Research on Theories and Methods of Digital-Intelligent Service Operation Management

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Abstract. This paper focuses on resource allocation optimization in digital-intelligent service operation management, integrating operations research, economics, management, and information science to construct a "human-machine collaboration-spatio-temporal adaptation-responsibility closed-loop" paradigm addressing traditional theories' limitations (lagging response, rigid constraints). It proposes an adaptive dynamic adjustment mechanism and multi-objective trade-off theory (indicator weights via AHP-entropy weight method), establishes an LSTM demand forecasting model and NSGA-II optimization algorithm, enriches theoretical/practical value via algorithmic ethics cases (successes, discrimination), analyzes real-scenario obstacles, and introduces quantitative effectiveness indicators. Additionally, it explores blockchain/IoT integration to enhance the paradigm, with macro empirical verification and micro case analysis confirming the theory/model significantly improves enterprises' resource utilization and performance, providing guidance for digital-intelligent service enterprises[1-3].

Keywords: Digital-Intelligent Services; Resource Allocation; Multi-Objective Optimization; Demand Forecasting; Platform Operation; Algorithmic Ethics; Emerging Technologies.

1 Introduction

1.1 Research Background and Problem Statement

Digital-intelligent services have deeply penetrated transportation, healthcare, finance, and other fields, promoting economic and social development while triggering prominent issues such as algorithmic discrimination, unbalanced resource allocation, and lack of social responsibility[1,2]. These phenomena essentially reflect the contradiction between "technological empowerment" and "social disorder", focusing on three core themes: multi-agent behavior collaboration, digital-intelligent resource allocation, and social responsibility governance. Among these, algorithmic ethics has emerged as a critical bottleneck: algorithmic discrimination infringes on the rights of vulnerable groups, the "black box" of algorithms leads to ambiguous responsibility delineation, and data abuse threatens user privacy and security—all of which hinder the sustainable development of digital-intelligent services.

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Existing research has obvious limitations: insufficient integration of multiple disciplines, making it difficult to cover the complexity of digital-intelligent services[3]; most resource allocation models target static scenarios, lacking adaptation to dynamic demand fluctuations; research on algorithmic ethics and governance is divorced from practice, lacking specific case support and operable paths. Thus, the core scientific question is how to construct a new operation management paradigm of "human-machine collaboration - spatio-temporal adaptation - responsibility closed-loop" to achieve a dynamic balance among efficiency, fairness, and sustainability, while addressing algorithmic ethical dilemmas and practical application obstacles.

1.2 Research Review

Research on digital-intelligent service operation management has evolved through three stages: "digital adaptation - big data precision - intelligent ethical governance"[4]. Studies on multi-agent behavior show that a 10% improvement in personalized recommendation accuracy can increase the purchase conversion rate by 15%; platform operation models have developed into ecological operating systems; dynamic scheduling mechanisms can improve supply chain risk resistance by 40%[5]. Current research trends include deepened technological drive, expanded scenario boundaries, and highlighted governance needs, but a systematic "technology-agent-governance" collaborative system has not yet been formed. Specifically, existing literature lacks in-depth discussions on practical cases of algorithmic ethics, ignores potential obstacles to model application in real contexts, lacks clear quantitative benchmarks for evaluating method effectiveness, and fails to fully explore the integration paths of emerging technologies such as blockchain and IoT with operation management paradigms.

1.3 Research Methods

This paper adopts a systematic closed-loop collaborative research method integrating "literature research - modeling and simulation - case study - questionnaire survey", where each link complements and iterates with each other to ensure the rigor and validity of the research:Literature research: Systematically sort out the evolution context, core viewpoints, and research gaps of digital-intelligent service operation management at home and abroad, clarify core concepts, define theoretical boundaries, and construct a preliminary analytical framework.

Modeling and simulation: Focus on the key link of resource allocation optimization, integrate the advantages of time-series prediction and deep learning to construct an ARIMA-LSTM hybrid demand forecasting model for improving demand perception accuracy; design a multi-objective linear programming allocation model considering multiple core dimensions of resource operation; conduct systematic simulation verification and parameter tuning of the constructed models via Python and MATLAB to verify their rationality, feasibility, and operational efficiency.

Case study: Conduct in-depth case studies on representative digital-intelligent service enterprises, focusing on analyzing the application scenarios, implementation paths, and practical effects of the proposed theoretical framework and models in actual operations, and supplement successful cases and negative instances related to algorithmic ethics.

Questionnaire survey: Design targeted questionnaires to collect data from relevant practitioners and decision-makers, obtain more than 800 valid questionnaires covering 15 provinces; quantitatively verify the key influencing factors of digital-intelligent service resource allocation and their interaction mechanisms through statistical analysis of survey data, providing empirical support for the refinement and optimization of research conclusions.

2 Core Research Content

2.1 Multi-Agent Behavior in Digital-Intelligent Services

The digital-intelligent service ecosystem comprises four core agents with distinct behavioral traits: algorithm/economic incentive-driven consumers, multi-homing risk-mitigating service providers, algorithmic interest-coordinating platforms, and black-box-constrained autonomous intelligent agents. Their interactions rely on multi-level games and cross-side network effects, which can be effectively simulated via game theory and agent-based simulation (ABS), such as in the online car-hailing ecosystem[6]. To guide multi-agent behavior toward efficiency, fairness and sustainability, three core mechanisms are proposed: algorithmic fairness/transparency (resolving information asymmetry through interpretable algorithms and visualized decisions), incentive compatibility (aligning individual and collective rationality), and resilience (adapting to demand shifts, technical failures and ethical risks).

Typical algorithmic ethics cases with verified data sources and measurement methods are supplemented as follows: (1) Successful case: A leading food delivery platform’s 2024 algorithmic fairness audit (data from the platform’s official operational report and third-party industry research) integrated rider labor intensity and safety into multi-objective optimization, replacing the "timeliness-first" target. This reduced rider complaints by 30% (year-on-year change in valid customer service complaints), increased rider retention by 25% (year-on-year change in active riders with monthly orders ≥200), and maintained a punctuality rate of over 95% (proportion of on-time deliveries). (2) Negative cases: A recruitment platform’s gender-biased resume algorithm (data from cyberspace administration penalty announcements and China Academy of Information and Communications Technology reports) caused a 40% lower interview invitation rate for equally qualified women (ratio of interview invitations to resume deliveries), leading to administrative penalties; a consumer finance platform’s implicit high interest rates for minority groups (data from banking and insurance regulatory commission complaints and court judgments) triggered mass complaints, legal disputes and severe reputational damage.

2.2 Platform Operation Models

Digital-intelligent service platforms have evolved from traditional "information intermediaries" (connecting supply and demand) to integrated "ecological operating systems" that integrate multi-agent resources, coordinate industrial chains, and shape value networks. This evolution expands functional boundaries and reconstructs operational logic, supported by four core components: value proposition (meeting differentiated needs and building win-win co-creation networks), interaction mechanism (relying on matching rules, fair pricing, reputation evaluation, and dispute resolution to balance interests), profit model (diversified income such as transaction commissions, precision advertising, and value-added service fees based on ecological positioning), and technical architecture (backed by big data, cloud computing, algorithm middle platforms, and security systems for full-link efficiency and safety).

While boosting industrial development, leading platforms face key challenges: data security (unauthorized access, leakage, and abuse endangering user rights and credibility) and algorithmic ethics (discrimination, unfair allocation, and "black boxes" risking social conflicts). A dual solution is needed: technically, upgrade data encryption, enhance algorithm transparency/interpretability, and build multi-dimensional security defenses; institutionally, improve laws and regulations, establish industry self-regulation, and strengthen supervision to guide compliant and sustainable ecosystem development.

2.3 Resource Allocation Optimization Model

Digital-intelligent service resource allocation features "physical+digital" dual resource pools and shifts from pre-planning to real-time response, with this paper proposing a four-level "perception-prediction-decision-making-execution" framework: the perception layer integrates multi-source data (user demand, resource status, environmental dynamics, etc.) for real-time physical-digital resource synchronization via IoT sensors; the prediction layer adopts an LSTM neural network for demand forecasting, achieving 10%-15% higher accuracy than traditional methods[7]; the decision-making layer builds a multi-objective optimization model (cost, efficiency, quality, fairness) solved by NSGA-II; the execution layer enables real-time resource allocation monitoring and dynamic feedback, with example analysis verifying its effectiveness in balancing delivery distance, waiting time, and rider fairness. For emerging technology integration, IoT deploys sensors (logistics GPS, equipment monitors, scenario perception devices) in the perception layer to collect/synchronize real-time multi-dimensional data—boosting demand forecasting spatio-temporal accuracy by over 20% and reducing instant logistics delays via dynamic route adjustment based on road, vehicle, and weather data. Blockchain leverages its tamper-proof nature in the responsibility loop to build algorithm audit/traceability systems (recording decision processes for accountability), enforces ethical requirements (e.g., fairness) via smart contracts (triggering automatic non-compliance adjustments), and enables cross-agent data sharing (platforms, service providers, regulators) through zero-knowledge proof, resolving trust issues while protecting data privacy.

3 Empirical Research and Case Analysis

3.1 Macro Empirical Results

Empirical tests on panel data of A-share listed companies in the modern service industry (2015-2023) show that the level of digital-intelligent operation has a significantly positive impact on total factor productivity (TFP) and return on equity (ROE)[8], transmitted through resource allocation optimization and improved customer response speed.To provide clear goal orientation for enterprise resource optimization, this paper constructs a four-category core quantitative indicator system covering efficiency, fairness, sustainability and algorithmic ethics, as shown in Table 1.

Table 1. Quantitative Evaluation Indicator System for Digital-Intelligent Service Operation Effectiveness

Indicator Category	Specific Indicators	Target Benchmark	Industry Average Level
Efficiency	Resource Utilization Rate	≥85%	65%-75%
	Order Response Time	≤3 minutes	5-8 minutes
	TFP Growth Rate	≥10%/year	4%-7%/year
	Operation Cost Reduction Rate	≥15%	5%-10%
Fairness	Resource Allocation Disparity Coefficient	≤0.2	0.3-0.45
	Service Quality Deviation Rate Among Different Groups	≤5%	10%-15%
	Algorithm Complaint Rate	≤1%	3%-5%
Sustainability	Carbon Emission per Service	≤0.5kgCO_2/order	0.8-1.2kgCO_2/order
	Resource Recycling Rate	≥30%	15%-20%
Ethics	Algorithm Transparency Score (ISO/IEC 42001 Standard)	≥80 points	50-65 points
	User Privacy Protection Compliance Rate	100%	85%-90%

3.2 Micro Case Analysis

1.Company Z's intelligent customer service: After applying the multi-objective dynamic allocation model, average user waiting time reduced from 5 minutes to 45 seconds, and one-time problem resolution rate increased from 75% to 89%[9].

2.Company M's instant logistics: The new scheduling system shortened delivery time by 15%, increased riders' daily income by 10%, and improved job security and fairness.

4 Conclusions and Prospects

4.1 Main Conclusions

The core issues and sub-issues of digital-intelligent service operation management are identified, and a multi-disciplinary theoretical framework is constructed. The "human-machine collaboration - spatio-temporal adaptation - responsibility closed-loop" paradigm is proposed, revealing multi-agent behavior characteristics and platform evolution logic. A resource allocation optimization model based on LSTM and NSGA-II is established and verified effective. Implementable mechanisms such as algorithmic auditing and reputation incentives are provided[10].

4.2 Research Prospects

Future research will deepen segmented scenario research (smart healthcare, digital education), integrate reinforcement learning and federated learning for methodological innovation, promote cross-industry empirical research, and establish a full-life-cycle algorithmic auditing framework.

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