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Last-minute coordination: Adapting to demand to support last-mile operations

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Abstract

In the highly competitive e-commerce industry, customer-facing warehouses are crucial as the "order penetration points" for e-commerce last-mile operations. This research examines how warehouses use last-minute coordination, an unstructured mechanism, to ensure sufficient inventory at the order penetration points. Previous research has focused on structured mechanisms like contracts and inventory management systems to enhance warehouse performance. However, these mechanisms can be ineffective when faced with unforeseen local contingencies. To adjust inventory and adapt to changes in supply and/or demand, warehouses need to engage in unstructured, last-minute coordination with other warehouses. Using coordination and loose coupling theories, we find that coordinating with many warehouses (i.e., large coordination scope) reduces the operational efficiency of individual warehouses. At the network level, we find that a centralized coordination structure improves the operational efficiency of the entire network. We also show that demand uncertainty reinforces the existing last-minute coordination patterns, using the Separable Temporal Exponential Random Graph Model (ST-ERGM). This research highlights the importance of last-minute coordination and reveals its effects on both individual warehouses and the overall network.

KEYWORDS

last-mile operations, last-minute coordination, operational efficiency, ST-ERGM, warehouses

Highlights

- The inventory turnover of a customer-facing warehouse, like a fulfillment center, declines when the warehouse coordinates with a larger number of other warehouses to adjust their inventory in response to unforeseen demand shifts.

- Improved network-level inventory turnover can be achieved through a more centralized coordination network, wherein the majority of last-minute coordination activities are concentrated around central warehouses.
- Increased demand uncertainty reinforces the existing last-minute coordination relationships among warehouses.

1 | INTRODUCTION

In today's highly competitive e-commerce industry, ensuring a seamless delivery experience for customers is crucial for a firm's overall success. Last-mile operations play an important role in shaping this experience. Delivering to customers begins at an *order penetration point* (Fernie & Sparks, 2009), defined as "an inventory location (e.g., fulfilment center, manufacturer site, or retail store) where a fulfilment process is activated by a consumer order" (Lim et al., 2018, p. 310). With the increasing trend of customers ordering through e-commerce platforms instead of visiting physical stores, customer-facing warehouses have become new storefronts for many businesses (Knowlton, 2022). For e-commerce firms, last-mile operations start from these warehouses, which serve as the order penetration points for the fulfillment process. Without sufficient inventory at these points, last-mile operations cannot effectively meet customer service requirements. For instance, if a city sees a surge in the demand for products but the warehouse (order penetration point) serving the city lacks inventory, last-mile operations cannot serve customers in a timely manner. This challenge is even more pronounced for e-commerce platforms selling large items like refrigerators, televisions, and dishwashers due to storage space constraints and additional handling costs.

E-commerce firms forecast and plan for demand at each of their warehouses to best serve their customers. However, at the last minute, local contingencies may emerge, and demand may change unexpectedly for particular warehouses. This is especially problematic for warehouses that serve as order penetration points and process large valuable items. To respond to demand changes, these warehouses will coordinate with one another to ensure that they can make their last-mile delivery commitments. This adaptive behavior, which we call *last-minute coordination* among warehouses, is unstructured and involves inventory transshipping to better position inventory at those order penetration points. For example, in our collaboration with a leading e-commerce logistics management company in China (hereafter "Alpha"), we have observed that Alpha's warehouses frequently engage in last-minute coordination to respond to demand fluctuations and ensure timely deliveries. This activity occurs and persists despite the company's use of advanced algorithms and management systems designed to account for demand uncertainty. This observation echoes the findings of Pavlou and El Sawy (2010) and Tenhiälä and Helkiö (2015), who noted that "formal procedures… tend to be incompatible with the kind of improvisation that is needed for… continuous small adjustments" (Tenhiälä & Helkiö, 2015, p. 149).

Previous research has highlighted the significance of inventory transshipment in e-commerce last-mile distribution (Janjevic & Winkenbach, 2020; Winkenbach & Janjevic, 2018) and its importance in designing effective last-mile supply networks (Lim & Winkenbach, 2019). However, last-minute coordination has received limited research attention despite its practical importance and prevalence. The predominant research focus remains on structured planning mechanisms that operate in a tightly connected system rather than last-minute coordination, which involves unstructured planning mechanisms in a loosely connected system. While scholars have explored related concepts such as emergency transshipment (Evers, 1997; Rabinovich, 2005) and supply chain agility (Müller et al., 2023; Richey et al., 2022), there is a notable gap in empirical research investigating the emergence and impact of last-minute coordination and the resulting inventory transshipment at order penetration points. This gap is especially critical in the context of last-mile operations for large, valuable items, where inventory positioning at the order penetration point is paramount to mitigate substantial transportation costs.

Although last-minute coordination can help maintain high levels of service, it might affect the operational efficiency of the warehouses engaging in such behavior. To better understand last-minute coordination, this study investigates three research questions: (1) How does last-minute coordination impact the operational efficiency of individual warehouses? (2) How does last-minute coordination influence the operational efficiency of the overall warehouse network? (3) What is the impact of demand uncertainty on the pattern of inter-warehouse last-minute coordination? Operational efficiency is a critical consideration in our investigation because customer-facing warehouses represent a major portion of operating costs, and their efficiency is critical for last-mile operations (Hughes, 2021; Mangiaracina et al., 2019). Drawing on coordination theory and loose coupling theory, we first propose that last-minute coordination with many different warehouses (i.e., large coordination *scope*) results in elevated coordination costs and a reduction in operational efficiency at the individual warehouse level. Second, at the network level, we contend that a *centralized* last-minute coordination structure[1] enhances network-level operational efficiency. Last, with a focus on network dynamics, we argue that heightened demand uncertainty reinforces the existing coordination structure, rather than prompting warehouses to seek new coordination partners. We employ a multi-method approach, including two-stage least squares (2SLS), time series regression, and separable temporal exponential random graph model (ST-ERGM), to empirically validate our hypotheses.

This research contributes to the literature in the following way. This study extends earlier studies on similar concepts like emergency transshipment (e.g., Evers, 1997; Rabinovich, 2005) and contributes to the last-mile operations research by investigating the adaptive behavior of the order penetration points (i.e., warehouses) in the last-mile operations process (Lim et al., 2018). We show that last-minute coordination, a concept that has been largely overlooked, has implications for the last-mile operations literature. This is particularly important as the expanding e-commerce industry demands faster and more reliable order fulfillment. Further, this study reveals how last-minute coordination affects the operational efficiency of individual warehouses and the corresponding coordination network. We show that last-minute coordination reduces an individual warehouse's efficiency but can improve the overall network efficiency, highlighting the benefits of a centralized coordination structure (Cardinal, 2001) in a loosely coupled system. Finally, the study helps us understand the evolution of last-minute coordination. The findings show that increasing demand uncertainty does not necessarily lead to new coordination partners but reinforces the existing coordination structure. These findings also provide practical insights for firms seeking to better the performance of their last-mile operations.

The rest of the article is organized as follows. We review the relevant literature in Section 2. We develop three hypotheses in Section 3. In Section 4, we describe the research context, data set, and variable operationalization. Section 5 presents the methods and analyses for the three hypotheses. Section 6 concludes the article with a discussion of theoretical contributions, managerial implications, and future research directions.

2 | LITERATURE REVIEW

2.1 | Last-mile operations and warehouses

The final phase of a business-to-consumer (B2C) parcel delivery service, known as last-mile operations, involves managing the products from the order penetration points to the final destinations preferred by the end recipient (Lim et al., 2018). In e-commerce, last-mile operations play an essential role in determining the overall customer experience (Akturk et al., 2022; Lim et al., 2017). However, it is also often considered "the least efficient and most expensive part of the delivery process" (Mangiaracina et al., 2019, p. 901). Online retailers are under constant pressure to deliver products quickly, while also keeping costs low. This can be a difficult balance to achieve, especially when dealing with factors like traffic congestion, unpredictable demand, and varying delivery locations. As a result, researchers and practitioners are always looking for innovative ways to improve delivery performance, including a better design of delivery networks (Janjevic et al., 2021), delivery vehicle routing (Özark et al., 2021), new delivery modes (El-Adle et al., 2021), leveraging sharing economy and crowd-sourcing (Castillo et al., 2018), improving customer satisfaction through better logistics performance (Deshpande & Pendem, 2022; Yang et al., 2023), and so on. We refer readers to studies such as Boysen et al. (2021), Lim et al. (2018), and Mangiaracina et al. (2019) for comprehensive reviews of last-mile operations research on delivery processes.

Nonetheless, few studies focus on order penetration points of the last-mile operations process. Customer-facing warehouses, or fulfillment centers, are crucial order penetration points, where goods are stored, picked, and packed to fulfill customer orders (Lim et al., 2018). These warehouses account for a major portion of the operational costs in the e-commerce supply chain (Hughes, 2021; Mangiaracina et al., 2019), and existing studies have largely focused on optimizing warehouse operations using structured coordination mechanisms that can maintain the desired service levels while reducing costs. For instance, Acimovic and Graves (2015) developed a heuristic that makes fulfillment decisions by minimizing the immediate outbound shipping costs plus an estimate of future expected outbound shipping costs. Chen and Graves (2021) developed models to determine the ideal fulfillment centers for an online retailer to minimize shipping and fixed costs over a planning period. Lim et al. (2021) developed robust optimization models to optimize the replenishment, allocation, and fulfillment decisions jointly for fulfillment centers to minimize the expected total operating cost. Lei et al. (2018) provided heuristics to solve the joint pricing and fulfillment optimization problem faced by online retailers. Overall, these studies aim to improve the efficiency of warehouse operations through structured mechanisms and analytical modeling.

However, even with well-designed management systems and carefully planned strategies, unforeseen events can still occur in warehouse operations. In such situations, predetermined replenishment and routing plans may not be timely or sufficient, and warehouses must take immediate action to meet customer needs and ensure timely order fulfillment. The importance of such prompt and reactive decision-making has been highlighted in supply chain agility and responsiveness literature. Studies, such as Müller et al. (2023) and Richey et al. (2022), emphasize that "instead of following planning processes, companies often rely on intuition and improvisation when building ad hoc supply chains" (Müller et al., 2023, p. 13). Some prior studies have observed and explored similar practices. For instance, Evers (1997) and Rabinovich (2005) noted that a wholesaler facility would use its inventory "to satisfy demand originating at locations outside its own (i.e., primary) consumer market when stock is unexpectedly unavailable at facilities primarily in charge of fulfilling demand at those locations" (Rabinovich, 2005, p. 80), which they refer to as emergency transshipments. Zhou and Wan (2017) observed a similar coordination mechanism in a sourcing network, where individual warehouses coordinate inventory and logistics decisions with each other on an as-needed basis. These studies underscore the critical role that spontaneous decision-making plays in ensuring the flexibility and adaptability of warehouse operations in response to unforeseen events. Nonetheless, the impact of such ad hoc coordination approach on warehouse operational efficiency remains unclear due to limited empirical data.

2.2 | Coordination in last-mile operations

Coordination theory can help understand ad hoc last-minute coordination. In general, coordination theory aims to understand how actors can work together harmoniously (Malone & Crowston, 1990). The key tenets of coordination theory include goals, activities, actors, and interdependencies among actors (Malone & Crowston, 1990). Actors perform activities to achieve goals, and interdependencies arise from the goal-related activities (Malone & Crowston, 1990). To achieve goals effectively, actors employ coordination mechanisms to manage interdependencies (Malone & Crowston, 1990). In our research context, actors are the customer-facing warehouses, and their goals are to make sure that supply meets demand at the warehouses; activities are the transshipment of inventory from one warehouse to another, and interdependencies originate from the inventory and personnel resources shared between the warehouses to conduct inventory transshipments. To manage the interdependencies effectively, warehouse managers communicate and share information, which composes the coordination mechanisms (Crowston, 1997). Inventory transshipment becomes more important for large valuable items like refrigerators, so they can be re-positioned in the right quantities at the order penetration point that serves a particular region. According to coordination theory, the cost of coordination is an important factor to consider when firms implement coordination mechanisms (Crowston, 1997) to manage the interdependencies between actors (Malone & Crowston, 1994).

Research shows that coordination mechanisms fall into two different types—structured coordination and unstructured coordination (Claggett & Karahanna, 2018). Structured coordination refers to the "mechanisms that predetermine how, when, and with whom to coordinate information via routine processes" (Claggett & Karahanna, 2018, p. 708), such as the inventory replenishment heuristics. Unstructured coordination, on the other hand, "occurs in situations where actors have the autonomy to make decisions about how coordination takes place, which is commonly associated with environments that leverage workers' knowledge" (Claggett & Karahanna, 2018, p. 708). Much of the existing literature in supply chain management has focused on structured coordination mechanisms. As previously discussed, however, these mechanisms may not work well when warehouses need to make last-minute adjustments to match supply and demand (Tushman & Anderson, 1986) due to changes in local conditions. Instead, warehouses conduct last-minute coordination, an unstructured coordination mechanism that leads to adjustments to inventory positions and transshipments of inventory between warehouses in response to emergent demand changes in the regions they serve.

2.3 | Last-minute coordination: Loose coupling among warehouses

The concept of coupling can further provide an overarching framework to help understand last-minute coordination. Coupling refers to how elements of a system are linked or connected (Weick, 1976). The connections may differ in their strength or frequency. Loose coupling, according to Weick (1976), "is a situation in which elements are separate but also coupled because elements are somehow connected and responsive to one another" (Liu et al., 2012, p. 357). Unlike a tightly coupled system where elements directly depend on one another, causing a change in one element to affect another, elements in a loosely coupled system remain largely independent but still exert a certain degree of mutual influence. Literature suggests several benefits of developing a loosely coupled system, including enhanced system persistence (Wilson & Dickson Corbett, 1983), buffers in the system (Weick, 1976), and increased system adaptability (Weick, 1979). Operations management (OM) scholars have applied loose coupling theory to various contexts. For example, Choo et al. (2007) argued that loose coupling between contextual and methodological elements in a comprehensive quality program can sustain a quality advantage. Liu et al. (2012) viewed supply chains as loosely coupled systems and examined how mutually perceived justice drives the coupling of joint interests between buyers and suppliers.

In our context, last-minute coordination is a loose coupling mechanism because local actors (i.e., warehouses) connect and transship inventory among themselves on an as-needed basis to adjust to the uncertainty inherent in the broader system (i.e., supply and demand uncertainties) (Holweg & Pil, 2008; Orton & Weick, 1990). The warehouses are interdependently connected because they have to coordinate for last-minute transshipment. At the same time, connected warehouses are also independent because such connections are subject to changes and needs. The last-minute coordination network is then a loosely coupled system, as each warehouse is independent, yet interdependently sharing resources and coordinating together to facilitate inventory transshipment, which helps achieve the goal of better matching supply with demand. This type of system can better handle occasional disruptions and adapt to changing market dynamics (Orton & Weick, 1990), as opposed to a tightly coupled system that is more efficient in stable environments. With this, we expect warehouses to conduct last-minute coordination, which is autonomous, reactive, and not predetermined, to address local changes in last-mile operations and fulfill customer demands.

3 | HYPOTHESIS DEVELOPMENT

In this section, we draw from coordination (Malone & Crowston, 1990, 1994) and loose coupling theory (Orton & Weick, 1990; Weick, 1976) to first examine the effect of last-minute coordination on individual warehouse performance. We then examine the effect of a last-minute coordination pattern on network-level performance. Last, we delve into the relationship between demand uncertainty and the dynamics of last-minute coordination network.

3.1 | Last-minute coordination and individual warehouse performance

When actors coordinate with each other in a system to manage interdependencies, they spend time, effort, and resources to communicate and share information to achieve goals and align their actions (Thompson, 1967). This incurs coordination costs (Handley & Benton Jr., 2013; Malone & Crowston, 1994). For warehouses engaging in last-minute coordination, such costs may include altering product mix, assessing inventory levels, locating specific shipments, responding to inquiries, and shipping products to other warehouses to manage the *transfer interdependencies* noted in Malone and Crowston (1994). An individual warehouse can potentially coordinate with many different warehouses or only a few warehouses. We define *coordination scope* as the number of warehouses with which the focal warehouse engages in last-minute coordination. Given that a larger coordination scope results in higher coordination costs, we argue that it has a negative effect on operational efficiency.

In a loosely coupled system that originates from last-minute coordination, a larger scope means more complex interdependencies that the focal warehouse must manage (Choi & Hong, 2002; Dooley, 2001; Zhou & Wan, 2017). In other words, increasing the number of interdependencies between the focal warehouse and its exchanged partners increases the complexity of coordinating the information and material flows (Bozarth et al., 2009), leading to a higher likelihood of "spending substantial time and effort to coordinate with a partner" (White & Lui, 2005, p. 925). This can lead to elevated coordination costs, as evidenced by heightened workloads related to communication and the processing of additional information stemming from warehouse heterogeneity (Anderson & Dekker, 2005; Handley & Benton Jr., 2013). The increased coordination costs subsequently reduce the operational efficiency of the focal warehouse (Choi & Krause, 2006; Grover & Malhotra, 2003). Collectively, we propose the following hypothesis.

> **Hypothesis 1.** A warehouse's operational efficiency decreases with the scope of its last-minute coordination.

3.2 | Last-minute coordination and network performance

Previous hypothesis examines the effect of the scope of last-minute coordination on an individual warehouse's performance, but what about the effect on the overall network? We conjecture that the configuration of last-minute coordination links among warehouses influences the overall coordination costs at the network level, further affecting the network-level operational efficiency. We propose that the *centralization* of a loosely coupled system, which reflects the degree of concentration of last-minute coordination among warehouses, is associated with network-level operational efficiency.

A centralized coordination network, that is, high network centralization, indicates that last-minute coordination activities are concentrated in a few warehouses (i.e., the central warehouses). In other words, a few actors in the network coordinate with other actors (through communication and information sharing) to manage the transshipment activities. This structure results in lower coordination costs at the network level in the following two aspects. First, this coordination structure spans several warehouses without engaging too many other warehouses (Rivkin & Siggelkow, 2007), which limits the extent of interdependencies to be managed through coordination mechanisms. Stated differently, in a centralized coordination network, peripheral (non-central) warehouses only coordinate with certain central brokers rather than many other warehouses, so they can focus on their routine operations without being distracted by managing many complex interdependencies. Compared to the situation where all warehouses are loosely coupled with each other, limiting most last-minute coordination activities to a few (central) warehouses reduces the overall coordination costs. Therefore, the resulting centralized network structure represents a more efficient loosely coupled system to match supply and demand at the last minute.

Second, as warehouse managers (i.e., actors) accumulate coordination experience, they can take advantage of learning to reduce marginal coordination costs (Crowston, 1997). In this sense, when a group of warehouses needs to conduct last-minute coordination, they would better coordinate in a centralized structure, which allows the central warehouse to take advantage of the reduced marginal cost. As a result, by making central warehouses (rather than peripheral ones) engage in most of the last-minute coordination, this centralized coordination pattern reduces the overall coordination costs, leading to better operational efficiency at the system level. In comparison, a decentralized or well-connected coordination pattern implies that last-minute coordination is less concentrated but conducted by many warehouses (Su et al., 2023). In this case, each warehouse has to manage a certain amount of interdependencies, which increases the overall coordination costs across the network, leading to reduced operational efficiency at the system level.

In sum, a more centralized structure of last-minute coordination network reduces the overall coordination costs to a larger extent and is perhaps the most efficient pattern among all possibilities (e.g., a completely decentralized or a well-connected coordination pattern) (Rivkin & Siggelkow, 2007). Indeed, as Cardinal (2001) pointed out, "centralization can improve processing efficiency" (p. 24) for the system. We contend that a more centralized last-minute coordination structure leads to better network-level operational efficiency.

> **Hypothesis 2.** The centralization of last-minute coordination is positively related to network-level operational efficiency.

3.3 | Demand uncertainty and last-minute coordination

In this subsection, we examine the relationship between demand uncertainty and the dynamics of last-minute coordination among warehouses. Demand uncertainty refers to the degree of variability or dynamism in customer demand that warehouses face (Child, 1972; Dess & Beard, 1984) and is often measured by the rate of change in demand for products. In the fast-paced e-commerce market, demand uncertainty increases the likelihood of warehouses experiencing sudden spikes or drops in demand. Consequently, this necessitates activities like inventory transshipments to match supply and demand in real time. In other words, demand uncertainty prompts warehouses to conduct last-minute coordination, resulting in loose coupling among warehouses. This perspective also aligns with the notion that uncertain conditions can lead to loose coupling within the system for adaptation purposes (Faulkner & Anderson, 1987; Weick, 1976).

We posit that high demand uncertainty *reinforces* the existing coordination pattern in a loosely coupled system. That is, under increasing demand uncertainty, warehouses are more inclined to conduct last-minute coordination with prior connections than to establish new connections with other warehouses. The reason is that establishing new connections requires actors to conduct coordination-related activities such as searching for potential partners, building trust, securing new transportation arrangements, and establishing ways to communicate and share information (Choi & Krause, 2006). These activities incur additional coordination costs. Given the likelihood of frequent last-minute coordination under high demand uncertainty, establishing coordination mechanisms with new actors would result in even higher coordination costs (Malone & Crowston, 1994). Therefore, focal warehouses would prefer to conduct last-minute coordination with the warehouses with which they have already invested in building trust and relationships, negotiated agreements, and established monitoring mechanisms (Grover & Malhotra, 2003).

That is, actors would prefer to coordinate with those whom they have developed coordination mechanisms with in the past. This is also in line with the finding that loosely coupled systems tend to "evolve to maximize some measure of 'goodness' or fitness" (Choi et al., 2001, p. 355), where the "measure of 'goodness' or fitness," in our context, refers to the reduction of coordination costs.

To conclude, we propose that, by relying more on the existing last-minute coordination partners, warehouses can effectively respond to demand uncertainty, all while avoiding additional coordination costs associated with creating new connections. The pattern of last-minute coordination evolves toward reducing the overall coordination costs across the entire set of warehouses.

Hypothesis 3. Increasing demand uncertainty reinforces existing last-minute coordination patterns among warehouses.

4 | RESEARCH CONTEXT AND VARIABLES

4.1 | Warehouse operations

We examine the last-minute coordination network among the warehouses of Alpha, a global leading logistics management company. Alpha has over 322 million square feet of warehousing and storage space worldwide, processes an average of over 57 million packages per day, and can ship through over 90,000 distribution routes in partnership with other couriers. Alpha manages warehouses that store, sort, and package products. It also provides services such as sales planning, demand forecasting, inventory replenishment, and order fulfillment to online business-to-consumer (B2C) merchants, worldwide. This study focuses on a portion of Alpha's warehouse network, that is, the customer-facing warehouses for large electric appliances such as refrigerators, dishwashers, washing machines, and air conditioners. Given that large electric appliances require higher shipping and handling efforts, it is important to manage inventory properly at the order penetration points to ensure the smooth progression of subsequent delivery processes. In addition, large electric appliances account for a large portion of Alpha's revenue, and their high margins prompt warehouses to conduct last-minute coordination to balance demand and supply. To improve the accuracy of the empirical analyses, we focus on one single product category that consists of relatively homogeneous products in terms of prices and costs. This approach helps reduce the confounding effects of product characteristics on operational efficiency, ensuring that our results are more precise and reliable.

We are able to track the last-minute coordination network for 80 weeks in 2017–2018 (dates remain unspecified due to confidentiality). Figure 1 presents a sample coordination network snapshot in week 50. Nodes are warehouses. Arrows represent last-minute coordination activities between warehouses in week 50. Coordination links vary across time because not all warehouses engage in last-minute coordination every week. According to Figure 1, the network of Alpha's customer-facing warehouses is designed for efficient last-mile operations across a broad region and relies on a decentralized allocation of inventory. For Alpha, last-minute coordination plays a crucial role in facilitating last-mile delivery and ensuring a high customer service level given dispersed inventory allocation across the network.

Online retailers place significant emphasis on maintaining a high service level to satisfy their customers. The service levels across Alpha's warehouses are high and comparable. Figure 2 presents a box plot of warehouse service levels provided by Alpha. The mean weekly service level is about 94%, with a standard deviation of 0.03. Last-minute coordination provides individual warehouses with the flexibility to make local adjustments and organize inventory transshipments. This enables the warehouses to effectively balance fluctuating demand and supply, thereby maintaining a high service level.

4.2 | Data, variables, and measurements

We obtain the data at the SKU-warehouse-day level from Alpha. Since the unit of analysis is the warehouse-week combination, we process the data as follows. We first aggregate stock-keeping units (SKUs) to the warehouse level each day. The aggregation makes practical sense because once inventory enters the warehouse, it is managed in the same way regardless of the supplier/merchant. The aggregation can also help smooth out random variations among SKUs. We then aggregate the daily data into weekly data to obtain demand uncertainty and smooth out daily noises.

Alpha records the number of daily transshipments (i.e., trips into and out of warehouses) as a result of last-minute coordination. Alpha also provides the daily total number of items moving into and out of every warehouse. The final data set has a total of 6054 observations at the warehouse-week level with 179 unique warehouses across 80 weeks.

4.2.1 | Operational efficiency

We measure operational efficiency using *inventory turnover*, which has been well established in the literature to

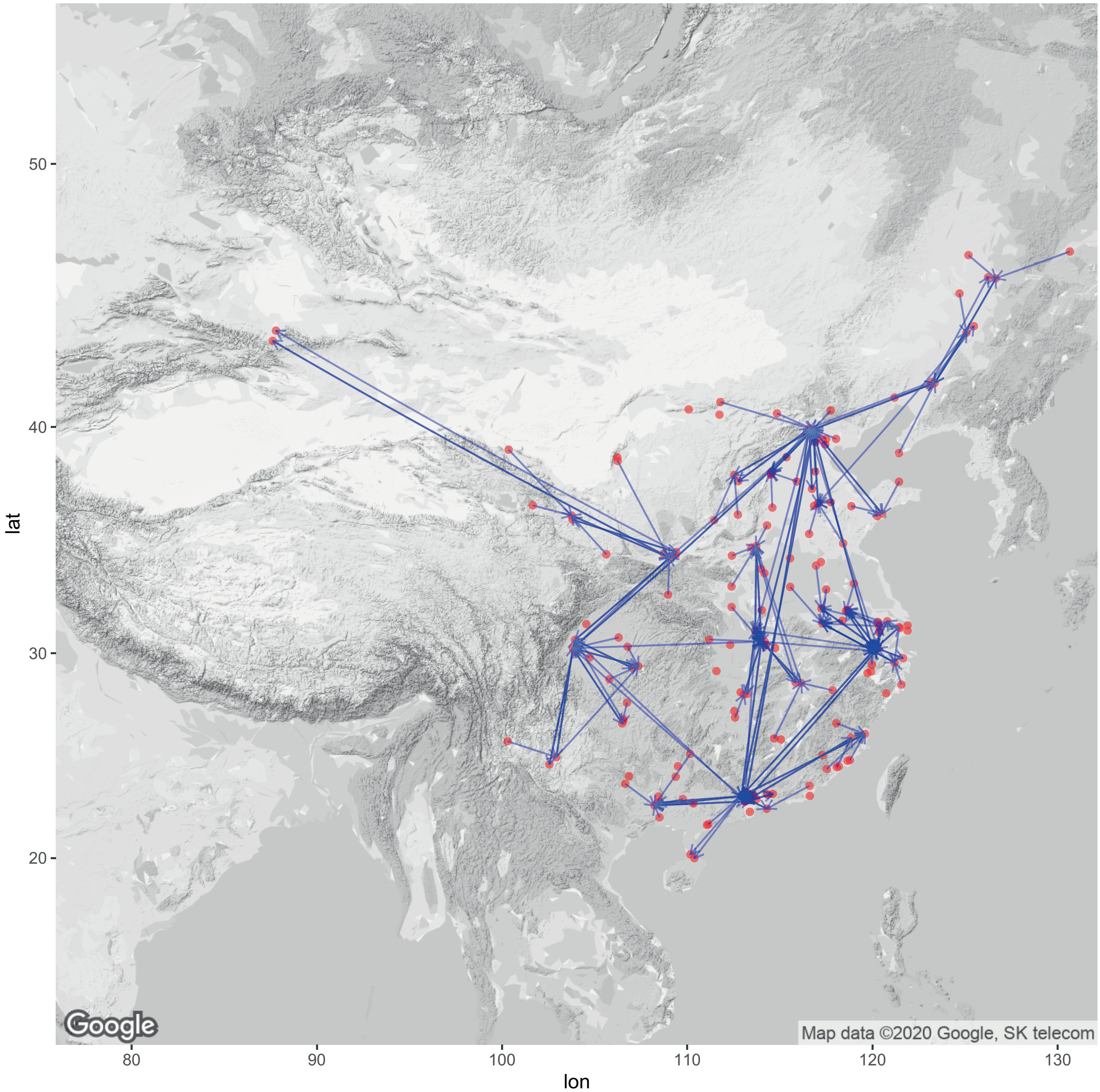

FIGURE 1 A sample warehouse coordination network in week 50.

assess warehouse performance (Lee, 2004; Mapes, 2015). Inventory turnover reflects the degree of economic benefits and is calculated as the total demand over the average inventory in a week. To measure sales and inventory levels in our estimation of inventory turnover, we use quantities in place of monetary amounts due to the confidential nature of product price and cost information.

At the warehouse level, we estimate inventory turnover for each warehouse-week combination in the following manner: (1) calculate the inventory turnover of each SKU in a warehouse in a week and (2) average across all SKUs in a warehouse to obtain the measure. At the network level, we operationalize operational efficiency as the ratio between the sum of all warehouses' sales quantities in a week and the average inventory level of the entire network in a week.

4.2.2 | Coordination measures

There are two variables related to the last-minute coordination network. First, the *scope* of a focal warehouse's

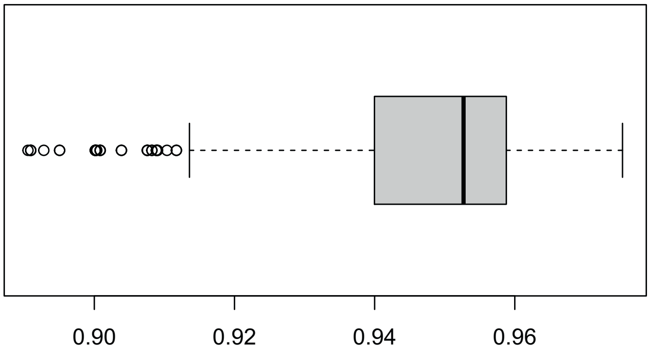

FIGURE 2 A box plot of warehouse service levels.

ego coordination network (i.e., *coordination scope*) is measured by the number of warehouses that the focal warehouse coordinates with. Particularly, we (1) count the daily number of warehouses that a warehouse coordinates with and (2) average the daily numbers within a week for each warehouse. Essentially, we operationalize coordination scope as the degree centrality of a warehouse, which we believe is the most appropriate among various centrality measures. From a conceptual sense, we argue that increasing the number of warehouses with which the focal warehouse coordinates (i.e., coordination scope) relates to coordination costs and the extent of system complexity. In the literature, degree centrality "builds on an observation that the more links a node has the more central it is" and is linked with "operational load" (Kim et al., 2011, p. 196). Hence, degree centrality provides a direct measure of coordination scope. In our context, a larger degree centrality indicates more last-minute coordination links and hence higher coordination costs and a more complex system. On the contrary, other widely used centrality measures such as betweenness and eigenvector centralities reflect different conceptual aspects such as informational independence, "gatekeeping," and flow control (Kim et al., 2011), which are conceptually distant to what we intend to measure.

Second, the *centralization* of the coordination network measures the extent to which there is a small number of highly central nodes in the network. The extent of network-level centralization is calculated based on node-level centrality measure (degree centrality) through the following formula:

$$C(G) = \sum_{i \in V(G)} \left(\max_{v} c(v,G) - c(i,G) \right), \tag{1}$$

where, G is the network, $V(G)$ is the set of all nodes in G, and $c(v,G)$ is the centrality of node v. For example, a star-shaped network tends to have a higher centralization score than a complete graph in which every node is connected to others.

4.2.3 | Demand uncertainty

Demand uncertainty represents the variability originating from customers and sales markets, which is beyond the individual warehouse's control. Demand uncertainty can significantly impact inventory turnover (Gaur et al., 2005). In this study, we consider demand related only to end-consumers and sales markets; that is, demand from other warehouses is not considered. Demand uncertainty is calculated as the coefficient of variation (CV) of a warehouse's daily demand across all SKUs within a week.

4.2.4 | Control variables

The following control variables are included in the analysis to ensure the validity of our results.

Throughput quantity measures the total items moving into and out of a warehouse in a week, capturing the effect of the physical flow of products. It is important to include the total quantity of items through a warehouse because the flow of large numbers of products through a warehouse usually implies high warehouse inventory turnover. We control for the effect of physical product flow on a warehouse's operational efficiency.

We follow Wan et al. (2012) and measure *SKU variety* in a warehouse as the number of stock-keeping units (SKUs) at a warehouse in a week. This is a simple yet well-accepted measure of product variety in the literature (Alfaro & Corbett, 2003; Fisher & Ittner, 1999). We provide an alternative measure using Shannon's entropy as a robustness check (see Online Appendix A.2).

Warehouse demand is a warehouse's weekly demand that could affect the warehouse's operational efficiency. Warehouse demand is calculated as the sum of a warehouse's daily demand across all SKUs within a week. It is included in the empirical model as a control variable.

Regional demand measures the sum of sales in the region(s) that the warehouse serves over a week, as a warehouse can ship to multiple cities or regions. Including regional demand mitigates the effects of factors such as the clustering of warehouses in certain geographic locations on the warehouse's operational efficiency.

Finally, we create *warehouse dummies* and *week dummies* to control unobserved individual and time heterogeneity.

4.2.5 | Network endogeneity and instrumental variables

The notion that locations of warehouses are not randomly chosen is well established in the empirical literature. For example, Holmes (2011) explicitly demonstrated this endogeneity issue. Houde et al. (2017) also provided similar evidence and used an instrumental variable (IV) approach to deal with this endogeneity issue. The choice of warehouse locations, or positions, may depend on proximity to potential customers, competition in the service area, customer characteristics in the service area, and so forth. Extant literature has indicated that not accounting for endogeneity is an issue in prior research on networks (Carpenter et al., 2012). To address the endogeneity of network-related variables, following previous literature (e.g., Zhou & Wan, 2017), we use lagged variables (lag by one period) as IVs for the related network measures.

Lagged variables meet both requirements for instruments—relevance (i.e., identifiability) and exogeneity (i.e., the exclusion restriction). Lagged coordination scope is strongly correlated with the current scope of the network and satisfies identifiability due to the equal number of endogenous variables. In terms of the exclusion restriction, lagged warehouse network-related variables (in the last period) do not directly affect the current period's inventory turnover. Moreover, inventory turnover is a performance metric that is evaluated *ex post*, that is, when the review cycle ends. Inventory turnover is by nature measured *after* the last-minute coordination activities occurred.

4.3 | Summary statistics

We report the summary statistics and the correlation matrix of the variables in Table 1. We observe that inventory turnover is strongly correlated with the scope of last-minute coordination and also correlated with several controls, justifying the inclusion of the control variables.

5 | RESEARCH METHODS AND ANALYSES

In this section, we describe the methods used to verify the three hypotheses and present the results. In addition, we perform robustness checks to ensure our findings are not driven by measurement, data sampling, or empirical specification. The robustness check results are included in the online appendix.

5.1 | Examining H1 (individual warehouse performance)

In this subsection, we examine the effect of coordination scope on a warehouse's operational efficiency. We employ a two-stage least-square fixed-effects (2SLS-FE) model. We include warehouse and time fixed effects to account for unobserved individual heterogeneity and potential time effects. For instance, warehouses may have managers with different experiences and coordination skills. A fixed-effects model accounts for this kind of heterogeneity and eliminates warehouse-specific effects. Empirically, the Hausman test supports our choice of the two-way fixed-effects model (Chisq = 895.05*** and df = 7 for the main model). Further, the widely adopted 2SLS method is integrated with the fixed-effects model to account for the network endogeneity in the panel data. We show the first and second-stage equations of main effects for illustrative purposes, whereas in the analysis we estimate the coefficients simultaneously using `R` package `plm` (Croissant & Millo, 2018), as running two separate regressions for two stages leads to biased standard errors for β in the second-stage regression (Stock & Watson, 2011).

Equation (2) shows the first-stage equation for coordination scope.

$$\begin{aligned} Coord\_scope_{it} = {} & \gamma_i + \phi_t + \delta Lag\_scope_{it} \\ & + \theta_1 Dmd\_unc_{it} + \theta_2 Thru\_quant_{it} \\ & + \theta_3 SKU\_var_{it} + \theta_4 Wh\_dmd_{it} \\ & + \theta_5 Region\_dmd_{it} + \eta_{it}, \end{aligned} \tag{2}$$

where, Lag_scope_{it}, Dmd_unc_{it}, $Thru\_quant_{it}$, SKU_var_{it}, Wh_dmd_{it}, and $Region\_dmd_{it}$ stand for the lagged coordination scope, demand uncertainty, throughput quantity, SKU variety, warehouse demand, and regional demand for warehouse i at time t, respectively; γ, ϕ, δ, θ are the parameters for the model; and η_{it} is the residual term. The second-stage equation is:

$$\begin{aligned} Inv\_Turn_{it} = {} & \alpha_i + \tau_t + \beta Coord\_scope_{it} \\ & + \xi_1 Dmd\_unc_{it} + \xi_2 Thru\_quant_{it} \\ & + \xi_3 SKU\_var_{it} + \xi_4 Wh\_dmd_{it} \\ & + \xi_5 Region\_Dmd_{it} + \pi \widehat{\eta}_{it} + \varepsilon_{it}, \end{aligned} \tag{3}$$

where, α_i and τ_t represent the unobserved individual and time heterogeneity; $Coord\_scope_{it}$ represents coordination scope for a warehouse; $\widehat{\eta}_{it}$ is the estimated residuals from the first-stage equation; and ε_{it} is the random error.

We have performed model diagnostics to ensure the validity of our results. We performed the variance inflation factors (VIF) analysis to check the multicollinearity. The VIFs for all variables in the analysis are below 5, which are lower than the critical value of 10 (Kutner et al., 2005), indicating that multicollinearity is not a

TABLE 1 Summary statistics and correlation matrix of the variables.

	Variables ($N = 6054$)	Mean	SD	Median	Min	Max	V1	V2	V3	V4	V5	V6
1	Inventory turnover	17.45	24.8	10.6	0.02	329.33						
2	Coordination scope	2.32	1.7	1.67	1	11	−0.21***					
3	Demand uncertainty	0.4	0.29	0.32	0.02	2.45	−0.05***	0.09***				
4	Throughput quantity	2999.55	16,268.99	200	0	645,748	0.15***	−0.16***	−0.05***			
5	SKU variety	315.81	16.43	317	198	339	−0.50***	0.61***	−0.24***	0.65***		
6	Warehouse demand	2498.75	9690.64	574.07	0.14	244,715.1	−0.04***	−0.01	0.52***	−0.07***	0.19***	
7	Regional demand	1,517,707	2,355,117	824,467.5	14,855	28,177,205	0.03*	0.17***	0.33***	−0.11***	0.04***	0.50***

Note: Variables are in their original scales. The last six columns show the correlation matrix. Pearson's paired test for the correlation matrix.
$^{\dagger}p < .1$; $^{*}p < .05$; $^{**}p < .01$; $^{***}p < .001$ (two-tailed).

concern. The studentized Breusch–Pagan test (Breusch & Pagan, 1980) indicates heteroskedasticity (BP = 559.1***, df = 7). The Breusch–Godfrey/Wooldridge test for serial correlation (Breusch, 1978; Godfrey, 1978) indicates serial correlation (Chisq = 1634.3*** and df = 1). The existence of heteroskedasticity and autocorrelation may cause inconsistent standard errors of the coefficients, reducing the explanatory power (Arellano, 2003). Hence, we have used a robust covariance matrix that allows a fully general structure with respect to heteroskedasticity and serial correlation to obtain consistent standard errors for the models.

Table 2 shows the results for the 2SLS-FE estimation. Model (1) in Table 2 presents the association between the control variables and inventory turnover. Warehouse throughput quantity increases inventory turnover, indicating the positive effect of physical product flow. SKU variety reduces inventory turnover, indicating that more SKUs add difficulty to inventory management. Warehouse demand increases inventory turnover, which confirms the notion that higher demand usually leads to quicker inventory turnover (Gaur et al., 2005). Model (2) shows a negative effect of coordination scope (coef = −0.137***), indicating that as the number of warehouses a focal warehouse coordinates with increases, there is a corresponding reduction in the focal warehouse's operational efficiency. Therefore, H1 is supported.

We conduct the following robustness checks to strengthen the validity of our findings. First, considering that the lagged independent variable could still be correlated with the error term because the safety stock or the overall stock level may directly impact inventory turnover, we include one additional instrument into our warehouse-level 2SLS model using the heteroskedasticity-based instrumental variable (HBIV) method (Quiroga, 2021) (see Online Appendix A.1). Second, we adopt alternative measures for *SKU variety* and *coordination scope* in the model (see Online Appendix A.2). Third, we reanalyze a smaller sample without temporary warehouses (see Online Appendix A.3). Fourth, we include operational effectiveness as a control variable to address the concern that operational efficiency and effectiveness interplay and affect each other (see Online Appendix A.4). Fifth, considering that an outgoing link that coordinates to ship out items may operate differently from an incoming link that coordinates to receive items, we take coordination directionality into account when measuring *coordination scope* (see Online Appendix A.5). The robustness check results are consistent with the main findings. We present more details in the online appendix.

TABLE 2 The effect of coordination scope.

	DV: Log(Inventory Turnover)	
Models	**(1)**	**(2)**
Dmd_unc	−0.001	−0.002
	(0.009)	(0.009)
Thru_quant	0.109***	0.127***
	(0.019)	(0.015)
SKU_var	−0.038***	−0.039***
	(0.005)	(0.005)
Wh_dmd	0.748***	0.753***
	(0.077)	(0.077)
Region_dmd	−0.147	−0.157
	(0.113)	(0.109)
Coord_scope		−0.137***
		(0.037)
Observations	6054	6054
Pseudo Adj. R^2	0.190	0.183
Pseudo *F* or Chisq	335.7***	1677***

Note: Standard errors of coefficients are displayed in the parentheses. Independent variables are log-transformed to mitigate skewness. Pseudo Adj. R^2 and *F* statistics may not be interpretable.
*$p < .05$; **$p < .01$; ***$p < .001$.

5.2 | Examining H2 (last-minute coordination and network performance)

The warehouse-level analysis demonstrates the negative effect of coordination scope on an individual warehouse's operational efficiency. In this subsection, we examine how the configuration of the last-minute coordination network affects network-level performance. To tease out the effect of network-level *centralization*, we include the density of the network and the number of last-minute coordination tasks to control for potential confounders. Particularly, the density of the network is measured as the ratio between the number of links and the number of total possible links that the network could have, and the number of last-minute coordination tasks is the count of coordination links across the entire network within a week. In this way, we obtain four time series for analysis. We conduct robustness checks by considering coordination directionality in the operationalization of the network-level variables (see Online Appendix A.5).

Methodologically, we follow Wooldridge (2016) and adopt a static multiple regression model with detrended variables to analyze multiple time series. The model is in the following form.

$$
\begin{aligned}
Net\_Inv\_Turn_t = \beta_0 + \beta_1 Net\_Dense_t \\
+ \beta_2 Coord\_Task_t \\
+ \beta_3 Net\_Centralization_t + \beta_4 t + \varepsilon,
\end{aligned}
\tag{4}
$$

where, *Net_Inv_Turn* is the network-level inventory turnover; *Net_Dense* is the network density; *Coord_Task* is the number of last-minute coordination tasks; *Net_Centralization* is the network-level centralization; β's are yet-to-be estimated coefficients; and the term $\beta_4 t$ plays the role of detrending based on the Frisch-Waugh theorem. Considering that the time series of network-level inventory turnover may share the same trend with the time series of density, coordination tasks, and/or centralization, which can affect the significance of the coefficients, we include the term $\beta_4 t$ to avoid spurious relationships between these variables. We apply the Arellano correction to standard errors because the error term in the model may suffer from heteroskedasticity and serial correlation.

Model diagnostics show that network performance is significantly correlated with the *current* centralization (see Figure 3, where the correlation at lag 0 is the largest and exceeds the blue dashed line of significance). Therefore, no lagged predictors are included in the model.

Table 3 shows the network-level results. We enter the three independent variables separately into models (1), (2), and (3) to show that the results are not driven by collinearity. Based on models (3) and (4), network centralization is positively significant (coef = 1.635*) after we apply regression diagnostics and the Arellano correction. Hence, the centralization of the last-minute coordination network is positively related to network-level operational efficiency. Therefore, H2 is supported.

5.3 | Examining H3 (demand uncertainty and last-minute coordination)

We employ the Separable Temporal Exponential Random Graph Model (ST-ERGM) to examine the antecedents to last-minute coordination. The ST-ERGM is an extension to the Exponential Random Graph Model (ERGM) (Holland & Leinhardt, 1981), which represents a general class of models based on exponential-family theory for specifying the probability distribution underlying a set of networks. While the ERGM provides a single model for the prevalence of links in a cross-sectional single network (we refer readers to Robins et al. (2007) for an introduction of the ERGM), the ST-ERGM can model dynamic networks in discrete time (Krivitsky & Handcock, 2014).

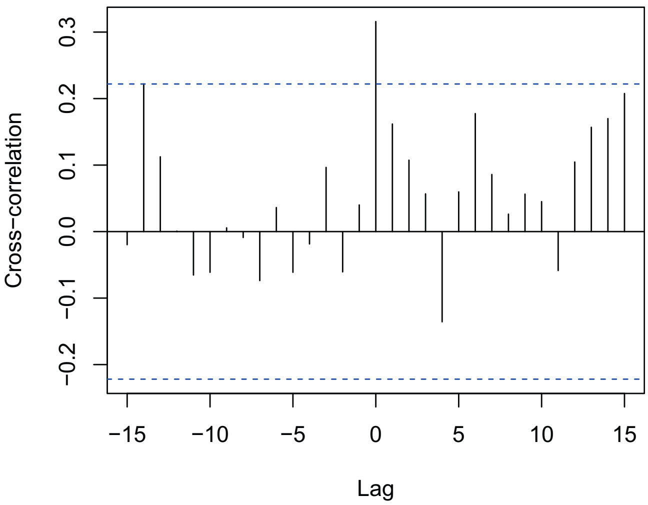

FIGURE 3 Cross-correlation between network centralization and network inventory turnover. Cross-correlation plots between other network measures and network performance show similar patterns.

Specifically, the ST-ERGM posits two models for the link dynamics in a network over time: one for link formation and the other for link dissolution. The ST-ERGM assumes formation is independent of dissolution within a time step and Markov dependent between steps.

The ST-ERGM in essence obtains maximum likelihood estimates for link formation and dissolution of a dynamic network model. In supply chain and operations management, Park et al. (2018) is one of the few studies that used the ST-ERGM, in which they investigated the evolution of the strategic alliance network. In this study, we build an ST-ERGM model that includes demand uncertainty to examine the degree to which demand uncertainty affects the formation and dissolution of last-minute coordination links. A simplified expression of the model is as below.

$$DynamicNetwork \sim Form(\sim Edges + Mutual + GWESP(\alpha = 0.5) + Dmd\_unc) + Diss(\sim Edges + Mutual + GWESP(\alpha = 0.5) + Dmd\_unc). \quad (5)$$

The "Form" part stands for the formation of the links while the "Diss" part represents the dissolution. A positive coefficient in the formation part is interpreted as a positive effect of the variable to increase the probability of link formation, while a positive coefficient in the dissolution part means to increase the probability of dissolution of the link. "Edges" and "Mutual" are added to the ST-ERGM as structure-related control variables. "GWESP" (geometrically weighted edgewise shared partner) is included to test for possible triad formation bias and account for the endogenous triangle formation. The α is the decay parameter between 0 and 1. We set α to a commonly used (middle) level of .5, to avoid drastic discounting applied to subsequent shared partners.

Table 4 displays the results of fitting the link formation and dissolution processes. We fit three ST-ERGM models, with demand uncertainty of a head in a link (1.a and 1.b), of a tail (2.a and 2.b), and of both nodes (3.a and 3.b).[2] The results show generally consistent patterns that demand uncertainty reduces both link formation and dissolution. Specifically, for models 3.a and 3.b that have the lowest AIC and BIC, ceteris paribus, a last-minute coordination link is less likely to form if the two nodes of the link have high demand uncertainty (the conditional log-odds of formation decreases by 2.6e−5), but the link is less likely to dissolve when demand uncertainty is high (the conditional log-odds of dissolution decreases by 1.558e−5). Taken together, when demand uncertainty is high, warehouses tend to coordinate with other warehouses that were previously coordinated with and reduce the likelihood of coordinating with new warehouses. Therefore, H3 is supported.

6 | DISCUSSION

6.1 | Theoretical implications

This research explores the effects of *last-minute coordination* at order penetration points, the starting points of last-mile operations. Unlike prior studies that focus on structured planning mechanisms in tightly connected systems, this study focuses on last-minute coordination, an unstructured, loosely coupled behavior that leads to inventory transshipment between customer-facing warehouses. Our empirical evidence underscores the importance of unstructured coordination in last-mile operations. The research findings represent an initial step toward comprehending this

TABLE 3 Network-level regression results with robust SE.

Models	Dependent variable: Log(Net Inv Turn) (1)	(2)	(3)	(4)
Num_coord_tasks	−0.001			−0.001
	(0.001)			(0.001)
Net_density		1.688		0.916
		(1.615)		(1.972)
Net_centralization			1.457*	1.635*
			(0.716)	(0.736)
Week	−0.005***	−0.005***	−0.005***	−0.004**
	(0.001)	(0.001)	(0.001)	(0.001)
Constant	2.517***	2.337***	2.107***	2.127***
	(0.136)	(0.110)	(0.171)	(0.218)
N	80	80	80	80
Adj R^2	0.237	0.230	0.271	0.286
F stat.	12.962***	12.499***	15.342***	8.707***

Note: Standard errors of coefficients are displayed in the parentheses.
*$p < .05$; **$p < .01$; ***$p < .001$.

TABLE 4 STERGM models and results.

Models	1.a Formation	1.b Dissolution	2.a Formation	2.b Dissolution	3.a Formation	3.b Dissolution
Edges	−7.232***	1.653***	−7.267***	1.610***	−7.173***	1.659***
	(4.524e−2)	(5.311e−2)	(4.924e−2)	(5.095e−2)	(4.887e−2)	(5.405e−2)
Mutual	6.467***	−1.259***	6.454***	−1.264***	6.407***	−1.271***
	(6.567e−2)	(7.876e−2)	(6.857e−2)	(7.580e−2)	(6.739e−2)	(7.698e−2)
GWESP ($\alpha = .5$)	5.463e−1***	−1.103***	5.587e−1***	−1.102***	5.436e−1***	−1.101***
	(2.897e−2)	(1.015e−1)	(2.822e−2)	(9.994e−2)	(2.748e−2)	(1.046e−1)
Dmd_unc (head)	−4.168e−5***	−3.316e−5***				
	(7.088e−6)	(7.404e−6)				
Dmd_unc (tail)			−2.568e−5***	−5.613e−6		
			(5.442e−6)	(6.619e−6)		
Dmd_unc (both)					−2.6e−5***	−1.558e−5***
					(3.829e−6)	(3.803e−6)
AIC	17,978		18,048		17,976	
BIC	18,069		18,140		18,067	

Note: GWESP stands for geometrically-weighted edgewise shared partner, which accounts for the endogenous triangle formation. α is a decaying parameter for discounting additional shared partners or degrees. Standard errors of coefficients are displayed in the parentheses.
*$p < .05$; **$p < .01$; ***$p < .001$.

adaptive behavior that warehouses engage in to ensure that they have sufficient inventory at the order penetration points when formal structured coordination mechanisms prove insufficient. Beyond order penetration points, our findings hold broader implications for the last-mile operations process. We outline three theoretical implications of this research.

First, this study extends prior research on emergency transshipments (e.g., Evers, 1997; Rabinovich, 2005) and supply chain responsiveness (e.g., Richey et al., 2022) to fill a gap in last-mile operations research (Lim et al., 2018). We unpack the effects of last-minute coordination at the order penetration points and the corresponding coordination network. Drawing on coordination and loose coupling theories, we show that last-minute coordination improves operational efficiency at the network level, which demonstrates the role of last-minute coordination in ensuring the efficiency of the last-mile delivery process and, consequently, customers' overall online shopping experience. This finding is particularly important for firms managing large, low-value-density products, where they must balance space constraints and high transportation costs to ensure efficient order fulfillment.

Second, the negative effect of last-minute coordination on individual warehouse operational efficiency demonstrates a tension between node-level and network-level outcomes, which resembles a long-standing global–local tension in operations (see for example Sterman et al. (2015)), that is, the tension between individual and collective interests. The analysis shows that increasing last-minute coordination scope decreases an individual warehouse's operational efficiency. However, the entire network of warehouses benefits from last-minute coordination even though a few central warehouses' operational efficiency decreases. In other words, when a few central warehouses do most of the last-minute coordination, they help improve the overall efficiency of the network but do so at an individual's cost. This observation reflects the adage that "a local optimal solution rarely equals the global optimal solution." In this setting, a few central warehouses play an important role in facilitating the transshipment of goods across the network of warehouses.

Third, prior studies have suggested that last-minute coordination, as an improvised activity, is a response to changes in the external environment (Richey et al., 2022). However, little research has explored how such activity emerges and unfolds over time. This study demonstrates that demand uncertainty affects the evolution of last-minute coordination. That is, within order penetration points, last-minute coordination emerges, and inventory transships, in order to adapt to increasing demand uncertainty. We further demonstrate the evolution pattern of last-minute coordination is that warehouses prefer persistence rather than change. Warehouses do not necessarily coordinate with other (new) warehouses but instead rely on coordination relationships with warehouses that they have coordinated with in the past. This implies that prior relationships could be a boundary condition for making last-minute coordination decisions and we encourage future studies to explore this direction.

Together, our findings show the importance of last-minute coordination at order penetration points, which could potentially impact the subsequent delivery process. More importantly, through the lens of loose coupling and coordination theory, the findings describe a preferred coordination pattern for last-minute coordination and imply that coordination cost is a determining factor when firms organize unstructured coordination.

Finally, the persistent adaptation pattern of last-minute coordination under increasing demand uncertainty demonstrates a *stable* internal structure of a loosely coupled system facing changes in the external environment. While past research discusses the adaptability of a loosely coupled system, this finding implies that such adaptability originates from the *stability* of the internal structure in our research context. We believe the inquiry into how the internal structure of a loosely coupled system in the context of last-mile operations affects its adaptability could also be a fruitful future research avenue.

6.2 | Managerial implications

This research also has several implications for supply chain managers. First, no matter how perfect planning and management systems are, local contingencies will arise, which require entities (i.e., warehouses) to improvise. Managers at different levels should be aware of how last-minute coordination helps improve overall inventory efficiency. If managers try to superimpose structured coordination mechanisms on the network of warehouses, they might undermine the benefits of last-minute coordination. Rather, managers should develop an enabling context that recognizes emergent local contingencies and encourages last-minute coordination among the warehouses. This may include discussion groups among the warehouse managers to talk about how last-minute coordination can improve overall performance, helping them understand how local warehouse performance impacts overall network performance and promoting learning around how to better execute last-minute coordination.

Managers need to recognize that last-minute coordination can negatively affect operational efficiency for individual warehouses. Network managers should carefully design incentives for warehouse managers, striking a balance between the warehouse's best interests and the overall system's optimal performance. When evaluating warehouse performance, network managers should account for the structural position that a warehouse occupies in the last-minute coordination network. This is especially important when some warehouses have lower performance but occupy central positions because they improve the overall performance of the system. Failing to recognize this could undermine the unstructured coordination that helps the system cope with local emergent contingencies. In addition, benchmarking warehouses against one another could be detrimental to performance. Instead, one should consider their position in the unstructured coordination network—central warehouses should be compared to other central warehouses rather than non-central warehouses.

Finally, the findings have practical implications for the design of transshipment networks. This research suggests that network managers should designate warehouses with historically high demand uncertainty as transshipment hubs. Peripheral warehouses should be directed to rely on these hubs for their transshipment needs. In other words, these "central facilitators" are responsible for most of the last-minute coordination and should not be penalized for low inventory efficiency.

6.3 | Limitations and future research

We discuss some limitations of this study and suggest two main avenues for future research. First, we call for research about different spontaneous activities in different segments of last-mile operations or different product categories. Practices such as last-minute coordination or inventory transshipments likely exist throughout a broader array of logistics processes, as it is unlikely to anticipate all potential challenges upfront. Focusing on one product category helps control confounding factors such as product life cycle but limits the generalizability of the findings. We encourage scholars to extend this study to other contexts and draw insights from other related literature streams, such as organizational improvisation (Vera & Crossan, 2004, 2005), to better understand the last-minute adjustments that match supply and demand.

For instance, future research can examine the effectiveness of pop-up space, an ad hoc practice adopted by retailers to address the mismatch between supply and demand. Walmart once created pop-up space in several regional distribution centers to create temporary infrastructure, which helped address peak demand in its e-commerce space without increasing the capacity of fulfillment centers (Leonard, 2020). Future research can clarify the mechanisms and effects of other similar improvised activities in last-mile operations and search for potential contingencies to deepen our understanding of these activities in last-mile operations.

Second, we call for research that takes different perspectives on coordination in last-mile settings. For instance, future research can take a dynamic network perspective and explore the evolutionary pattern of the coordination network over time. Since warehouse managers autonomously interact with one another to coordinate inventory adjustments, the theory of organizational dynamics (Dooley & Van de Ven, 1999) may presumably predict different dynamic patterns for the coordination network evolution, which reflects that "different participants enacting actions in a system are influenced by one another but only in a limited fashion" (Dooley & Van de Ven, 1999, p. 368).

Future research can also take an individual manager's perspective to better understand last-minute coordination at the micro level. A detailed case study on warehouse managers is necessary to understand their decision-making process and the coordination challenges facing them. This kind of study could enrich our understanding of last-minute coordination and help devise practices to improve transshipment efficiency.

In sum, we do not view last-minute coordination as a substitute for or an elimination of formal structured coordination mechanisms, but rather something that augments structured mechanisms. We hope that this study stimulates research interest in examining ad hoc practices such as last-minute coordination within operations and logistics processes. This research line can have enormous potential to contribute to the supply chain management and last-mile operations literature.

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ENDNOTES

[1] As defined by Freeman (1978), featuring a small number of central nodes and many peripheral nodes within the last-minute coordination network.

[2] For a directed edge/arc/arrow $e = (u,v)$, which goes from u to v, we call u the tail and v the head.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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