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Integration Research of Blockchain and Social Networks in Rural Management Systems under Fuzzy Cognitive Environment

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Abstract

This study investigates integrating and optimizing an intelligent rural management system leveraging advanced technologies, including the Internet of Things (IoT), blockchain, and social networks. Initially, it identifies and scrutinizes prevailing issues in rural development processes, emphasizing the role of rural cultural dissemination, with a specific focus on the impact of social networks. Subsequently, by incorporating fuzzy set theory and adopting an enhanced blockchain consensus algorithm—the Byzantine Fault Tolerance (BFT) algorithm— a comprehensive rural management system is established, combining fuzzy sets and blockchain. Lastly, an intelligent traffic management system is developed to address logistics and distribution challenges in rural revitalization, facilitating efficient interurban delivery. The system automatically invokes the Matlab dynamic link library and employs a hybrid genetic algorithm to plan delivery routes. This study presents key findings on implementing an intelligent rural management system incorporating fuzzy sets, blockchain, and IoT technology. The system notably enhances transparency and traceability in agricultural production and supply chain processes, optimizes logistics and distribution efficiency, and reduces operational costs through intelligent management techniques. Additionally, the integrated application significantly bolsters consumer trust in the quality and safety of agricultural products, leading to heightened overall user satisfaction.

Keywords: Fuzzy set theory, Blockchain, Physical information system, Rural management system, Social network, Internet of things.

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1 | Introduction

In the rapidly evolving information technology landscape, rural management systems are undergoing transformative shifts driven by the integration of blockchain and social networks. Rural areas, characterized by lower population density and dispersed resource allocation, grapple with developmental challenges stemming from inadequate infrastructure, deficiencies in essential public facilities (e.g., transportation, water, and electricity), and a scarcity of talent in rural education, technology, and cultural skills [1]–[3]. These regions face obstacles in information acquisition, resource integration, and community participation within their management systems. Furthermore, conventional management systems contend with issues such as information silos and data barriers, constraining overall efficiency and impeding sustainable development in rural management [4]. The deployment of blockchain and social networks in a fuzzy cognitive environment holds considerable promise for addressing the complexities of rural management. By integrating fuzzy set theory, these technologies can be seamlessly incorporated into management systems to tackle challenges related to incomplete information and uncertainty, ultimately fostering the effective operation of rural management [5], [6]. Consequently, exploring integrating blockchain technology and social networks to construct a more inclusive and adaptable rural management system has emerged as a central focus for numerous scholars.

The Internet of Things (IoT) technology can collect, monitor, and manage data in the agricultural production process in real-time, enabling farmers to make informed decisions and improve production efficiency and output [7], [8]. Furthermore, the IoT can facilitate the intelligent management of rural infrastructure, improving the quality of life for rural residents and narrowing the urban-rural divide [9]–[11]. Blockchain technology can optimize the rural governance model [12]–[14]. It can promote the openness, transparency, and traceability of grassroots construction information, providing new methods and tools for rural governance. Additionally, blockchain technology can establish a decentralized credit system that enhances rural financial services' reliability and efficiency, supporting rural economic development [15]–[17]. Social networks can also advance rural informatization construction. They provide farmers with an online platform for communication and interaction, promoting rural informatization construction and information sharing. In rural settings, the characteristics of information and resources often exhibit ambiguity, and leveraging fuzzy set theory proves to be a more effective approach to address such uncertainties. Integrating fuzzy sets, blockchain, and social networks enables management systems to adeptly handle vague and imprecise information, thereby enhancing the robustness and adaptability of decision-making processes [18], [19]. In essence, integrating technologies such as fuzzy sets, blockchain, and social networks presents opportunities and challenges for rural management and revitalization. Examining relevant application cases and technological solutions can propel rural development, stimulate economic growth in rural areas, and contribute to broader societal progress.

This study aims to tackle current challenges in rural development and delve into the significance of employing social networks for disseminating rural culture within a fuzzy cognitive environment framework. To accomplish this, an innovative approach was adopted. Building upon the principles of fuzzy set theory, an integrated rural management system was developed using an enhanced Byzantine Fault Tolerance (BFT) algorithm based on a blockchain consensus algorithm. Additionally, an intelligent transportation management system was crafted to address logistics and distribution challenges in rural development, harnessing the IoT for efficient urban-rural distribution. These technological solutions offer fresh perspectives for the advancement of rural areas.

The methods proposed in this study demonstrate innovation in several key aspects:

I. Introduction of fuzzy set theory integrated with blockchain technology for addressing multivariable and uncertain information in rural management systems, thereby enhancing decision-making robustness.

II. Optimization of the BFT consensus algorithm to mitigate inconsistent information in agricultural supply chain management, tailored to specific agricultural production requirements, thus enhancing system efficiency and reliability.

III. Incorporation of IoT technology and utilization of a hybrid genetic algorithm to optimize logistics management in rural revitalization strategies, facilitating swift and accurate market access for agricultural products and resolving logistical resource allocation challenges in rural areas.

This study presents significant contributions across multiple dimensions:

I. Innovative framework: a pioneering framework for an intelligent rural management system is introduced, integrating fuzzy set theory, blockchain technology, and the IoT. By leveraging fuzzy sets to address information uncertainty in agricultural processes, the system enhances adaptability to complex decision environments.

II. Optimized blockchain application: addressing efficiency concerns in practical scenarios, the BFT algorithm is optimized for blockchain applications. This optimization enhances transparency in critical areas like agricultural product traceability and credit assessment, bolstering consumer trust in the agricultural supply chain.

III. Smart transportation management: a smart transportation management system integrating IoT technology is developed. This system optimizes distribution routes by leveraging Matlab dynamic link libraries and a hybrid genetic algorithm, significantly improving logistics and distribution efficiency in rural revitalization strategies.

Overall, the study underscores the effectiveness of the proposed systems in reducing rural management costs, enhancing customer satisfaction, and catalyzing the digital transformation of rural economies.

2 | Literature Review

Numerous experts and scholars have expressed their views on rural development, focusing on the potential applications of modern technologies such as IoT and blockchain. Wang and Wang [20] suggested that the IoT has potential in modern tourism development due to its capacity for information collection, storage, and processing. Innovative research on rural tourism systems utilizing the IoT and other information technologies can effectively upgrade rural tourism industries and optimize the use of tourism resources. Under the guidance of the new urbanization, Chen et al. [21] emphasized that urban and rural areas should transition from "one-way flow" to "two-way interaction" and from "urban bias" to "urban-rural integration". Ahmed et al. [22] proposed a scalable network architecture to monitor and control farming and farms in rural areas, reducing network latency compared to existing IoT-based farming solutions. Podder et al. [23] established an IoT-based intelligent agricultural technology system that increased overall yields through improved monitoring and sporadic irrigation management and suggested parameters for verifying the development level of urban agriculture.

Moreover, researchers have delved into applying fuzzy set theory in rural development. Jia et al. [24] employed a fuzzy comprehensive evaluation model to gauge the sense of gain among farmers regarding the infrastructure of tourism-oriented villages in China. This model, which integrates fuzzy set theory, comprehensively assesses complex fuzzy factors influencing farmers' perceptions, offering a nuanced perspective for enhancing rural infrastructure development by considering the varied viewpoints of residents. In a study by Yang et al. [25], spatiotemporal analysis was combined with fuzzy set theory to investigate factors influencing rural resilience. The research underscores the dynamics and complexity inherent in rural development, emphasizing the application of fuzzy sets to analyze the multifaceted and evolving aspects of rural resilience, thereby providing insights for crafting sustainable rural development strategies. Additionally, Yizhen and Linghan [26] employed a fuzzy set qualitative comparative analysis to explore the influencing factors and path selection in rural green development. This approach recognizes rural development's intricate nature and qualitative factors, contributing to a nuanced understanding of successful factors and paths for rural green development.

Prieto-Egido et al. [27] analyzed the inaugural Rural Mobile Infrastructure Operator (RMIO) in Peru, catering to underprivileged rural areas. The study discerned that RMIO strategies significantly contribute to Sustainable Development Goals (SDGs) 3, 9, and 17. These findings offer key insights for major stakeholders to devise strategies addressing connectivity gaps and fostering SDG realization in rural contexts. Zhou et al. [28] empirically examined farmers' adoption of low-carbon agricultural technology. Results indicate that internet usage notably facilitates farmers' adoption of low-carbon tillage and low-carbon fertilization technologies. However, its impact on adopting low-carbon pesticides, irrigation, plastic film recycling, and straw recycling technologies is insignificant. Mechanism analysis reveals that internet usage primarily influences the adoption of low-carbon fertilization technology through economic benefit cognition and low-carbon tillage technology through ecological benefit cognition. Lanchimba et al. [29] employed a fixed-effects model and panel data from 49 countries (2006–2015) to confirm the positive effects of franchising on national economic, social, infrastructure, and institutional development. Earlier adoption of franchise systems in a country correlates with stronger positive effects on economic, social, institutional, and infrastructure development. Ghasemi et al. [30] focused on reducing logistics costs and optimizing supply chain design. They proposed a dual-objective mathematical location-path model to minimize costs and maximize reliability, ensuring timely delivery of goods. The study contributes a method for optimizing supply chain management, aligning with the objectives of logistics cost optimization addressed in this paper. Shitharth et al. [31] addressed security issues in IoT technology, proposing a blockchain-based external technique for secure data processing. The study provides a novel approach to enhancing data processing security in IoT applications, aligning with the theme of integrating IoT and blockchain in this research.

Babazadeh et al. [32] proposed metrics guiding the application of blockchain technology in financial systems. The study aims to foster the application and development of blockchain technology and cryptocurrencies in the financial sector. Colombo et al. [33] used entropy-weighted multi-attribute decision-making methods to analyze the relationship between cryptocurrencies and financial and social media indicators. The study sheds light on the complex interaction between cryptocurrencies and various indicators. Torabi et al. [34] explored the benefits of integrating blockchain technology with Wireless Sensor Networks (WSNs). This integration addresses security and storage issues in WSNs, offering decentralized, secure management to enhance system security and reliability. Cao et al. [35] provide valuable insights for improving and renovating urban old building organizations pertinent to factors addressed in this study related to urban building renovation management. Kumar and Thomaz [36] discussed the current application status of IoT technology and future trends in agriculture, emphasizing its importance and potential. The study contributes important references for the application of IoT technology in agriculture, aligning with the WSNs application in agriculture addressed in this research. The collective findings of these studies enrich the background knowledge and theoretical foundation, elucidating the innovations in this study—enhancing decision robustness through fuzzy set theory, improving transparency and trust with blockchain, optimizing logistics distribution via IoT technology, and ultimately achieving intelligence and efficiency in rural management. Simultaneously, this study aims to bridge existing literature gaps in integrating multiple technological solutions in rural management systems, providing practical guidance and policy recommendations for promoting sustainable development in rural areas.

The aforementioned studies comprehensively explore the application of various modern technologies in rural development, encompassing the IoT, network architecture, and the implementation of fuzzy set theory. These investigations have significantly advanced the enhancement of rural life quality, resource management, and agricultural development. Despite these achievements, research gaps exist about incorporating blockchain and social networks in rural management within a fuzzy cognitive environment. Consequently, this study employs fuzzy set theory to tackle information uncertainty and endeavors to integrate blockchain and social networks into rural management. This integration is anticipated to yield a more comprehensive and efficient management solution for rural management systems, introducing novel perspectives and strategies to the realm of rural development.

3 | Research Methodology

3.1 | Analysis of Rural Culture Communication Based on Social Networks

The utilization of social networks for disseminating rural culture can significantly impact the development of the rural economy and the popularity of rural areas. By sharing information about rural tourist attractions and characteristic agricultural products through social network platforms, more tourists and consumers can be attracted to the countryside, thereby promoting local economic growth. Similarly, sharing successful cases and experiences of rural entrepreneurship can inspire more people to contribute to the development of the rural economy, resulting in its further advancement. In addition, disseminating rural culture through social networks can promote its inheritance and innovation, thereby increasing its influence and attractiveness. Publishing content related to traditional festivals and folk culture stories can enhance rural culture's appeal. Additionally, promoting new cultural products and activities through social networks can enhance the competitiveness of rural culture by promoting its innovation.

However, the successful dissemination of rural culture through social networks requires good network infrastructure support. This includes improving network coverage and speed in rural areas and providing technical support for rural cultural dissemination through social networks. Strengthening the network infrastructure and combining rural cultural dissemination through social networks with other rural development measures are essential to establishing a cultural brand for rural areas and achieving diversified development while enhancing the comprehensive benefits of rural development. It should be noted that communication of rural culture through social networks alone is not sufficient to achieve the goal of rural revitalization. Therefore, it is crucial to strengthen the construction of network infrastructure, cultivate and introduce talent, establish rustic cultural brands, and promote diversified development in combination with the dissemination of rural culture through social networks to achieve the goal of rural development.

3.2 | Rural Integrated Management System Based on Fuzzy Set and Blockchain Consensus Algorithm

Fuzzy sets can manage fuzzy, imprecise, or incomplete information, a critical attribute for rural management systems characterized by multiple variables and uncertainties [37]. Blockchain technology can address many challenges in rural management through a consensus algorithm that maintains the ledger's consistency. One key advantage is transparency and traceability for agricultural products, enabling consumers to verify their quality and safety. By recording the production, processing, transportation, and sales of agricultural products on the blockchain, consumers can trace the origin of the products, establishing credibility and transparency. Furthermore, blockchain can be used to establish a rural credit evaluation system to encourage honesty, collaboration, and innovation among villagers. The credit records of villagers can be reliably recorded and disclosed through blockchain technology, building trust among nodes.

An improved Byzantine formula algorithm is used to connect all consensus nodes, achieving consensus among nodes to create a reliable integrated rural management system. The Consensus BFT algorithm can tolerate a certain number of malicious nodes, ensuring the distributed system can still operate normally in the presence of node failures or attacks. BFT requires nodes to use private keys to sign messages and other nodes to verify authenticity with public keys. The consensus process of BFT involves four stages: 1) request, 2) preparation, 3) commit, and 4) confirmation. Throughout the preparation and submission stages, introducing fuzzy set theory enhances the system's capacity to integrate diverse node opinions, thereby improving robustness in the decision-making process. This adaptation allows the system to handle fuzzy information from various nodes better, ultimately increasing consensus stability.

Consequently, nodes engage in intricate message exchanges to achieve consensus. When more than two nodes reach consensus, new blocks are added to the blockchain. BFT is an efficient and secure consensus

mechanism suitable for high-rust scenarios, such as consortium chains. *Fig. 1* provides a detailed overview of the consensus process.

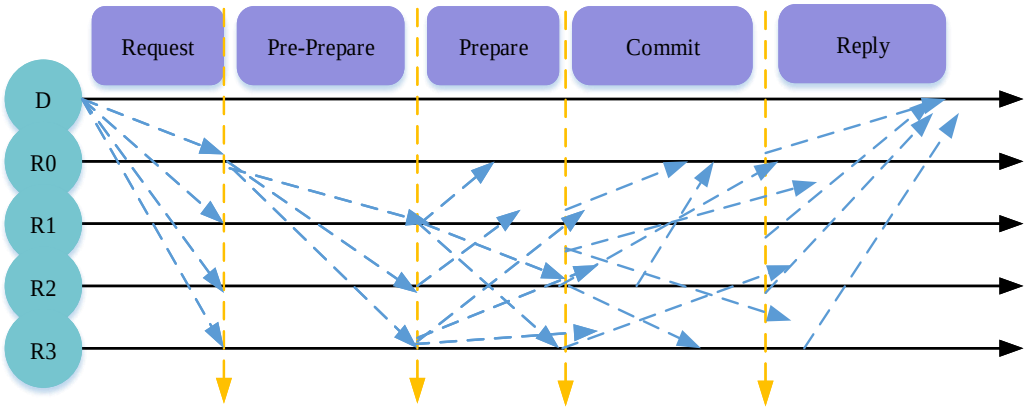

Fig. 1. BFT consensus process.

Fig. 1 illustrates the transaction confirmation process using blockchain technology in a distributed system. The Request phase begins with the client sending a transaction request to the master node, broadcasted in the Pre-Prepare phase under the master node's signature. Then, all nodes broadcast confirmation information to each other and enter the Prepare phase. In this phase, nodes verify the confirmation information of 2/3 of the nodes, sign it, and then enter the Commit phase. In the Commit phase, nodes confirm that the status of the other 2/3 nodes has entered the Commit phase and announce their confirmation results to the client.

This system employs a consensus algorithm. Here, the BFT algorithm is optimized, constructing a Simplify-BFT consensus algorithm. The rural comprehensive management system established by the paper involves two types of nodes: consensus and ordinary. The consensus nodes are classified as primary and secondary nodes, while normal nodes are linked to these nodes. During the consensus process, the client initiates a transaction request to the master node, which then verifies the transaction information, adds a signature, and sends the verification to the slave node. After verification, the sub-node sends it to other sub-nodes, and if all nodes pass the verification, the message can be written into the block and sent to the normal node to synchronize the block. Ordinary nodes do not actively partake in the consensus; however, they play a crucial role in validating and synchronizing to ensure the effectiveness of information transfer. Incorporating fuzzy set theory empowers ordinary nodes to comprehend and process validation information from primary and secondary nodes more effectively. This enhancement contributes to the system's capability to address uncertainty in the information transfer process, thereby ultimately improving consensus efficiency.

Subsequently, taking into account the existing state of rural management, this study introduces fuzzy set theory to delve into party-building management, key construction project management, village affairs information management, meteorological management, and natural disaster management from the viewpoint of rural managers. *Fig. 2* illustrates a comprehensive rural management system founded on the fusion of fuzzy set theory and blockchain, incorporating a simplified BFT consensus algorithm.

The management system illustrated in *Fig. 2* can be divided into several layers: the basic, resource, data network, consensus, access, and application. The basic layer consists of infrastructure and IoT devices, while the resource layer mainly focuses on data and technical resource collection and storage. Data resources encompass governmental, collected, and internet data, often exhibiting fuzziness and uncertainty in specific contexts. Fuzzy set theory plays a pivotal role in aiding the system in comprehending and managing these data intricacies, thereby enabling more precise information extraction. This approach facilitates the system in leveraging fuzzy information to support diverse services and decision-making processes. Technical resources involve blockchain, Java, and Spring Boot, among others. The data network layer executes distributed storage through a peer-to-peer network to ensure uniformity across all databases. The system adeptly manages

information uncertainty by employing fuzzy set theory to address data exchange and storage fuzziness among different nodes, ensuring data consistency and accuracy. This, in turn, enhances system resilience and reliability. The consensus layer employs a simplified version of the consensus algorithm to guarantee the consistency of all data on the chain. Applying fuzzy set theory offers a comprehensive approach to information processing, particularly when discrepancies exist in data or information provided by different nodes. It assists the system in better adapting to the fuzziness and uncertainty of information between nodes, thereby enhancing the stability of consensus and the overall reliability of the system. The access layer is responsible for implementing the access function for different identities, giving visitors distinct node identities. Finally, the application layer is divided into three categories: 1) governance center, 2) development center, and 3) service center. It provides party building management and video surveillance services for key construction projects, village affairs, food traceability, fields, aquatic products, livestock and poultry breeding, weather, natural disasters, and other types of information.

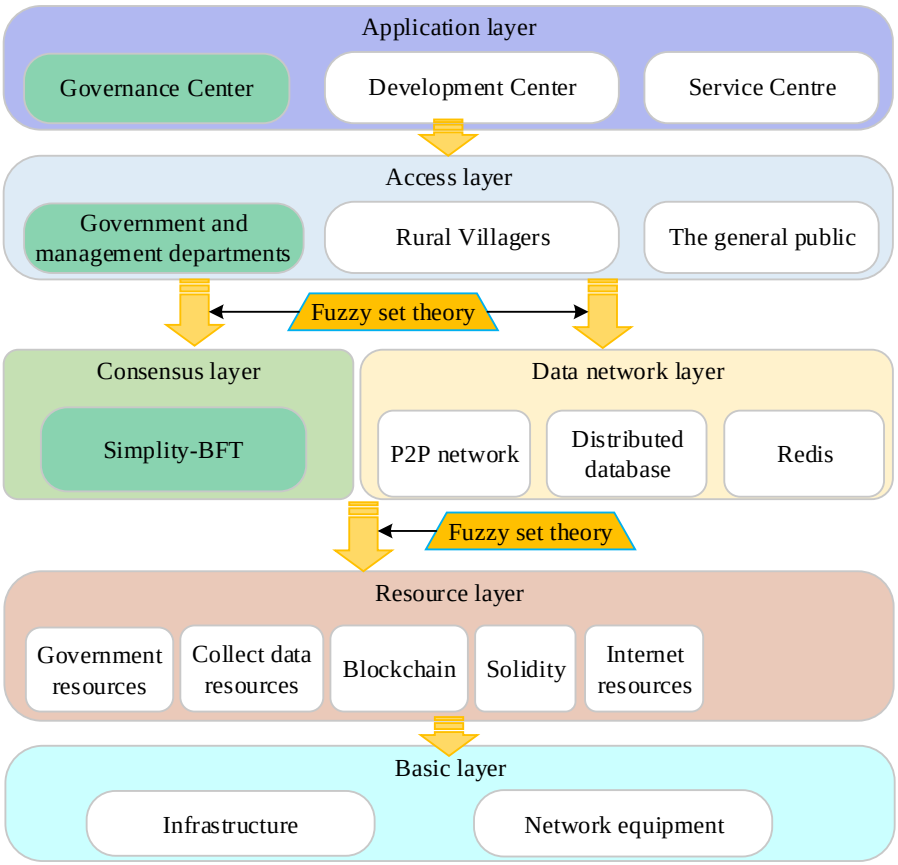

Fig. 2. Rural comprehensive management system based on the fusion of fuzzy set theory and blockchain.

In this study, the following uncertainties are addressed using fuzzy set theory: firstly, to manage information fuzziness, a fuzzy prediction model is constructed to enhance the accuracy of agricultural demand forecasting. Secondly, in response to the variability of external environmental factors, a set of fuzzy control rules is designed to optimize logistics distribution routes under uncertain weather conditions. Finally, to reduce subjective biases in management decisions, a fuzzy comprehensive evaluation method is adopted to assess the benefits and risks of various agricultural inputs objectively.

3.3 | Urban and Rural Efficient and Intelligent Logistics Operation System via the IoT

Certainly, within the realm of rural development, its integrated management system incorporates an efficient logistics infrastructure connecting urban and rural areas. This logistical network serves as a pivotal component, facilitating the seamless flow of agricultural production materials, rural consumer goods,

agricultural products, and pertinent information. A comprehensive logistics network and information platform can contribute to rural revitalization by providing better access for agricultural and specialty products to enter the urban market, thereby expanding sales channels and increasing profits, leading to the economic growth of rural areas. In this regard, the IoT can play a crucial role in optimizing routes, reducing costs, and improving efficiency in urban and rural distribution systems. It is necessary to innovate logistics network thinking, combine regional and national networks, and integrate urban and rural logistics networks to establish and enhance the national urban and rural distribution system. This study employs cutting-edge information technology, such as cloud computing, big data, IoT, and artificial intelligence, to construct an intelligent system that transforms the urban-rural two-way distribution chain into an online-offline efficient distribution system. *Fig. 3* shows the system architecture for intelligent operation.

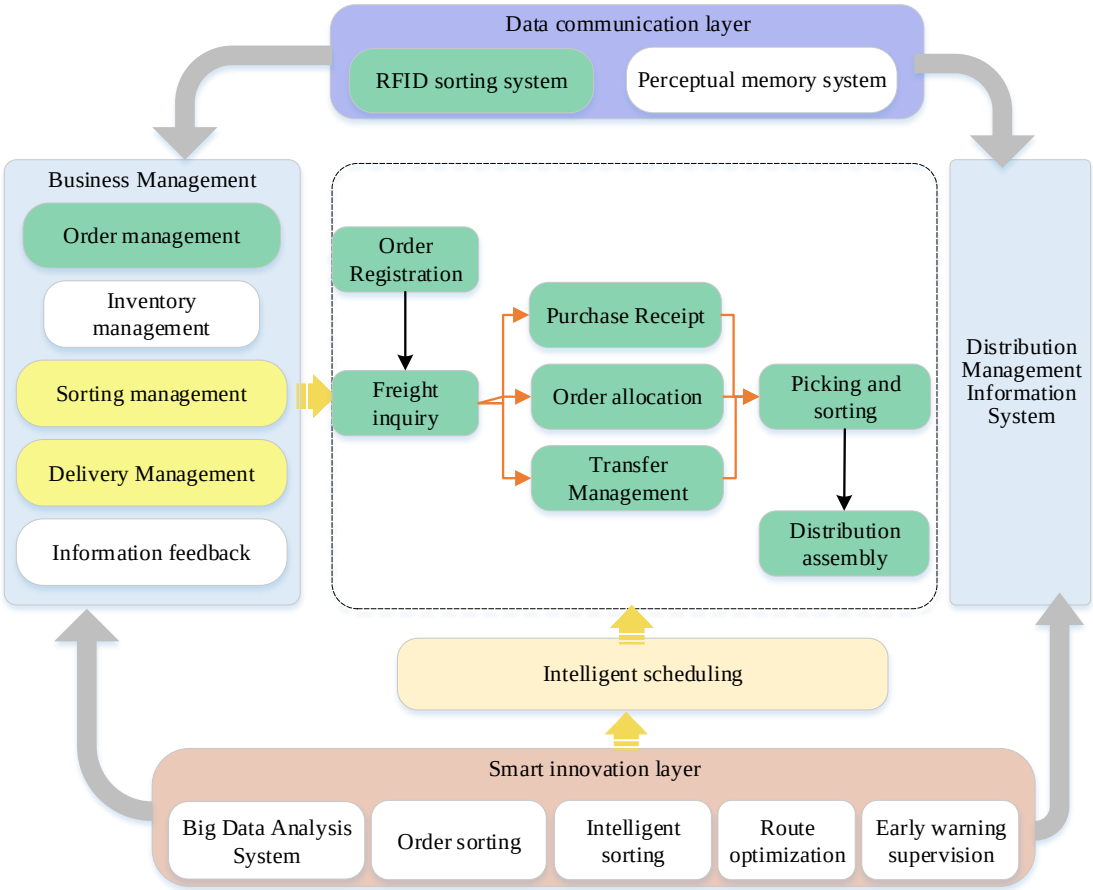

Fig. 3. Intelligent operation system structure of urban and rural efficient distribution.

Fig. 3 illustrates that the data communication layer performs various functions, such as collecting, screening, storing, and transmitting information using information perception, barcode identification, and satellite positioning. This layer provides critical data and information for other business activities in the system, and data communication is essential for achieving coordination among different components. The distribution management information system serves as the core of business management, encompassing several areas such as order management, inventory management, sorting, distribution and transportation, and information feedback. It also functions as a direct channel of interaction with customers. When receiving an order, the distribution center must conduct a strict order review, check inventory, and decide whether to replenish it to ensure timely delivery of the goods to customers. Hence, the system is crucial for managing and monitoring the distribution process, maintaining customer satisfaction, and ensuring stable business growth.

Intelligent warehouse management is a significant aspect of modern logistics operations. Intelligent three-dimensional warehouses have been developed using information technology, IoT, mechatronics technology, smart equipment, and automation equipment. *Fig. 4* displays the primary modules that constitute the intelligent warehouse management system.

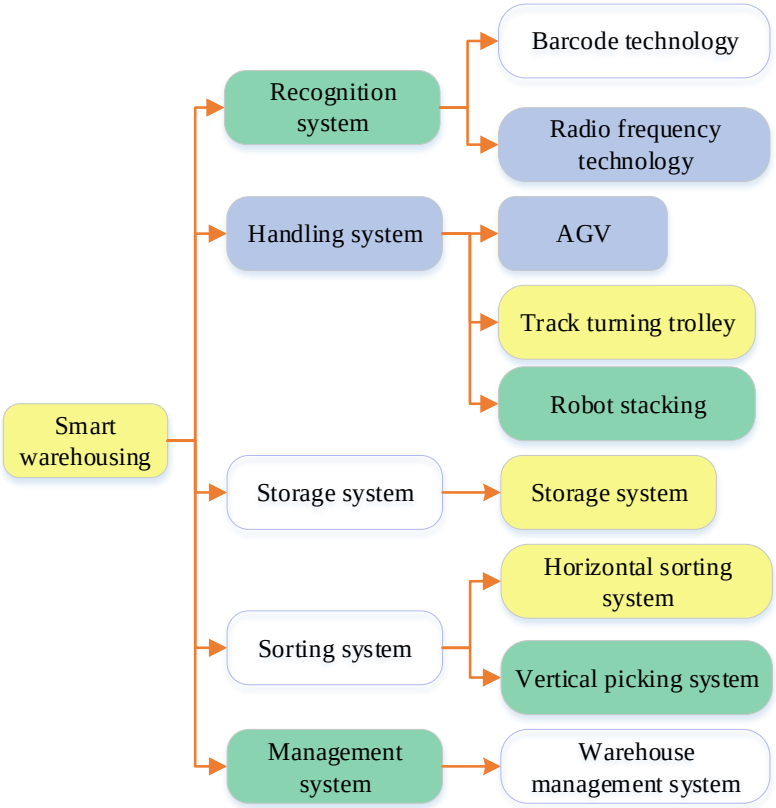

Fig. 4. Main modules of the smart storage system.

Intelligent warehouses employ machines such as robots and intelligent terminals to achieve smart cargo sorting and automated handling during actual operations. Furthermore, digital management is a critical component of intelligent warehouse management that involves various processes such as goods storage, inventory, sorting, management, and storage, all of which need to be digitally managed to enhance warehouse management efficiency and accuracy.

The urban-rural efficient distribution operation system incorporates functions such as smart warehousing, smart distribution, and smart transportation, making it complex. As such, this study uses demand, vehicle-cargo matching, and route optimization in two-way distribution as variables to carry out distribution modeling and case analysis. Rural nodes in this study include farmers, agricultural product cooperatives, daily necessities supply and marketing cooperatives, and rural supermarkets, which serve as rural demand points. At each demand point, goods are unloaded first, followed by industrial products, and then agricultural products. Given the complexity of distributing agricultural materials like pesticides and fertilizers, which are toxic and volatile, this study does not consider their distribution. City nodes consist of convenience stores, supermarkets, production and processing enterprises, and wholesale centers, which serve as urban demand points. Each demand point has unique requirements for agricultural products. Consequently, loading industrial products and daily necessities is necessary while unloading agricultural products for urban demand points.

Eq. (1) demonstrates the computing approach of the overall shipping expenses.

$$\max Z_1 = C_1 + C_2 + C_3. \quad \textbf{(1)}$$

Eq. (1) represents the calculation method of the overall transportation cost. In *Eq. (1)*, C_2 signifies the transportation cost; C_3 represents the penalty cost; C_1 denotes the fixed cost, including driver compensation, vehicle repair, maintenance, etc. *Eq. (1)* is used to simulate the variation of total transportation costs under different shipment volumes. Building upon *Eq. (1)*, further consideration is given to the penalty costs incurred due to delivery delays. For instance, if the goods are not delivered within the specified time frame by the customer, additional economic losses or customer dissatisfaction may occur. These costs are defined as C_p,

and combined with fixed costs C_k (including vehicle maintenance, driver wages, etc.) to calculate the total costs, that is, the total fixed cost is equal to the sum of the costs of multiple vehicles, which is calculated according to *Eq. (2)*.

$$C_1 = \rho k. \tag{2}$$

In *Eq. (2)*, ρ stands for the fixed cost of the distribution vehicle, and k signifies the number of distribution vehicles. Various factors, including the timely completion of deliveries, the service attitude of the delivery personnel, and other related aspects, influence the satisfaction of customers. However, unforeseen events such as weather and traffic conditions can lead to delays that may affect the customer's satisfaction during the delivery process. A function that accounts for all the relevant factors is established to ensure customer, as shown in *Eq. (3)*.

$$\max Z_2 = \frac{\sum_{a \in s} f(t_a)}{m+n}. \tag{3}$$

Eq. (3) represents the customer satisfaction function, depicting the influence of goods delivery efficiency on customer satisfaction. In *Eq. (3)*, t_a represents the time when the vehicle arrives at demand point a, m refers to the number of rural demand points, and n denotes the number of urban demand points. Because there are many targets in the model, the linear weighted summation method is used here to unify the dimensions. Then, the multi-objective model can be simplified to *Eq. (4)*.

$$\min F = \xi_1 \times \frac{Z_1^r - \min Z_1^r}{\max Z_1^r - \min Z_1} + \xi_2 \times \frac{Z_2 - \min Z_2}{\max Z_2 - \min Z_2}. \tag{4}$$

Eq. (4) represents the single-objective transformation form of the multi-objective optimization problem, where Z_1^r and Z_2 denote the objective function values of total delivery cost and customer satisfaction, respectively.

In *Eq. (4)*, ξ_1 and ξ_2 are the weight coefficients of the total distribution cost and customer satisfaction, respectively, which can be selected according to the actual needs of different enterprises. Besides, these two coefficients satisfy *Eq. (5)* and *Eq. (6)*.

$$\xi_1 + \xi_2 = 1. \tag{5}$$

$$\xi_1 > 0, \xi_2 > 0. \tag{6}$$

Then, the model's objective function seeks to minimize total delivery costs and maximize customer satisfaction. A genetic algorithm is utilized for this purpose. Subsequently, the multi-objective function is converted into a single-objective function to determine the minimum value of F. As such, the reciprocal of F is utilized as the fitness function for the genetic algorithm, denoted by *Eq. (7)*.

$$f = \frac{1}{F}. \tag{7}$$

Eq. (7) indicates that as the target value F decreases, the corresponding fitness value increases, and the likelihood of the individual being retained increases as well. *Eq. (7)* defines the fitness function (f), which is the reciprocal of the objective value (F), used in genetic algorithms to determine the likelihood of individuals being retained. The smaller the objective value (F), the larger the corresponding fitness value (f).

While the genetic algorithm is a powerful optimization algorithm with global search ability, it may encounter local optimal solutions during the search process, causing a reduction in efficiency. On the other hand, the simulated annealing algorithm boasts a strong local search ability and is able to make sudden jumps, enabling it to escape from local optimal solutions. They can be combined to harness the strengths of both algorithms. The process involves generating a new population through the genetic algorithm's selection, crossover, and mutation operations, followed by adjusting the neighborhood structure of the individuals in the new

population to derive a new solution. Subsequently, the new solution is substituted into the objective function for calculation, and the Metropolis criterion is employed to determine whether the new solution should be retained. This approach balances global and local search capabilities, enhances search efficiency, and prevents premature convergence issues.

The simulated annealing algorithm first assumes that x is the optimal solution of the genetic algorithm after genetic operations such as selection, crossover, and mutation and then sets it as the current solution. The current temperature is set to T_s; the new solution generated by adjusting the neighborhood construction is set to x_1; the corresponding objective function value of x_1 is assigned to y_1; the increment of the objective function is indicated by Δy. Following these steps, *Eq. (8)* is presented.

$$\Delta y = y_2 - y_1. \tag{8}$$

In the population of solutions, if the new solution has a lower energy value than the previous one (i.e., $\Delta y<0$), it is kept without any conditions. On the other hand, if the new solution has a higher energy value, it is discarded with a probability of $\exp\left(-\frac{\Delta y}{T_s}\right)$, as shown in *Eq. (9)*.

$$P_z = \begin{cases} 1, & \Delta y < 0, \\ \exp\left(-\frac{\Delta y}{T_s}\right), & \Delta y \geq 0. \end{cases} \tag{9}$$

Eq. (10) holds when annealing with an attenuation rate of v.

$$T_{s+1} = T_s + v. \tag{10}$$

This study proposes a hybrid genetic algorithm combining two methods to improve local optimization ability and algorithm running speed. The termination condition is evaluated to determine whether to output the current solution. *Algorithm 1* depicts the pseudocode of the hybrid genetic algorithm and simulated annealing algorithm.

Algorithm 1. Pseudocode of hybrid genetic algorithm and simulated annealing algorithm.

```
Algorithm: Hybrid Genetic Simulated Annealing Algorithm
Input: Initial population, crossover rate, mutation rate, initial temperature, cooling rate, termination condition
Output: Optimal solution
Initialize population
Evaluate the fitness of the initial population
Set the current temperature to the initial temperature
while not satisfying the termination condition do
   for each individual in the population do
      Perform selection operation
      Perform crossover operation
      Perform mutation operation
   end for
   Generate a new population
   for each individual in the new population do
      Calculate the objective function value of the individual
      if the new individual is better than the old one then
         Accept the new individual
      else
         Accept the new individual with a certain probability (according to the Metropolis criterion)
      end if
   end for
   Update the current temperature (reduce according to the cooling rate)
end while
Return the current optimal solution found
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Fig. 5 illustrates the specific flow of the algorithm.

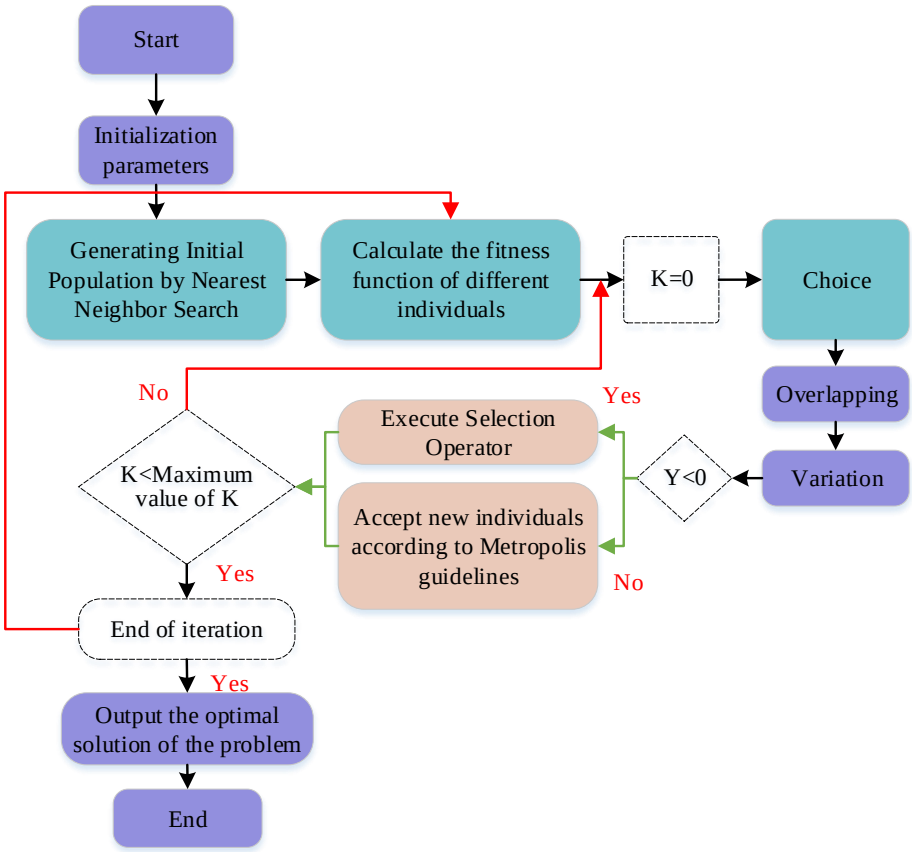

Fig. 5. Flowchart of the hybrid algorithm.

3.4 | Example Verification

This study conducts a series of scalability experiments to comprehensively evaluate the universality and efficiency of the proposed intelligent rural management system. These experiments aim to validate the system's performance across a wider range of application scenarios. Initially, the study considers 50 rural nodes and 100 urban nodes. However, to ensure the accuracy of the simulation results, 10 rural nodes and 25 urban nodes are randomly selected for simulation. Additionally, various network environments and traffic conditions are simulated to assess the system's robustness under non-ideal conditions. Finally, the proposed model is compared with several existing typical distributed management systems using performance indicators, including total operating costs, system response time, and user satisfaction. These comparisons demonstrate the superiority of the proposed solution. The rural nodes sign contracts with selected urban nodes to supply agricultural products to all 25 urban nodes, while the urban nodes supply industrial products to the rural nodes. The intelligent transportation management system performs path planning using a hybrid genetic algorithm and Matlab dynamic link library. In constructing the model, initial variables and parameters are determined based on existing research and industry reports. Subsequently, in-depth interviews are conducted with personnel relevant to agricultural production and logistics companies to collect actual operational data. Nearly a year's worth of agricultural product delivery records, including delivery frequency, route lengths, types of goods, and customer feedback, are gathered for statistical analysis. This analysis identifies key factors influencing delivery efficiency and costs, providing a basis for setting model parameters. After building the initial model, simulation experiments are conducted to adjust key parameters of the genetic algorithm, such as crossover rate and mutation rate, to ensure effectiveness and accuracy in solving real-world delivery problems. Optimal parameter settings for the genetic algorithm are obtained through a series of experiments.

Initially, with a fixed mutation rate of 0.01, crossover rates ranging from 0.4 to 0.8 are tested, with increments of 0.1, recording the convergence speed and solution quality for each setting. A crossover rate of 0.6 is found to strike a balance between solution quality and convergence speed. Subsequently, with the crossover rate set at 0.6, mutation rates ranging from 0.005 to 0.02 are tested, revealing that a mutation rate of 0.01 yielded stable and high-quality solutions. Ultimately, the decision is made to set the crossover rate and mutation rate of the genetic algorithm to 0.6 and 0.01, respectively. After multiple iterations, the model demonstrated good stability and consistently found high-quality solutions with these parameter settings. *Algorithm 1* presents the average results of 10 independent runs under different parameter settings, further validating the effectiveness of the selected parameter configurations. *Table 1* provides the service demand of rural nodes.

Table 1. Representative industries and their number.

Rural Node	Demand (Kg)	Loading Capacity (Kg)	Service Time (Minutes)
1	1100	1060	35.8
2	940	810	103.5
3	530	490	60.9
4	530	490	32.6
5	850	810	96.3
6	460	430	51.2
7	420	410	50.6
8	1030	860	123.5
9	0	490	23.6

The experimental parameters are defined as follows. The host has a 2.10 GHz CPU, 16GB memory, and a 474GB hard disk. The operating system used is Windows 10.

4 | Results and Discussion

4.1 | Feasibility of the Blockchain Consensus Algorithm

The system nodes are divided into two groups to evaluate the viability of the Simplify-BFT algorithm: one group employs the Byzantine algorithm, and the other group employs the Simplify-BFT algorithm. The number of nodes is varied between 5 and 40 for each experiment. Five nodes act as consensus nodes in every case, while the others are ordinary. *Fig. 6* displays a comparison of consensus delay.

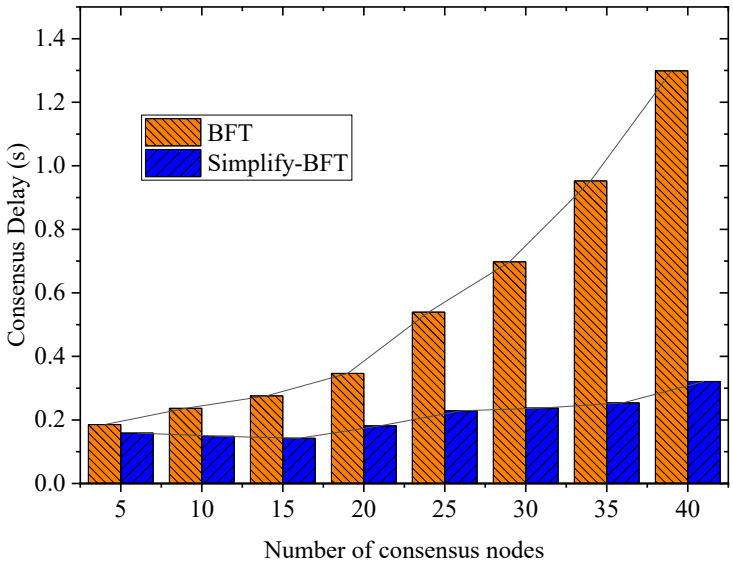

Fig. 6. Consensus delay comparison between Simplify-BFT and BFT.

Fig. 6 reveals that the consensus time exponentially increases with the number of nodes adopting the Byzantine consensus algorithm. In contrast, with the Simplify-BFT algorithm, the consensus time delay is

significantly reduced as the number of participating nodes remains the same. Any increase in consensus time due to data synchronization between ordinary and consensus nodes is negligible and will not affect user experience. Thus, the Simplify-BFT algorithm can substantially reduce consensus time while maintaining the original algorithm's reliability, security, and fault tolerance, as the consensus process remains unchanged.

4.2 | Comparison between the Smart Distribution System Based on the IoT and Traditional Methods

Using the MATLAB dynamic link library, the intelligent transportation management system can automatically call and read relevant information into the database. Moreover, the system utilizes the above hybrid genetic algorithm to address the path-planning problem based on model features. After computation, the system displays the best route via the Application Programming Interface of Baidu Map, enabling users to visualize it easily. *Fig. 7* and *Fig. 8* depict the optimal rural and urban delivery routes for the previously mentioned scenarios.

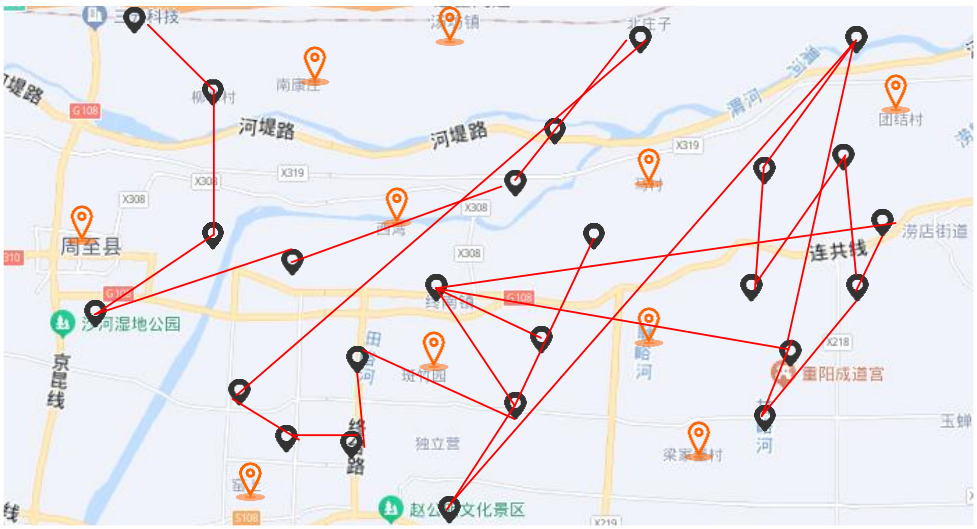

Fig. 7. Optimal route map for city delivery.

Fig. 8. Optimal route map for rural distribution.

Fig. 7 and *Fig. 8* present the distribution plans, which require dispatching six and five vehicles for urban and rural areas, respectively. The corresponding delivery costs and customer satisfaction are displayed in *Fig. 9*.

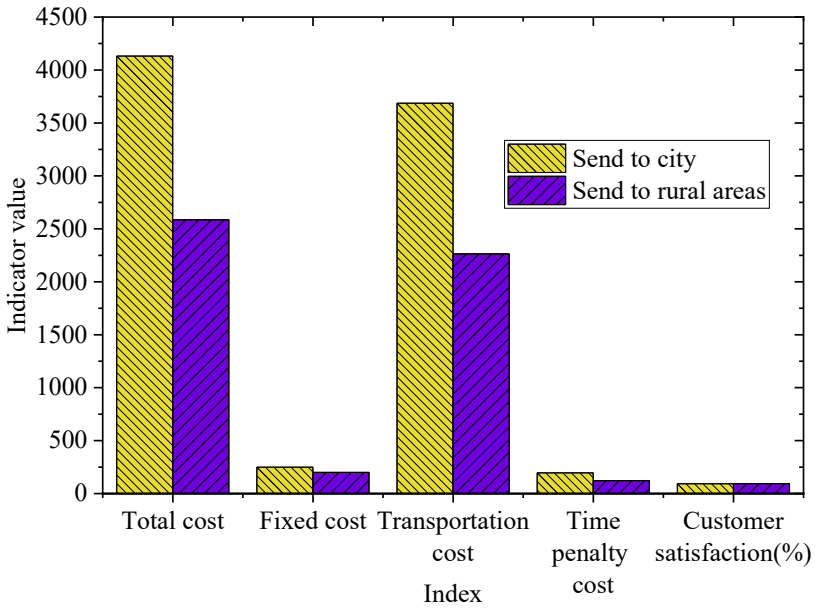

Fig. 9. Delivery cost and customer satisfaction.

The data presented in *Fig. 9* reveals that the total cost for delivery to the city is 4,132.27, of which the transportation cost makes up 75.3%, while the remaining costs comprise fixed and time penalty costs. The total cost for delivery to the rural areas is 2,585.99, with the transportation cost accounting for 87.2%. The satisfaction rate for customers in the city is 93.5%, while for customers in rural areas, it is 94.25%, both exceeding 90%. These rates indicate high levels of customer satisfaction. However, various factors, such as traffic flow and road conditions, can influence the driving routes during transportation. As a result, the intelligent transportation management system can provide real-time information on the goods and vehicles in transit, including the speed, coordinates, and road conditions of passing places, to the command center. This enables the optimization of delivery routes, thus ensuring timely delivery.

The traditional distribution method requires sending vehicles to rural locations to collect goods, which are then transported to urban areas for delivery before returning to the starting point empty. Similarly, the distribution of industrial products to rural areas also involves a similar process. However, this approach is associated with challenges such as waste of resources and high transportation costs. In this study, *Fig. 10* presents the comparison between the smart urban and rural distribution systems based on the IoT and the traditional distribution model.

According to *Fig. 10*, the IoT-based smart urban and rural distribution system incurs a total cost that is 2307.91 CNY lower than the traditional distribution system while also increasing customer satisfaction by 13.11% for the same distribution task. The conventional distribution system requires four additional vehicles, leading to a fixed cost increase of 200 CNY. Additionally, the traditional system's delivery vehicles have a high empty rate, which requires them to travel to the node to load goods with an empty vehicle before returning with an empty vehicle after completing the delivery task. This results in an increase in transportation costs by 1956.33 CNY. These vehicle round trips also reduce delivery time costs and customer satisfaction.

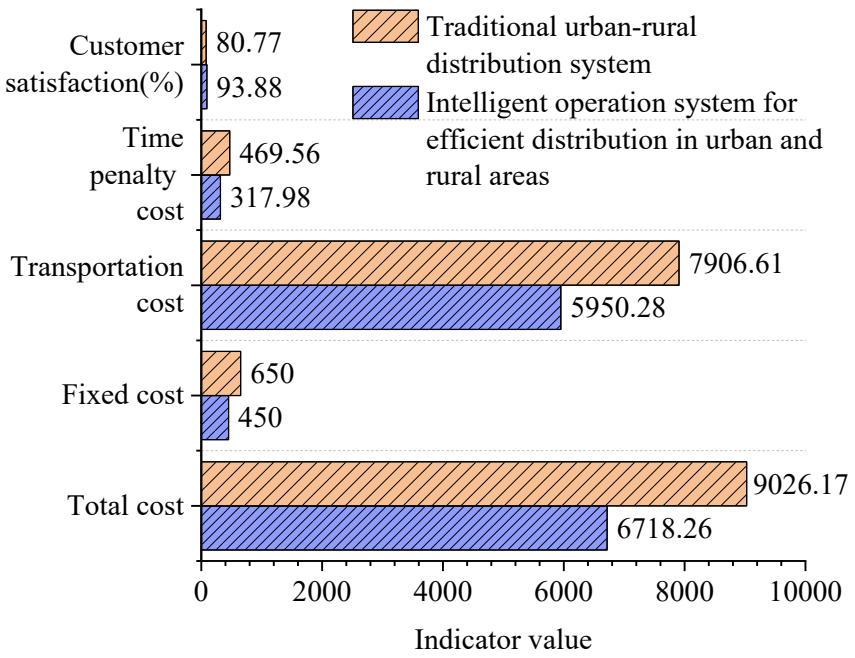

Fig. 10. Comparison of distribution costs and customer satisfaction between two distribution systems.

4.3 | Discussion

Based on the aforementioned research, it is evident that the intelligent system of urban and rural efficient distribution offers significant advantages over the traditional distribution system in terms of total distribution task cost and customer satisfaction. Thus, this system holds important value for promotion and application, particularly in the context of rural revitalization. This is consistent with the theory proposed by Mahajan et al. [38], who suggested an efficient and scalable protocol for remote monitoring and decision-making on farms in rural areas. This protocol somewhat reduces energy consumption, communication overhead, and end-to-end latency compared to the then-state-of-the-art IoT-based farming methods. Almalki et al. [39] proposed a low-cost platform for comprehensive environmental parameter monitoring using the Internet of Flying Things. This experimental work addresses the requirement for automatic and real-time monitoring of environmental parameters using subsurface and aboveground sensors. Malik et al. [40] provided a detailed discussion on implementing smart and digital villages using various new digital technologies. The authors emphasize that digitization is only possible with a reliable and robust network and communication infrastructure installed in rural areas. Hence, it is imperative to apply information technology to the rural management process and actively explore new development models to foster economic growth and social progress in rural areas. In practical applications, managers must weigh both the immediate costs and long-term benefits of technological innovation, considering its impact on agricultural production, logistics distribution, and cultural communication. For example, while blockchain technology can enhance transparency and consumer trust, its implementation relies on stable network infrastructure and user digital literacy. Thus, widespread adoption in rural areas necessitates bolstering infrastructure development, such as expanding broadband coverage and improving network speed. Essential training is also vital to enable effective use and continuous development of technology, enhancing farmers' technical capabilities and fostering acceptance and innovation awareness.

Moreover, constructing and optimizing a smart rural logistics system requires collaboration between the government, enterprises, and farmers. This study shows that leveraging the IoT and hybrid genetic algorithms for route planning can significantly enhance material distribution efficiency, facilitating seamless connectivity

between rural and urban products. However, successful implementation hinges on considering rural areas' unique geographical and social environments and the diverse characteristics of agricultural products.

5 | Conclusion

The digitalization, informatization, and intelligent upgrading of rural management can enhance rural development and governance efficiency and quality. This study analyzes the issues in the current rural development process and explores the role of rural cultural dissemination based on social networks. This study introduces a blockchain-based rural management system incorporating an enhanced BFT algorithm and integrating fuzzy set theory. A smart transportation management system is also developed to address the distribution issues in urban and rural areas. The IoT-based system is established to enable efficient distribution as a part of rural development. This intelligent transportation management system reduces the distribution cost and optimizes the distribution route compared to traditional urban and rural distribution management methods. The system serves as a means of communication between urban and rural areas and significantly promotes rural economic growth. While this study has yielded promising initial findings, numerous prospects and challenges lie ahead for future research. For instance, applying fuzzy cognitive theory and blockchain technology to urban energy management holds potential for enhancing system sustainability and energy efficiency. Furthermore, the current framework of rural management systems warrants further refinement, particularly in developing sub-modules like rural finance and education, presenting opportunities for more precise and impactful enhancements. Lastly, interdisciplinary collaboration, such as integrating sociology, economics, and information technology, is crucial for advancing the implementation of rural revitalization strategies through a multidimensional understanding.

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Author Contribution

"Conceptualization, T.Y.; Methodology, W.W.; Validation, C.H., T.Y.; Analysis, D.Z.; writing-creating the initial design, W.W., and D.Z.; writing-reviewing and editing, C.H.

All authors have read and agreed to the published version of the manuscript.

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Data Availability

The data used in this study are available upon request from the corresponding author, subject to ethical or legal restrictions.

Conflicts of Interest

The authors declare no conflict of interest.

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