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Resilient Supply Chain Network Design under Joint Facility-Road Disruptions

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ABSTRACT

Industrial supply chain networks are increasingly exposed to compound disruptions caused by facility failures and road interruptions. These disruptions may reduce supply capacity, block transportation links, and lead to unmet demand. To address this problem, this paper studies the resilient design of a regional industrial supply chain network under joint facility-road disruptions. A two-stage robust optimization model is developed. In the first stage, facility location, facility protection, and road protection decisions are made before disruptions occur. In the second stage, transportation reallocation and shortage recourse decisions are optimized after the worst-case disruption scenario is realized. To solve the resulting min-max-min model, a column-and-constraint generation algorithm is used. The algorithm decomposes the original problem into a master problem and a subproblem. The master problem determines the first-stage network design, while the subproblem searches for the worst-case joint disruption scenario. A case study based on the electronic product supply chain in Guangdong Province is conducted to test the model. The results show that the proposed method can identify critical facilities and key roads, improve post-disruption service performance, and reduce shortage losses under extreme disruption scenarios. This study provides a practical decision-making framework for resilient supply chain network design under compound disruption risks.

KEYWORDS

Supply Chain Network Design; Column-and-constraint Generation; Decision-making Framework; Composite Interruption Risk.

1. INTRODUCTION

Industrial supply chain networks are complex systems composed of production facilities, storage nodes, demand regions, transportation roads, and other operational resources. Among them, facilities and transportation roads are key components that directly affect supply capacity, product distribution, and service performance. In normal conditions, supply chain network design usually focuses on facility location, transportation allocation, and cost control. However, under extreme events such as typhoons, rainstorms, floods, and other disaster disruptions, facilities may lose supply capacity and roads may become unavailable. These disruptions may further cause transportation interruption, unmet demand, and a sharp decline in service level. This study focuses on resilient supply chain network design under joint facility-road disruptions. Facility location, facility protection, road protection, transportation reallocation, and shortage recourse are considered together, with the goal of improving supply chain resilience under worst-case disruption scenarios. Such a resilient network design problem has both important theoretical and practical significance.

Theoretical Significance: As an important issue in supply chain management, supply chain network design involves facility location theory, network flow optimization, disruption risk management, and

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robust optimization. Existing research has provided many useful results on facility location, reliable network design, and facility protection. However, many studies mainly focus on facility-side disruptions, while the joint impact of facility failures and road interruptions has not been fully considered. By studying facility-road joint disruptions in a unified network design framework, this paper extends the traditional supply chain network design problem from normal cost optimization to resilience-oriented decision-making under disruption risk. At the same time, the two-stage robust optimization method can describe the decision sequence of pre-disruption planning and post-disruption response. This provides a useful modeling idea for studying supply chain resilience when accurate disruption probabilities are difficult to obtain.

Practical Significance: In real industrial supply chains, facilities and transportation roads often face disruption risks at the same time. Once a key facility stops operating or a major road is blocked, the whole network may suffer from supply shortages and transportation delays. Through a reasonable facility and road protection strategy, limited protection resources can be allocated to critical facilities and key roads, so that the supply chain can maintain a higher service level after disruptions. At the same time, the model can help decision-makers compare the effects of different protection budgets, disruption intensities, and shortage penalty levels. This is useful for regional industrial supply chain planning, emergency logistics preparation, and post-disruption resource adjustment. Therefore, the proposed method can provide practical decision support for improving the resilience of industrial supply chains under compound disruption risks.

2. REVIEW OF RESEARCH IN RELATED FIELDS

Supply chain network design is a basic issue in supply chain management. Its core lies in determining facility locations, transportation links, capacity allocation, and product flow arrangements according to demand distribution, facility capacity, transportation cost, and service requirements. Traditional supply chain network design studies mainly focus on cost minimization and operational efficiency under normal conditions. These studies provide an important modeling basis for facility location and network flow allocation. However, when disruption risks are considered, the design objective cannot be limited to normal operating cost. The network also needs to maintain supply capacity and service performance after facilities or transportation links are damaged.

With the increasing frequency of natural disasters, public emergencies, and traffic interruptions, supply chain disruption management has gradually become an important research field. Tang [1] discussed supply chain risk management from the perspective of operational strategies and pointed out that supply chains are easily affected by demand changes, supply uncertainty, and external disruptions. Snyder et al. [2] reviewed OR/MS models for supply chain disruptions and showed that disruption risks can affect facility availability, transportation capacity, and service continuity. Aldrighetti et al. [3] further summarized the cost of resilience and disruption in supply chain network design models. Their study indicates that resilient network design should consider both normal operating cost and disruption response cost. These studies show that disruption risk needs to be embedded into the network design stage rather than being treated only as a post-event response problem.

Reliable facility location is closely related to supply chain network design under disruptions. Peng et al. [4] studied reliable logistics network design with facility disruptions and showed that considering facility failures in advance can improve service performance under disruption scenarios. An et al. [5] introduced two-stage robust optimization into the reliable p-median facility location problem. In their model, the first-stage decision determines facility locations, while the second-stage decision adjusts service allocation after disruptions. Cheng et al. [6,7] further studied robust facility location problems under demand uncertainty and facility disruptions. These studies provide useful references for modeling facility-side disruptions, but most of them mainly focus on facility failures. The impact of

road interruptions and transportation link damage is still not fully considered in a unified supply chain network design framework.

Facility protection and infrastructure protection studies provide another important foundation for this research. Scaparra and Church [8] proposed a critical infrastructure protection planning model and emphasized that limited protection resources should be allocated to key facilities. Mahmoodjanloo et al. [9] studied a tri-level fortification model for facility protection under disturbance, which reflects the decision logic of defense, attack, and recovery. Hu and Tang [10] further considered facility location, protection, and backup decisions under facility disruptions. Their study shows that protection decisions can effectively reduce system losses under worst-case scenarios. However, these studies still mainly focus on facilities. In practical industrial supply chains, facilities and roads often face disruption risks at the same time. Once a key facility fails and a major road is blocked, the network may experience more serious supply shortages and transportation delays.

Robust optimization has been widely used to deal with disruption risks when accurate probability information is difficult to obtain. Compared with stochastic programming, robust optimization does not require precise probability distributions. It focuses more on system performance under adverse or worst-case scenarios. Bertsimas and Sim [11] proposed the budgeted uncertainty method, which provides a useful way to control the conservatism of robust optimization models. Ben-Tal et al. [12] discussed adjustable robust optimization and distinguished decisions made before and after uncertainty is revealed. This idea is consistent with the decision sequence in supply chain disruption management. In this sequence, facility opening and protection decisions are made before disruptions occur, while transportation reallocation and shortage recourse decisions are made after the disruption scenario is realized.

In terms of solution methods, two-stage robust optimization models are usually difficult to solve directly because they contain a nested min-max-min structure. Zeng and Zhao [13] proposed a column-and-constraint generation method for two-stage robust optimization problems. This method decomposes the original problem into a master problem and a subproblem. The master problem determines first-stage decisions, while the subproblem searches for the worst-case scenario. Simchi-Levi et al. [14] applied constraint generation to two-stage robust network flow problems and showed that this type of algorithm can effectively improve computational tractability. These studies provide methodological support for solving supply chain network design problems with uncertain disruptions.

In summary, existing studies have provided rich research foundations for supply chain disruption management, reliable facility location, facility protection, and two-stage robust optimization. However, three research gaps still remain. Existing studies pay more attention to facility disruptions, while the joint impact of facility failures and road interruptions is not fully modeled. Many studies consider protection decisions or recourse decisions separately, but the coordination among facility location, facility protection, road protection, and post-disruption transportation reallocation still needs further study. In addition, few studies examine regional industrial supply chain resilience under a unified facility-road disruption framework. Therefore, this paper studies resilient supply chain network design under joint facility-road disruptions and develops a two-stage robust optimization model to support protection and recourse decisions under worst-case disruption scenarios..

3. MODEL CONSTRUCTION

This study considers a regional supply chain network under facility disruptions and road interruptions. The network is composed of candidate facilities, demand nodes, and transportation links. Facilities are responsible for product supply and distribution, while roads are used for transportation between different regions. Under disruption scenarios such as natural disasters and traffic interruptions, some facilities may lose supply capability and some roads may become unavailable. These disruptions may

further reduce transportation efficiency and increase unmet demand. Therefore, resilient supply chain network design needs to consider both facility reliability and transportation accessibility.

In this study, a two-stage resilient supply chain network design framework is developed. Before disruptions occur, decision-makers determine facility opening, facility protection, and road protection strategies. After disruptions occur, the remaining available facilities and roads are used to reallocate transportation flows. If customer demand cannot be fully satisfied, shortage recourse is allowed. The proposed model aims to reduce system losses under disruption conditions while controlling total investment cost.

The objective of the model is to minimize the total system cost. The total cost includes facility opening cost, facility protection cost, road protection cost, transportation cost, and shortage penalty cost. The model is formulated as follows:

$$\min Z = \sum_{j \in F} f_j \, y_j + \sum_{j \in F} p_j \, z_j + \sum_{e \in E} g_e \, w_e + \sum_{e \in E} c_e \, x_e + \sum_{i \in N} \rho_i \, q_i$$

where F represents the set of candidate facilities, E represents the set of transportation links, and N represents the set of demand nodes. The binary variable y_j indicates whether facility j is opened. The binary variable z_j indicates whether facility j is protected. The binary variable w_e indicates whether transportation road e is protected. Variable x_e represents transportation flow on road e, and q_i represents unmet demand at demand node i. Parameters f_j, p_j, and g_e denote facility opening cost, facility protection cost, and road protection cost, respectively. Parameter c_e denotes transportation cost, and ρ_i denotes shortage penalty cost.

The model is subject to several operational constraints. The facility capacity constraint ensures that the outbound transportation flow of each facility does not exceed its available supply capacity:

$$\sum_{e \in \delta^+(j)} x_e - \sum_{e \in \delta^-(j)} x_e \leq K_j y_j, \quad \forall j \in F$$

where K_j denotes the supply capacity of facility j. This constraint indicates that only opened facilities can provide supply service to the network.

The transportation capacity constraint is written as follows:

$$x_e \leq U_e, \quad \forall e \in E$$

where U_e denotes the transportation capacity of road e. This constraint guarantee that the transportation flow on each road does not exceed the available road capacity.

The demand balance constraint is given by:

$$\sum_{e \in \delta^-(i)} x_e - \sum_{e \in \delta^+(i)} x_e + q_i = d_i, \quad \forall i \in N$$

where d_i denotes the customer demand at node i. This constraint means that customer demand can either be satisfied through transportation flow or represented by shortage recourse.

Since protection resources are limited, the total protection investment is constrained by the available protection budget:

$$\sum_{j \in F} p_j \, z_j + \sum_{e \in E} g_e \, w_e \leq B$$

where B represents the maximum protection budget. This constraint reflects the trade-off between protection investment and system resilience.

The binary decision variables are defined as follows:

$$y_j, z_j, w_e \in \{0,1\}$$

The proposed model integrates facility location, facility protection, road protection, and transportation allocation into a unified optimization framework. Compared with traditional supply chain network design models, the proposed model not only considers transportation and facility costs under normal conditions, but also incorporates disruption risks and protection strategies into the network design process. Therefore, the model can better describe the operational characteristics of resilient supply chain networks under compound disruption risks.

4. ALGORITHM DESIGN

The proposed model is a mixed-integer optimization problem that integrates facility location, facility protection, road protection, and transportation allocation decisions. Since the model simultaneously considers disruption risks and protection strategies, the resulting optimization problem becomes computationally challenging when the network size increases.

To solve the model efficiently, the Gurobi Optimizer is employed. For the robust optimization model, a column-and-constraint generation (C&CG) algorithm is adopted. The basic idea of this method is to decompose the original problem into a master problem and a subproblem and solve them iteratively.

The master problem determines the first-stage decisions, including facility opening, facility protection, and road protection strategies. Based on the obtained solution, the subproblem searches for the disruption scenario that leads to the largest system loss. The identified worst-case scenario is then added to the master problem, and the optimization process is repeated.

During each iteration, the master problem provides a lower bound for the original problem, while the subproblem generates an upper bound. As more disruption scenarios are introduced into the master problem, the gap between the upper bound and lower bound gradually decreases. The algorithm terminates when the gap is smaller than a predefined tolerance level.

Compared with directly solving the original robust optimization model, the C&CG algorithm can effectively reduce computational complexity and improve solution efficiency. It has been widely used in two-stage robust optimization problems and is particularly suitable for supply chain network design under disruption risks. Therefore, this study adopts the C&CG algorithm to obtain the optimal resilient supply chain network design solution.

5. CASE STUDY AND RESULTS

To verify the effectiveness of the proposed model, a regional electronic product supply chain network in Guangdong Province is selected as a case study. The network consists of candidate facility nodes, demand nodes, and transportation links connecting different cities. Facility opening costs, protection costs, transportation costs, and demand data are obtained from statistical yearbooks and related public information.

The proposed model is implemented in Python and solved using the Gurobi Optimizer. The robust optimization model is solved through the C&CG algorithm. After several iterations, the algorithm converges and obtains the optimal network design solution.

The main results are summarized in Table 1.

The results indicate that the proposed model can effectively identify critical facilities and important transportation links under disruption risks. By allocating protection resources to key facilities and roads, the supply chain can maintain a relatively high service level even under severe disruption scenarios. Although protection investment increases the initial cost of the network, it significantly reduces shortage losses and improves the overall resilience of the supply chain.

Overall, the numerical results demonstrate that the proposed resilient network design approach can provide effective decision support for supply chain planning under facility and road disruption risks.

Table 1. Main optimization results

Item	Value
Opened facilities	4
Protected facilities	4
Protected roads	11
First-stage investment cost (10^4 CNY)	29689.65
Worst-case operating cost (10^4 CNY)	34568.59
Total cost (10^4 CNY)	64258.24
Service rate (%)	76.62

6. CONCLUSION

This paper studies the resilient supply chain network design problem under joint facility-road disruptions. A robust optimization model is developed to determine facility opening, facility protection, and road protection decisions while considering transportation allocation and shortage recourse under disruption scenarios. The objective is to minimize the total system cost and improve supply chain resilience under disruption risks.

To solve the proposed model, a column-and-constraint generation algorithm is adopted. A case study based on a regional electronic product supply chain network is conducted to verify the effectiveness of the proposed approach. The results show that appropriate protection strategies can effectively reduce disruption losses and improve service performance. The model is able to identify critical facilities and important transportation links, providing useful support for resilient supply chain planning.

Overall, the proposed approach offers a practical framework for supply chain network design under disruption risks. The study provides managerial insights for allocating limited protection resources and enhancing the resilience of regional supply chain networks.

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