes. Improvement in the safety system has also been identified, where these models allowed for timely detection and management of potential risks. In addition, the application of digital modelling technologies has contributed to a significant reduction in negative impact on the natural environment, implementing more environmentally sustainable methods of resource extraction and processing. The integration of digital technologies has allowed optimising work processes, making them more efficient and resilient. The study also emphasises the importance of using digital models in the context of predictive analysis and decision-making. The overall conclusion is that

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digital modelling technologies are a key tool for achieving optimal functioning of modern mining enterprises. A detailed study of modern optimisation methods for mining enterprises will allow optimising work processes, increasing efficiency, and reducing negative environmental impact

Keywords: competitiveness; impact on the environment; work processes; strategy; modelling; digitisation

INTRODUCTION

Studying digital modelling technologies in the mining industry holds significant importance in the modern world. With the rapid growth of the mining sector and the constant pursuit of increased competitiveness, the integration of digital models becomes an integral part of optimising open-pit mining enterprises. The implementation of these technologies leads to a substantial increase in productivity in the mining sector. This is achieved by refining extraction processes and resource management through digital models, which allows for more efficient resource utilisation and cost reduction. Digital modelling technologies help avoid excessive resource use, optimise energy efficiency, and minimise emissions of harmful substances. Examples of technology use include drone utilisation for ore deposit monitoring, risk prediction and process optimisation through artificial intelligence, and virtual reality for personnel training, among others. Thus, integrating digital models into the mining industry serves not only as a means of achieving economic efficiency but also as a key element of sustainable development, contributing to the preservation of natural resources and environmental resilience.

The research issue lies in the fact that mining enterprises face challenges of rapid industry development and the need to enhance competitiveness. The negative impact of mining on the environment and workplace safety instability are pressing issues. The absence of optimal strategies and effective use of digital modelling technologies may limit industry development and lead to adverse environmental consequences. However, exploring this issue can identify ways to optimise work processes, increase efficiency, and reduce environmental impact, critical for the sustainable development of the mining industry.

Findings from research by O. Denysiuk & A. Panasiuk (2023) indicate that implementing digital modelling technologies in the mining industry not only enhances productivity but also enables more effective risk management and ensures workplace safety. However, it's important to note that the research does not address potential challenges and limitations that may arise from implementing digital modelling technologies in the mining industry. The work by O. Medvedeva *et al.* (2023) highlights key aspects of environmental sustainability achievable through using digital models to optimise mining enterprises' impact on the environment. Nevertheless, the study does not focus on the social interaction aspects and the impact of digital technology implementation on miners and local communities.

According to research by M. Adamenko *et al.* (2021), which focuses on developing integrated digital models as a strategic tool for enhancing mining enterprises' competitiveness, it's important to consider adaptation strategies and potential difficulties in implementing integrated digital models in various mining enterprise contexts. Researchers A. Burkovskaya & Yu. Syzonenko (2023) discuss optimising work processes and determining effective methods for implementing digital technologies in mining enterprises. However, their work lacks attention to the significant potential for developing and improving personnel management systems in mining enterprises through digital technologies.

The study of M. Nazarenko (2021) emphasises the importance of considering various methods in developing and implementing digital models for optimising mining processes. However, the research does not explore effective implementation strategies and personnel training regarding digital model use. B.I. Yatsikovsky & G.S. Golybka (2022) raise the critical issue of the interaction of digital technologies with various types of mining resources and their potential synergy to enhance overall productivity and efficiency. However, the study does not consider potential risks and challenges associated with the synergy of digital technologies with older, traditional resource extraction methods.

The aim of the research was to provide specific practical recommendations for implementing digital technologies in mining enterprises in the context of contemporary technological development.

MATERIALS AND METHODS

The analytical method helped in thorough examination of the initial data and identification of key parameters influencing the effectiveness of digitisation in mining enterprises. As a result of this study, optimal strategies for implementing digital technologies were identified, which would contribute to increased productivity and sustainable development of the mining industry. The analytical method proved to be an effective tool for considering complex relationships in the field of digitisation of mining enterprises and developing optimal implementation strategies.

Deep analyses were conducted using the statistical method to assess the effectiveness of implementing digital technologies in mining enterprises. This method allowed for collecting and processing large volumes of data to determine statistically significant trends and dependencies. Research results from the statistical method provided detailed indicators of

digitisation effectiveness, particularly regarding increased productivity, risk reduction, and cost optimisation. This statistical study serves as the basis for a comprehensive assessment of the impact of digital technologies on mining enterprises and facilitates the development of well-founded strategies for further enhancing digital transformation in this sector.

By applying the functional method, key functions and roles of digital technologies in the mining industry were identified. This method enabled a detailed examination of how digital innovations could optimise production processes, improve monitoring systems, and risk management in mining enterprises. Based on the acquired data, strategies for implementing digital technologies were developed, which maximally consider the functional needs of the industry and contribute to achieving optimal results in the context of technological advancements and global challenges in the mining sector. The functional method allowed for systematising and determining the role of digital technologies as an effective tool for achieving strategic goals of mining enterprises.

The deductive method helped in determining the basic principles underlying the effective implementation of digitisation in the mining industry. By studying general digitisation principles and existing theoretical concepts, key aspects influencing the success of this process in the resource extraction industry were identified. The deductive approach established connections between theoretical concepts and specific requirements of digital transformation in mining enterprises. This method served as the foundation for developing implementation strategies oriented towards achieving maximum efficiency and compliance with theoretical principles of digitisation in the context of the mining industry.

Through the synthesis method, diverse components and aspects of digitisation in the mining sector were combined to create a comprehensive and integrated model. This approach allowed for the integration of various technologies, methods, and strategies into a unified system aimed at optimising the functioning of mining enterprises. Synthesis proved to be an effective tool for creating a harmonious and interactive digital environment covering all aspects of production and management. The results of the synthesis method serve as the basis for developing integrated digital models that contribute to increasing productivity, efficiency, and resilience of mining enterprises in the modern digital landscape.

The classification method helped in organising various aspects of digitisation in mining enterprises by identifying key categories and types of technological solutions. By studying different approaches to digital transformation in the mining industry, commonalities, and differences between various strategies were identified. This method facilitated the categorisation of digital initiatives based on their key characteristics and functions. Such an approach contributes to the development of individual strategies for implementing digital technologies for different classes of mining enterprises, ensuring consideration of their specific needs and conditions.

RESULTS

In design institutes, digital systems can be used to address various tasks related to planning and designing open-pit mining operations. These systems feature diverse tools and functions that allow mining engineers to create and analyse complex geological models, assess economic feasibility, and plan work at the extraction site. One of the main advantages of these digital systems is their ability to create and enhance geospatial information support. This support can be used to create detailed maps and plans of mining areas, including horisontal plans that can be automatically generated in interactive mode. In addition to geospatial information, these digital systems can also be used for modelling and designing multi-variant quarry spaces, taking into account a wide range of techno-economic data (Kunytska *et al.*, 2023). Digital modelling technologies in the mining industry play a key role in increasing the efficiency and competitiveness of open-pit mining enterprises. These technologies enable the resolution of complex management, safety, and production efficiency tasks.

Ukraine, rich in natural resources including minerals, has significant potential for the development of the mining industry. Zhytomyr region, located in the northwestern part of Ukraine, is one of the regions where open-pit mining enterprises play an important role in economic development and providing employment opportunities. Zhytomyr region is renowned for its geological diversity and the presence of valuable minerals. Ores containing valuable metals as well as construction materials such as limestone and clay are mined in this region. Geological reserves create favourable conditions for the development of open-pit mining enterprises. Modern technologies are used for the detection, extraction, and processing of minerals in this region (Avramchuk, 2021).

As of the end of 2023, the Golovinske deposit of labradorite in the Chernyahivsky district of Zhytomyr region actively employs advanced technologies at all stages of stone extraction and processing. Its development history spans over a century, starting in 1894 with the industrial development of decorative and facing stone. In the 1980s, the deposit underwent a reassessment of reserves and modernisation to meet new standards and technological developments. Additional licensing areas within the deposit, namely North and South, were allocated in 2018, indicating ongoing development and expansion. Geological exploration technologies are used to accurately determine the reserves of labradorite, while modern drilling machines and specialised equipment ensure efficient extraction of

blocks. Automation systems are used for processing and cutting blocks into facing products, ensuring high quality. The modernisation and expansion encompass the allocation of new licensing areas and the application of digital technologies for monitoring and process management. The Golovinske deposit actively utilises advanced tools and methods to achieve efficiency and high product quality, indicating its confident course towards sustainable development (Golovinske deposit, n.d.).

The Omelyanivske deposit of granite employs advanced technologies for efficient extraction and processing of granite stone. Their technological scheme includes modern drilling machines for precise extraction, specialised equipment for block processing, lifting machines for moving large blocks, and transport for their transportation. The machinery and equipment fleet includes automated cutting and polishing systems, as well as transport vehicles for logistical operations. Qualified permanent and shift personnel effectively utilise machinery and control production. Plans for the future may involve the implementation of even more efficient technologies, such as artificial intelligence (AI) for process optimisation, environmentally friendly technologies to reduce environmental impact, and the expansion of automated systems to increase productivity. Continuous modernisation of machinery and equipment may also be part of the plans to achieve greater competitiveness in the market (Omelyanivske deposit, n.d.).

Implementation of automated systems, remote monitoring, and other digital solutions enhances the efficiency of mining processes and ensures worker safety. Mining activities in the region significantly impact the economy and provide new job opportunities for the local population. Revenues from mineral extraction contribute to infrastructure development and social projects, improving the quality of life for residents of the region. An important aspect of open-pit mining enterprises' activities is their social responsibility. Many companies implement social programs and environmental initiatives aimed at preserving nature and improving living conditions for local residents. Despite all the positive aspects, open-pit mining enterprises also face challenges related to ecology and resource management (Marimuthu *et al.*, 2021). It is important to improve technologies and implement innovations to reduce negative environmental impact.

Building sands, pyrophyllite shales, large reserves of gabbro, granite, labradorite, and marble represent valuable minerals in this region. Deposits of rare earth elements such as vanadium, scandium, hafnium, and thorium are in high demand on the international market. The region has nine major deposits (Fig. 1). The Irshansk titanium ore district exploits titanium oxide, known as ilmenite. Among semi-precious stones, the region extracts beryl, topaz, and quartz (Mineral resources of Zhytomyr region, n.d.).

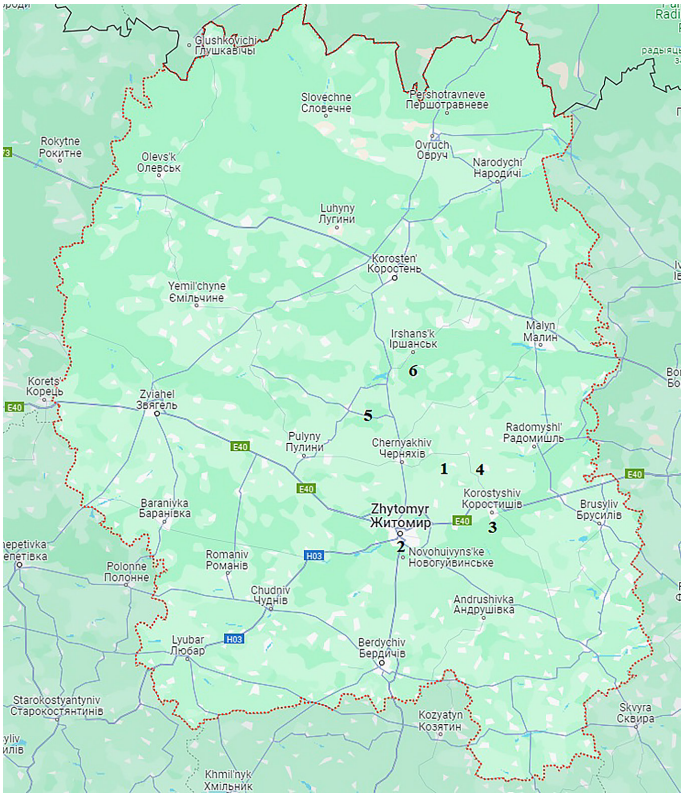

Figure 1. The largest mineral deposits located in the Zhytomyr region
Notes: 1 – Golovinske deposit of labradorite; 2 – Omelyanivske deposit of granite; 3 – Korosten granite deposit; 4 – Korostyshiv granite deposit; 5 – Leznikivske deposit of granite; 6 – Irshansk titanium ore district
Source: compiled by the authors

One of the promising directions in the mining industry is the implementation of autonomous transport vehicles and drilling rigs. Automated systems can accelerate extraction and reduce labour costs, as well as mitigate risks for workers in hazardous conditions. Autonomous transport vehicles, such as drones and unmanned vehicles, can be used for monitoring and surveying the area, identifying extraction sites, and transporting materials. This reduces transportation time and costs while ensuring precision and efficiency in process management. Drilling rigs with automated systems can accurately determine drilling locations, optimise angles and depths of wells, leading to increased productivity and cost reduction.

Monitoring and control systems play a crucial role in ensuring safety and efficiency in the mining industry. The use of modern technologies such as sensors, Internet of Things (IoT) technologies, and remote monitoring systems allows real-time monitoring of equipment parameters and working conditions. IoT systems enable the collection and analysis of data from equipment, facilitating the timely detection of potential issues and avoidance of accidents. Sensors measure various parameters such as temperature, pressure, and humidity, aiding in maintaining optimal conditions for equipment operation. The use of remote monitoring systems allows operators to receive real-time information about the equipment's status and remotely control its operation. This ensures prompt response to any malfunctions or changes in production processes. The implementation of autonomous transport vehicles, automated drilling rigs, and monitoring systems allows for increased efficiency and competitiveness of the extraction process, while simultaneously ensuring optimal working conditions and worker safety.

Digital transformation is a key factor in the modern development of the mining industry, where the use of advanced technologies can improve productivity, safety, and environmental efficiency (Feroz *et al.*, 2021). The process of digital transformation goes through several stages, including automation, digitisation, and the transformation itself (Fig. 2).

Figure 2. Development process of digital transformation of a mining enterprise
Source: compiled by the authors

In the first stage, the mining enterprise implements automation to optimise specific processes and tasks. This may involve the use of automated production systems, automated drilling rigs, intelligent transport vehicles, and monitoring systems. As a result of automation, the enterprise achieves increased efficiency, reduced labour costs, and minimisation of risks for workers. However, this is only the initial step in the adoption of digital technologies. In the second stage, the mining enterprise transitions to broader use of digital technologies, which includes converting analogue information into digital format. The use of sensors, IoT technologies, data analytics, and cloud services allows for the collection and processing of large volumes of information in real-time. Digitisation enables the enterprise to gain a deeper understanding of its operations, react to changes in real-time, and improve decision-making strategies. The final stage is digital transformation, where the mining enterprise changes its philosophy, business model, and culture, using advanced digital technologies. This includes the adoption of artificial intelligence (AI), blockchain technologies, big data analytics, and other innovations. Digital transformation enables the enterprise to move from reactive management to forecasting and strategic planning. It also improves interaction with customers, ensures sustainability, and addresses environmental challenges.

The evolution of digital transformation in the mining industry is a process that reflects the transition from automation to deep digital transformation. Each stage aims to improve efficiency, ensure safety, and environmental responsibility, making mining enterprises more competitive and resilient in the modern world of technology. In the modern world of technology, virtual and augmented realities (VR/AR) become integral parts of the industry, especially in resource extraction. One of the key applications of VR/AR in the mining sector is the use of virtual environments for training operators and personnel. Virtual simulators allow for the creation of realistic scenarios where personnel can learn to work efficiently and safely with equipment. This is particularly relevant in cases where work requires a high level of skill and safety, such as operating heavy machinery or robots in extraction sites. Virtual simulations also allow personnel to adapt to unforeseen situations and emergencies, making training more realistic and effective, leading to improved employee readiness and risk reduction.

VR/AR is also widely used to optimise design and planning processes in the mining industry. Virtual environments allow engineers and designers to interact with extraction objects and examine them under real conditions. Work planning may include the use of AR for overlaying virtual models onto real objects, allowing for precise marking of work areas, equipment placement, and infrastructure layout. This approach improves planning efficiency and reduces errors in project implementation. The use of VR/AR in the mining industry not only ensures safety and high levels of personnel training,

but also greatly facilitates project planning and design (Xie *et al.*, 2022). These technologies bring innovation to the industry, contributing to its development and increasing overall productivity. AI and machine learning (ML) address a wide range of tasks in the industrial sector, including resource extraction (Sircar *et al.*, 2021).

The use of ML algorithms enables the analysis of large volumes of data to forecast various parameters in the extraction field. AI systems can analyse data on extraction, energy consumption, and other key indicators to provide accurate and predictive results. For example, algorithms can forecast extraction volumes based on historical data, climatic conditions, and equipment technical parameters. This allows companies to plan production processes, optimise resource utilisation, and reduce costs. The implementation of visual surveillance and object recognition systems ensures a high level of safety and efficiency at extraction sites. AI systems can recognise objects, detect anomalies, and take action in real-time. For example, recognition systems can detect hazardous situations, such as gas leaks or transportation accidents, and send automatic signals for evacuation or other safety measures. The use of AI and ML in resource extraction contributes to increased productivity and provides significant advantages in forecasting and labour safety (Waltersmann *et al.*, 2021). These technologies open up new opportunities for efficient resource utilisation and industrial process optimisation, making a significant contribution to the modern industry. Digital technologies play a crucial role in improving processes and optimising management across various sectors of industry.

The application of blockchain technology in supply chains is intended to enhance transparency and trust in this crucial aspect of industry. The Blockchain enables the creation of a continuous and immutable registry of transactions that can be easily tracked and verified. Through blockchain, accuracy, and reliability of information regarding the sources of resources, their movement, and processing at various stages of the supply chain can be ensured. This provides parties with the ability to verify conditions of extraction, storage, and transportation, thereby contributing to the improvement of product quality and safety.

The use of digital technologies for automating the processing and storage of documentation is another important part of digital transformation. Electronic document management systems replace traditional paper-based processes with efficient and environmentally friendly solutions. These systems automate the processes of document creation, processing, signing, and storage, ensuring their availability, integrity, and security. This reduces time, costs, and the likelihood of errors associated with manual operations. Digital technologies make a significant contribution to modern industry, particularly in the resource extraction sector (Calvão & Archer, 2021). The use of blockchain for supply chains and electronic document management systems contributes to enhancing transparency, security, and efficiency in various aspects of industrial processes. The implementation of digital solutions in resource extraction allows for the efficient use of energy and water while reducing emissions into the atmosphere and water bodies. The use of modern technologies for monitoring and controlling processes enables companies to accurately regulate resource consumption while considering production needs and environmental standards. For example, the use of sensors and IoT technologies allows for real-time monitoring and optimisation of energy usage in equipment. Data analysis also helps identify effective ways to reduce costs and environmental impact.

The use of models to forecast the ecological consequences of mining operations is a key step in ensuring sustainable development. These models allow scientists and engineers to understand the potential impact of actions on the natural environment. Developing strategies to mitigate negative environmental impacts is based on modelling results. These strategies may include implementing technologies for wastewater treatment, implementing measures to restore soil fertility, and using environmentally friendly mining methods. The introduction of digital technologies in the mining sector promotes more efficient resource utilisation and reduces negative environmental impact. Combining optimisation and modelling of environmental consequences makes the industry more sustainable and responsible towards nature (Xiong *et al.*, 2022). Digital modelling technologies can significantly increase the productivity and resilience of mining enterprises while reducing their environmental impacts, creating more efficient and environmentally sustainable working conditions.

DISCUSSION

In the modern world, open-pit mining enterprises are taking the forefront of digital transformation, implementing new modelling technologies to optimise and enhance production processes. This trend creates new opportunities and challenges for the industry that should be carefully considered. Digital modelling technologies allow miners to precisely calculate and forecast mining processes. The use of virtual models enables the optimisation of open-pit mining operations, managing extraction, resources, and minimising time and resource losses. Digital technologies facilitate the implementation of automation and robotics in open-pit mining enterprises. The use of drones, autonomous vehicles, and other automated systems simplifies and accelerates production processes, reducing labour costs and increasing safety. Digital technologies enable more efficient use of natural resources and minimise negative environmental impact. Modelling allows for deeper analysis of energy, water, and other resource usage, contributing to the creation of more environmentally friendly and sustainable mining activities.

The growth of digitisation demands new skills and competencies from workers in the mining industry. Ensuring cybersecurity and compliance with standards are critical tasks. The implementation of digital technologies may change the employment profile and require retraining of workers. Simultaneously, this may create new opportunities for development and skill enhancement. Digital modelling technologies open new horizons for open-pit mining enterprises. Their efficiency, contribution to sustainable development, and increased worker safety make this digital transformation crucial for the future of the mining industry. However, it is important to manage this process wisely, considering social, ethical, and environmental aspects, to achieve a balance between innovation and sustainability.

According to recent research by J. Duarte *et al*. (2021), the digitisation of open-pit mining operations is marked by significant advantages, particularly in the implementation of a new approach to monitoring and controlling rock fragmentation. The use of advanced digital technologies enables precise and efficient tracking of rock fragmentation processes, defining the direct importance of digital monitoring in mining. One key advantage is the use of modern sensors and IoT technologies for continuous real-time monitoring of mining parameters. This provides operators and engineers with access to real-time data on fragmentation, allowing timely responses to any changes in rock conditions. The use of digital systems also facilitates automated data collection and analysis, ultimately improving the accuracy and timeliness of decision-making. These findings align with the themes presented in the previous section. An important aspect of digitisation in this context is the implementation of AI technologies for forecasting fragmentation implications and optimising material removal processes. This allows not only reacting to current conditions but also planning future operations based on trends and historical data. This new approach to monitoring and controlling rock fragmentation ensures high levels of efficiency, safety, and stability in mining operations.

One can refer to the definition by G. Wang (2022) that the new technological progress in coal exploration is characterised by significant achievements, yet certain problems arise that require attention and solutions. One key advantage is the use of advanced geoinformation systems and modern satellite probing technologies for accurately determining coal deposit locations. This ensures high accuracy in determining the locations of coal reserves, allowing for effective planning of extraction and optimisation of work processes. However, against the backdrop of technological progress, environmental and social problems arise. Coal mining is often associated with a significant impact on the environment and the health of local residents. Air, water, and soil pollution, gas emissions, as well as ecosystem degradation, can have serious consequences. Additionally, social aspects such as preserving the health and safety of workers, adequate living conditions for local populations, are necessary requirements in the development of the coal industry. It is worth noting that these mentioned problems require a comprehensive approach and the search for innovative solutions to balance technological development with environmental preservation and socio-economic well-being in coal regions.

Researchers P.V. Hartlieb-Wallthor *et al*. (2022) have identified that sustainable intelligent mineral extraction defines the modern approach to mining, focusing on ensuring safety, economic efficiency, environmental cleanliness, and digital enhancement. One of the key characteristics of this approach is the application of advanced technologies and intelligent systems to enhance worker safety in mining sites. Monitoring and forecasting systems help prevent accidents and incidents, while artificial intelligence can analyse data to anticipate potential risks. Economic efficiency is ensured through optimisation of extraction processes, use of autonomous technical means, and improved resource management. Digital technologies, such as blockchain, can enhance the transparency and reliability of supply chains, crucial for the sustainable economic activities of mining enterprises. The environmental cleanliness of sustainable intelligent extraction is determined by the use of environmentally friendly technologies, implementation of measures for restoring natural resources, and minimisation of emissions. This includes the adoption of energy-efficient solutions and the use of renewable energy sources. These results confirm the aforementioned research, as sustainable intelligent mineral extraction promotes the harmonious combination of industrial development with nature preservation and improvement of the quality of life for communities involved in mining activities.

Researchers Q. Qi *et al.* (2021) demonstrated in their work that the use of technologies and tools for Digital Twins is marked by revolutionary capabilities in many fields – from industry and infrastructure to science and medicine. A digital twin is a virtual model of a real object or system that reflects its state, parameters, and interaction with the surrounding environment in real-time. In industry, digital twins can be used for monitoring and managing equipment, predicting potential breakdowns, optimising production processes, and increasing manufacturing efficiency. In infrastructure, this may involve creating virtual models of cities to manage traffic, water supply, and other municipal systems. However, along with the benefits, there are also challenges. Ensuring high accuracy and truthfulness of data, ensuring cybersecurity, and addressing confidentiality issues are key tasks in the use of digital twins. It is also important to consider the cost of implementation and maintenance of such technologies. With this view, one can

agree, more specifically, that governments, businesses, and scientific sectors should work together to develop standards, regulations, and ethical norms to ensure successful integration of digital twins into various spheres and make them safe and beneficial for society.

As noted by Y. Uteshov *et al*. (2021), the use of digitisation and advanced analytics in the field of designing and developing solid mineral deposits opens up wide opportunities for improving process efficiency. One of the key advantages is the use of digital twins of mining objects, which virtualise the entire geological structure and resource locations. This allows geologists and engineers to conduct more precise modelling and analysis of potential deposits, contributing to the study of geological conditions and optimisation of extraction design. Advanced analytics involves the use of intelligent algorithms and AI to process large volumes of data collected during geological surveys and drilling. This contributes to improving forecasts regarding ore presence, depth of mineralisation, and other important parameters that determine the profitability of deposit development. Additionally, digital technologies enable the implementation of real-time monitoring systems on mining objects. This provides a continuous flow of data on equipment conditions, ore reserves, and other factors, facilitating prompt response to changes in production processes. Analysing the results and conclusions obtained, it can be concluded that digitisation and advanced analytics in the mining industry create prospects for improving development strategies and increasing production efficiency, while reducing risks and optimising resource utilisation. Researchers T. Li *et al*. (2022) identified that thematic research on the effectiveness of technological innovations in enterprises is influenced by digital transformation. This process significantly changes approaches to production, management, and customer interaction. One of the main advantages of digital transformation is the ability to quickly integrate cutting-edge technologies, leading to increased innovation within the enterprise. This allows companies to improve the quality of their products and services, as well as to respond more promptly to changes in market conditions.

Technological innovations driven by digital transformation can encompass various areas, including production processes, logistics, marketing, and customer service. Automation of production lines, implementation of AI systems for data analysis, and the use of IoT for equipment monitoring are just a few directions that can improve enterprise productivity. It is worth noting that companies can quickly adopt and adapt to advanced innovations, which becomes a key factor in a changing business environment. This ability to rapidly integrate allows enterprises to leverage the latest technological solutions, leading to increased levels of innovation.

CONCLUSIONS

In the conclusions, it is expedient to emphasise the significance of digital modelling technologies in the mining industry, as well as to identify their potential benefits and prospects for open-pit mining enterprises. For successful implementation of digital technologies into the business model of a mining enterprise, it is necessary to overcome traditional conservative approaches in the mining industry, activate systematic training and skill enhancement of employees, taking into account industry-specific features and organisational-technological aspects of the enterprise. Another important element is the creation of an industry innovation system aimed at intensifying technology transfer.

Digital modelling technologies applied in the mining industry define a new level of efficiency and management of production processes in open-pit mining enterprises. They enable accurate forecasting and optimisation of mining operations, ensuring optimal resource utilisation and maximising production productivity. The efficiency of digital technologies lies in their ability to enhance decision-making quality, minimise risks, and ensure workplace safety. Implementation of automated systems, remote monitoring, and other innovative solutions simplifies tasks and enables flexible response to changing conditions in mining activities. The prospects of digitisation for open-pit mining enterprises include productivity growth, resource loss reduction, increased worker safety, and reduced environmental impact. It is noted that these technologies open up new opportunities for industry development and contribute to its sustainable growth.

Digitisation in the mining industry not only transforms technological processes but also contributes to the formation of the concept of a "green" mining enterprise. This process involves the implementation of environmentally friendly technologies, optimisation of resource use, and reduction of atmospheric emissions, leading to the creation of environmentally safe and economically efficient production. This direction is characterised not only by the use of advanced technologies to increase productivity but also by active implementation of energy-efficient and environmentally friendly solutions. However, it is important to consider challenges such as staff training, ensuring cybersecurity, and addressing social and ethical issues. Overall, digital modelling technologies are a key factor in transforming open-pit mining enterprises into high-tech, productive, and environmentally friendly complexes.

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CONFLICT OF INTEREST

None.

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Цифрові технології моделювання в гірничій індустрії: ефективність та перспективи цифровізації відкритих гірничих підприємств

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Анотація. У зв'язку зі стрімким розвитком гірничої індустрії та необхідністю підвищення її конкурентоспроможності, цифрові технології моделювання відкритих гірничих підприємств стають актуальним і важливим напрямком дослідження. Метою даного дослідження є аналіз інтегрованих цифрових моделей для оптимізації відкритих гірничих підприємств, спрямованих на підвищення продуктивності, забезпечення безпеки та зменшення впливу на навколишнє середовище. Серед використаних методів слід зазначити аналітичний метод, метод класифікації, функціональний метод, статистичний метод, метод синтезу та інші. У ході дослідження був проведений аналіз інтегрованих цифрових моделей для оптимізації функціонування відкритих гірничих підприємств. Впровадження інтегрованих цифрових моделей в гірничі підприємства призвело до значного зростання рівня продуктивності в видобутку ресурсів, забезпечивши ефективнішу організацію робочих процесів. Також виявлено покращення в системі безпеки, де ці моделі дозволили вчасно виявляти та управляти потенційними ризиками. Крім того, застосування цифрових технологій моделювання сприяло значному зменшенню негативного впливу на природне середовище, реалізуючи більш екологічно сталі методи видобутку та обробки ресурсів. Інтеграція цифрових технологій дозволила оптимізувати робочі процеси, роблячи їх більш ефективними та стійкими. Дослідження також підкреслило значення використання цифрових моделей у контексті прогностичного аналізу та прийняття рішень. Загальний висновок полягає в тому, що цифрові технології моделювання є ключовим інструментом для досягнення оптимального функціонування сучасних гірничих підприємств. Детальне вивчення сучасних шляхів оптимізації гірничих підприємств дозволить оптимізувати робочі процеси, підвищить ефективність та зменшувати негативний вплив на довкілля

Ключові слова: конкурентоспроможність; вплив на навколишнє середовище; робочі процеси; стратегія; моделювання; цифровізація

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Development and implementation of a smart home automation system in the context of the Ukrainian housing sector: Challenges and prospects

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Abstract. Due to the rapid development of technology and the growing interest in the concept of "smart home", the relevance of the study is to identify obstacles and opportunities, contributing to the effective implementation of these technologies in modern life. The purpose of this study is to analyse the modern state and determine the possibilities of developing and implementing smart home automation systems in the Ukrainian residential sector to increase the level of comfort, safety, and energy efficiency. The methods used include the analytical method, classification, functional method, statistical method, synthesis, etc. The results of the study reveal the profound impact of technology on the efficiency and security of a smart home. The modern state of smart home automation systems in the Ukrainian residential sector was analysed. Modern cybersecurity methods for protecting against potential threats were considered. Electronic keys, including Face Identification, fingerprint and voice recognition technologies, are being implemented to provide access and increase security in the smart home. The study reveals various methods that are used in different countries to implement smart homes, presenting various examples of development and features of their implementation. As a result, key technical and financial challenges are identified that call into question the effectiveness of implementing such systems. In addition, the possibilities of optimising these systems were considered based on market features and infrastructure constraints. According to the analysis, specific recommendations were developed for creating affordable and effective solutions for Ukrainian consumers. Based on these recommendations, it can be concluded that, despite the existing difficulties, the introduction of smart home systems in Ukraine has potential and prospects. However, to achieve full success, it is important to overcome technological challenges and consider the financial capabilities of the population. The study made a significant contribution to understanding the factors influencing the successful implementation of modern technologies in the residential sector of Ukraine, contributing to the practical development of science and providing concrete conclusions for the possibilities of implementing smart home automation systems

Keywords: technologies; energy efficiency; technical methods; recommendations; infrastructure constraints

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INTRODUCTION

The growing interest in the smart home concept is driven by the desire to improve comfort, safety, and energy efficiency in residential areas. Smart home automation systems, due to their capabilities, provide automated control of various devices and systems in the home, which leads to numerous advantages. They contribute to increased comfort by automatically performing routine tasks such as controlling lighting, adjusting temperature, and opening doors. This not only frees up the time and effort of residents, but also makes their lives convenient. An important aspect is to increase security, as automation systems can control access to the home, detect and prevent hazards, and provide remote home management. This is important to protect against burglary,

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fire, and other potential hazards. In addition, automation systems help to improve energy efficiency by optimising energy use in the home. This reduces energy supply costs and minimises the negative impact on the environment.

The research focuses on identifying and developing optimal strategies for implementing smart home automation systems in the Ukrainian residential sector. This includes a thorough analysis of the technical and financial challenges that arise when implementing modern technologies, identifying market constraints, and infrastructure challenges. Confronting these aspects is a key issue, as it determines the success or failure of implementing smart technologies in the housing sector of Ukraine. Insufficient standardisation, financial constraints, and infrastructure variability are becoming important aspects that need to be studied and addressed to ensure the effective implementation of smart systems in the home environment.

The study by K. Halahura *et al.* (2022) highlighted the rapid development of technology and increased interest in the smart home concept, which determines the relevance of the study. The study did not address specific technical aspects of implementing smart systems in the residential sector. E. Khomenko and O. Lemeshchuk (2023) identified key technical and financial challenges that arise when implementing smart home automation systems in the Ukrainian residential sector. The study does not focus on the interaction between different manufacturers of smart systems and the possibility of standardisation. N.G. Aksak *et al.* (2024) noted the importance of considering the possibilities of optimising systems considering market characteristics and infrastructure constraints in the context of implementing a smart home. The study did not address the impact of financial constraints on the decision to implement smart home systems. A.V. Kharytonovych and M.O. Nazarenko (2023) noted that identifying and solving problems of technical and financial challenges is a critical stage for the successful implementation of automation systems. The researchers did not analyse the possibilities of optimising automation systems with regard to infrastructure constraints.

Research conducted by L.M. Vilinska *et al.* (2023) highlighted the importance of energy efficiency and the possibility of reducing resource consumption when implementing smart systems in residential areas. The paper did not address aspects of efficiency and reduced resource consumption in the context of smart residential systems. The study by Yu. Hasiuk *et al.* (2023) raised the issue of standardisation in the context of implementing smart home systems, which determines consistency and compatibility between different manufacturers and platforms. The possibility of developing affordable solutions for Ukrainian consumers was not considered by the researchers. M.I. Hrytsaienko and H.I. Hrytsaienko (2021) analysed the concept of a "smart home", established the composition and interrelation of the main components of this hierarchical system, and based on a survey of residents of two-room apartments with underfloor heating, a conclusion was made about the feasibility of investing in its energy efficiency. The study did not consider the possibility of using the integration of electronic keys and security systems based on Face ID (Identification), fingerprint and voice recognition technologies to increase the level of protection and comfort of smart home users.

As part of a study conducted by Ya. Kovivchak *et al.* (2021), an information system was developed aimed at optimising and controlling electricity consumption in a smart home. The study did not examine the impact of using alternative energy sources, such as solar panels or wind turbines, on power management in a smart home. I.M. Lukyanovets and N.K. Lysa (2022) stressed the importance of paying attention to the risks and security of a smart home, which include the collection and processing of personal data, the possibility of confidential information leakage, cyber-attacks, and unforeseen situations in the operation of systems, which highlights the need for security measures to ensure the reliability and protection of privacy in a smart home. The researchers did not address the possibility of implementing data encryption or blockchain technologies to provide an additional layer of security and privacy protection in smart homes.

The purpose of this study was to explore how smart home automation systems can be implemented in Ukraine to make housing more comfortable, safe, and energy efficient.

MATERIALS AND METHODS

The analytical method helped to consider and investigate key aspects of the functioning of smart home automation systems. Using this method, it was possible to analyse the various technical and operational characteristics of these systems, and determine their effectiveness and possible areas of improvement. The analysis of the data obtained provided a sound understanding of the advantages and limitations of using smart technologies in the housing sector.

Using the functional method, the functionality of smart home automation systems was identified and studied in detail. This approach determined how systems interact with different devices and equipment, and how they affect different aspects of the household environment. The study of functional characteristics revealed the possibilities of controlling lighting, heating and air conditioning systems, safety systems, and other aspects of living space. Considering such functionality, recommendations were developed for the optimal use of automation systems, contributing to maximum comfort and safety for residents.

The deduction helped in determining the logical conclusions and patterns underlying the implementation of smart home automation systems. Investigating the general principles and principles on which these systems work, key aspects that determine their effectiveness and capabilities were identified. The deduction

has contributed to the formulation of predictions and strategies for the future improvement of smart housing. Exploring the limitations and opportunities, the study identified ways to optimise and develop new functionality that will contribute to further growth of comfort and safety in modern residential premises.

The synthesis combined various elements and components to create complete and optimal smart home automation systems. This approach allowed integrating different technologies, ensuring their interaction to achieve maximum functionality. By exploring various aspects from basic technical characteristics to user interfaces, the synthesis has made it possible to create systems that effectively meet the needs and expectations of users. Considering the principles of design and interaction of components, solutions have been synthesised that improve the comfort, safety and energy efficiency of residential premises.

The classification method helped to systematise and categorise the diversity of smart home automation systems according to their technical characteristics and functionality. The operational inspection identified groups of systems by their purpose, scope of functions, and level of automation. This method allowed identifying key features and distinguishing between different types of systems depending on their application. The classification was useful for understanding and determining the best options for choosing automation systems based on the individual needs and preferences of users. Using the induction method, various scenarios for using smart home automation systems in the Ukrainian residential sector were studied. This method analysed previous cases of successful implementation, identifying key aspects that lead to positive results. The induction also identified important factors for successful implementation, such as providing the appropriate technical infrastructure, user training, and developing data security systems. Consideration of these factors when planning and implementing automation systems is important to ensure stability and long-term efficiency.

RESULTS

The development and implementation of smart home automation systems in the Ukrainian residential sector can be an effective solution for improving comfort, safety, and energy efficiency. The Internet of Things (IoT) is a network of interconnected devices that can transmit and process data. These devices are equipped with software and built-in sensors that allow them to exchange information on a global or local network. Using IoT systems can simplify everyday tasks, providing people with a more dynamic and comfortable lifestyle. For example, in smart homes, IoT devices can automatically activate lighting when a person enters a room or adjust the temperature according to the specified parameters. In addition, home IoT devices can interact with each other and provide various services to users. For example, a smart assistant can play music from the owner's library or perform certain tasks on other IoT devices according to saved daily tasks. Thus, IoT devices can make a person's life easier by performing various tasks without direct intervention or at the user's command.

Smart technologies in modern homes are becoming increasingly popular, attracting the attention of both individual owners and government agencies around the world. Some countries are already successfully implementing smart home systems that promote comfort, safety and energy efficiency. In the United States, voice assistants are popular, allowing users to control various aspects of the home using voice commands. Technologies such as Amazon Alexa, Google Assistant, and Apple HomeKit are becoming an integral part of modern homes, providing convenient management of various systems. Sweden is actively using energy-efficient solutions aimed at optimising energy consumption and reducing emissions. Much attention is paid to the use of solar panels, renewable energy systems, and intelligent power consumption management systems. In the Netherlands, homes are equipped with integrated smart home systems for easy management of all aspects of life. This includes automated control of lighting, heating, air conditioning and safety systems, making their homes comfortable and efficient. In South Korea, smart technologies are being implemented in new housing construction to ensure optimal comfort and safety for residents. Innovative lighting, heating, and safety control systems are becoming the standard in new buildings. China, as a leader in smart technologies, actively uses systems to manage energy consumption and infrastructure in cities. Major cities such as Shanghai and Beijing illustrate the diversity of innovative approaches in the world of smart construction, where the use of artificial intelligence and smart city systems helps improve the comfort and quality of life of residents.

Smart technologies in construction not only make life easier, but also become a key factor in ensuring safety, energy efficiency and convenience for residents around the world. These technologies continue to evolve and be implemented, creating new opportunities to improve the quality of life and save resources. The world is becoming increasingly dependent on technology, and in this context, the concept of a "smart home" is becoming not only a novelty, but also a necessity. The smart home system embodies the idea of integrating various devices and sensors into one complete system that provides convenience, comfort, and safety for residents (Fig. 1). This system works by collecting data from various sensors and devices, analysing them through special software, and executing appropriate commands to control various home systems. A central part of a smart home system is its ability to collect and analyse data. Light, motion, temperature, humidity, and other sensors provide a constant flow of information about the state of the house and its surroundings. This data is then transmitted to a central controller, where it is analysed and used for decision-making. Light sensors

detect the level of illumination in different areas of the house and transmit this information to the central controller. Based on this information, the system can automatically turn on or off indoor lights, adjust the brightness of the light according to the time of day, or act according to certain specified scenarios. A smart home system can manage other aspects of home life, such as heating, ventilation, air conditioning, water management, and other systems. This provides comfortable living conditions for the residents of the house and reduces energy consumption by optimising the operation of heating and air conditioning systems.

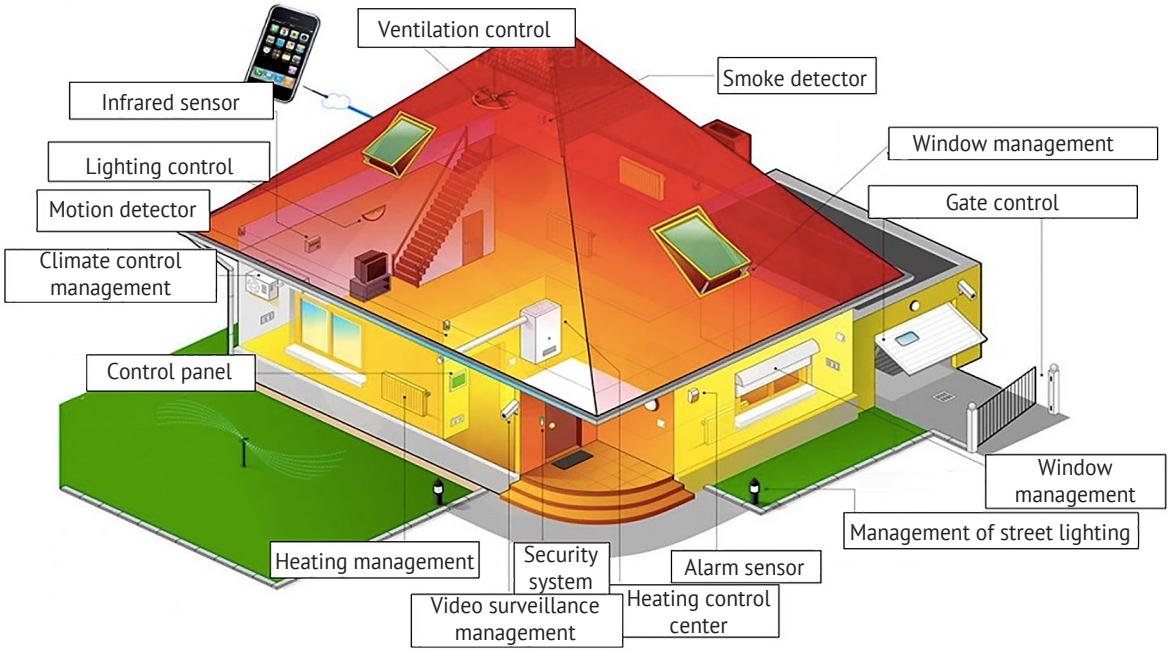

Figure 1. Smart home system operation diagram

Source: compiled by the author

Figure 2 shows signal management tools within the network, such as a smartphone, router, and cloud server. In this topology, the smartphone is used to manage IoT devices and make changes to their settings. The router is responsible for automating the process of managing devices on the local network, ensuring effective oordination of their work. The cloud server is used for remote management of device settings, providing convenient and accessible management even from a distance. This configuration allows effectively managing IoT devices in a smart home, providing convenience and flexibility in their use.

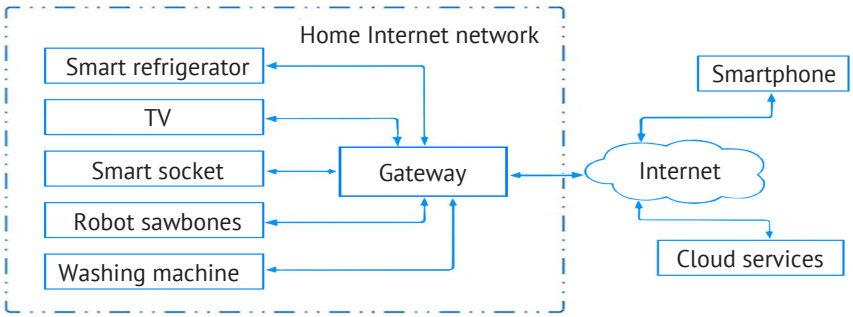

Figure 2. Network used in the smart home ecosystem for IoT devices

Source: compiled by the author

Smart home automation systems can be divided according to several key characteristics and functionality. In particular, they differ in control method, power consumption, security systems, device integration, automation of routine tasks, and scalability. As for the control method, the systems can use voice or mobile control. The main areas of energy consumption include energy efficiency and the use of renewable energy sources. Security systems may include video surveillance and access control. In terms of device integration, IoT support and integration with entertainment electronics (TVs, music centres, etc.) are important. Automating routine

tasks may include controlling lighting and climate control. Scalability systems can be single-level or integrated, covering all aspects of the home. This systematisation helps to understand the diversity of systems and determine their relevance to the specific needs and ideas of users. Software for smart home systems can have a variety of forms and interfaces designed for different target audiences and user needs. The most common options include web applications, mobile applications, and specialised platforms.

Web applications are one of the available smart home management software options. They usually work via a web browser and provide users with the ability to remotely manage various aspects of their home environment. This is a convenient solution for those who want to have access to the home management system from any device with an internet connection. Mobile applications have become an integral part of modern smart home systems. They provide users with convenience and mobility, allowing them to control lighting, heating, security, and other functions via their smartphone or tablet. Mobile applications often also include monitoring and notification features, making them an essential tool for keeping home safe and comfortable. Specialised platforms are more advanced and integrated solutions for smart home management. They often combine various functions, including automation, monitoring, and management, and can also be integrated with other systems, such as security systems or energy management systems. In modern smart homes, sensors play a key role in collecting a variety of information about the environment, including temperature, humidity, lighting, and movement. This data can be used to automate various home systems, such as heating, air conditioning, lighting, and security systems.

Controllers in smart homes are responsible for controlling various devices and systems based on the received data. They can make decisions automatically or using user-developed programmes. For example, the controller can automatically turn off the heating when sensors detect that the room has become warm enough. Other IoT devices that are connected to a smart home can include various household devices, such as refrigerators, washing machines, coffee makers, and many others. These devices can be controlled remotely via mobile applications or voice assistants, giving users more convenience and control over their home. One of the most important aspects of IoT systems in smart homes is their ability to interact and integrate with other systems. For example, motion sensors can turn on the lighting system, or the heating system can turn off when the windows are open. This makes smart homes not only convenient, but also more efficient in using energy and resources. Conventional door keys are gradually being replaced by electronic identification systems that offer a higher level of security and convenience. The use of electronic keys such as fingerprints, Face ID, or voice recognition is becoming the standard for providing security and access to homes in modern smart systems.

One of the most common methods of electronic identification in smart homes is the use of fingerprints. This method is based on the unique biometric characteristics of each person, which makes it reliable and almost unforgeable. In addition, the use of fingerprints allows quickly and conveniently opening the door without having to carry a physical key. Face ID, based on facial recognition, is another innovative method of electronic identification. This technology is used in smartphones and other devices to unlock by scanning the user's face. In smart homes, Face ID systems can be integrated with smart doors or access control systems, allowing owners to access their home with just their face. Voice recognition is another advanced electronic identification method that finds its application in smart homes. This technology allows users to authorise their access to the home using voice commands or simply by recognising their voice. It is especially convenient for those who have a limited ability to move or have various physical limitations.

Cybersecurity is becoming an important aspect for ensuring data security and privacy in smart homes. Given the constant growth in the number of connected devices and the relationship between them, protection against unauthorised access and abuse by intruders is becoming an important task for smart home owners. One of the key aspects of cybersecurity in smart homes is network protection. It is important to have a strong and secure network protocol to prevent unauthorised access to home management systems. Setting passwords, using Secure Wi-Fi (Wireless Fidelity) networks, and regularly updating software are just a few of the ways to protect the network from potential cyber-attacks. Data encryption is another important aspect of cybersecurity in smart homes. All data transmitted between devices on the network must be encrypted to prevent interception and abuse. The use of modern encryption methods, such as Secure Sockets Layer (SSL) or Advanced Encryption Standard (AES), can significantly increase the level of data protection in smart homes. Authentication also plays a key role in ensuring cybersecurity in smart homes. To access home management systems, users must go through an authentication procedure, such as entering a password or using biometric identification methods. This ensures that only authorised users have access to smart home functions.

Financial restrictions are related to the cost of high-tech automation systems. Most innovative solutions in this area are characterised by high purchase and installation costs. For many Ukrainians who have limited financial resources, this becomes the main barrier to access to the benefits of smart housing. The cost of technological solutions, such as intelligent lighting, video surveillance systems, or automated heating systems, can be a big obstacle to their implementation. Overcoming this problem will require developing new

pricing strategies and financial support. Citizens should have access to special credit programmes or subsidies that will help reduce the financial barrier and promote greater adoption of smart technologies in households. In addition, it is necessary to actively work on improving the financial literacy of citizens. Providing information about the efficiency and long-term benefits of using high-tech systems can help to understand not only the cost of installation, but also reduce utility costs in the future (Li *et al.*, 2021). Initiatives to improve financial literacy may include information campaigns, trainings, and seminars for the public. In addressing this issue, it is also important to involve governmental and non-governmental organisations, develop social support programmes and promote the development of the market for high-tech systems at affordable prices. Providing access to modern technologies for all segments of the population can improve the quality of life and make society more efficient and environmentally conscious.

Smart homes, with their innovative technologies, define a new level of comfort and safety in modern housing construction. However, in Ukraine and other countries where the technical infrastructure may remain insufficient, ensuring the full operation of smart home systems can be a serious challenge. One of the key aspects that determine the functionality of smart home systems is access to a fast and stable Internet. In some regions of Ukraine, there may be limited availability of high-speed Internet, which limits the possibility of implementing modern technologies in households. The lack of a reliable internet connection can lead to a gap in the operation of automation systems, reduce their efficiency, and limit interaction between different devices (Aliero *et al.*, 2021). To solve this problem, it is necessary to focus on the development of technical infrastructure, in particular the Internet. Public and private initiatives should be aimed at expanding access to high-speed internet in all regions of the country. This may include building new networks, improving existing infrastructures, and using the latest technologies to improve data transmission efficiency. In addition, it is important to encourage initiatives and partnerships between government agencies, Internet service providers, and smart home technology developers. Support and cooperation in these areas can help ensure not only a fast and stable Internet connection, but also raise public awareness about the benefits of using smart technologies. An additional step may be the introduction of IoT technologies to create a network that works efficiently at low Internet speeds and ensures stable data exchange between devices. This approach can be particularly useful for regions with limited access to high-speed Internet.

Solving the problem of insufficient technical infrastructure for smart home systems in Ukraine requires a comprehensive approach that combines technical, social, and economic aspects. Only through joint efforts can conditions be created for the full implementation and development of smart living in Ukrainian households. One of the main security threats in smart home systems is the potential vulnerability to cyber-attacks. Increasing the number of connected devices on the same system creates many points for possible attacks. Such attacks can target leaks of sensitive personal data, such as lighting schedules, video surveillance, or even information about residents' habits. To ensure the security of such systems, it is important to develop high-tech encryption tools and security mechanisms that make it difficult for unauthorised persons to access. Another important aspect is control over data storage and processing. Smart home systems usually collect a large amount of information about users' lifestyle. Ensuring the confidentiality and security of this data requires effective storage rules, strict access policies, and the use of advanced encryption technologies (Abdi *et al.*, 2021). In addition, users should have full control over what information is stored and how it is used, ensuring transparency and trust.

Preventing unfair actions of internal or external threats is also important for ensuring data security in smart home systems. Developers and manufacturers should constantly update their software and hardware, and provide users with automatic update capabilities to fix detected vulnerabilities. Regular security cheques, audits, and system monitoring can help to identify and fix potential problems in a timely manner. To increase user confidence in smart home systems, it is important to perform effective educational work. Explaining and providing information about the security measures taken in systems can help build a conscious attitude to technologies and confidence in their security. Standardisation is defined as a key factor in the successful implementation and adoption of smart home technologies. One of the main advantages of setting standards in the smart home industry is to ensure compatibility between devices and systems from different manufacturers (Van de Kaa *et al.*, 2021). The lack of a single standard platform can lead to the fact that devices from different manufacturers may not interact effectively or may not be compatible at all. This becomes a serious limitation for consumers who may want to combine devices from different manufacturers into a single integrated system. Standardisation also helps to improve the level of security. If all manufacturers adhere to the same standards for data protection and device security, this allows creating a single reliable framework for protecting against cyber threats and abuse. However, it is important to note that the effectiveness of standardisation depends on active participation and cooperation between manufacturers, industry organisations, technical experts, and government agencies. The process of developing and agreeing on standards should be open and transparent to consider the diverse needs of the industry and protect the interests of end users.

Addressing the lack of standards also opens up opportunities for innovative solutions and industry development. The introduction of a single standard platform

can make the smart home market more attractive to manufacturers and consumers, driving competition and innovation. The use of smart home systems can significantly facilitate the daily life of residents, starting with lighting automation. Residents can control the light in the house, adjust its brightness and colour scheme using a mobile phone or voice commands. This not only creates an atmosphere that matches the mood of residents, but also effectively saves electricity. Heating and air conditioning are also becoming part of an integrated system that can be controlled remotely (Yang *et al.*, 2021). Residents can adjust the temperature in the house using their smartphones or tablets, which ensures optimal comfort even before returning home. One of the important advantages is also the ability to control various household devices through a centralised smart home system. From kitchen appliances to security systems, residents can effectively interact with various aspects of their home environment. Smart home systems can also adapt to the rhythm of life of residents. They can learn habits and adapt home settings for optimal comfort. For example, the system can automatically adjust the lighting and temperature, providing a pleasant environment during dinner or evening relaxation.

Smart home systems allow to effectively control lighting. Automatic switching off of light in rooms where its use is not required is just one example of optimising energy consumption. Motion sensors and presence recognition systems can adjust the light intensity depending on the activity of residents, ensuring efficient use of energy without excessive lighting. Managing electrical appliances and household appliances through a centralised system also contributes to the rational use of energy (Mahapatra & Nayyar, 2022). Remote shutdown or switching to power-saving mode allows saving energy when the devices are not in use. It is also important to note that saving energy through smart home systems not only reduces utility bills, but also helps reduce carbon dioxide and other harmful substances. Thus, these technologies make an important contribution to environmental sustainability. Smart home systems are an important tool for increasing the level of protection of residents and their property, providing innovative approaches to solving security problems. One of the key advantages is the ability to install monitoring and video surveillance systems in different areas of the house. These systems allow residents to monitor events in the house or its surrounding area in real time using mobile devices. Such access provides a sense of security and control, even when residents are not at home. Smart home systems can integrate motion sensors and door sensors that detect unwanted activity or intrusion (Taiwo & Ezugwu, 2021). If suspicious events are detected, the system can send instant notifications to residents' mobile devices or automatically activate security systems such as alarms or security calls.

Security systems in a smart home can also be linked to other functions, such as access control. The use of electronic keys or face recognition systems allows access only to authorised persons, increasing the overall level of protection. Increased security is also made possible by remote system management. Residents can remotely lock doors, turn on or off alarms, and monitor other aspects of security, even when they are away from home. The growing popularity and integration of smart technologies in homes open up new prospects for increasing the value of real estate. This trend not only reflects modern technological trends, but also has a potentially significant impact on the real estate market. One of the key benefits is to improve the comfort and functionality of homes. Smart systems allow residents to remotely control lighting, heating, air conditioning, security systems, and many other aspects, making their lives more comfortable and efficient. Potential buyers may be willing to pay for this level of convenience and automation. Increased security can also have a positive impact on the value of real estate. Homes with installed monitoring and video surveillance systems can be more profitable for buyers who value their security and privacy highly (Vetrivel *et al.*, 2023). This can lead to an increase in demand for such properties and, accordingly, to an increase in their cost. Energy efficiency measures can also be a significant factor in increasing the value of real estate. Consumers are increasingly aware of the importance of energy conservation, and having systems that aim to optimise energy use in the home can make real estate more attractive. In addition, the smart housing market is constantly evolving, and qualified buyers may be interested in homes equipped with advanced technologies. This can contribute to an increase in demand for such properties and increase their value.

DISCUSSION

Smart home automation systems in the Ukrainian residential sector represent an innovative industry that promises to transform the way residents can interact with their environment in everyday life. The growing interest in these technologies in Ukraine is conditioned by the need to improve comfort, energy efficiency and safety in residential premises. In the course of reviewing the study, a general structure of the home network was created, considering the elements of a smart home. This generalised model identified the key components that make up a smart home system, helping to understand their relationships and their impact on the overall network architecture. Increased comfort is an important factor, as automation systems can perform routine tasks such as controlling lighting, temperature, and safety systems. This makes everyday life not only more convenient, but also more efficient.

Energy efficiency is another key advantage, as smart home systems allow optimising energy use, resulting in lower costs and a positive impact on the environment. The integration of environmentally oriented technologies can contribute to the creation of energy-efficient solutions. Security is also an important aspect in the

Ukrainian housing sector. Monitoring, video surveillance, and alarm systems can provide a high level of security for residents and their property. However, for the successful implementation of smart home systems in Ukraine, it is necessary to consider some challenges. Financial constraints, technical infrastructure, and data security issues require comprehensive investigation and development of appropriate strategies. In general, the introduction of smart home automation systems in the Ukrainian residential sector opens the way to improving the quality of life, optimising energy costs, and creating safe and comfortable housing. However, to achieve these goals, it is important to carefully consider all aspects and develop solutions that consider the specifics of the Ukrainian market and the needs of users.

Based on the results of recent study by C. Stolojescu-Crisan *et al*. (2021), the IoT-based smart home automation system is an innovative technology solution that combines a variety of devices and systems to increase efficiency and comfort in the home environment. This system involves the interaction of various devices, such as lighting, thermostats, video surveillance cameras, electrical appliances, and others that can be connected to the Internet and controlled via special applications or voice commands. One of the key advantages of such a system is the ability to remotely control the house. Users can turn devices on and off, adjust the temperature, monitor security, or even track power consumption, all using smartphones or other devices with network access. This approach allows residents to manage their homes conveniently and efficiently at any time and from any place. The data is consistent with the theses outlined in the previous section regarding the growing popularity and introduction of smart home systems. With the growing interest and adoption of such systems, there are questions about data privacy and security, as well as the need for standardisation. Ensuring reliability and protection from external threats becomes crucial for the further successful development of this technology, as it depends on the decision of consumers and investors to implement such innovative systems in their homes.

Turning to definition by B. Mustafa *et al*. (2021), a low-cost IoT-based smart home automation system opens up new opportunities for a wide range of users looking to improve their lives at an affordable price. This approach makes smart home technologies accessible to a wide range of consumers, providing the ability to automate basic home functions without significant costs. One of the key advantages of such a system is its ease of installation and use. The availability of the technology allows users to install and configure devices themselves, which makes it convenient to use even for those who do not have deep technical knowledge. Along with expanding accessibility, it is important to consider security and privacy issues. Low-cost systems may have limited protection measures against cyber threats, so the choice and configuration of devices are crucial to ensure the security and privacy of users. Increased attention to these aspects becomes necessary in the context of the widespread use of technology in everyday life. Ensuring data security and protection is becoming an important task for solving potential threats and ensuring the reliability of systems in real-world operating conditions.

S. Venkatraman *et al*. (2021) determined that smart home automation based on voice control is becoming an important aspect of modern life, offering a secure and integrated approach to managing various devices and systems in the home. One of the main advantages of such a system is the ease of use – the user can interact with the home using voice commands, which ensures ease and efficiency of management. The use of voice control also contributes to the security of the smart home. The absence of the need for physical contact with remote controls or sensors reduces the risk of entering incorrect commands or unauthorised access. Such a system can be integrated with security devices, such as video surveillance systems or motion sensors, to instantly respond to events at home. These results confirm previous research, pointing out the importance of taking privacy issues into account and ensuring reliable protection of users' personal data in a high-tech smart home environment. Achieving full integration and security requires a comprehensive approach to data management, and improving cybersecurity technologies. Consideration of these aspects becomes a key to creating an enabling environment for the use and development of smart home systems, which ensures the reliability and confidentiality of information in this ecosystem.

Researchers H. Yar *et al*. (2021) showed in their study that smart home automation through the use of the peripheral computing and IoT paradigm represents a promising way to introduce innovation in modern households. The peripheral computing paradigm involves using the built-in computing resources of smart home devices to process and analyse data on-site, reducing the need to transfer large amounts of information to the cloud. This approach helps to increase the response rate of the system, because calculations are performed at the device level, which reduces delays and improves efficiency. In addition, the use of peripheral computing can contribute to ensuring data privacy and privacy, since sensitive information data remains on the device itself, without being transferred to external computing clouds. While agreeing with this view, it is important to consider security and standardisation aspects when implementing solutions in smart homes. This will ensure the compatibility and reliability of automated systems based on peripheral computing and IoT. Proper compliance with standards will avoid compatibility issues and ensure efficient operation of systems. Consideration of these aspects will ensure the safety and reliability of smart homes, increasing their suitability and convenience for users and contributing to the further development of this technology.

As noted by O. Taiwo *et al*. (2022), an advanced smart home management and security system based on the deep learning model marks a new stage in the development of modern technologies for households. The use of deep learning allows the system to analyse and interpret large amounts of data received from sensors and devices in real-time. This allows the system not only to respond to changes in the environment, but also to learn independently and improve its functions over time. The use of deep learning in smart homes can improve security systems, allowing the automatic recognition of abnormal situations and a timely response. In addition, such a system can adapt to unique user preferences, optimising resource usage and providing a higher level of comfort. When implementing such technologies, it is necessary to consider ethical and privacy issues, guaranteeing the protection of personal data and control over their use. In addition, the system must be resistant to cyber-attacks and have a high level of reliability, as it provides security and management of important aspects of the home environment. Careful consideration of these aspects will help prevent possible problems and ensure the effective functioning of smart systems, which will contribute to a comfortable and safe life in modern households.

M.J. Iqbal *et al*. (2021) determined that the introduction of smart home automation using intelligent electricity dispatching is an important step towards optimising energy consumption and management in domestic settings. This innovative system allows effectively regulating the use of electricity in the home, providing an optimal balance between comfort and energy efficiency. Intelligent power dispatching allows automatically distributing energy between different devices and systems in the home based on their needs and operating modes. For example, the system can automatically turn off electrical appliances during periods of low consumption or adjust the operation of heating and air conditioning systems for optimal energy consumption.

Among other things, attention should be paid to aspects of cybersecurity and data privacy protection when using such systems. Effective security measures and the definition of standards are crucial for the successful implementation of intelligent electricity dispatching in smart homes. Strict security measures and standards will help avoid possible threats to systems and ensure the reliability and safety of use in different households. Addressing these aspects is important for ensuring the stability and efficiency of the system and user confidence in the smart home.

CONCLUSIONS

The development and implementation of smart home automation systems in the Ukrainian residential sector is an urgent and promising task that faces significant challenges and has powerful opportunities for further development. The study notes that the rapid development of technology and the growing interest in the concept of a "smart home" determine the need to explore opportunities and identify obstacles to the effective implementation of these technologies in modern life.

One of the key conclusions is that financial constraints can complicate the process of implementing smart home automation systems for many Ukrainians. It is necessary to actively work on developing more accessible and effective solutions to ensure broad public access to these technologies. Technical infrastructure, in particular the quality and stability of the Internet, is an important component for the full operation of smart home systems. For successful implementation, it is necessary to develop and improve infrastructure, in particular high-speed and stable Internet.

Data security is identified as one of the main concerns in the implementation of smart home systems. Protecting personal data and ensuring that smart home systems cannot be abused requires serious attention and balance in the development and operation of such systems. The lack of a single standard platform is defined as another important aspect that can affect the success of implementing smart home systems. It is important to work on standardisation to ensure compatibility and integration between different manufacturers. Smart technologies can have a positive impact on various aspects of life, including comfort, safety, and energy efficiency. However, for their successful implementation, it is necessary to develop and improve technologies, solve financial and infrastructure problems, ensure security and compliance with standards.

Areas for future research include investigation of the impact of smart home systems on environmental aspects and improving their energy efficiency, considering the specific conditions of the Ukrainian residential sector.

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CONFLICT OF INTEREST

None.

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Розробка та впровадження системи автоматизації розумного будинку в умовах українського житлового сектору: виклики та перспективи

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Анотація. У зв'язку зі стрімким розвитком технологій та зростаючим інтересом до концепції «розумного будинку», дослідження є актуальним для визначення перешкод та можливостей, сприяючи ефективному впровадженню цих технологій в сучасне життя. Мета даного дослідження полягає в проведенні аналізу сучасного стану та визначенні можливостей розробки та впровадження систем автоматизації розумного будинку в українському житловому секторі для підвищення рівня комфорту, забезпечення безпеки та підвищення енергоефективності. Серед використаних методів слід зазначити аналітичний метод, метод класифікації, функціональний метод, статистичний метод, метод синтезу та інші. Результати дослідження розкривають глибокий вплив технологій на ефективність та безпеку розумного будинку. Під час проведення дослідження було проаналізовано сучасний стан систем автоматизації розумного будинку в українському житловому секторі. Були розглянуті сучасні методи кібербезпеки для захисту від потенційних загроз. Електронні ключі, включаючи технології Face Identification, відбитку пальця та голосового розпізнавання впроваджуються для забезпечення доступу та підвищення рівня безпеки у розумному будинку. Дослідження відкриває різноманітні методики, які використовуються у різних країнах для впровадження розумних будинків, де презентовано різні приклади реалізації та особливості їх розвитку. В результаті виявлено ключові технічні та фінансові виклики, які ставлять під сумнів ефективність впровадження таких систем. Окрім того, були розглянуті можливості оптимізації цих систем, враховуючи особливості ринку та інфраструктурні обмеження. Згідно з проведеним аналізом, були розроблені конкретні рекомендації щодо створення доступних та ефективних рішень для українських споживачів. На підставі цих рекомендацій можна зробити висновок, що, незважаючи на існуючі труднощі, впровадження систем розумного будинку в Україні має потенціал та перспективи. Однак, для досягнення повного успіху, важливо подолати технологічні виклики та врахувати фінансові можливості населення. Дослідження зробило вагомий внесок у розуміння факторів, що впливають на успішну імплементацію сучасних технологій у житловому секторі України, сприяючи практичному розвитку науки та надаючи конкретні висновки для можливостей впровадження систем автоматизації розумного будинку

Ключові слова: технології; енергоефективність; технічні методи; рекомендації; інфраструктурні обмеження

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Efficient electricity generation forecasting from solar power plants using technology: Integration, benefits and prospects

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Abstract. Accurate prediction of electricity generation from renewable sources is an essential element to ensure the stability of electricity systems and the transition to more sustainable energy production. The study aims to optimise the operation of Ukrainian power systems through the introduction of the required share of renewable energy sources to ensure the reliability of the power system. To study the accuracy of forecasting electricity generation by photovoltaic power plants in Ukraine, data analysis, a review of existing forecasting models and methods, and comparative analysis using satellite images and meteorological observations were used. Low accuracy of forecasting output is a feature of electricity generation from renewable energy sources, which is explained by the random nature of energy sources and related meteorological conditions. In Ukraine, the problem of qualitative forecasting of electricity generation from renewable sources is becoming more relevant. The importance of finding effective methods for forecasting electricity generation in Ukraine has increased with the emergence of the electricity market. This study addresses the issue of forecasting electricity generation by photovoltaic power plants for the day ahead in the conditions of the Ukrainian energy market. As part of the study, the issues of Ukrainian legislation regarding the requirements for the accuracy of electricity generation forecasting and the consequences of their failure were considered. The study also reviewed modern models and methods for forecasting electricity generation by photovoltaic power plants and explored the new "forecasting system market" in Ukraine. The study presents accepted forecasting metrics that allow estimating errors and comparing the effectiveness of different forecasting methods. Considering the dependence of electricity generation forecasting on meteorological parameters, a comparative analysis of forecasting accuracy using satellite images and meteorological observations was carried out. The study will determine the material presented in determining the model for forecasting electricity generation, thus increasing the efficiency of energy companies in the conditions of the Ukrainian energy market. The study will also reduce the negative impact of the energy sector on the environment and contribute to a more efficient and stable electricity system in the future

Keywords: capacity; generation; power system balance; renewable energy sources; energy market

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INTRODUCTION

Growing demand for electricity and the need to reduce emissions from traditional sources are becoming major challenges for the energy sector. Constant changes in meteorological conditions and technological innovations in the industry require the development of accurate methods for forecasting electricity generation using solar power plants. Research in this area will improve the reliability and efficiency of solar power plants, promote the development of renewable energy sources and ensure sustainable energy development in general. This study was important for improving the efficiency of Ukraine's electricity system by taking into account the introduction of the required share of renewable energy sources. The low accuracy of forecasting

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electricity output, especially with the use of photovoltaic power plants, has become an urgent problem that requires careful analysis and development of effective forecasting methods. Increasing the share of renewable energy sources in the electricity system requires accurate and reliable forecasting of electricity generation, which makes this study important for ensuring the stability and efficiency of the energy sector in the modern energy market.

The analysis of publications on effective forecasting of electricity generation from solar power plants revealed several problems that exist in the field. M. Konstantinou *et al.* (2021) determined that the problem is the insufficient accuracy of power generation forecasting in the face of significant changes in meteorological conditions. The study results highlighted the need to improve forecasting methods to ensure the stability and reliability of energy systems. T.M. Alabi *et al.* (2022) investigated the possibilities of integrating modern machine learning algorithms to improve power generation forecasting. They demonstrated the prospects of this approach in improving the accuracy and reliability of forecasting in the energy sector. A study conducted by F. Shaik *et al.* (2023) focused on the reliability of solar power plants and studied the impact of unpredictable factors on their efficiency. This study pointed out the significant impact of unforeseen factors on the operation of solar power plants and the need for further optimisation of control systems to ensure the stability and reliability of electricity production. L. Liu and L. Wu (2021) concentrated on the development of new mathematical forecasting models to reduce forecast errors. The results of this study showed a positive effect of using new mathematical models to improve the accuracy of power generation forecasting. A study conducted by K. Bandara *et al.* (2021) highlighted the need to improve data collection and analysis methods to improve the accuracy of electricity generation forecasts from solar power plants. The results of the study indicate the need to introduce new approaches in these processes to achieve more accurate and reliable forecasts.

V. Prema *et al.* (2021) focused on analysing the impact of the technical parameters of solar power plants on the results of power generation forecasting. The study identified key factors affecting forecasting accuracy and identified ways to optimise forecasts in the context of the technical characteristics of the plants. Ch. Chen *et al.* (2022) highlighted the challenges associated with improving forecast accuracy on a large scale, especially when tens or hundreds of solar power plants are considered. The results of their study identified key difficulties and suggested methods to improve forecasting in such conditions. D. Markovics and M.J. Mayer (2022) determined the optimal ratio between different data sources for power generation forecasting. The results helped to identify key aspects of using different sources of information and develop recommendations for improving the efficiency of electricity forecasting. The study by M. Sotnyk *et al.* (2023) analysed a general aggregation model in the electricity sector known as the Virtual Power Plant. This analysis provided insight into the key aspects of operation and the potential benefits of implementing such models in power systems.

M.O. Kyzym *et al.* (2022) conducted a study of global challenges and opportunities for the structural development of the electricity sector in Ukraine. The study identified the main trends in this area and suggested ways to optimise the development of the country's energy sector. V.Ya. Brych *et al.* (2022) analysed the development of technologies that are critical to ensuring Ukraine's energy security and increasing the stability and efficiency of the energy system. The study findings identified key areas of technology development that should be prioritised for implementation to ensure the reliability and optimisation of Ukraine's energy sector. While various studies already contributed to addressing these issues, gaps that still need to be explored include improving forecasting algorithms, increasing accuracy in the face of changing meteorological conditions, developing new models that incorporate technical parameters of power plants, and optimising the process of collecting and analysing large amounts of data for forecasting.

The study aim was to improve the efficiency of Ukraine's electricity systems by introducing an appropriate share of renewable energy sources to ensure the stability and reliability of the electricity grid. The objective of the study was to conduct a comparative analysis of the accuracy parameters of methods for forecasting electricity generation using satellite images and meteorological forecasts and meteorological observations, which would allow to identify the difference in accuracy between these methods.

MATERIALS AND METHODS

The study was conducted on actual data on electricity generation by the Petrivka photovoltaic power plant, which is located in the southern part of Ukraine, specifically in the Ivanivskyi district of the Odesa region. It was commissioned in 2019 and has a capacity of 8.85 MW (PV plant Petrivka, n.d.). After collecting this data, the forecasting results were compared with the actual data. To objectively assess the performance of each forecasting model, calculated accuracy indicators, such as mean absolute error (MAE), mean absolute percentage error (MAPE), mean absolute error concerning the base model (MASE), and root mean square error (RMSE), were used in the study. This highlighted the effectiveness of each model in predicting the electricity generation of the Petrivka PV (Photovoltaic) power plant during May 2021.

As part of the study, a detailed analysis of the accuracy of forecasting electricity generation by photovoltaic power plants was carried out. For this purpose, various forecasting models were used, which took into account various factors and methods. The analysis made

it possible to assess the effectiveness of each model in predicting electricity generation using solar radiation. The results were processed and analysed to determine the most accurate and reliable forecasting model that can be used to improve the efficiency of photovoltaic power plants in electricity generation.

A real-time power generation forecasting model based on satellite imagery, supported by the Solcast satellite nowcasting system, used a global fleet of meteorological satellites to obtain information on cloud cover and other atmospheric phenomena. This model used satellite data to obtain up-to-date information on cloud cover and other atmospheric phenomena such as temperature, humidity, precipitation and other parameters. The information obtained from the satellites allowed to incorporate the dynamics of atmospheric conditions in real-time, which improved the accuracy of forecasting power generation from photovoltaic power plants.

Solargis Forecast Cloud Motion Vector-based power generation forecasting model depended on intensive monitoring and analysis of satellite imagery to get an accurate picture of cloud movement. This method was based on the systematic study and analysis of real-time changes in cloud location and movement. Using Cloud Motion Vector data, which described the speed and direction of cloud movement, the model could predict the impact of cloud cover on the generation of electricity from solar panels. This increased the accuracy of the forecasts, as it took into account specific dynamic changes in cloud cover that could affect the efficiency of solar power generation.

The Solcast Advanced PV model was developed specifically for photovoltaic installations, taking into account various system parameters and characteristics. This model addressed key aspects such as solar panel array geometry and tracking type, module and inverter parameters, horizon shading, dust and other losses including degradation, availability of tracking algorithms, and support for bifacial modules. This model enabled a more accurate consideration of the specifics of each PV installation, which helped to improve the accuracy of forecasting its efficiency and electricity production. Accounting for these parameters and characteristics in the model allowed for more accurate and realistic forecasts of electricity generation by photovoltaic installations, which was important for the effective management and planning of solar power plants.

A UTP (Univariate Time-series Prediction) forecasting model based on meteorological observation and weather forecast data was used as input to the neural network. This method was based on meteorological data and was used to predict the amount of solar radiation reaching the photosensitive surface, considering astronomical, geographical and topographical factors, as well as the absorption and scattering of solar radiation in the atmosphere. These meteorological parameters were used to build a neural network that analysed the input data and predicted the electricity generation by the photovoltaic plants. The UTP model allowed for forecasting based on actual meteorological conditions, which helped to improve the accuracy of forecasts and the efficiency of managing electricity generation in solar energy systems.

RESULTS

Software for efficiently forecasting power generation from solar power plants is critical in the modern energy industry, where the use of renewable energy sources is becoming increasingly important. Such software is used to predict the amount of electricity that solar power plants will be able to generate in the future based on various inputs. There are several well-known software solutions on the market for efficient forecasting of electricity generation from solar power plants. One of these solutions is Solcast, an online platform that provides accurate forecasts of solar radiation and electricity generation. It uses a variety of data, including satellite imagery and meteorological data, to improve forecasting accuracy. Another well-known software tool is PVsyst, which allows for the design, analysis, and forecasting of solar power plants, taking into account various factors such as geographic location and technical characteristics of the plants. In addition, HelioScope is an online platform that allows modelling and forecasting of power generation based on various inputs, helping solar power plant engineers and operators obtain reliable forecasts to optimise plant performance and plan efficient operations.

One of the main functions of forecasting software is to analyse information about weather conditions, including solar radiation, cloud cover, temperature, humidity, etc. The data is collected from weather stations, satellite images, meteorological models, and other sources. Based on this data, forecasting models are developed to determine the expected electricity generation for a certain period. Such software solutions can use a variety of forecasting methods, including statistical models, neural networks, machine learning algorithms, and other analytical techniques. They can accommodate factors that affect the operation of solar power plants, such as panel orientation, equipment specifications, energy losses, etc.

The main advantage of solar power generation forecasting software is that it allows energy companies, grid operators and other market participants to effectively plan electricity generation, optimise plant operating modes and avoid under- or overproduction. The continuous development of information and communication system technologies is making power generation forecasting software more accurate, reliable and accessible to various energy market players. In the future, these technologies may become the basis for the development of modern smart grids and the integration of distribution systems with renewable energy generation, which will contribute to the stability and efficiency of the energy infrastructure.

The intensive development of renewable energy creates risks of disrupting the balance reliability of the power system, and this requires accurate forecasting of electricity generation. In many countries, scientists are working on this problem, as a new concept, "energymeteorology" has been introduced as a new scientific discipline, the subject of which is the quantitative assessment of electricity generation from renewable energy sources at time intervals from minutes to decades, and much attention is paid to the development of economic forecasting (forecasting losses/profits depending on the accuracy of forecasting power plant output) (Fiedler *et al.*, 2022). When choosing a forecasting method, it is necessary to take into account what data should be obtained as a result of calculations. The choice of methods for forecasting the operation of a photovoltaic power plant depends on the periods for which solar radiation forecasts are required. For short-term forecasting (up to 6 hours), physical forecasting methods such as Numerical Weather Prediction (NWP) or NWP models are used, i.e., the level of illumination, cloud cover, air temperature, wind speed and humidity in a particular area is considered (Schultz *et al.*, 2021). To predict energy generation for a short period (10-30 minutes) with high accuracy, sky view analysis is used. This includes obtaining an image of the sky, determining the type and condition of clouds, and analysing cloud movement to make a forecast of the future generation capacity of the plants compared to actual levels. In the global solar industry, short-term power generation forecasting does not have a proven and fully tested model. The generation forecast of a photovoltaic power plant is a forecast of the amount of solar insolation received by solar panels. All existing available methods for forecasting electricity generation by solar power plants can be divided into groups (Fig. 1).

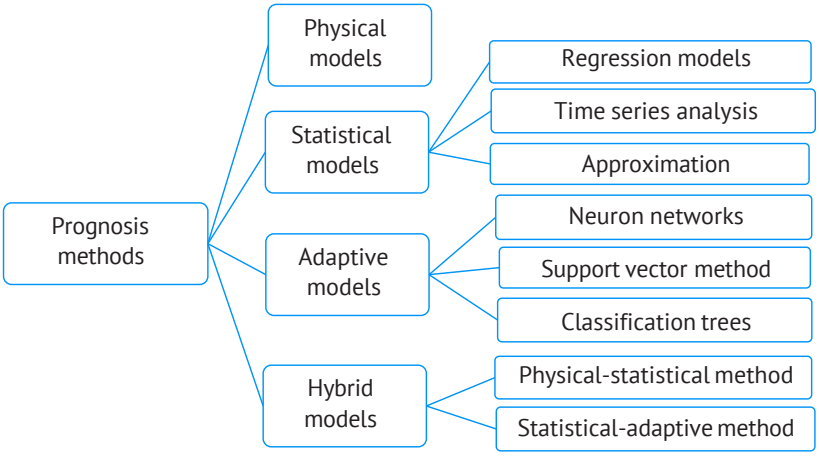

Figure 1. Classification of methods for forecasting electricity generation by solar power plants
Source: B. Yang *et al.* (2021)

Physical models are physical relationships between meteorological conditions and solar radiation, where the input data are: numerical weather forecasts; terrain; retrospective data on the power plant's output power; and the possibility of using satellite systems. The power output of a solar power plant is determined based on the predicted level of horizontal illumination and ambient temperature. Additional factors may include wind speed and air humidity, but their influence is generally negligible (Duan *et al.*, 2021).

Statistical (probabilistic) models determine the relationship between solar radiation density predicted by a numerical weather forecast and the power output of a solar power plant by analysing time series of past data, ignoring physical aspects. This dataset is used to train models, such as autoregressive or artificial intelligence models, that can predict the output of a solar power plant at a given point in time based on historical records. ARX methods (Autoregressive exogenous) are accurate methods for short-term forecasting (up to 2 hours) of solar radiation that incorporate both geographic location and time (Oliveira *et al.*, 2021). There are methods for forecasting solar energy generation that take into account historical data. Two common methods are ARIMA (Autoregressive Integrated Moving Average) and ARIMA-GARCH (Generalised Autoregressive Conditional Heteroskedasticity), which are suitable for stationary and non-stationary time series, respectively (Mboso, 2022). These methods are designed to process large amounts of data and identify patterns in it to build predictive models. They are widely used in short-term electricity forecasting due to the availability of a large amount of historical data on electricity generation at enterprises. However, the disadvantage of these methods is the lack of forecast accuracy.

Adaptive models use artificial intelligence systems to establish a link between predicted weather conditions and the power plant's production capacity. The learning process of these models is based on the analysis of historical data. The main factor that determines the accuracy of the forecast is the choice and structure of the input data used to create the model. Furthermore,

the time required to train the network depends on the characteristics of the training sample. The advantage of the method is a fast training algorithm and the ability to work in the presence of noisy input signals.

According to studies on the use of electricity generation forecasting methods, the average forecast error is 21-26% for physical models, 20-24% for statistical models, 15-19% for adaptive models, 19-24% for hybrid physical-statistical models, and 5-10% for statistical-adaptive models (Bakay & Ağbulut, 2021). A study of the effectiveness of various methods shows that a linear autoregressive model is best suited for forecasting periods with predominantly sunny weather (e.g., spring or summer). Neural networks with the inclusion of exogenous parameters can be useful only during limited periods with high cloud cover, especially in autumn and winter. The improved results demonstrate a standard deviation of the error in solar radiation estimates of 16-18%, which is significantly higher than the low-performing constancy model of 30-50%. The effectiveness of short-term forecasts is determined by the criteria of accuracy, stability and validity of the results. Numerical indicators (metrics) are based on standardised values:

1. Mean Absolute Error (MAE) (1):

$$\mathrm{MAE} = {}^{1}/_{\mathrm{N}} \sum_{\mathrm{i}-1}^{\mathrm{N}} |\mathrm{x_i}|. \quad (1)$$

2. Mean Absolute Relative Error (MARE) (2):

$$\mathrm{MARE} = {}^{1}/_{\mathrm{N}} \sum_{\mathrm{i}-1}^{\mathrm{N}} \mathrm{x_i} \cdot 100. \quad (2)$$

3. Mean Absolute Scaled Error (MASE) (3):

$$\mathrm{MASE} = \frac{1}{\mathrm{N}} \sum_{\mathrm{i}=1}^{\mathrm{N}} (\mathrm{x_i} - \bar{\mathrm{x}}). \quad (3)$$

4. Root Mean Squared Error (RMSE) (4):

$$\mathrm{RMSE} = \sqrt{{}^{1}/_{\mathrm{N}} \sum_{\mathrm{i}-1}^{\mathrm{N}} \mathrm{x_i^2}}. \quad (4)$$

5. The Mean Squared Error (MSE) is used to determine the prediction error of the most possible (5):

$$\mathrm{MSE} = \frac{1}{\mathrm{N}} \sum_{\mathrm{i}=1}^{\mathrm{N}} (\mathrm{x_i} - \bar{\mathrm{x}})^2, \quad (5)$$

where x_i – the difference between the forecast and actual values; N – the size of the sample of values representing.

Table 1 shows the interpretation of the forecast error depending on MARE.

Table 1. Forecasting and interpretation of data

MARE, %	Interpretations
<10	High precision
10-20	Good precision
20-50	Satisfactory precision
>50	Unsatisfactory precision

Source: D. Chicco *et al.* (2021)

The reliability of the forecast is assessed using the ratio between the number of explained emissions and the total number of emissions. Extreme errors can be defined as those that fall outside the confidence interval. Since the assessment of validity requires a case-by-case analysis, in practice this indicator is calculated only in certain cases.

The forecasting model was created using a global fleet of meteorological satellites. Nowcasting is an ultra-short-range weather forecast with a 5-15-minute time step. This forecast is reduced to the task of extrapolating observed meteorological phenomena (Ozbek *et al.*, 2021) (6):

$$p(x_{t+1\ldots t+k|}x_{1\ldots t}) = \prod_{i=1}^{k} p(x_{t+i}|x_{1\ldots t+I-1}), \quad (6)$$

where *x* – meteorological satellite image; *t* – the number of images used to make the forecast; *k* – number of projected images.

Assessment of solar resources and forecast data for illumination and photovoltaic power in the range of -7 days to +7 days – forecast of time horizons (Fig. 2).

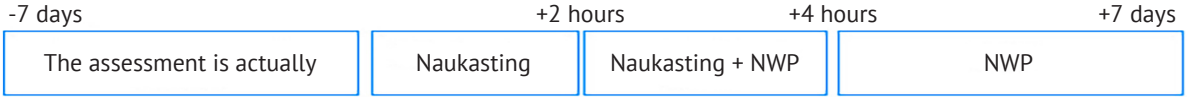

Figure 2. Forecasting time horizons

Source: compiled by the author

Forecast efficiency on the +3:45 time horizon the forecasting system uses mainly NWP numerical weather forecasts from several models. On the day-ahead horizon (which includes the +4 hour window), machine learning-based bias corrections are included, which are applied based on observed cloud opacity from satellite imagery. The performance in the first 0-3 hours will always be better than +4 hours, as it uses satellite forecasting of actual information with a fast update for 0-3 hours (individual clouds are

tracked at a resolution of 1-2 km^2, with updates every 15 minutes).

The energy generation of photovoltaic converters depends on climatic conditions, and their power varies in proportion to changes in solar irradiation exposure of their working surface over time (Libra *et al.*, 2021). The amount of solar radiation that reaches a photosensitive surface at any given time depends on astronomical, geographical, and topographical conditions. This amount of radiation is determined by parameters such as the angle of incidence of the sun's rays on the earth's surface, as well as the processes of absorption and scattering of solar radiation in the atmosphere. Among the meteorological parameters that have the greatest impact on electricity generation are solar insolation, temperature, wind speed, humidity and sky conditions (cloud cover). The neural network "learns" to predict solar power generation based on meteorological parameters such as temperature, humidity, pressure and wind speed (Fig. 3).

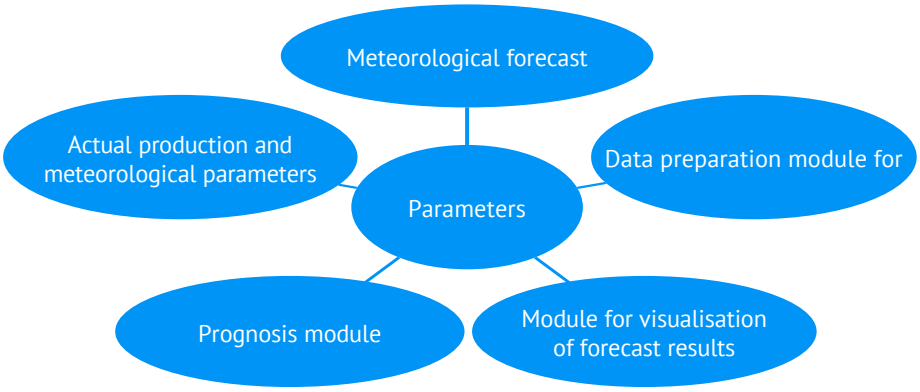

Figure 3. Generation forecasting model based on weather observation data
Source: X. Luo *et al.* (2021)

This method is a variation of the classical gradient descent method. Since neural networks need to adapt to geolocation and be able to retrain for other stations, the backpropagation algorithm is used for this purpose. The main concept of this method is to transmit error signals from the network outputs to its inputs in the opposite direction to the direct flow of signals during normal operation. The training sample is retrospective power generation data for an interval of one year before the forecast day. The number of neurons in the input layer is determined by the input parameters, and the output neuron is the forecast of the photovoltaic power plant generation. The forecasting method based on meteorological observations has advantages, such as the ability to use a wide range of input data (electricity consumption, air temperature, cloud cover, insolation, time of day) and the speed of the neural network. It is an effective tool for forecasting electricity generation, which is an alternative to traditional statistical methods.

Satellite images provide highly accurate data on solar radiation and atmospheric conditions (Nespoli *et al.*, 2022). Forecasting models based on these images are used to predict electricity generation by solar power plants. The main advantage of such models is their ability to respond quickly to changes in weather conditions and accurately predict electricity generation for several hours or even days in advance. Solcast nowcasting system is one of the most advanced platforms for predicting solar activity and power generation. It uses data from satellites and meteorological stations to calculate and forecast solar radiation. The artificial intelligence technologies used in Solcast improve the accuracy of forecasts and ensure the stability of electricity generation from solar sources. One of the key advantages of using forecasting models based on satellite imagery is the ability to manage the operating modes of solar power plants. Operators can adapt their power generation to the forecasted weather conditions, maximising the use of solar energy and maintaining the stability of the grid. The scheme for forecasting electricity from solar power plants is shown in Figure 4.

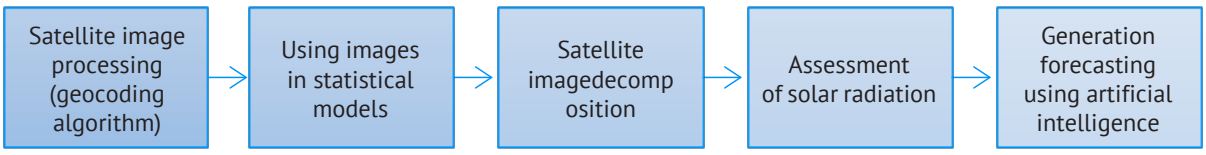

Figure 4. Generation forecasting algorithm based on real-time satellite imagery data with the support of the Solcast satellite nowcasting system
Source: Q. Paletta *et al.* (2023)

Solargis Forecast, a power generation forecasting model based on the Cloud Motion Vector model, is one of the most advanced forecasting systems in the solar industry. This model uses sophisticated intensive monitoring algorithms based on satellite image analysis to obtain accurate data on cloud movement and other atmospheric phenomena. The main advantages of the Solargis Forecast model are its ability to predict the dynamics of cloud movement and changes in the direction and speed of their movement. This provides a clear, high-quality view of the weather conditions at the location of solar power plants. For example, by analysing changes in cloud positions over a short time interval, it is possible to determine whether solar panels will be shaded shortly, which is important for accurate forecasting of electricity generation. Cloud Motion Vector technology allows taking into account various factors such as wind speed, humidity, temperature, atmospheric pressure, and others that affect cloud movement and the overall weather situation (Aicardi *et al.*, 2022). Integration of these data into a forecasting model allows for more accurate results in predicting electricity generation by solar power plants. One of the key advantages of such a model is its ability to respond to changes in weather conditions in real-time. This allows for prompt adjustments to solar power plant operation plans, minimising losses and maximising electricity generation in the face of weather uncertainty.

The Solcast Advanced PV model is an important tool in the field of photovoltaic installations that allows for more accurate forecasting of electricity generation. This model was developed for use in installations where system characteristics are known, which means that it takes into account the various parameters and conditions that affect the operation of PV systems. One of the key features of the model is its ability to exploit installation specifications such as array geometry and solar panel tracking type (Zohner *et al.*, 2023). For example, the size and orientation of solar panels can have a significant impact on solar energy collection efficiency, and these parameters are important to consider when predicting electricity generation. In addition, the model also considers other factors that affect the efficiency of a photovoltaic system, such as module and inverter information, horizon shading, dust losses, and other losses, including panel degradation over time. This data creates more accurate forecasts of electricity production and scheduling of photovoltaic installations. The model also supports tracking algorithms that optimise the position of solar panels to maximise solar energy collection throughout the day. The support for a double-sided module is also important, allowing the use of sunlight reflection for additional power generation.

The model for predicting UTP (installed capacity) from meteorological observation and meteorological forecast data plays an important role in predicting the generation of electricity by photovoltaic power plants (PVPPs). Astronomical, geographical, and topographical conditions are among the main factors that affect the amount of solar radiation reaching a photosensitive surface (Kitamura *et al.*, 2022). The amount of solar energy that reaches the earth's surface depends on the angle of the sun's rays and atmospheric processes such as absorption and scattering. The proposed meteorological parameters, such as temperature, humidity, precipitation, and wind, are used as input to neural networks in the UTP forecasting model. These parameters allow taking into account the dynamics of changes in weather conditions, which affect the generation of electricity by solar power plants. The study of the parameters of the accuracy of forecasting electricity generation by a photovoltaic power plant was carried out based on actual data from the PV power plant in May 2021. The results of this study help to improve the UTP forecasting model and assess its accuracy and reliability in a real operating environment. This approach is important for ensuring the efficiency of solar power plants and planning their operations taking into account the forecasted weather conditions (Table 2; Table 3).

Table 2. Forecast data based on real-time satellite imagery with the support of the Solcast satellite science system, the Solcast Advanced PV model and the actual generation of the Petrivka PV plant for May 2021

	Solcast				Solcast_Update			
	Actual, MWh	Forecast, MWh	Remainder	Square	Actual, MWh	Forecast, MWh	Remainder	Square
01.05	45.641	50.124	4.483	20.097	45.641	50.359	4.718	22.26
04.05	54.989	55.782	0.793	0.629	54.989	55.308	0.319	0.102
05.05	52.656	54.069	1.413	1.997	52.656	54.495	1.839	3.382
06.05	40.996	30.976	10.02	100.4	40.996	31.768	9.228	85.156
07.05	33.471	33.614	0.143	0.02	33.471	34.431	0.96	0.922
08.05	33.959	21.685	12.274	150.651	33.959	23.28	10.679	114.041
11.05	51.88	45.907	5.973	35.677	51.88	45.266	6.614	43.745
12.05	41.816	43.798	1.982	3.928	41.816	43.495	1.679	2.819
13.05	29.792	30.625	0.833	0.694	29.792	29.718	0.074	0.005
14.05	51.571	41.979	9.592	92.006	51.571	43.214	8.357	69.839
15.05	49.637	57.682	8.045	64.722	49.637	58.114	8.477	71.86
19.05	15.89	19.661	3.771	14.22	15.89	19.702	3.812	14.531

Continued Table 2.

	Solcast				Solcast_Update			
	Actual, MWh	Forecast, MWh	Remainder	Square	Actual, MWh	Forecast, MWh	Remainder	Square
21.05	35.825	28.308	7.517	56.505	35.825	27.806	8.019	64.304
24.05	50.033	46.733	3.3	10.89	50.033	46.92	3.113	9.691
26.05	54.059	56.58	2.521	6.355	54.059	55.757	1.698	2.883
27.05	54.497	54.046	0.451	0.203	54.497	53.881	0.616	0.379
28.05	50.223	47.865	2.358	5.56	50.223	48.551	1.672	2.796
29.05	42.612	34.586	8.026	64.417	42.612	33.981	8.631	74.494
31.05	34.375	25.891	8.484	71.978	34.375	26.107	8.268	68.36
Average value	41.976	39.348			41.976	39.264		

Source: PV plant Petrivka (n.d.)

Table 3. Forecast data from the Solargis Forecast model based on the Cloud Motion Vector model, the UTP forecast model based on weather observation data using neural networks and the actual generation of Petrivka FES for May 2021

	Solargis Forecast				UTP			
	Actual, MWh	Forecast, MWh	Remainder	Square	Actual, MWh	Forecast, MWh	Remainder	Square
01.05	45.641	0	45.641	2083.101	45.641	32.487	13.154	173.028
04.05	54.989	0	54.989	3023.79	54.989	41.346	13.643	186.131
05.05	52.656	0	52.656	2772.654	52.656	45.267	7.389	54.597
06.05	40.996	0	40.996	1680.672	40.996	33.106	7.89	62.252
07.05	33.471	27.027	6.444	41.525	33.471	29.477	3.994	15.952
08.05	33.959	33.679	0.28	0.078	33.959	33.889	0.07	0.005
11.05	51.88	51.081	0.799	0.638	51.88	38.131	13.749	189.035
12.05	41.816	40.771	1.045	1.092	41.816	28.678	13.138	172.607
13.05	29.792	28.266	1.526	2.329	29.792	34.987	5.195	26.988
14.05	51.571	48.556	3.015	9.09	51.571	39.714	11.857	140.588
15.05	49.637	54.474	4.837	23.397	49.637	44.716	4.921	24.216
19.05	15.89	22.827	6.937	48.122	15.89	30.122	14.232	202.55
21.05	35.825	25.586	10.239	104.837	35.825	49.025	13.2	174.24
24.05	50.033	47.545	2.488	6.19	50.033	39.401	10.632	113.039
26.05	54.059	49.398	4.661	21.725	54.059	42.861	11.198	125.395
27.05	54.497	53.808	0.689	0.475	54.497	38.956	15.541	241.523
28.05	50.223	48.937	1.286	1.654	50.223	25.895	24.328	591.852
29.05	42.612	43.4	0.788	0.621	42.612	37.42	5.192	26.957
31.05	34.375	30.5	3.875	15.016	34.375	32.722	1.653	2.732
Average value	41.976	40.39			41.976	36.4		

Source: PV plant Petrivka (n.d.)

Based on the actual and forecasted electricity generation of Petrivka SPP for May 2021, a comparative graph was built, which is shown in Figure 5. This graph shows a comparison of actual and forecast electricity generation during this period. The graph shows how the forecast values differed from the actual values on different days in May 2021. This comparison helps to evaluate the efficiency and accuracy of electricity forecasting at Petrivka PVP by using the appropriate forecasting model (Table 4).

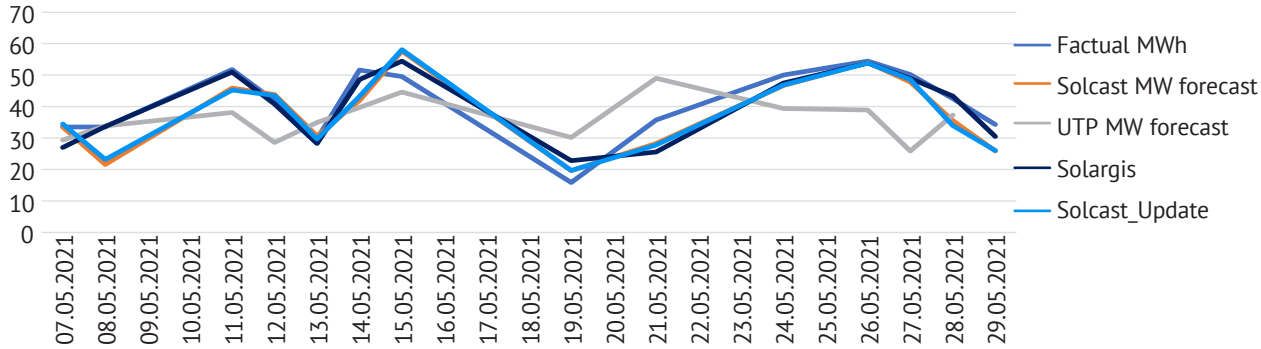

Figure 5. Graph of actual and forecast electricity generation at Petrivka PVP in May 2021
Source: compiled by the author

Table 4. Comparison of the calculated data of the PV power generation forecasting accuracy indicators by the studied generation forecasting models

Indicators	Solcast	Solcast_Update	UTP	Solargis
MAE	5.018	4.845	9.927	3.261
MAPE, %	11.95	12.31	23.65	8.07
MASE	0.11954	0.11541	0.23648	0.07767
RMSE	6.207	6.004	11.684	4.296

Source: compiled by the author

Analysing the calculated indicators of forecasting errors of PV power generation by different forecasting models that were the subject of the study, based on the graph of actual and forecast generation, some important conclusions can be drawn. Based on the results of the analysis, it is possible to emphasise that the most accurate method is forecasting using the Solargis Forecast model, which is based on the Cloud Motion Vector model. This method demonstrates a MARE of 8.07%, which is close to a high level of accuracy. The Solcast and Solcast_Update models also show good accuracy results with MAREs of 11.95 and 12.31%, respectively, which indicates that they are suitable for practical use. The worst performer among the analysed methods is the UTP model based on weather forecast and weather observation data, which demonstrates a MARE of 23.65%. This indicates that this method may be less accurate and will require further development to improve forecasting results. Thus, it can be reasonably stated that in the context of the considered forecasting models, the Solargis Forecast model based on the Cloud Motion Vector model is the most accurate and efficient for forecasting the electricity generation of PV power plants.

DISCUSSION

The analysis demonstrated that the introduction of modern technologies in the process of forecasting electricity generation does indeed improve the accuracy of forecasting and optimisation of electricity production. Analysing the research results, it can be noted that the integration of the latest technologies into power generation forecasting allows obtaining more accurate forecasts of electricity generation from solar power plants. This is because modern technologies allow for a more detailed consideration of various input data, such as meteorological parameters, equipment characteristics and other factors that affect the efficiency of solar power plants. The use of advanced data analytics and artificial intelligence methods in the process of power generation forecasting is becoming particularly important. These methods allow automating the process of processing and analysing large amounts of data, which in turn improves the quality of forecasts and allows for a prompt response to changes in electricity generation from solar power plants.

When analysing the results of the study, the effectiveness of forecasting models for electricity generation from solar power plants is important to consider. One of the key aspects that was considered was the effectiveness of specific forecasting models. For example, when analysing the results, the Solargis Forecast model, which is based on the Cloud Motion Vector model, was found to be highly accurate in predicting electricity generation. This shows that the use of modern cloud and weather analysis technologies can significantly improve forecasting efficiency. In addition, other models, such as Solcast and Solcast_Update, also demonstrated positive results in terms of forecasting accuracy. This confirms the wide range of possibilities in choosing an effective model for forecasting electricity generation from solar power plants.

Effective forecasting has several significant advantages, the most important of which are the ability to respond quickly to changes in weather conditions and ensure the stable operation of power plants. This advantage is crucial for planning and managing electricity

systems. One of the main advantages of effective forecasting is the ability to respond to changes in weather conditions in real-time. For example, with an accurate forecast of solar radiation and cloud cover, solar power plants can be scheduled to operate optimally, increasing their efficiency and overall power generation. Forecasting meteorological conditions also help ensure reliable and stable operation of power plants. Considering the intensity of solar radiation, the presence of clouds and other meteorological factors, it is possible to effectively regulate the operation of equipment to ensure optimal performance and maximum use of solar energy. In the future, the development of forecasting methods will focus on the use of artificial intelligence, big data analysis and improved algorithms. It is also important to pay attention to the integration of data from IoT (Internet of Things) systems and the expansion of data sources to improve the accuracy and reliability of forecasting. In general, effective forecasting of power generation from solar power plants plays an important role in modern energy systems and contributes to the development of renewable energy sources.

According to the results of recent studies by E. Kim *et al.* (2023), the development of methods for predicting solar power generation is a key research area in the relatively young field of solar energy. With a large increase in the number of installed solar power plants around the world, the need for accurate forecasting of electricity generation is becoming increasingly important. Accurate forecasting of solar power generation allows for an increase in the efficiency of solar power plants, optimises their operation and ensures a stable electricity supply. These data are consistent with the theses presented in this paper. One of the key aspects in the development of forecasting methods is the use of modern technologies and data analysis methods, such as artificial intelligence, machine learning, and big data analysis. These methods account for numerous factors affecting solar energy production, such as weather conditions, geographical location, types of panels, etc. This approach improves forecasting accuracy and ensures the reliable operation of solar power plants in different conditions.

Referring to the definition of M. Elsaraiti and A. Merabet (2022), solar power generation forecasting using deep learning techniques is one of the ways to improve forecasting accuracy and optimise the efficiency of solar power plants. Deep learning methods, such as neural networks, combine many layers and nodes, which allows them to effectively learn complex dependencies in data, factoring in various factors that affect solar power generation. It is worth noting that neural networks can automatically detect and adjust for various patterns and trends in the data, which allows for more accurate and reliable solar power generation forecasts. The use of deep learning in solar energy forecasting opens up prospects for further improving the efficiency of solar power plants and increasing their contribution to clean energy production.

Yu. Natarajan *et al.* (2021) determined that forecasting energy production at large PV power plants is an important task in the management and optimisation of solar power plants. Especially on a large scale, where numerous panels and plant components make it difficult to manage and forecast power generation. Accurate forecasting allows for efficient production planning, resource management and stable operation of power plants. These results support the above study, as a variety of methods and technologies are used to forecast power generation at large-scale PV plants. This includes the use of meteorological data, analysis of solar panel performance, and consideration of the impact of weather conditions and other factors on power generation efficiency.

L. Fara *et al.* (2021) demonstrated that forecasting energy production for PV systems is a key task in the optimisation and planning of solar power plants. This is especially true in the modern environment when the use of alternative energy sources is increasingly important and the scale of solar PV systems is expanding. To achieve effective forecasting, advanced models such as ARIMA and ANN (Artificial Neural Networks) are used. The ARIMA model is a popular method in time series forecasting and is used to analyse and predict the relationships between previous time series values. In the context of solar power generation forecasting, ARIMA can handle seasonality, tendencies, and other regular patterns that affect power generation. Also, ANNs have become a powerful tool in forecasting, especially in the energy sector. ANNs can effectively account for complex relationships between input parameters, such as weather conditions, geographical factors, system characteristics, and others. Their ability to learn from a large amount of data allows them to create accurate and reliable models for predicting electricity production from solar PV systems. This opinion can be agreed that the application of such advanced methods in power generation forecasting helps energy companies and plant operators to ensure stable and efficient operation of the grid. Consideration of power generation forecasting is a key element for optimising electricity production and planning the operation of power companies, considering variable weather conditions and other factors affecting solar energy production.

As noted by R. Tawn and J. Browell (2022), very short-term solar energy forecasting is an important component of solar power plant management. This type of forecasting is typically focused on a time frame of several minutes to several hours ahead. Its main goal is to provide operational data to adjust the operation of power plants to take into account instantaneous changes in weather conditions. Analysing the results and conclusions obtained, algorithms and models based on fast processing of meteorological and power generation data are often used for very short-term solar energy forecasting. Such models can accommodate cloud dynamics, solar radiation intensity, temperature

changes and other factors that have an immediate impact on solar energy generation. However, it is not only the accuracy of the forecast that is important but also the speed of its preparation and processing to respond to changes in energy production promptly.

S.C. Lim *et al.* (2022) determined that solar energy forecasting is a key task for the efficient use of solar power plants. One advanced approach is to use hybrid models, such as a convolutional neural network with LSTM (CNN-LSTM (Convolutional Neural Network, Long Short-Term Memory)). This combined model combines the advantages of both architectures and provides more accurate solar power generation forecasts. The hybrid CNN-LSTM model allows for the efficient use of spatial and temporal information obtained from meteorological and energy generation data. The CNN enables the model to detect spatial dependencies in meteorological data, such as cloud cover and solar radiation intensity at different locations. At the same time, the Long Short-Term Memory (LSTM) layer allows for time dependencies and trends in energy production, which is critical for accurate forecasting, as noted by C.M. Zohner *et al.* (2023).

This approach to solar energy forecasting is quite promising and can be widely used in modern solar power plant control systems. The use of hybrid models can improve forecasting accuracy and optimise the operation of energy systems, considering variable weather conditions and other factors affecting solar energy generation.

CONCLUSIONS

Effective forecasting of electricity generation from solar power plants is an important aspect of optimising production and ensuring the stability of the electricity supply. This report discusses the key aspects of effective forecasting, its benefits and prospects. The use of modern technologies, such as the integration of data from meteorological stations and satellite imagery, allows for more accurate and timely power generation forecasting data. This reduces energy losses and optimises the operation of solar power plants. An important aspect is the ability to respond quickly to changes in weather conditions. Integrated forecasting systems allow power plants to plan operations based on predictable changes, such as cloud cover, solar radiation intensity and temperature changes. This improves the reliability and stability of the energy supply. In particular, the integration of deep learning and artificial neural networks can improve forecasting accuracy by analysing large amounts of data and identifying complex relationships between various factors affecting electricity generation.

Analysing the calculated errors in forecasting PV power generation by different forecasting models, it can be noted that the results highlight important trends and performance indicators. The study confirmed that the Solargis Forecast forecasting model based on the Cloud Motion Vector model is the most accurate among the methods considered, which is confirmed by the low average absolute percentage error (MARE). Other models, such as Solcast and Solcast_Update, also demonstrated positive accuracy results, but still require some attention to detail to optimise and improve their performance in practical applications. In general, effective forecasting is an important step towards optimising the use of solar energy, which contributes to resource conservation, reducing CO2 emissions and improving the sustainability of energy supply for consumers. An additional area for research is the development of more accurate and reliable forecasting models, considering the impact of climate change and the technological development of solar energy.

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Ефективне прогнозування електрогенерації від сонячних електростанцій за допомогою технологій: інтеграція, переваги та перспективи

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Анотація. Точне прогнозування виробітку електроенергії з використанням відновлюваних джерел є важливим елементом для забезпечення стабільності електричних систем та переходу до більш сталого енергетичного виробництва. Метою цього дослідження є оптимізація роботи електричних систем України з урахуванням впровадження необхідної частки відновлювальних джерел енергії для забезпечення надійності електричної системи. Для дослідження точності прогнозування генерації електроенергії фотогальванічними електростанціями в Україні використовувалися аналіз даних, огляд сучасних моделей та методів прогнозування, а також порівняльний аналіз за допомогою супутникових знімків та метеорологічних спостережень. Низька точність прогнозування відпуску є особливістю виробництва електроенергії з відновлюваних джерел енергії, що пояснюється випадковим характером джерел енергії та супутніми метеорологічними умовами. В Україні стає більш актуальною проблема якісного прогнозування виробітку електричної енергії з використанням відновлюваних джерел. Значення пошуку ефективних методів прогнозування генерації виробництва електроенергії в Україні зросло з появою ринку електроенергії. Дана дослідницька робота скерована на вирішення проблемного питання щодо прогнозування генерації електроенергії фотогальванічними електростанціями на добу наперед в умовах енергетичного ринку України. У рамках роботи були розглянуті питання законодавства України щодо вимог до точності прогнозування генерації електроенергії та наслідки їх невиконання. Також було проведено огляд сучасних моделей та методів прогнозування генерації електроенергії фотогальванічними електростанціями та досліджено новий «ринок систем прогнозування» в Україні. У дослідженні були представлені прийняті метрики прогнозів, які дозволяють оцінити похибки і порівняти ефективність різних методів прогнозування. З урахуванням залежності прогнозування генерації електроенергії від метеопараметрів, був проведений порівняльний аналіз точності прогнозування за допомогою супутникових знімків та метеорологічних спостережень. Запропоноване дослідження дозволить враховувати викладений матеріал при визначенні моделі прогнозування генерації електроенергії, таким чином підвищуючи ефективність роботи енергетичних компанії в умовах енергетичного ринку України. Дослідження також сприятиме зменшенню негативного впливу енергетичного сектору на навколишнє середовище та сприятиме створенню більш ефективної та стабільної електричної системи у майбутньому

Ключові слова: потужність; генерація; баланс енергосистеми; відновлювані джерела енергії; енергетичний ринок

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