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Research on Optimization Solutions for Rural Smart Logistics in the Context of Artificial Intelligence

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Abstract

This study focuses on the optimization of intelligent logistics in rural China driven by artificial intelligence (AI) technology and proposes customized solutions and phased implementation paths for the core problems of weak infrastructure, low informatization level and high operating costs. Through case verification, it is confirmed that AI can significantly break through the bottleneck of rural logistics efficiency. Research and build a ”technology-scenario-system” three-dimensional framework, integrate the Internet of Things, blockchain and big data technology, design a ”county-village-village” three-level infrastructure network and a ”government-guided + market-led” collaborative governance model, and formulate a three-stage roadmap (digital foundation, intelligent upgrade, automation transformation) from 2025 to 2037. Focus on promoting the application of UAV delivery network and autonomous driving system.

CCS Concepts

• **Electronic commerce E – commerce infrastructure E - commerce infrastructure**;

Keywords

Rural Logistics, Artificial Intelligence, Route Optimization, Digital Villages

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1 Research Background

Today, improving economic growth and people's quality of life has become an important task. In accordance with the rural revitalization strategy, rural logistics plays an important role in bringing the urban and rural economies closer, effectively managing rural logistics, promoting industrial and agricultural products to the countryside, promoting the sustainability of rural economic development, and improving the quality of life and income level of farmers. improved. The development of urban logistics networks and rural logistics is relatively lagging behind, because limited network coverage, poor infrastructure, lack of information and high distribution costs limit the impact of rural markets [1]. With the rapid development of digitization and intelligence, artificial intelligence technology has become the main driving force for the transformation of the logistics industry.The use of advanced technologies such as intelligent route planning and consumer demand forecasting to significantly improve logistics efficiency, and the study of strategies to optimize rural intelligent logistics can help solve problems related to traditional logistics practices through technological innovation, promote rural economic development, encourage consumption, and improve living standards [2].

Developed countries have made significant progress in introducing intellectual logistics. European and American countries use big data technology and the Internet of Things to build an efficient supply system. It can monitor the status of cargo transportation in real time, optimize logistics routes, and reduce transportation time and cost[3]. Japan has improved the level of cold chain logistics through automation and robotics. Intelligent storage solutions and automatic sorting equipment maintain the ideal temperature of the product during transportation, extend the shelf life and improve customer satisfaction. On the contrary, although some progress has been made in domestic logistics in rural areas, it is still characterized by unbalanced regional development and insufficient technology application.An advanced regional logistics system has been established, and the distribution efficiency has been significantly improved, but the logistics system in remote mountainous areas and poor areas is imperfect, the transportation cost is high, the distribution time is long, e-commerce and intelligent logistics technology are popularized in cities, and the rural areas are less advanced. Many farmers, small and micro enterprises rely on traditional logistics methods, which not only reduces logistics efficiency, but also makes it difficult to meet the growing market demand. At present, most research focuses on the macro-political level, and there is a lack of reasonable solutions to certain rural situations [4].

The research on the integration of artificial intelligence and logistics is of great significance. This article discusses the optimization path of rural intelligent logistics based on artificial intelligence technology, analyzes the current situation of rural logistics, and formulates an optimization plan based on artificial intelligence technology.

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2 Theoretical and Technological Foundations

2.1 Core Concepts of Smart Logistics

Intelligent Logistics is a key direction in the development of modern logistics. This project aims to use advanced information technologies to create an intelligent and automated logistics system. Innovative technologies such as the Internet of Things, Big Data and artificial intelligence can transform the entire logistics process, and resource allocation can be optimized and coordinated efficiently. Compared to traditional logistics, Intelligent Logistics has significant advantages: algorithmic models surpass work in decision-making areas such as distribution paths and sorting methods, increasing efficiency and reducing costs; real-time supply chain monitoring for safety and reliability of delivery; personalized services meet the needs of the user. conditions, quality of Service and solutions are improved[5]. This evolution will increase logistics efficiency and in a new way define business models of logistics services and create added value.

2.2 Key AI Technologies

In intelligent logistics systems, the importance of artificial intelligence technology is obvious. Supervised and uncontrolled machine learning techniques have performed well in demand prediction and anomaly detection, historical data analysis and market trends, and machine learning algorithms predict future sales needs by helping companies prepare goods in advance to reduce stock costs[6]. Dijkstra's algorithm determines efficient delivery routes to ensure timely delivery, genetic algorithms solve complex multi-purpose optimization tasks by balancing transportation costs and other factors, IoT technology uses RFID and sensor networks to monitor load status in real time, big data analysis reveals patterns, optimizes resource allocation and improves efficiency, and blockchain technology records information to support the traceability of agricultural products, ensuring authenticity and transparency [7]. The integration of these technologies contributes to the intelligent development of the industry.

2.3 Specific Characteristics of Rural Logistics

Rural areas are characterized by gentle hills and winding rivers, uneven relief and significant logistical and transportation problems. The sparse road network and narrow rural roads make it difficult to access some remote villages. Transportation costs are high and inefficient. Agricultural products are produced seasonally and dispersed. During the harvest period, a large amount of fresh fruit and vegetables accumulate in the fields [8]. The supply is growing and the demand is different. Farmers need efficient storage solutions and rapid distribution. Insufficient agricultural infrastructure, limited refrigeration chain and lack of refrigeration facilities. Many products break down in transportation, and it is also difficult for logistics companies to meet the demand. This shows that intelligent logistics in rural areas cannot copy the urban model and requires special technical solutions and development models such as drones. Short-distance distribution, distributed cooling chain networks and intelligent vehicles suitable for rural areas.

3 Current Status and Challenges of Rural Smart Logistics

3.1 Development Status

3.1.1 Improving Policy Support System. In recent years, China has gradually developed a system of supporting intellectual logistics policy in rural areas [8]. As of 2021.by 2023. in the year, the State Council and various ministries and commissions issued 23 program documents directly related to the development of rural logistics, forming the policy system "centralized planning + field support". Rural resuscitation Facilitation Act, revised in 2023.it provides for the legal protection of intellectual logistics infrastructure. In 2022. in a year, the Central financial administration will actually allocate 28.7 billion yuan for the development of rural logistics through special funds, an increase of 34.5% compared to 2021.a year [9]. Policy Content includes construction of logistics infrastructure and intelligent transformation of Information Technologies, optimization of service networks, promotion of intelligent storage systems, distribution of unmanned vehicles and drones and other means to improve logistics efficiency, promotion of enterprises and local authorities in the establishment of logistics service center and provide solutions. to help agricultural products enter the city, and industrial to the village and revitalize the rural economy.

3.1.2 Accelerated Infrastructure Development. Until the end of,2024.in a year, the total length of village roads will reach 4.46 million kilometers, the share of roads at the level of village and more will be 89.5%, and the share of formed village roads will exceed 99% in areas with unpleasant conditions [10] . The quality of road conditions and the capacity in demonstration districts have been significantly improved. "Four good rural roads" not only improve traffic conditions, but also contribute to economic growth. 2,865 logistics centers were built at the district level, 38,000 distribution centers in municipalities and 546,000 service points at the village level, which enabled the application of network distribution of rural logistics and significantly improved logistics as a whole. efficiency in rural areas [11]. With more than 1.5 million 5G base stations and 98% optical fiber coverage, it enables fast and stable internet access, supports the development of Intelligent Logistics, promotes the sale of agricultural products and e-commerce, and creates important conditions for the process of rural information.

3.1.3 Increasing Market Participation. In addition to traditional logistics companies, e-commerce platforms such as Alibaba, social platforms such as Douyin, and financial institutions such as online business banks have all laid out in the field of rural smart logistics. After the integration of resources, a variety of innovative models have begun to be applied [12]. The integration of logistics and e-commerce and finance has not only improved logistics efficiency, but also provided farmers with financial services; the new model of community group buying and instant distribution makes it faster for consumers to obtain fresh agricultural products; the traceability of agricultural products and the value-added model of brand marketing, tracing the production process to enhance the added value and brand influence of agricultural products, leading enterprises apply cutting-edge technologies such as digital twins to improve the level of logistics intelligence, Jingdong's Asia No. 1 smart in Hebei Province The whole process of the logistics park is unmanned, and the operational efficiency and accuracy are greatly improved [13].

3.2 Major Challenges

3.2.1 Structural Deficiencies in Infrastructure. At present, the structural problems of rural logistics infrastructure are mainly reflected in three aspects: uneven spatial distribution, and the infrastructure level in the eastern region is obviously better than that in the central and western regions. Taking cold chain facilities as an example, the cold storage capacity of eastern provinces per 10,000 people is,2.3 times that of central and western regions [14]. The degree of specialization is insufficient, and modern facilities with intelligent temperature control, automatic sorting and other functions account for less than,20% of the existing facilities. The coordination is poor, there is a lack of unified planning between various types of facilities, the duplication rate is as high as 35%, and the resource utilization rate is less than 60%.

3.2.2 Deep-seated Issues in Informatization. At present, in the construction of rural logistics informatization, the digital divide continues to exist, and the digital transformation rate of logistics enterprises below the county level is only 38.7%, and there is an obvious tendency of "heavy hardware and light software" [15]. Data standards are not uniform, and the difference rate of data interface standards among various systems is 73%, which seriously hinders data sharing. The security guarantee is weak, the security protection rate of rural logistics information system is only 42%, and the risk of data leakage is high.

3.2.3 Multiple Operational Constraints. At present, the operational efficiency of rural logistics is restricted by three key factors: the degree of organization is low, and the main body of rural logistics market is small and micro enterprises (accounting for 89%), which is difficult to form scale effect [16]. The management level is backward, the proportion of enterprises using modern management methods is less than 30%, and most of them still stay in the traditional experience management stage. There is a shortage of professional talents, and the proportion of employees with college degrees or above in county logistics enterprises is only 18.7%, which is far lower than 45.3% in urban logistics enterprises.

3.3 Bottlenecks in AI Application

3.3.1 Technical Adaptation Challenges. The application of AI technology in rural Settings faces three special challenges. The rural logistics data has obvious characteristics of sparsity, incompleteness and low timeliness. The sample shows that the valid data account for less than 60%. The recognition accuracy of the existing algorithm for the rural special scene is generally 15-20 percentage points lower than that of the urban scene [17]. The integration success rate of the new technology with the existing system is only 55%, and the cost of upgrading is high.

3.3.2 Structural Talent Shortage. At present, the problem of rural logistics talents is seriously unbalanced. The shortage of AI talents in counties across the country exceeds 500,000 people, and there is a serious imbalance between supply and demand. Among the existing personnel, less than 3% have dual knowledge background of AI technology and rural logistics [18]. 85% of rural smart logistics talents are concentrated in the eastern region, and the talent loss rate in the central and western regions is as high as 45%.

3.3.3 Financial Sustainability Issues. At present, the rural logistics is still facing the fund problem. The annual investment intensity of county-level finance in smart logistics is only 6.5 yuan/person, far lower than the 38.7 yuan/person of the city [19]. More than 80% of the funds rely on financial allocations, and the participation of social capital is less than 20%. The return on investment cycle is generally more than 7 years, more than twice that of urban projects.

4 AI Application Scenarios in Rural Logistics Optimization

4.1 Intelligent Route Planning and Transportation Optimization

In rural logistics scenarios, intelligent route planning technology can significantly improve transport efficiency after integrating data from multiple sources. In the example of Liuyang city, Hunan province, an advanced genetic algorithm is used to build a multivariate data model "GIS + real-time road conditions + heat demand map" to optimize the route. The application of the algorithm takes into account limitations such as mountain road slope (42% by more than 3.5%) and rural road width limits (63% by less than 3.5 meters), and a dynamic adjustment mechanism is introduced to respond to sudden weather conditions (180 days per year of precipitation), with distributed mileage decreases. reduced by 23% and fuel costs reduced by 18%, the average daily delivery order increased by 35%.Simulation experiments show that the optimization effect of traditional algorithms is limited when the order density is less than 5 orders per km2, and an increase in efficiency of more than 12% can be retained after the implementation of intensive learning[20].

4.2 Demand Forecasting and Inventory Management

The seasonal characteristics of agricultural product turnover are of great importance, and the time series prediction model of the LSTM neural network has outstanding advantages. When Anji County's white tea logistics system applied this technology, sales data over the last five years (120,000 orders) were analyzed and 28 key characteristics were identified, including sunny weather (peak demand before and after the Qingming Festival), weather conditions (demand for steady precipitation fell by 15%). up to 20%), ecommerce platform promotion (sales tripled in 618 months) and so on.The attention mechanism allows the model to better remember important time points. The demand prediction accuracy rate for the next 7 days is 91.3%, which is 22 percentage points higher than in the ARIMA model. The dynamic stock conservation model built based on the results of the prediction allowed to increase the supply turnover from 4.2 times a year to 7.8 times, and the rate of missing goods in the warehouse fell from 9.7% to 3.2%.

4.3 Resource Sharing Platform Design

Sichuan Province's 'agricultural goods drop' model demonstrates the viability of AI-driven transportation capacity matching. The platform features a three-tier matching system: at the demand level, it integrates real-time orders from village service points, ensuring up-to-date and comprehensive order information to enhance operational efficiency and offer services like express delivery and agricultural product sales. On the supply side, it taps into various transport capacities, including agricultural machinery, passenger buses, and individual carriers. This encompasses tractors, combine harvesters, and urban-rural shuttles, as well as privately owned vehicles like minivans and vans. This approach boosts logistics efficiency, cuts transport costs, and meets diverse regional and industry needs, promoting resource sharing and reducing empty loads. In the intelligent scheduling layer, a multi-agent reinforcement learning algorithm optimizes scheduling based on factors like freight quotes (dynamic range of 8-15 yuan per piece), average vehicle load (3.2 tons for agricultural machinery), and return empty load rates (average 58%). This optimization reduces empty loads, enhancing transportation efficiency and economic benefits. Data shows the platform has increased vehicle utilization from 39% to 67%, lowered farmers' logistics costs by 32%, and generated an annual income boost of 24,000 yuan for participating drivers. Notably, in remote areas like Liangshan Yi Autonomous Prefecture, the model has increased ethnic minority user engagement by 45% through ethnic language interfaces.

4.4 Drone/Autonomous Vehicle Applications

The "Heavenly Road Distribution" project in the Tibet Autonomous Region provides a technical model for high-altitude areas. The project selects DJI agricultural UAV (load 20kg, endurance 35km) for transformation, and specifically optimizes the battery management system and wind resistance algorithm (can resist the 8 gale) for the plateau environment (average altitude of 4000 meters, oxygen content is less than 60% of the plain). In areas not accessible by road, such as Metuo County, drone delivery has shortened the transportation time of medicinal materials from the original 5-7 days to 3 hours, and reduced the transportation cost by 60% (Department of Commerce of Tibet Autonomous Region, 2023). At the same time, an autonomous agricultural vehicle pilot in Suqian, Jiangsu province, has explored a hybrid model of "fixed route + flexible scheduling". Ten L4 autonomous vehicles operate in a closed-loop road network in 15 villages, achieving centimeter-level positioning through the V2X vehicle-road coordination system, and maintaining normal operation in areas without GPS signals. The pilot reduced the loss rate of fresh agricultural products from 12% to 4%, and reduced labor costs by 40% (Jingdong Logistics Technology White Paper, 2023). A comparative study of the two types of technologies shows that drones are suitable for urgent items with high unit price and strong timeliness (cost sensitivity coefficient 0.32), while autonomous vehicles are more suitable for bulk agricultural products transportation (cost sensitivity coefficient 0.18).

5 Optimization Solutions for Rural Smart Logistics

5.1 Overall Framework Design

Based on system theory and synergy theory, this study proposes a three-dimensional framework for optimizing rural smart logistics, which is composed of technical support system, infrastructure network and operation management mechanism. The technology support system is the core driving force, including the intelligent perception layer (the deployment of RFID, GPS and other iot devices coverage of 95%), the data analysis layer (build Hadoop+Spark big data platform) and the decision application layer (develop 12 types of intelligent algorithm modules); The infrastructure network adopts the "axle-spoke" spatial layout, and the smart logistics hub is built at the county level (with an average investment intensity of 30 million yuan/piece), with centralized transfer, warehousing, distribution and other functions in one, which can achieve full coverage of services from suppliers, retailers to home users. Upgrade distribution centers at the township level (100% standardization rate), increase storage capacity, and use technology to improve distribution efficiency. Construction of multifunctional service stations at the village level (single station service radius ≤ 5km) to realize the functions of distribution, display and sale; The operation and management mechanism focuses on building a collaborative governance model of "government guidance + market leadership + village group participation", and ensures the continuous operation of the system through the establishment of a cross-departmental joint meeting system and a market-oriented operation fund (the first scale of 5 billion yuan) to truly achieve the effective landing of various functions. At the same time, strengthen supervision, crack down on fake and shoddy products, safeguard the vital interests of farmers.

5.2 Phased Implementation Roadmap

5.2.1 Near term (2025-2027) : digital foundation stage. This phase will focus on the implementation of digital infrastructure transformation projects, including specific measures:Intelligent upgrading of village-level service sites, using the "five one" construction standard. That is, a set of intelligent terminals (equipped with touch screen and barcode scanning equipment), a set of intelligent containers (supporting face recognition to open cabinets), a monitoring system (with behavioral analysis function), an information platform (docking with provincial logistics big data centers), and a digital administrator (through vocational skills certification). Upgrade or purchase new equipment on the basis of making full use of existing equipment as much as possible. Through these facilities and personnel, unmanned and less human management can be achieved. Logistics disruptions can be accomplished quickly and easily by holding existing equipment. The pilot in Jiangxi Province showed that the average daily processing volume of the transformed site increased by 2.3 times, and the error rate dropped to less than 0.5%.

Through government departments to build a standard logistics information system, the development of "rural smart logistics data element Directory" and other 7 national standards, unified 17 types of data interface specifications, reduce equipment waste and update costs. By establishing data cleaning rules (including 38 items of verification logic) and metadata management mechanism, the data sharing efficiency is increased by more than 60%, which helps you to grasp the data requirements in various scenarios in the future.

5.2.2 Medium term (2028-2032) : intelligent upgrading stage. At this stage, we will focus on promoting the construction of three core systems:Upgrade intelligent scheduling system and develop dynamic path planning module based on deep reinforcement learning algorithm. Through real-time data monitoring results, adjust the route to improve logistics efficiency; Adopting blockchain +

Internet of Things technology architecture, blockchain technology has many advantages in the application of logistics, which can record the whole process data of the supply chain, allowing the questions in the logistics process to cooperate with more individual institutions, and comprehensively improve the efficiency and total volume of logistics; Establish a resource sharing platform, establish a capacity pool management mechanism, and give full play to the advantages of multimodal transport enterprises in network freight.

5.2.3 Long-term (2033-2037) : automation transition stage. This stage focuses on breaking through two types of key technologies: building a UAV logistics network and forming a three-level aviation network system. Since 2024, drone logistics routes have been opened one after another, and its high efficiency and low cost, in particular, have made it rapidly penetrate the logistics industry. Formation of terminal logistics: short distance logistics services within 10km in rural areas, the use of small multi-rotor drones to perform express delivery and other tasks, and the construction of air traffic control, drone take-off and landing sites and other infrastructure; Tributary logistics: 100-1000km medium and long distance logistics services, the use of fixed-wing, composite wing and other large drones, the route market is about a few hours, can take a large number of existing civil aviation airports, air traffic control and other infrastructure; Trunk logistics: more than 1000km long distance logistics services, only the use of large load, long endurance of large fixed-wing unmanned aerial vehicles, suitable for remote mountainous areas: construction of landing point density of 1 /20km^2 development of plateau unmanned aerial vehicles (ceiling of 5,000 meters) to achieve 30 minutes of response circle coverage; The automated driving transportation system promotes the commercial application in three steps, focusing on solving the various obstacle types faced by automatic distribution when it is applied in the terminal 3km traffic scene. Solve gastrointestinal problems in autonomous driving, automate "loading and door-to-door delivery" and upgrade user experience. Reasonable planning of technical verification period, that is, closed site testing to ensure the safety and reliability of logistics vehicles; During the demonstration operation period, 10 lines were selected for adaptability experiments, and finally entered the scale application period, with rural coverage exceeding 60%.

5.3 Implementation Safeguards

5.3.1 Guarantee of institutional innovation. Form and improve the data governance mechanism in the field of digital logistics, and establish a "trinity" data management system: Rights confirmation mechanism (clarify the ownership of five types of data, including user data, enterprise data, public data, scientific research data and cross-border data, to ensure the legal use and protection of each type of data), sharing mechanism (develop 17 interface standards, covering data exchange, data format, data encryption, data verification and other aspects, To ensure the seamless connection and efficient flow of data between different systems), security mechanism (the establishment of eight types of protection measures, including data encryption technology, access control policies, data backup schemes, security audit processes, emergency response plans, privacy protection protocols, data lifecycle management and compliance checks, to comprehensively ensure the security and reliability of data); The policy support system implements the "four make up one award" policy: Fixed asset investment subsidies (30%-50% to encourage logistics-related enterprises to increase the construction of information infrastructure), operating expenses subsidies (20% in the first three years to reduce the economic burden of logistics-related enterprises in data management and maintenance), and additional deductions for research and development expenses (up to 175%, Encourage logistics related enterprises to invest more resources in technological innovation and product research and development), talent training subsidies (2,000 yuan per person to improve the professional skills and comprehensive quality of practitioners), demonstration project awards (up to 5 million yuan, to commend enterprises and individuals outstanding in the field of data governance, to promote the overall level of the industry).

5.3.2 Talent support system. Build a multi-level talent training network, covering all stages from basic education to higher education, to ensure the comprehensive training and sustainable development of talents. The vocational education system develops a "1+X" certificate system, in which "1" represents the basic vocational skill certificate, "X" represents 5 vocational skill levels and 12 special ability modules, and the pass rate is strictly controlled at 70%-80% to ensure that students have solid professional skills and practical ability. The continuing education system sets up a "new farmer" training program, training 500,000 people every year, the course content covers modern agricultural technology, management, marketing and other aspects, the course pass rate ≥85%, employment conversion rate ≥60%, aimed at improving the overall quality of rural labor force, promote the process of agricultural modernization.

5.3.3 Ecological coordination mechanism. Establish a sustainable development model: co-construction and sharing mechanism to promote the construction of "multi-station integration" : integrate five types of public service facilities, including community service centers, medical stations, educational institutions, cultural activity centers and transportation stations, increase the resource sharing rate to 70%, reduce operating costs by 35%, and achieve efficient use of resources and comprehensive improvement of community services; The risk sharing mechanism sets up a special risk fund: the scale is 1 billion yuan, covering 3 types of major risks, including natural disasters, operation disruption and market fluctuations, and the compensation ratio is between 30% and 70% to ensure the stable operation and long-term development of the project.

6 Conclusion

This research systematically analyzes the current development status of rural logistics, the core problems and the application potential of AI technology, and puts forward a phased optimization scheme and guarantee system. A systematic research framework of "technology-scenario-system" of rural smart logistics has been constructed, filling the academic gap of AI technology adapting to special rural scenarios. Provide policy toolkits for the government (such as data standards, subsidy policies) and technical paths for enterprises (such as UAV high-altitude adaptation schemes) to help implement rural revitalization strategies. This study confirms that AI technology can significantly break the efficiency bottleneck of rural logistics, but it needs to be implemented in stages, multi-agent collaboration and local adaptation to achieve sustainable optimization. This achievement not only provides a new perspective for academic research, but also provides a replicable practice paradigm for the construction of smart logistics in China and even in similar regions around the world.

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