IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received 7 November 2022, accepted 12 December 2022, date of publication 15 December 2022,
date of current version 23 December 2022.

Digital Object Identifier 10.1109/ACCESS.2022.3229870

RESEARCH ARTICLE

The Analysis of Blockchain Digital Currency Product Innovation Based on Artificial Immune Algorithm

HONG CHEN[1], KECHENG SU[2], AND WANDONG GAO[3]
[1]School of Management, Guangzhou Xinhua University, Guangzhou 510520, China
[2]Marshall Business School, University of Southern California, Los Angeles, CA 90007, USA
[3]School of Economics and Management, Weifang University of Science and Technology, Shouguang 262700, China

Corresponding author: Wandong Gao (gwd.2022-3@wfust.edu.cn)

ABSTRACT In recent years, with the rapid growth of the digital currency industry, blockchain technology has attracted wide attention, and its research mostly focuses on the protection of economic security and privacy. In order to study the application and development mechanism of currency products, this work investigates the practical application of digital currency products under blockchain technology at the present stage, and analyzes the potential security risks. The Artificial Immune Algorithm (AIA) is an intelligent method to imitate the function of the biological immune system, which provides a new solution for solving complex distributed problems. Firstly, a blockchain digital currency product is proposed based on AIA. Secondly, taking the credit risk of innovation risk in financial currency products as an example, the Diffie-Hellman (DH) with blockchain technology is used. Finally, the generation and optimization of the plan are realized, and an innovative risk plan is proposed for blockchain digital currency products on the basis of AIA. The results show that: (1) The improved AIA implements a guided AIA with adaptive parameter update. (2) The digital signature technology using the DH algorithm has a stronger anti-attack ability than the traditional blockchain digital signature technology. It improves the security of blockchain digital currency. This work has successfully established the risk-immune system of digital currency product innovation, laying a theoretical foundation for the innovation and development of blockchain digital currency products in the future.

INDEX TERMS Artificial immune algorithm, blockchain, DH algorithm, digital currency, innovation risk, potential risk.

I. INTRODUCTION

A. RESEARCH BACKGROUND AND MOTIVATIONS

With the rapid development of Artificial Intelligent (AI), cross-penetration is possible between various subjects. Scholars continue to transform research results from one field to another. With the swift growth of computer network technology, it is not difficult to use biotechnology to solve engineering problems, including algorithms such as the Artificial Neural Network (ANN), DNA computing, and the Artificial Immune System (AIS) [10]. Among them, AIA is an optimization algorithm based on evolution and immune mechanism, aiming at promoting high-affinity antibodies and inhibiting high-concentration antibodies, and maintaining the diversity of antibodies [16]. The Artificial Immune Algorithm (AIA) retains the advantages of good diversity, strong robustness, and implicit parallelism of the biological immune system. It has been widely used in AI, information security, control theory, and other fields in recent years. Nowadays, the analysis and improvement research of AIA by scholars has become an important topic in intelligent computing [28].

Digital currency is one of the representatives of information technology innovation. It is a new form of currency formed after natural currency, metal currency, and paper currency. It has brought great changes to public life, reducing

The associate editor coordinating the review of this manuscript and approving it for publication was Fabrizio Marozzo.

information and transaction costs, expanding transaction space, and is not limited by time and place [12]. In addition, digital currency plays a very important role in current social life. It is convenient and precise, making public life more convenient. The development of technology has brought the golden age of entrepreneurship. Capital markets have invested in blockchain innovation companies, and everyone strives to develop a blockchain that represents the future [11]. The most mature application of blockchain technology in the market is Bitcoin and various digital currency transactions. Its essence is to use computer algorithms and cryptography to create a decentralized digital currency system, thereby realizing the issuance of currency and transactions [7].

At present, there are endless news and start-ups about blockchain technology in digital currency and digital asset trading, but there are very few products with the introduction of AIA that can be tested by the market [25]. AIA can be employed to solve various complex projects and can be widely used in intelligent computing systems for optimization problems. Moreover, the mature theoretical foundation of AIA's product innovation for blockchain digital currency has not been reached, and there are few reference materials. By comparing the cases of blockchain in digital asset transactions, this work analyzes its innovative ways from multiple perspectives to bring more enlightenment for the implementation of AIA technology applied to blockchain digital currency asset transactions and bring broad prospects for social and economic development.

B. RESEARCH OBJECTIVES

This work mainly explores and analyzes the optimization of AIA and its key issues, including stability, redundancy, and convergence. The AIA is introduced into the research of blockchain digital currency products to discuss the development path and standardized innovation mechanism of blockchain technology to the digital currency market at the current stage. The evolutionary depth feedback and the equivalence division mechanism are organically integrated to provide new research tools and methods for innovative research on digital currency products in AIA. Research on the theory and AIA is carried out. In addition, a new type of heuristic intelligent optimization algorithm, from both theoretical and application aspects, not only has important academic significance but also has a broad application space. It will bring huge social and economic benefits, and bring certain changes to human science and social life. Meanwhile, empirical analysis is performed in combination with relevant landing projects in the transaction of blockchain digital currency assets, and relevant suggestions are given to provide a reference value for other enterprises or financial institutions to use this technology.

II. LITERATURE REVIEW

de Souza et al. analyzed the application of AI technology in financial market transactions based on the development status of currency market business and introduced the feasibility and application effect of the combination of AI and this business [17]. Moşteanu pointed out that the reasonable application of AI in the currency market can effectively improve business scale, reduce operational risks, improve transaction efficiency, and achieve the effect of cost reduction, efficiency improvement, and quality enhancement [20]. Sabry et al. showed that the application of AI technology in financial market trading was still in its initial stage. It mainly solves high-frequency and repeated manual operations, reduces operational risks, improves transaction efficiency, and makes digital currency trading strategies more rational and objective [8].

In the coding mechanism of AIA, De Castro first proposed the clone selection algorithm in 2000 according to the principle of clone selection and formed the basic execution flow of the basic AIA [22]. De Castro and Calos put forward a multi-objective AIA based on multi-objective optimization. The algorithm uses a memory set model to record better antibodies, and the memory set is continuously updated during the algorithm search process [23]. For fewer constraints or weak nonlinear constraints, Calos et al. proposed further improved measures based on the multi-objective AIA [2].

China's study on AIS and immune algorithms (IA) is relatively late, but the development speed is fast, and its research results have a certain international influence. Since 2001, doctoral and master's theses on AIS and AIA have emerged one after another [1]. The first conference on AIS was successfully held at Harbin Engineering University in August 2006, providing a good platform for the exchange of scholars [21]. In the operator research of AIA, Kong and Liu et al. improved the antibody density and antibody reproduction rate of the IA based on a brief introduction to the related concepts and operation steps of the IA [26]. In terms of the structure of AIA, Corus et al. conducted in-depth research on the cloning mechanism of the algorithm, focusing on the immune monoclonal mechanism and immune multi-cloning mechanism [5].

The impact of blockchain on buyers' payment procedures is focused on the following areas. Firstly, the application and challenges of the new international settlement model with blockchain as the underlying technology are studied. Secondly, the application of digital currency in international settlement has changed the traditional way of international trade settlement. Efanov and Roschin believed that digital RMB was expected to open a new window for global trade settlement [7]. Thirdly, it studied the application and challenges of intelligent contracts. Zhang and Huang argued that although the intelligent contract had the advantages of improving transaction efficiency and promoting the development of international commercial trade, there were still some difficulties in the universal application of smart contracts for transactions. It cannot be widely and unconditionally applied to international commercial transactions [24].

In summary, the research on AIA and blockchain digital currency products has achieved initial results. The application of blockchain has expanded beyond the financial sector, and

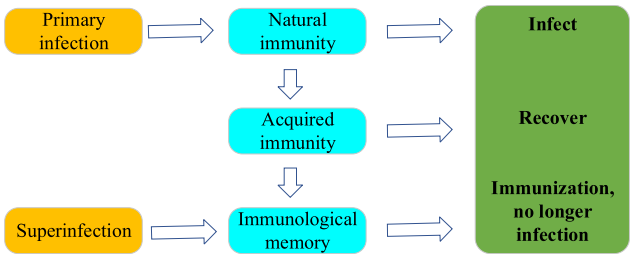

FIGURE 1. Biological immune process.

the monetary and economic spheres, covering all aspects of socio-economic activities. However, there is a lack of innovation to combine AIA and blockchain technology for digital currency products, and combining the advantages of the two can achieve more results with less. By comparing the research on AIA, it is found that in recent years, the research on it has attracted the attention of scholars from biological information science, AI, mathematics, and other disciplines. The blockchain digital currency product innovation based on AIA will become an emerging research hotspot in contemporary science and technology. The application and development mechanism of currency products are studied, and the practical application of digital currency products under blockchain technology is investigated at the present stage. The combination of AIA and blockchain technology is adopted to design innovative digital currency products, thereby ensuring the security of economic privacy.

III. RESEARCH METHODOLOGY

A. AIA

AIA is a kind of intelligent optimization algorithm based on the immune evolution mechanism and information processing mechanism of the biological immune system, which has some excellent characteristics of the biological immune system. The related research results have been widely used in many aspects [9]. To better understand the immune principle in the IA, this section mainly introduces the immune process in the biological immune system. The specific process is displayed in Figure 1:

The functions of the biological immune system include immune homeostasis, immune defense, and immune surveillance. These three functions of the biological immune system are mainly realized through the following mechanisms: (1) Immune recognition; (2) Immune tolerance; (3) Immune response; (4) Immune regulation; (5) Immune memory. Immune regulation refers to the interaction between immune cells and immune molecules in the immune system, as well as with other systems so that the immune response is maintained at the most appropriate level in the most appropriate form. The levels of immune regulation can be grouped into three categories: autoregulation, global regulation, and population regulation. Immune memory stands for the generation of stronger antibodies than the initial one when immunized with the same antigen again. Under the action of associative memory, the immune memory mechanism can effectively speed up the optimization search process [18].

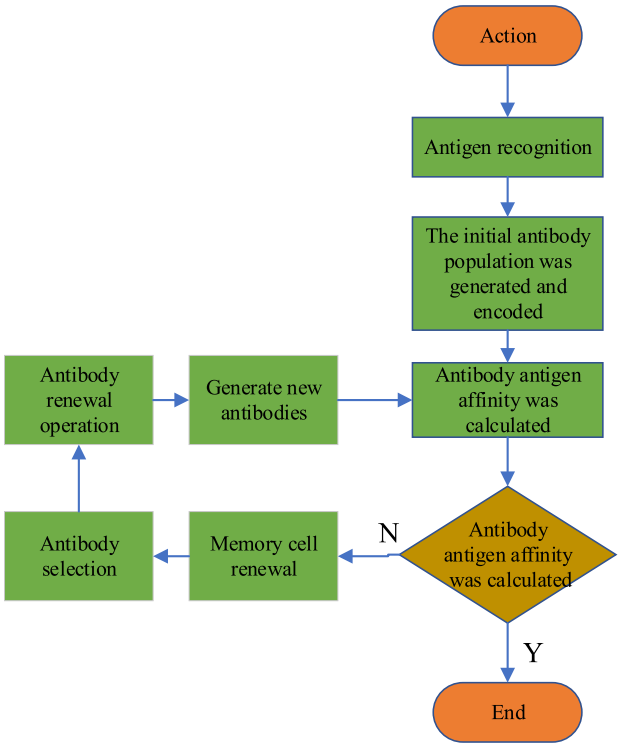

FIGURE 2. AIA framework.

By analyzing and summarizing the relevant immune principles and mechanisms of various types of AIA, it is concluded that the central idea of the AIA is to simulate a series of processing of antigen recognition, including the generation, proliferation, and updating of immune antibodies. Moreover, the biological immune system is a huge and complex information interaction system, all kinds of immune mechanisms and information processing features contained in it intersect, penetrate and complement each other. Therefore, AIA developed by different immune mechanisms has some common features or characteristics [6]. Accordingly, the general algorithm structure flowchart of the AIA is revealed in Figure 2:

The basic definitions and calculation methods of several main immune operators involved in the AIA are explained as follows. The affinity evaluation operator can be described as the function aff(x): S→R. S is the feasible solution interval of the problem and R is the real number field [4]. The affinity between antibodies reflects the degree of similarity between antibodies. The main calculation methods are as follows:

(1) Antibody-antigen affinity calculation method

$$\mathrm{aff}(ab_i, ab_j) = \begin{cases} 1 & \mathrm{aff}(ab_i) = \mathrm{aff}(ab_j) \\ \dfrac{1}{1 + \left|\mathrm{aff}(ab_i) - \mathrm{aff}(ab_j)\right|} & \text{else} \end{cases} \quad (1)$$

ab_i refers to the ith antibody in the population; ab_j expresses the jth antibody in the population.

(2) Affinity calculation method of Euclidean distance

$$\mathrm{aff}(\mathrm{ab_i}, \mathrm{ab_j}) = \sqrt{\sum_{k=0}^{L-1} (\mathrm{ab_{i,k}} - \mathrm{ab_{j,k}})^2} \quad (2)$$

$\mathrm{ab_{i,k}}$ and $\mathrm{ab_{j,k}}$ represent the kth position of antibody i and the kth position of antibody j respectively; L stands for the total dimension of antibody encoding. When the antibody is encoded in binary, equation (2) is equivalent to:

$$\mathrm{aff}(\mathrm{ab_i}, \mathrm{ab_j}) = \sum_{k=0}^{L-1} \left|\mathrm{ab_{i,k}} - \mathrm{ab_{j,k}}\right| \quad (3)$$

(3) Affinity calculation method of information entropy
Let M be a character set containing m characters, and a group G be a set consisting of N strings of length l, namely:

$$G = \{X = x_1 x_2 \ldots x_l, x_i \in M, 1 \le i \le l\} \quad (4)$$

Then the information entropy of locus j in G is described as:

$$H_j(G, N) = \sum_{i=1}^{m} -p_{ij} \log p_{ij} \quad (5)$$

p_{ij} means the probability that the ith symbol in M appears at locus j. The average information entropy of the group G is written as equation (6):

$$\mathrm{H}(\mathrm{G}, \mathrm{N}) = \frac{1}{\mathrm{l}} \sum_{\mathrm{j}=1}^{\mathrm{l}} \mathrm{H_j}(\mathrm{G}, \mathrm{N}) \quad (6)$$

If M is a binary character set, then the affinity of antibodies $\mathrm{ab_{i,k}}$ and $\mathrm{ab_{j,k}}$ is denoted in equations (7) and (8):

$$\mathrm{aff}(\mathrm{ab_i}, \mathrm{ab_j}) = \mathrm{H}(\mathrm{G}, 2) \quad (7)$$

$$\mathrm{G} = \left\{\mathrm{ab_{i,k}}, \mathrm{ab_{j,k}}\right\} \quad (8)$$

The antibody concentration evaluation operator can be described as a function den(x): S→[0,1], and its specific calculation method is usually defined as:

$$\mathrm{den}(\mathrm{ab_i}) = \frac{1}{\mathrm{N}} \sum_{\mathrm{j}=0}^{\mathrm{N}-1} \mathrm{aff}(\mathrm{ab_i}, \mathrm{ab_j}) \quad (9)$$

N means the population size; $\mathrm{ab_i}$ indicates the ith antibody in the population; $\mathrm{aff}(\mathrm{ab_i}, \mathrm{ab_j})$ signifies the affinity between antibody i and antibody j.

Antibody excitation degree refers to the comprehensive ability of antibodies in the antibody group to respond to antigens and to be activated by other antibodies. Generally, antibodies with high affinity and low concentration will obtain a greater excitation degree. The calculation method of antibody incentive can usually be expressed as:

$$\mathrm{act}(\mathrm{ab_i}) = \mathrm{a} \times \mathrm{aff}(\mathrm{ab_i}) - \mathrm{b} \times \mathrm{den}(\mathrm{ab_i}) \quad (10)$$

$\mathrm{act}(\mathrm{ab_i})$ implies the excitation degree of antibody $\mathrm{ab_i}$; a and b represent constants, which can be set accordingly in the actual application process.

B. BLOCKCHAIN ENCRYPTION ALGORITHM

In the blockchain system, to reach a consensus for different nodes, a lot of information must be published on the entire network so that each node can be synchronized. However, while the information is public, the blockchain also has confidentiality requirements for some sensitive transaction information (such as the user's holding amount, private key, and other private information), and the user must encrypt this information to ensure privacy and security. The DH algorithm is one of the most representative key exchange algorithms. It was proposed by Whitfield Diffie and Martin Hellman in 1976. The name of the algorithm consists of the initials of their surnames [19]. Before introducing the algorithm, the concepts of primitive root and discrete logarithm were given first.

Primitive root means that if m mod p, $\mathrm{m^2}$mod p,…, $\mathrm{m^{p-1}}$ are integers that are different from each other and form all integers from 1 to p-1, then m is called a primitive root of prime number p. The discrete logarithm means that if a primitive root m of a prime number p and an integer n satisfy $\mathrm{n=m^a}$mod p, 0≤a≤p-1, then a is called the discrete logarithm of n module p in base m. The principle of the DH algorithm is: given a large prime number p and one of its original roots m, it is quite difficult to calculate the discrete logarithm a given n, but it is very simple to calculate n with the given a. The specific process of the DH algorithm is plotted in Figure 3:

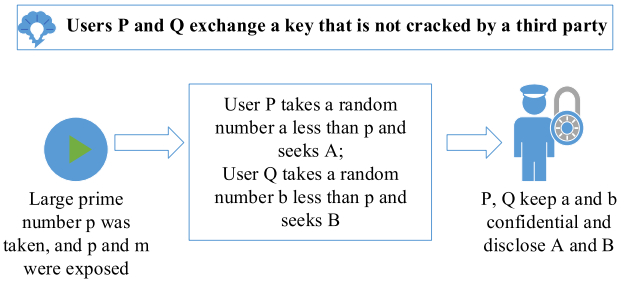

FIGURE 3. Process of DH algorithm.

Because *a* and *b* are kept secret, the only information available to the third party is A, B, m, and a large prime number p. To crack the key, the discrete logarithm of the large prime number p must be calculated, which is difficult to achieve, so the key exchange is realized.

IV. EXPERIMENTAL DESIGN AND PERFORMANCE EVALUATION

A. DATASETS COLLECTION

This work randomly selects 160 enterprises from the national enterprise joint credit information system as sample enterprises so that the sample data and the overall data in the joint credit information system maintain the same distribution, ensure the prediction ability of the model, and avoid the phenomenon of overfitting of the prediction model. These 160 samples are all valid samples and they are divided into 2 groups, each with 80 samples. The first 80 samples from the

experimental group are selected as the risk factor to generate the financial product innovation risk plan with the greatest affinity. The last 80 samples are from the experimental group and used as a control group to test the effect of the generated plan to deal with the risk of financial product innovation.

B. EXPERIMENTAL ENVIRONMENT

The simulation program of the AIA is developed by using the software development environment Lab Windows/CVI based on the C language. It is a graphical programming environment for virtual instrument applications and has a powerful data analysis function. The operating system is Windows XP, using Intel(R) i5-2400 CPU @3.10GHz processor, 4.00GB installed memory, and MATLAB R2013a software platform.

The test environment of the DH algorithm is as follows: the hardware configuration processor is Intel(R) Core(TM) i5-4210H CPU @2.90GHz, the memory is 8.00GB, the hard disk is KINGSTON SUV400S37240G, the network card is Intel(R) Dual Band Wireless-AC 3160, and the graphics card is Intel(R) HD Graphics 4600. The software configuration operating system is Windows 10, the programming language environment is Spyder 3.3.1, the system development framework is Flask 0.12.2, and the database is MySQL 8.0.15.

C. PARAMETERS SETTING

When designing the AIA, it mainly includes the following parameters: population size, mutation probability, refresh probability, maturity factor, and the number of clones. Population size refers to the total number of items contained globally, which is generally related to the complexity of individual genes. Mutation probability is used to determine whether any individual needs variation. Refresh probability stands for the antibody with a low excitation degree in the population that needs to be refreshed. Maturity factor means the repair of a system damaged by a physical factor. The number of clones refers to the number of individuals who have the same genes as the original by biotechnology reproduction. The parameter settings of each operation process are exhibited in Table 1:

TABLE 1. Parameter setting.

Environmental parameters	Design value
Population size	20
Mutation probability	0.2
Refresh probability	0.2
Maturation factor	0.2
Number of clones	20

Setting a large population size will help the algorithm to search for the feasible solution interval of the problem. However, it will increase the computational complexity of the algorithm which is usually set to 15-100, and is set to 20 here. If the antibody coding length is too small, it will reduce the search accuracy of the algorithm. If the coding length is too large, it will increase the computational complexity of the algorithm. Usually, the coding length of each independent variable is set to 10-30, and set to 17 in this work. Mutation operation in AIA is an important operator to generate affinity mutation. It is necessary to set a high mutation probability to ensure the search ability of the algorithm, which is usually one order of magnitude higher than the mutation probability. In this work, it is set to 0.2. If the mature factor is too low, it will affect the convergence speed of the algorithm. If the mature factor is too high, it will increase the computational complexity of the algorithm. Usually, the setting range is 0.1∼0.4, and is set to 0.2 here. The number of clones set too low will reduce the local search performance of the algorithm, and too high will increase the computational complexity of the algorithm, usually set to 10∼30, which is set to 20 here.

D. PERFORMANCE EVALUATION

Based on the AIA, the optimization simulation operation is optimized, including the LAIA (Local _ search _ enhanced artificial immune algorithm) based on local search, the guiding GAIA (Guiding artificial immune algorithm), and the multiple mutation rate MAIA (Multiple _ mutation _ rate artificial IA). The main simulation data obtained by the optimization operation of each algorithm are aggregated to obtain the data, as illustrated in Figures 4 and 5.

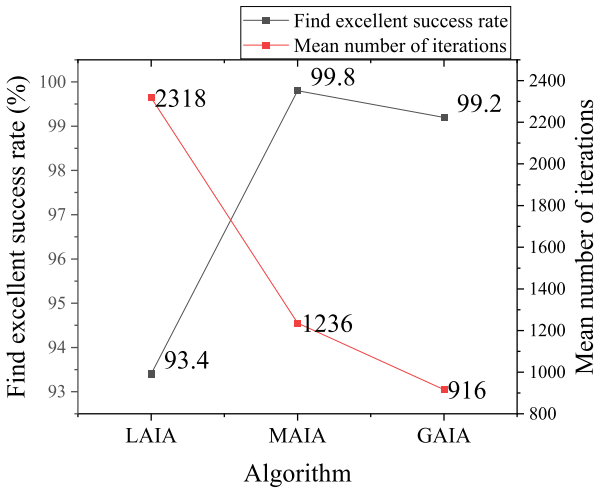

FIGURE 4. Comparison of the success rate of optimization and number of iterations.

The simulation data of the GAIA are obtained when the parameter k is 1.0. The data results show that the evaluation results obtained by GAIA are the best, which show the best overall performance. Overall, the success rate of the improved AIA is very high, close to 100 %. It effectively improves the local search ability of the algorithm, reduces the number of iterations required for the success of the algorithm, greatly improves the success rate of the algorithm, and has practical value in the combination with blockchain technology.

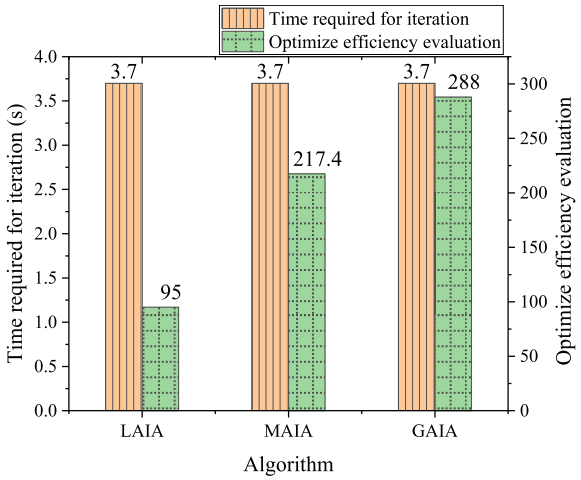

FIGURE 5. Comparison between iterative operation time and optimization evaluation.

The overall process of the DH algorithm runs 50 times, and the average execution time of the scheme is obtained, which is divided into pre-preparation stage P_1 and key exchange stage P_2. The preparation stage starts from the creation of the session to the end of the query to get the session public key and other related information. In the key exchange stage, the two sides obtain the shared session key by calculation. The execution time of the scheme is indicated in Table 2.

TABLE 2. Program execution time.

Period	Elapsed time/ms
Preliminary preparation	401
Key exchange	1.82
Total	402.82

After testing, the blockchain-based key exchange scheme proposed here can be successfully implemented. The current and latest session private key and shared key calculated by both parties each time are stored in the local database, and the storage space required is small. In addition, in this scheme, after both parties disclose their session public keys, the shared key can be obtained only by calculation, the number of interactions is greatly reduced, and the key exchange efficiency is improved. When applied to digital currency transactions, it not only guarantees the security of transaction risks but also improves work efficiency.

E. DISCUSSION

Rashid and Iqbal and others pointed out that artificial immunology caused by biological immunology is an interdisciplinary subject of biology and computer science. From the perspective of biological immunology theory, they studied the risk plan system of commercial bank financial product innovation. Nowadays, it has been widely used in various fields of economic development. The study on the financial product innovation plan system of commercial banks based on artificial immunology provides a new idea and method for better research on the management of financial product innovation risks [18]. However, this work is still based on artificial immunology and does not have the advantage of studying the innovative AIA in depth. In addition, it explores the AIS in the innovation of blockchain digital currency products, and also confirms that the AIS can be used in the digital currency economy, reducing the risk of currency transactions in financial enterprises and improving the security of the digital currency.

Owoh and Singh proposed a digital signature technology based on the DH algorithm in the study of the development of financial currency under the blockchain, which realized the two-way authentication between the two parties in the communication process. Digital signatures made it difficult for network attackers to authenticate or tamper with user data, ensure the integrity and reliability of transaction data, and improve the security of digital currency [19]. This work mainly integrates the application of blockchain technology in financial currency, providing a theoretical basis for the study of the DH algorithm to ensure the security of the digital currency. After studying the DH encryption algorithm of the blockchain, this work obtains the private shared key generated by the DH algorithm established between the sender and the receiver so that the two parties of the transaction can realize two-way identification and authentication in the communication process. It improves computing speed and enhances the performance of blockchain technology while ensuring the security of the digital currency.

V. CONCLUSION

A. RESEARCH CONTRIBUTION

The innovative risk immunity model of blockchain digital currency products is constructed, emphasizing that risk management is the center. On account of self-protection, the objects that need to be protected, such as programs, information flow, interface, and capital flow, are evaluated and certified. The object in the running process is subjected to risk analysis to determine whether to protect the object. According to the management strategy, the process of detecting whether the object is protected, whether the response is blocked or not, and the restoration of the continuity of the product innovation business is controlled.

The innovation risk immunity module of digital currency financial products based on the innovation process is constructed, and the immunity strategy is proposed. The model points out that the basic model of the innovative risk AIA for digital currency products includes: the processes of antigen recognition, initial antibody group generation, affinity calculation, clone selection, antibody group update, and termination. It constitutes the whole process of risk management of financial digital currency product innovation. On the basis of the improvement of the corporate financial management system, an immunity strategy based on risk

management awareness and a risk immunity strategy are proposed. At the same time, it has a broad development space in practical application, which will bring significant social and economic benefits, and bring certain changes to human technology and social life, thereby providing reference value for other enterprises or financial institutions when using this technology.

B. FUTURE WORKS AND RESEARCH LIMITATIONS

Accelerating the innovation of standardized digital currency products is the only way to develop China's financial industry. For China's social economy, both the positive role of financial and monetary product innovation and the hidden risks should be paid attention to. It is a vital aspect of modern financial institutions to establish a sound financial product innovation about how to implement an effective digital currency product innovation risk immunity mechanism, risk early warning mechanism, and comprehensive risk management system. This work draws on the knowledge of biological immunity to study the application of AIA in the blockchain digital currency economy, implements a digital currency product innovation risk immunity module, a residual antigen-based risk immunity monitoring system of digital currency financial product innovation, etc., and completes case studies. The measures and suggestions for the innovation of blockchain digital currency products are put forward.

The research is still confined to ideological innovation, and the operability of the research results is limited. For China's blockchain digital currency economy, although the AIA has its characteristics and advantages, it also has some shortcomings in the actual engineering application process, such as poor stability, data redundancy, and limited local search capabilities. The construction and system development of the practical risk immune system also needs to be further strengthened, which should become an important aspect of future exploration.

REFERENCES

[1] A. J. Saleh, A. Karim, B. Shanmugam, S. Azam, K. Kannoorpatti, M. Jonkman, and F. D. Boer, "An intelligent spam detection model based on artificial immune system," *Information*, vol. 10, no. 6, p. 209, Jun. 2019.
[2] A. Y. Hatata, G. Osman, and M. M. Aladl, "An optimization method for sizing a solar/wind/battery hybrid power system based on the artificial immune system," *Sustain. Energy Technol. Assessments*, vol. 27, pp. 83–93, Jun. 2018.
[3] B. J. Bejoy, T. V. Bijeesh, and J. Subbiah, "Artificial immune system based frameworks and its application in cyber immune system: A comprehensive review," *Lect. Notes Comput. Vis. Biomech.*, vol. 15, no. 6, pp. 123–132, 2018.
[4] D. Corus, P. S. Oliveto, and D. Yazdani, "Artificial immune systems can find arbitrarily good approximations for the NP-hard number partitioning problem," *Artif. Intell.*, vol. 274, pp. 180–196, Sep. 2019.
[5] D. Corus, P. S. Oliveto, and D. Yazdani, "When hypermutations and ageing enable artificial immune systems to outperform evolutionary algorithms," *Theor. Comput. Sci.*, vol. 832, pp. 166–185, Sep. 2020.
[6] D. C. de Oliveira, F. R. Chavarette, and F. P. D. A. Lima, "Structural health monitoring using artificial immune system," *Brazilian J. Develop.*, vol. 6, no. 4, pp. 16948–16963, 2020.
[7] D. Efanov and P. Roschin, "The all-pervasiveness of the blockchain technology," *Proc. Comput. Sci.*, vol. 123, pp. 116–121, Jan. 2018.
[8] F. Sabry, W. Labda, A. Erbad, and Q. Malluhi, "Cryptocurrencies and artificial intelligence: Challenges and opportunities," *IEEE Access*, vol. 8, pp. 175840–175858, 2020.
[9] G. C. Silva, E. E. Carvalho, and W. M. Caminhas, "An artificial immune systems approach to case-based reasoning applied to fault detection and diagnosis," *Expert Syst. Appl.*, vol. 140, Feb. 2020, Art. no. 112906.
[10] J.-Q. Li, Z.-M. Liu, C. Li, and Z.-X. Zheng, "Improved artificial immune system algorithm for type-2 fuzzy flexible job shop scheduling problem," *IEEE Trans. Fuzzy Syst.*, vol. 29, no. 11, pp. 3234–3248, Nov. 2021.
[11] J. L. Zhao, S. Fan, and J. Yan, "Overview of business innovations and research opportunities in blockchain and introduction to the special issue," *Financial Innov.*, vol. 2, no. 1, pp. 1–7, 2016.
[12] K. Saito and M. Iwamura, "How to make a digital currency on a blockchain stable," *Future Gener. Comput. Syst.*, vol. 100, pp. 58–69, Nov. 2019.
[13] L. Ricci, D. D. F. Maesa, A. Favenza, and E. Ferro, "Blockchains for COVID-19 contact tracing and vaccine support: A systematic review," *IEEE Access*, vol. 9, pp. 37936–37950, 2021.
[14] M. E. Peck and S. K. Moore, "The blossoming of the blockchain," *IEEE Spectr.*, vol. 54, no. 10, pp. 24–25, Oct. 2017.
[15] M. Duma and B. Twala, "Optimising latent features using artificial immune system in collaborative filtering for recommender systems," *Appl. Soft Comput.*, vol. 71, pp. 183–198, Oct. 2018.
[16] M. Gao, M. Chen, A. Liu, W. H. Ip, and K. Leung Yung, "Optimization of microservice composition based on artificial immune algorithm considering fuzziness and user preference," *IEEE Access*, vol. 8, pp. 26385–26404, 2020.
[17] M. J. S. de Souza, F. W. Almudhaf, B. M. Henrique, A. B. S. Negredo, D. G. F. Ramos, V. A. Sobreiro, and H. Kimura, "Can artificial intelligence enhance the Bitcoin bonanza," *J. Finance Data Sci.*, vol. 5, no. 2, pp. 83–98, 2019.
[18] N. Rashid, J. Iqbal, F. Mahmood, A. Abid, U. S. Khan, and M. I. Tiwana, "Artificial immune system–negative selection classification algorithm (NSCA) for four class electroencephalogram (EEG) signals," *Frontiers Hum. Neurosci.*, vol. 12, p. 439, Nov. 2018.
[19] N. P. Owoh and M. M. Singh, "Applying Diffie–Hellman algorithm to solve the key agreement problem in mobile blockchain-based sensing applications," *Int. J. Adv. Comput. Sci. Appl.*, vol. 10, no. 3, p. 59, 2019.
[20] N. R. Moşteanu, "International financial markets face to face with artificial intelligence and digital era," *Theor. Appl. Econ.*, vol. 26, no. 3, pp. 123–134, 2019.
[21] R. Pinto and G. Gonçalves, "Application of artificial immune systems in advanced manufacturing," *Array*, vol. 15, Sep. 2022, Art. no. 100238.
[22] R. Shang, W. Zhang, F. Li, L. Jiao, and R. Stolkin, "Multi-objective artificial immune algorithm for fuzzy clustering based on multiple kernels," *Swarm Evol. Comput.*, vol. 50, Nov. 2019, Art. no. 100485.
[23] S. Aldhaheri, D. Alghazzawi, L. Cheng, B. Alzahrani, and A. Al-Barakati, "DeepDCA: Novel network-based detection of IoT attacks using artificial immune system," *Appl. Sci.*, vol. 10, no. 6, p. 1909, Mar. 2020.
[24] T. Zhang and Z. Huang, "Blockchain and central bank digital currency," *ICT Exp.*, vol. 8, no. 2, pp. 264–270, 2022.
[25] W. Lu, L. Wu, R. Zhao, X. Li, and F. Xue, "Blockchain technology for governmental supervision of construction work: Learning from digital currency electronic payment systems," *J. Construct. Eng. Manage.*, vol. 147, no. 10, 2021, Art. no. 04021122.
[26] X. Kong, D. Liu, J. Xiao, and C. Wang, "A multi-agent optimal bidding strategy in microgrids based on artificial immune system," *Energy*, vol. 189, Dec. 2019, Art. no. 116154.
[27] Y. Wu, L. Song, L. Liu, J. Li, X. Li, and L. Zhou, "Consensus mechanism of IoT based on blockchain technology," *Shock Vib.*, vol. 2020, Oct. 2020, Art. no. 8846429.
[28] Y. Wang and T. Li, "Local feature selection based on artificial immune system for classification," *Appl. Soft Comput.*, vol. 87, Feb. 2020, Art. no. 105989.