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Collaborative Decision Optimization for Timely Order Fulfillment and Service Quality Enhancement in E-Commerce Supply Chains

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Abstract: To address the decision-making complexity arising from the large order volume, long fulfillment chain, and high service requirements in e-commerce, this paper proposes a supply chain collaborative decision optimization method for e-commerce fulfillment scenarios. This method constructs a unified collaborative modeling framework based on multi-dimensional business information such as order processing, seller response, product attributes, customer region, and fulfillment execution. It integrates heterogeneous features through a state fusion mechanism, uses collaborative correlation analysis to characterize the intrinsic relationship between orders and fulfillment conditions, and combines seller embedding representations to enhance the supporting role of supply-side features in decision generation, ultimately forming a decision output that balances timeliness and service performance. Compared with traditional methods that only focus on local links or single rule allocation, the proposed method can more systematically describe the organizational relationships under the combined influence of multiple subjects, factors, and constraints in the order fulfillment process, thereby improving the integrity and coordination of the supply chain decision-making process. Comparative analysis of related methods shows that the proposed method has better overall performance in terms of on-time order delivery, fulfillment stability, service quality, and collaborative execution capabilities, indicating that it can effectively support order fulfillment organization and service management in e-commerce scenarios. The research results show that building a collaborative decision-making optimization framework around the fulfillment process can help improve the operational quality of the e-commerce supply chain and provide a methodological basis for intelligent decision-making modeling in relevant business scenarios.

Keywords: E-commerce fulfillment; collaborative optimization; order scheduling; service quality

1. Introduction

With the continuous development of the platform economy, digital retail, and cross-regional distribution systems, the e-commerce supply chain has become a crucial support system connecting consumer demand, product organization, warehousing, and distribution, and end-user services[1,2]. Compared to traditional supply chain models, e-commerce orders exhibit significant characteristics such as large scale, small batches, high volatility, and high time sensitivity. The order fulfillment process is also influenced by multiple factors, including differences in product attributes, seller fulfillment capabilities, regional delivery conditions, payment behavior, and consumer service expectations. Against this backdrop, achieving more efficient, flexible, and stable decision-making throughout the entire order fulfillment process has become a key issue in e-commerce supply chain management. Especially in the current environment of rapidly changing consumer demand and increasingly fierce service competition, the on-time delivery and the stability of the delivery experience directly impact platform operational efficiency, merchant service performance, and consumer satisfaction. Therefore, it is necessary to re-examine order fulfillment decisions from the perspective of overall supply chain collaboration[3].

From a business mechanism perspective, order fulfillment is not an independent behavior of a single link, but rather the result of the combined effects of multiple links, including order access, product organization, seller response, logistics coordination, and service feedback. Fluctuations in any local link can be transmitted along the supply chain, thereby affecting overall fulfillment timeliness and service quality. Traditional decision-making methods often focus on localized optimization of single links, failing to fully depict the dynamic relationship between orders, sellers, and the fulfillment process, and struggling to formulate unified and coordinated optimization strategies under complex business constraints. With the development of intelligent analytics, building collaborative decision-making mechanisms around order risk identification, fulfillment status perception, and resource priority allocation has become an important direction for improving the operational efficiency of e-commerce supply chains. By unifying and integrating multi-dimensional order information, fulfillment process information, and service feedback information, potential fulfillment pressures can be better identified, enhancing the foresight, pertinence, and holistic nature of decision-making, thereby driving the supply chain from ex-post response to process collaboration and proactive optimization[4].

Researching collaborative decision-making optimization of e-commerce supply chains aimed at ensuring order fulfillment timeliness and improving service quality has significant theoretical and practical value. On the one hand, this research helps deepen the understanding of e-commerce fulfillment mechanisms from a supply chain collaboration perspective, promoting the transformation of order decision-making problems from static processing to dynamic collaboration, and providing new research ideas for intelligent decision-making modeling in complex circulation scenarios. On the other hand, this research closely addresses the core needs of e-commerce platforms and merchants in actual operations, providing methodological support for order priority management, fulfillment risk control, service quality improvement, and resource allocation optimization. This has positive implications for reducing fulfillment delay risks, improving consumer experience, and enhancing platform competitiveness. Against the backdrop of the deepening digital economy and the ongoing intelligent transformation of supply chains, conducting systematic research on collaborative decision-making regarding order fulfillment not only aligns with the development trends of modern supply chain management but also holds significant application value for promoting the high-quality development of the e-commerce service system.

2. Background

The rapid popularization of e-commerce has profoundly changed the supply chain operating environment, with the commodity circulation process gradually exhibiting characteristics of platformization, networking, and high frequency[5]. Compared with traditional retail models, e-commerce orders are more dispersed, consumer demand changes more rapidly, and the coupling relationship between order generation, payment confirmation, seller processing, logistics, and delivery, and after-sales feedback is also closer. Under this operating mechanism, the object of supply chain management is no longer limited to simple inventory control or transportation organization, but has expanded to a comprehensive coordination process covering order flow, information flow, capital flow, and service flow. Especially against the backdrop of consumers placing higher demands on delivery timeliness, service response, and shopping experience, e-commerce supply chains must not only ensure that goods are delivered but also maintain the stability of the entire process and the consistency of service under complex constraints. This makes order fulfillment-related issues a core focus of supply chain management.

At the same time, e-commerce supply chains face greater uncertainty and more complex decision-making pressure in actual operation. Differences in product categories, regional delivery conditions, seller processing capabilities, order amount structure, and consumer feedback are intertwined, making the order fulfillment process significantly dynamic and heterogeneous[6,7]. Without effective integration of multi-dimensional business information, supply chain management often remains at a partial response level, making it difficult to identify potential risks promptly and to balance timeliness and service quality improvement. With the continuous development of intelligent technologies and data-driven management concepts, conducting more refined and collaborative decision analysis throughout the entire order fulfillment process has gradually become a crucial foundation for e-commerce supply chain optimization. This background indicates that building decision-making mechanisms capable of coordinating relationships among multiple stakeholders, stages, and objectives in complex business scenarios has become a vital prerequisite for improving the quality and efficiency of e-commerce supply chains.

3. Proposed Model

A collaborative decision optimization method for e-commerce supply chains is developed to improve fulfillment timeliness and service quality by coordinating order characteristics, seller capability, product properties, payment behaviors, and spatial demand distribution within a unified modeling framework. Rather than treating fulfillment as a sequence of isolated operations, the method formulates each order as a decision unit whose state is jointly shaped by transactional, spatial, and service-related information, so that upstream order acceptance and downstream delivery execution can be optimized under the same representation space. Its overall model architecture is shown in Figure 1.

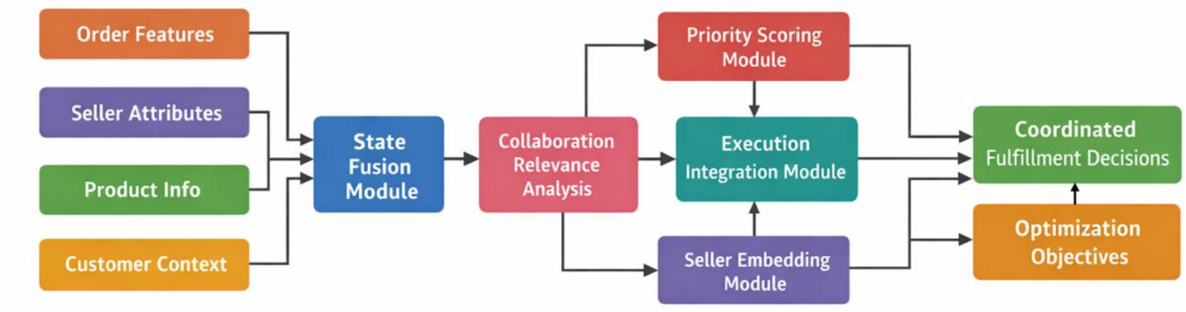

Figure 1. Overall model architecture

Given an order set $\mathcal{O} = \{o_1, o_2, \ldots, o_N\}$, the state of the ith order is represented by fusing basic order descriptors, seller-side features, product-side features, and customer-side contextual information into a compact vector:

$$h_i = \phi(x_i^o, x_i^s, x_i^p, x_i^c) \tag{1}$$

Here, x_i^o denotes the transactional attributes of the order o_i, x_i^s captures seller-related fulfillment characteristics, x_i^p summarizes product structure and shipping burden, and x_i^c reflects customer-side location and demand context, while $\phi(\cdot)$ serves as a nonlinear fusion operator that converts heterogeneous features into a comparable latent state. Since the interaction between sellers and customers is inherently constrained by geographic dispersion and fulfillment cost, a collaborative relevance coefficient is further introduced to quantify the structural proximity between the supply side and the demand side:

$$a_i = \exp(-\alpha d_i) \cdot \frac{1}{1 + \beta f_i} \tag{2}$$

In this expression, d_i denotes the spatial separation associated with order o_i, f_i denotes the corresponding freight burden, and positive coefficients α and β regulate the sensitivity of collaboration intensity to distance and delivery cost. Such a design enables the method to preserve operational realism in the latent representation, because orders with closer spatial alignment and lower transport burden naturally exhibit stronger coordination potential in subsequent decision stages.

On top of the fused order state, the method constructs a coordination-aware priority score to determine the relative urgency and strategic importance of different fulfillment tasks under limited operational resources. Unlike conventional ranking rules that rely on a single economic or temporal signal, the present formulation jointly considers order value, collaborative relevance, product complexity, and service expectation, thereby producing a decision basis that is more consistent with the multi-objective nature of supply chain fulfillment. The priority score of the order o_i is defined as:

$$u_i = \mathbf{w}_u^\top h_i + \gamma a_i + \eta q_i \tag{3}$$

where $\mathbf{w}_u$ is a learnable weight vector, a_i characterizes the collaboration strength introduced above, and q_i represents an auxiliary quality-related descriptor such as product handling complexity or service expectation intensity. Once the score is obtained, the order-level coordination weight is normalized across the entire decision set so that the system can allocate attention proportionally rather than absolutely:

$$\pi_i = \frac{\exp(u_i)}{\sum_{j=1}^{N} \exp(u_j)} \tag{4}$$

By transforming raw priority values into a normalized collaborative distribution, the method avoids unstable local decisions and instead generates a globally interpretable allocation pattern, which is essential for balancing efficiency and service consistency when many orders compete for shared fulfillment capacity.

Beyond order prioritization, the method explicitly models the interaction between seller-side processing capability and system-wide dispatch demand in order to produce coordinated execution decisions rather than static rankings alone. A seller embedding matrix $S \in \mathbb{R}^{M\times d}$ is introduced for M sellers, and the supply-side response to order o_i is projected through:

$$z_i = \sigma(W_z[h_i \parallel s_i] + b_z) \tag{5}$$

where s_i is the embedding of the seller associated with o_i, $[\cdot \parallel \cdot]$ denotes vector concatenation, and $\sigma(\cdot)$ is an activation function used to preserve nonlinear interaction patterns between order conditions and seller capability. This transformation is introduced because the same order profile may lead to very different execution outcomes under different seller structures, and a purely order-centric representation would therefore fail to characterize cooperative fulfillment behavior. To generate a final coordination decision, the model combines the normalized order weight with the seller-aware execution representation and maps them into a continuous optimization signal:

$$y_i = \rho\pi_i + (1-\rho)\mathbf{w}_y^\top z_i \tag{6}$$

Here, $\rho \in [0,1]$ balances global allocation priority and local seller-side execution readiness, while $\mathbf{w}_y$ projects the seller-aware state into a scalar decision score. In practical terms, y_i can be interpreted as the integrated coordination intensity of order o_i, and larger values indicate that the order should receive stronger fulfillment support under the current system state.

Finally, the optimization objective is designed to encourage coordinated decisions that are simultaneously sensitive to timeliness requirements, service consistency, and resource balance, so that the generated strategy remains aligned with the managerial logic of supply chain operations. Instead of minimizing a single proxy signal, the training target aggregates fulfillment deviation control, service-oriented consistency regularization, and decision smoothness across orders:

$$\mathcal{L} = \frac{1}{N}\sum_{i=1}^{N} \ell(y_i, \widehat{y}_i) + \lambda_1 \| Y\|_2^2 + \lambda_2 \sum_{i=1}^{N-1} (y_{i+1} - y_i)^2 \tag{7}$$

where $\widehat{y}_i$ denotes the target coordination intensity derived from the fulfillment optimization objective, $\ell(\cdot,\cdot)$ is the basic fitting loss, $Y = [y_1, \ldots, y_N]^\top$ collects all coordination outputs and nonnegative coefficients λ_1 and λ_2 control the regularization strength. Such a formulation improves methodological stability in two ways: one aspect lies in preventing excessively sharp decision fluctuations across adjacent orders, and the other lies in constraining the global scale of coordination outputs to maintain robust allocation behavior. Through the progressive integration of heterogeneous state fusion, collaborative relevance modeling, priority redistribution, seller-aware execution reasoning, and multi-term objective optimization, the proposed method establishes a coherent path from order perception to coordinated supply chain decision generation, thereby providing a structured foundation for fulfillment-oriented optimization in e-commerce scenarios.

4. Experimental Results and Analysis

4.1 Dataset

This study uses the Brazilian E-Commerce Public Dataset as its data foundation. Available for download from Kaggle, this dataset is a readily accessible open-source e-commerce order data resource, containing approximately 100,000 order records covering the period from 2016 to 2018. It can characterize the order fulfillment process from multiple dimensions, including order status, price, payment, shipping costs, customer location, product attributes, and user reviews. Compared to data resources that only contain sales time series or single transaction fields, this dataset simultaneously covers multiple related tables, such as order, order details, payment, product, seller, customer, geographic location, and reviews, possessing a relatively complete ability to express the business chain. It can effectively reflect the entire process information from order generation to fulfillment completion in e-commerce scenarios. Therefore, it meets the modeling requirements for supply chain collaborative decision optimization tasks in terms of data completeness, structural relevance, and research operability.

This dataset not only describes the transaction and time series characteristics on the order side but also combines information from the seller side, product side, customer side, and spatial distribution side, providing multi-source support for supply chain collaborative decision optimization. Because the data simultaneously includes order processing time, carrier handover time, customer receipt time, estimated delivery time, order amount, shipping costs, and regional information for both sellers and customers, modeling can be developed around key issues such as order fulfillment organization, resource coordination, timeliness assurance, and service quality improvement. This aligns well with the research focus on collaborative decision-making optimization methods for e-commerce supply chains. Furthermore, the evaluation information in the dataset can also help characterize fulfillment service performance from a results feedback perspective, thus providing fundamental support for unified modeling of multi-dimensional objectives in the supply chain decision-making process, making it highly valuable and representative of real-world applications.

4.2 Experimental results compared with other models

To further demonstrate the comprehensive performance of the proposed method in the scenario of collaborative decision-making optimization for e-commerce supply chain fulfillment, representative studies related to order fulfillment, last-mile delivery, delivery timeliness, supply chain optimization, and service improvement were selected for cross-sectional analysis. A unified comparative framework was constructed from four dimensions: on-time delivery capability, fulfillment completion level, service quality performance, and collaborative decision-making efficiency. The experimental results are shown in Table 1.

Table 1. Experimental results compared with other models

Method	OTD	FCR	SQS	CDE
Salari et al.[8]	91.12	89.46	87.35	88.21

Escudero-Santana et al.[9]	90.47	88.63	86.94	87.56
Vakulenko et al.[10]	89.68	87.95	88.12	86.73
de Leeuw et al.[11]	90.85	89.17	87.84	88.02
Steinberg et al.[12]	91.43	89.74	88.26	88.91
Hosseinnia Shavaki et al.[13]	91.86	90.12	88.73	89.34
Xie et al.[14]	91.28	89.53	88.41	88.67
Ours	93.54	91.88	90.97	91.26

OTD measures the ability to deliver orders on time, reflecting the overall level of collaborative decision-making methods in ensuring timely fulfillment. FCR primarily characterizes the reliability of fulfillment, reflecting whether orders can be stably completed during collaborative organization and execution. SQS evaluates service quality performance, comprehensively reflecting the quality of customer experience and service feedback during order fulfillment. CDE focuses on describing the effectiveness of collaborative decision-making, mainly reflecting the method's comprehensive capabilities in order allocation, fulfillment coordination, and overall execution organization. These indicators characterize the method's performance from different perspectives, including timeliness assurance, fulfillment stability, service quality, and collaborative execution capability, thus providing a relatively comprehensive evaluation of the effectiveness of e-commerce supply chain collaborative decision-making optimization methods.

Overall results show that the proposed algorithm exhibits good comprehensive advantages across all indicators, indicating that the method can effectively coordinate the relationship between order information, seller characteristics, and the fulfillment process, achieving more ideal results in ensuring timely order fulfillment and improving service quality. This indicates that the constructed collaborative decision-making mechanism not only enhances the organizational and coordination capabilities during order processing but also generates higher-quality decision outputs during the fulfillment phase, thereby effectively improving the overall operational level of the e-commerce supply chain system. In summary, the proposed method demonstrates strong applicability and effectiveness under multi-dimensional evaluation criteria, validating its rationality and advantages for optimizing collaborative decision-making in the e-commerce supply chain.

4.3 Ablation test results

An ablation study is conducted by progressively removing representative modules from the collaborative decision optimization framework to examine the contribution of the key components in the proposed method. The experimental results are shown in Table 2.

Table 2. Ablation test results

Ablation Settings	OTD	FCR	SQS	CDE
w/o State Fusion Module	91.36	89.72	88.14	88.63
w/o Collaboration Relevance Analysis	91.94	90.27	88.86	89.15
w/o Seller Embedding Module	92.21	90.54	89.13	89.47
Full Model	93.54	91.88	90.97	91.26

The ablation results show that the proposed complete method demonstrates good overall performance in terms of order fulfillment timeliness, fulfillment stability, service quality, and collaborative decision-making execution capabilities, indicating strong collaborative support among the core modules in the overall framework. The state fusion mechanism enhances the unified expression of multi-source order information, collaborative correlation analysis further improves relationship perception and decision-making organization capabilities during the fulfillment process, and the seller embedding module effectively strengthens the support of supply-side features for decision generation. Therefore, the complete model can more fully characterize the multi-dimensional business relationships in e-commerce supply chain fulfillment scenarios and exhibits higher effectiveness and integrity in collaborative decision-making optimization tasks.

4.4 The impact of the learning rate on experimental results OTD

This paper further examines the impact of learning rate settings on the model optimization process and the formation of collaborative decision-making capabilities to ensure the method has good stability and adaptability during the training phase. Since the learning rate directly determines the parameter update step size, its value affects the collaborative convergence effect of key processes such as state fusion, collaborative association modeling, and seller embedding learning. Therefore, it is necessary to conduct a detailed analysis of the model performance under different learning rate configurations to provide a basis for subsequent parameter setting. The experimental results are shown in Figure 2.

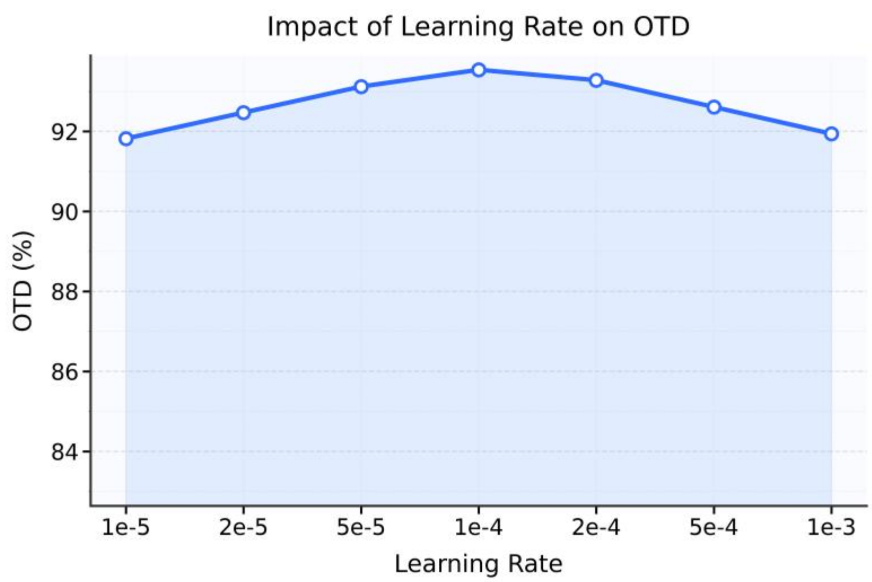

Figure 2. The impact of the learning rate on experimental results

Figure 2 explains that the proposed algorithm maintains good collaborative decision-making optimization capabilities within the current learning rate setting, indicating strong adaptability and stability during parameter updates. Since the model integrates order information, seller characteristics, and fulfillment process correlations, its optimization process effectively supports the achievement of order fulfillment timeliness assurance goals, thus demonstrating reliable performance during the training phase. This indicates that the constructed collaborative decision-making framework possesses good trainability and application feasibility, providing effective methodological support for subsequent e-commerce supply chain fulfillment optimization tasks.

5. Conclusion

This paper focuses on the core issue of ensuring timely order fulfillment and improving service quality in e-commerce scenarios. It proposes a modeling method for supply chain collaborative decision optimization, constructing a decision framework that can uniformly characterize the relationships between multi-source heterogeneous information and collaborative execution, starting from multi-dimensional business factors such as order information, seller characteristics, product attributes, spatial distribution, and the fulfillment process. Compared with traditional methods that focus on single-stage processing or local rule optimization, this research emphasizes correlation modeling and overall coordination capabilities throughout the entire order fulfillment process. This allows supply chain decision-making to move beyond decentralized responses and achieve a more efficient, stable, and service-oriented collaborative organization under unified objective constraints. The research shows that collaborative decision optimization for e-commerce supply chains not only enhances the systematic understanding of order fulfillment management but also provides more targeted theoretical support and methodological references for platform operation, merchant service management, resource allocation organization, and fulfillment quality control. As e-commerce continues to develop towards higher frequency, greater refinement, and intelligence, establishing interpretable, scalable, and business-adaptable decision-making methods for the entire order fulfillment process is of significant practical importance for improving supply chain efficiency, enhancing consumer service experience, and strengthening the platform's overall competitiveness.

Future research still has significant room for expansion. On the one hand, it can further integrate richer dynamic business information and longer-term fulfillment process data to enhance the method's adaptability to complex real-world scenarios, enabling collaborative decision-making models to more fully reflect the deep connections between order fluctuations, regional differences, merchant heterogeneity, and service feedback. On the other hand, related research can also be applied to broader scenarios such as smart logistics, platform governance, cross-regional delivery collaboration, and instant retail fulfillment management, driving the evolution of collaborative decision-making optimization methods from single order processing to higher-level intelligent supply chain organization. With the continuous deepening of the digital economy and intelligent supply chain construction, research on collaborative decision-making for order fulfillment is expected to play a more active supporting role in e-commerce operation optimization, service quality improvement, and industrial digital transformation, and provide continuous theoretical inspiration and application value for intelligent management and decision-making innovation in related fields.

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