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МОДЕЛИРОВАНИЕ ПРОЦЕССОВ И УПРАВЛЕНИЕ В ТЕХНИЧЕСКИХ СИСТЕМАХ
MODELLING OF PROCESSES AND MANAGEMENT IN TECHNICAL SYSTEMS

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DIGITAL CERTIFICATE SYSTEM IN EDUCATION BASED ON THE ETHEREUM BLOCKCHAIN PLATFORM

Modern education is constantly adapting to the dynamically changing technological landscape, looking for innovative solutions to support learning processes. Among these solutions, blockchain technology is emerging as a promising area, potentially revolutionary for the field of education. The implementation of digital certificates in education enhances the efficiency, security, and global recognition of qualifications, making the process of verifying achievements more modern and transparent. The article analyzes the main features of using blockchain technologies in the education system, based on a number of fundamental theoretical concepts, and describes the author's software tool for the academic certification system. The core of the application is a decentralized database built on the Ethereum platform. The application utilizes smart contracts for secure issuance and verification of digital diplomas. The key modules of the application and their software implementation features are described. One of the features of the system under consideration is the implementation of a tokenization mechanism based on the Ethereum Request for Comments 20, ensures that these tokens are fungible and compatible with other tokens and applications within the Ethereum ecosystem. Examples of practical use of the application are also presented.

Keywords: blockchain technology, education system, Ethereum platform, hash function, consensus algorithm, software.

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СИСТЕМА ЦИФРОВЫХ СЕРТИФИКАТОВ В ОБРАЗОВАНИИ НА ОСНОВЕ БЛОКЧЕЙН-ПЛАТФОРМЫ ETHEREUM

Современное образование постоянно адаптируется к динамично меняющемуся технологическому ландшафту, ищет инновационные решения для поддержки процессов обучения. Среди этих решений технология блокчейн становится перспективной областью, потенциально революционной для сферы образования. Внедрение цифровых сертификатов в образование повышает эффективность, безопасность и глобальное признание квалификаций, делая процесс подтверждения достижений более современным и прозрачным. В статье анализируются основные особенности использования технологий блокчейн в системе образования, базирующиеся на ряде фундаментальных теоретических концепций, а также описывается авторское программное средство для системы академической сертификации. Основой приложения является децентрализованная база данных, построенная на платформе Ethereum. Приложение использует смарт-контракты для безопасной выдачи и проверки цифровых дипломов. Описаны ключевые модули приложения и особенности их программной реализации. Одной из особенностей рассматриваемой системы является реализация механизма токенизации, основанного на наборе правил для смарт-контракта токена в сети Ethereum (ERC-20), который гарантирует, что эти токены взаимозаменяемы и совместимы с другими токенами и приложениями в экосистеме Ethereum. Представлены также примеры практического использования данного приложения.

Ключевые слова: технология блокчейн, система образования, платформа Ethereum, хэш-функция, алгоритм консенсуса, программное обеспечение.

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Introduction. Modern education is continuously adapting to the rapidly evolving technological landscape, seeking innovative solutions to support learning processes [1–3]. Among these, blockchain technology is emerging as a promising area with the potential to revolutionize the field of education. The basic idea of this technology (Satoshi Nakamoto [4]) is that the network timestamps transactions by hashing them into an ongoing chain of hash-based proofs of work, forming a record that cannot be changed without redoing the proof-of-work. The longest chain serves as proof of the sequence of events witnessed. Originally developed as the backbone for cryptocurrencies, blockchain has become a foundation for new models of secure and transparent data storage.

There are several main areas of research on the use of blockchain technology in education. These include the following.

1. Theoretical Foundations and Conceptual Approaches. Many authors emphasize the unique properties of blockchain – immutability of records, decentralization, and automation through smart contracts (see, for example, [5, 6]). These features create prerequisites for reducing the risks of certificate forgery and increasing trust in learning outcomes.

2. Application of Blockchain for Storage and Verification of Academic Achievements. Research shows that blockchain enables the creation of digital diplomas and certificates that are easily verifiable by employers and educational institutions [7, 8].

3. Management of Student and Educator Records and Portfolios. Decentralized platforms for storing students' achievements and educators' methodological materials provide control over such data and facilitate their exchange among participants in the educational process [9].

4. Skills Certification. Studies indicate the prospects of using blockchain for issuing micro-certificates for individual modules or skills [10, 11]. This approach promotes flexible learning and validation of specific competencies.

5. Security, Privacy, and Regulatory Issues. Despite its advantages, research also raises concerns regarding personal data protection [12], compliance with regulatory requirements (European Commission, 2020), and the need for standardization of solutions.

The analysis shows a high potential for using blockchain technologies in the education system to increase trust in learning outcomes, simplify administrative processes and protect data [13–18]. In practice, blockchain only allows for adding information without the possibility of editing or deleting it [12–14]. Each subsequent block is permanently linked to the previous ones, creating a chain resistant to manipulation.

The authors of [15] conducted a meta-analysis with elements of a literature review, in which they distinguished both current and future potential applications of blockchain technology in the education sector. Here, they analyzed, among others, the use of this technology in the field of certificate management, maintaining student records, building educational platforms and implementing smart contracts.

Other literature reviews also emphasize the convergent features of blockchain technology. For example, in the article [16] such features as decentralization, transaction tracking, immutability of records and currency properties of blockchain were distinguished. In turn, the article from MDPI lists interesting advantages such as transparency, security, efficiency and the possibility of creating decentralized applications and smart contracts [17]. However, for widespread implementation, further research is needed on issues of standardization, regulatory control and integration with existing systems and, most importantly, it is necessary to create and study the main features of the practical use of relevant software platforms.

It is also worth noting that in 2017, Sony Global Education (SGE) announced the development of a blockchain-based system in the education sector. It was intended to mutually use records of educational achievements and activities of several educational institutions [19].

The purpose and content of this article is precisely to present the process of development and practical use of blockchain technology in education. Specifically, it pertains to verifying the authenticity of digital educational diplomas.

Main part. ***System model and application architecture***. The basic assumption of the proposed solution in the author's application is to ensure transparency, security and automation of the process of issuing and verifying academic certificates using blockchain technology and smart contracts.

The functionality of the developed diploma authentication system and the interaction of its main modules are based on the approaches described in [20]. Fig. 1 shows an adapted functional diagram of the specified system.

The system is based on a decentralized platform operating in the Ethereum Virtual Machine (EVM) environment. EVM is responsible for executing the code of smart contracts, which automatically execute the terms of the contract when certain criteria are met. They are based on the Solidity language, which is specially designed for creating applications on the Ethereum blockchain.

Each transaction in a block is hashed and stored in a Merkle tree, which is a type of binary tree with many leaf nodes. The root of a Merkle tree is a hash of its descendant nodes, which ensures data integrity and verifiability. Ethereum also uses Patricia Merkle Tries (also known as Radix Tries), which are used to store key-value pairs with cryptographic authentication. The block header contains three roots from the three trees, representing state, transactions, and confirmations, respectively [21].

The application was developed and tested using Truffle Suite, which is a comprehensive solution for building and testing decentralized applications. Ganache, a local platform for visualizing blockchain data and testing contracts in a local environment, without the overhead of the Ethereum mainnet, was also used. Data is stored in MongoDB, and the front-end, built using the React framework, communicates with the back-end and the Ethereum network via a JavaScript API. The general scheme of the developed application is presented in Fig. 2.

Front-End. The application uses a decentralized interface (DApp) to interact with the Ethereum blockchain.

The front-end is built using the *React.js* framework with MetaMask wallet integration, which allows users to securely authenticate and manage certificates. With DApp browsers (e.g., with the MetaMask extension), users can upload and verify certificates directly through smart contracts.

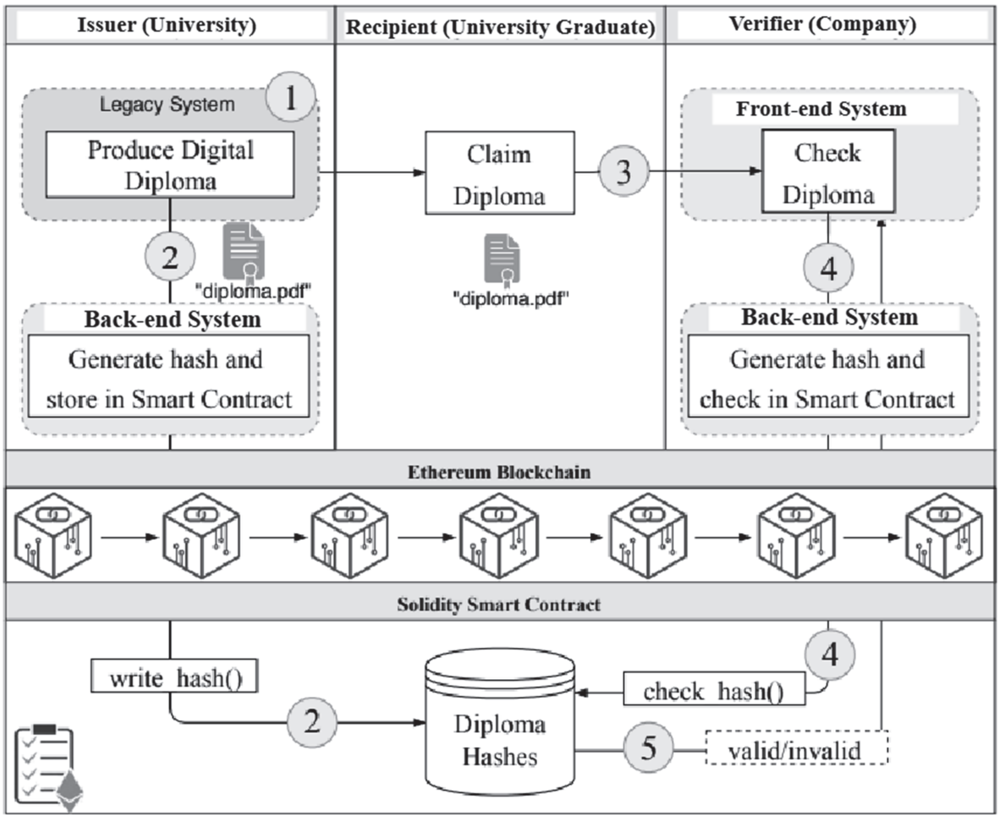


Fig. 1. Architecture and functionality of electronic processing of certificates based on blockchain

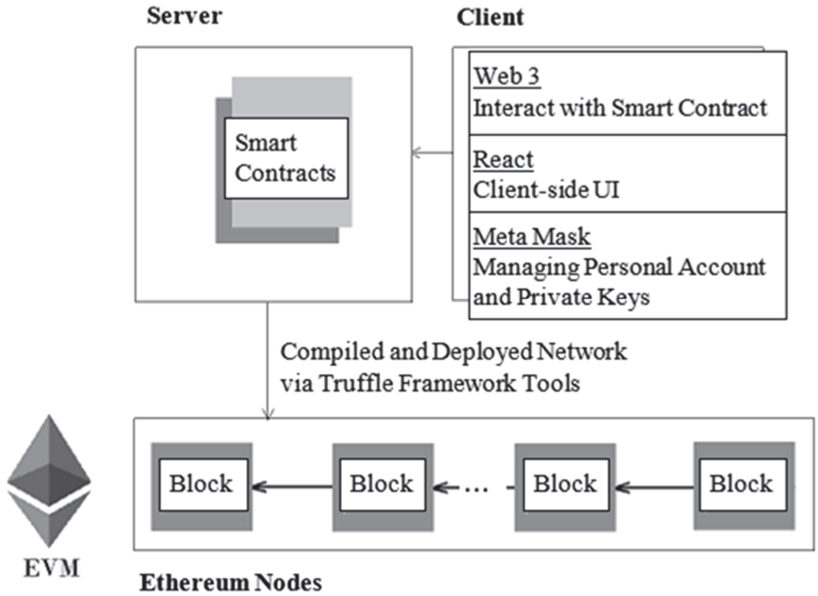


Fig. 2. The general scheme of the developed application

Basic frontend software modules.

Registration module. The user registers using a MetaMask account, whose unique identifier replaces traditional login data. Additionally, they provide information such as name, surname, email address, and role.

Login module. After registration, the user logs in only using MetaMask, which eliminates the need to remember passwords and increases security.

Certificate management module. Educational institutions can issue certificates, assign them to students, and verify the authenticity of documents.

Certificate issuing module. Administrators manage the entire system, create new certificates, and supervise the process of issuing them.

Download and viewing module. Students can view certificates assigned to them and download them in PDF format.

Payment module. Payments for issuing a certificate are made via ERC-20 tokens (described in Chapter 4), integrated with the MetaMask wallet.

Verification module. Each certificate is recorded in the blockchain, and its authenticity can be verified by the university or other institutions using a unique identifier.

Back-End. The application uses the MongoDB database (DB) to store user data and certificate metadata. Communication between the frontend and backend layers is carried out via the REST API JSON interface. The *Ganache* environment, which simulates the operation of the private Ethereum network, was used to test smart contracts. This solution allows testing without the need to incur transaction costs. Integration with the blockchain was implemented using the *Web3.js* library, used to send transactions and read data from smart contracts running on the Ethereum platform.

REST API *RestAPI* organizes work with two databases: the application DB (MongoDB) and the blockchain. In this regard, the methods in *RestAPI* are divided into three categories: methods of the identification level (*Identity*), methods of registering reference information in the application database (MongoDB) and methods of making transactions with the blockchain DB. The methods of the *Identity* category are used to authorize the participant and obtain a JWT token in order to further use *RestAPI* methods, as well as to register and confirm participants at the web application level. The architecture of this DB is presented in Fig. 3, where the detailed structure of all tables used by the application is presented.

The process begins with the admin generating a digital certificate, which is then sent to the blockchain network. The certificate contains important information, such as the student's name and surname, the name of the institution, the date of issue, and the title of the diploma. Each certificate is saved in the form of an immutable hash and associated with the admin's public key. In the second step, the consensus layer plays a key role. It can be seen as a combination of internal infrastructure (MongoDB, *Node.js* server, and private Ethereum node), which constantly monitors the implemented smart contract. Institutions can easily verify the document without the need to involve the admin. It is enough to compare the generated certificate hash with those saved in the blockchain. After successful verification, the certificate is issued to the student in digital form and is notified via e-mail.

The educational institutions participating in the system are mainly universities or teachers who are members of the network. The blockchain-based system for issuing and verifying diploma certificates has been designed as a complete solution.

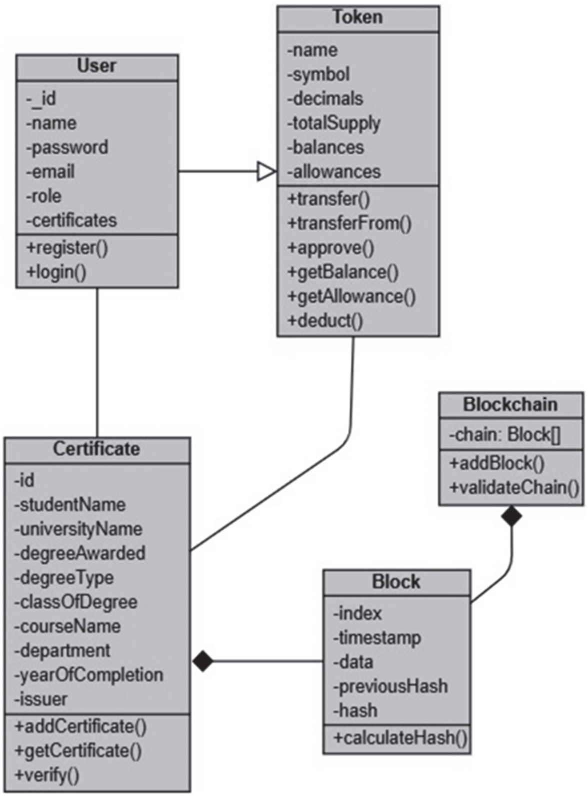


Fig. 3. Database schema

A blockchain written in *JavaScript* was used to verify certificates, which allows for storing information and verifying certificates.

Fig. 4 and Fig. 5 show a fragment of the code implementing the blockchain, which includes creating a new block for each verification, checking the integrity of the chain, ang updating the status of the certificate.

Block class representing a single block in the blockchain. Each block contains an index, timestamp, data, hash of the previous block and its own hash.

Blockchain class representing the entire blockchain. Contains methods for creating a genesis block, adding new blocks and verifying the integrity of the chain.

```
class Block {
    constructor(index, timestamp, data, previousHash = "") {
        this.index = index;
        this.timestamp = timestamp;
        this.data = data;
        this.previousHash = previousHash;
        this.hash = this.calculateHash();
    }
    calculateHash() {
        return crypto
            .createHash("sha256")
            .update(
                this.index +
                    this.timestamp +
                    JSON.stringify(this.data) +
                    this.previousHash
            )
            .digest("hex");
    }
```

Fig. 4. Implementation of the *Block* class

```
class Blockchain {
    constructor() {
        this.chain = [this.createGenesisBlock()];
    }
    createGenesisBlock() {
        return new Block(0, Date.now().toString(), "Genesis Block", "0");
    }
    getLatestBlock() {
        return this.chain[this.chain.length - 1];
    }
    addBlock(newBlock) {
        newBlock.previousHash = this.getLatestBlock().hash;
        newBlock.hash = newBlock.calculateHash();
        this.chain.push(newBlock);
    }
    isChainValid() {
        for (let i = 1; i < this.chain.length; i++) {
            const currentBlock = this.chain[i];
            const previousBlock = this.chain[i - 1];

            if (currentBlock.hash !== currentBlock.calculateHash()) {
                return false;
            }
            if (currentBlock.previousHash !== previousBlock.hash) {
                return false;
            }
        }
        return true;
    }
```

Fig. 5. Implementation of the *Blockchain* class

The certificate verification process includes the following steps (see Fig. 1):

1) the user sends a verification request based on the certificate's unique identifier;

2) the system searches for the certificate in the DB;

3) for each verified certificate, a new block is created containing its unique data;

4) the new block is added to the blockchain;

5) the system verifies the integrity of the entire chain.

6) the certificate is assigned the status "Valid" and a response is returned.

Smart contracts on the token platform. the proposed application also integrates a tokenization mechanism based on the ERC-20 standard. Tokens are used to manage payments related to the issuance and purchase of certificates [22, 23]. The token contract additionally incorporates elements of extended smart contract standards, which are sub-standards of the ERC-20 token. In particular, transfer functionality is implemented using the *transfer()* and *transferFrom()* functions, based on the ERC-677 standard [23]. In both cases, parameters such as the recipient address, sender address, and the number of token units are passed to the function as arguments.

For managing user wallets and executing transactions, the MetaMask extension is used, providing access to the *web3.js* interface.

For educational institutions, such as universities, this process has been further extended. Before gaining access to the generated certificate and the ability to verify it, the university is required to purchase tokens in order to redeem the respective certificate. In other words, users must have a sufficient balance to proceed with the transaction. The purchase of tokens is carried out based on a predetermined fee. Once the transaction is completed, the purchased tokens are transferred to the institution's wallet address in MetaMask. Only after the certificate has been redeemed does the university obtain access to the generated document and its verification within the system. The tokens used for purchasing the certificate are then transferred to the administrator's account.

Error "Stack too deep" in Solidity and its solution. During the implementation of smart contract functionality in Solidity, one of the characteristic compilation errors for this environment was encountered: "Stack too deep when compiling inline assembly". This error is caused by too many local variables or parameters passed to the function, which exceeds the limits of the stack available during the function execution. The error appeared in the *addCourse()* function, which accepted as many as 12 parameters, including many of type string memory (Fig. 6*a*). Each of these parameters occupies a separate slot on the stack, and the total number of slots for local variables in the function is a maximum of 16. Exceeding this limit results in the inability to generate code, preventing the proper compilation of the contract.

To bypass the stack limit, the *addCourse()* function was modified to accept a single parameter of this type (Fig. 6*b*). Thanks to the changes, the number of local variables in the function has been reduced to one, which allowed avoiding a stack overflow error and enabled successful compilation and migration of the contract.

Issuing certificates. A certificate confirming the attainment of a scientific degree is an official document issued by an academic institution, such as a university. It contains key information, including the date of award, the name of the awarding institution, the recipient's personal details, and the title of the obtained degree. This document serves as formal confirmation of academic achievements and is often required in recruitment processes or further education. The process begins with assigning the certificate to a specific student. The system verifies the user's identity and the certificate's status, then generates a personalized document containing student data such as first name, last name, identification number, field of study, and year of graduation. To ensure security, the certificate is encrypted and digitally signed. After generation, the certificate is automatically sent to the student via email.

The message includes information about the document's availability and instructions for downloading it. This allows students to have immediate access to their certificate without waiting for traditional postal delivery. The system also enables students to download certificates at any time. During this process, the system verifies the user's identity and the authenticity of the certificate. If everything is in order, the student can download a PDF version of the document, which can be used in recruitment processes or job applications. After generating the certificate, it is encrypted and sent to the specified address.

The certificate encryption process is as follows:

1) based on the *userId* and certificateId identifiers, the appropriate user and certificate data are retrieved from the DB;

2) the presence of the user and certificate, as well as the certificate's status, are checked. If the certificate is revoked, the process is halted;

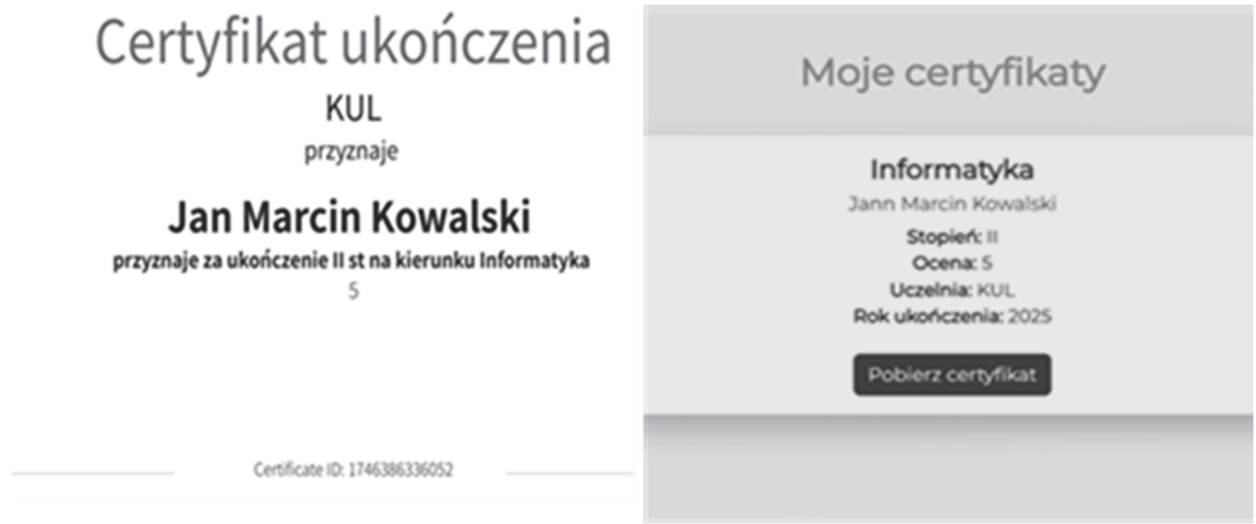
```
function addCourse(
    string memory lastname,
    string memory firstname,
    string memory middlename,
    string memory degreeAwarded,
    string memory degreeType,
    string memory classOfDegree,
    string memory courseName,
    string memory department,
    string memory yearOfCompletion,
    int256 p,
    int256 e_id
)
```

a

```
function addCourse(Course memory input) public {
    require(isEducator[msg.sender], "Not authorized to add course");
    courseCount++;
    courses[courseCount] = Course({
        id: courseCount,
        lastname: input.lastname,
        firstname: input.firstname,
        middlename: input.middlename,
        degreeAwarded: input.degreeAwarded,
        degreeType: input.degreeType,
        classOfDegree: input.classOfDegree,
        courseName: input.courseName,
        department: input.department,
        yearOfCompletion: input.yearOfCompletion,
        certificateStatus: input.certificateStatus,
        author_id: input.author_id,
        price: input.price,
        users: 0
    });
    educators[input.author_id].courses_id.push(courseCount);
}
```

b

Fig. 6. The code fragment causing the error (*a*) and modified *addCourse()* function (*b*)



a *b*

Fig. 8. The examples of a generated certificate for the student (a) and its appearance and content in the student's accoun

3) the certificate data is encrypted using the user's private key (*user.privateKey*) with the RS256 algorithm. For this purpose, a JWT token containing the certificate data is generated, which is then encoded into base64 format and stored in the *encryptedData* field of the certificate;

4) a new entry containing the certificate ID, assignment date, status, and encrypted data is added to the user's list of certificates;

5) an email notification is sent to the user informing them about the availability of the certificate, along with an attachment in PDF format of the certificate.

The examples of a generated certificate for the student (Jan Marcin Kowalski) and its appearance and content in the student's account, are presented (in Polish) respectively in Fig. 8*a* and Fig. 8*b*.

Results and discussion. The system for generating and issuing digital certificates in the education system based on blockchain technology developed and described in the article is a decentralized, automated and cryptographically secure structure for issuing and verifying academic documents. The main features of this and similar systems are as follows:

1) *tamper-proof certification* – by storing certificates as cryptographic hashes on the Ethereum blockchain, the system ensures immutability, eliminating the risk of falsification;

2) *automated smart contract execution* – the use of Solidity-based smart contracts removes manual verification steps, reducing administrative delays and human errors in credential validation;

3) *decentralized identity management* – integration with MetaMask replaces traditional login systems, enhancing security by eliminating password vulnerabilities and enabling seamless wallet-based authentication;

4) *tokenized incentives* – the ERC-20 token system streamlines payments for certificate issuance, with automated balance checks and transaction approvals;

5) *instant verification* – educational institutions can verify credentials in real-time by comparing blockchain-stored hashes, significantly reducing the time and cost associated with manual verification.

The proposed blockchain-based system for issuing and verifying educational certificates on the Ethereum platform presents a promising approach to addressing challenges inherent in traditional credentialing methods. To obtain reliable and comprehensive results, further testing in real-world conditions will be necessary, along with the collection of sufficient data for thorough analysis and comparison.

Conclusion. Blockchain technologies in education represent a groundbreaking approach to managing academic data, verifying achievements, and building trust in certification systems. This study analyzes the potential of this technology in combating document forgery, streamlining administrative processes, and increasing transparency in the education sector.

The proposed original application, utilizing smart contracts and decentralized data storage, demonstrates the practical use of blockchain in creating immutable and verifiable digital diplomas. The adoption of standards such as ERC-20 and integration with tools like MetaMask indicate that mature technological solutions already exist to support the implementation of such systems. At the same time, challenges such as Solidity stack limitations and the need to balance transparency with data privacy highlight that the adoption of blockchain in education requires further research and optimization.

Further development efforts will focus on addressing current limitations, including the integration of external data sources, improvements in user experience for non-technical participants, and optimization of operational costs associated with the Ethereum network. Particular attention will also be given to ensuring compliance with relevant data protection regulations.

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