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考慮排隊庫存效應於永續韌性供應鏈隨機最佳化研究

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摘要

在當今的商業環境中，為應對氣候變遷而採取碳減排措施以實現永續營運至關重要。另一方面，自然災害、流行病和地緣政治緊張局勢等因素造成供應鏈中斷議題值得關注。雖然設計一個整合永續性與韌性的強健供應鏈網路是很有價值的，但大多數現有文獻大多從個別角度處理這些問題，而且忽略了供應鏈風險對戰術規劃層面的影響。本研究提出一個整合碳排放和設施可靠性供應鏈設計模型，並考慮了風險對生產和庫存規劃的影響。我們將所研究的問題建構為一個帶有追索權的隨機混合整數非線性規劃模型，並使用商業套裝軟體進行求解。

關鍵詞：永續韌性、排隊庫存、帶有追索權的隨機混合整數非線性規劃

Stochastic Optimization for Sustainable and Resilient Supply Chains Considering Queueing-Inventory Effects

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Abstract

In today's business environment, achieving sustainable operations through carbon reduction measures in response to climate change is crucial. On the other hand, factors such as natural disasters, pandemics, and geopolitical tensions have caused disruptions in supply chains. While it is worthwhile to design robust supply chain networks that integrate sustainability and resilience, most existing literature either approaches these issues from individual perspectives or overlooks the impact of supply chain risk on the tactical planning level of a supply chain. This study proposes an integrated model that incorporates carbon emissions and facility reliability and consider the impact of risk on production and inventory planning. We formulate the studied problem as a stochastic mixed-integer nonlinear programming with recourse and use AMPL with Gurobi to solve it.

Keywords: Sustainable-Resilient, Queueing-Inventory, Stochastic Mixed-Integer Nonlinear Programming with Recourse, AMPL, Gurobi

Introduction

Traditionally, supply chain management encompasses strategic, tactical, and operational levels. The strategic level primarily addresses long-term issues such as supply chain network design (SCND), while the tactical level mainly involves transportation modes, production capacity, inventory planning, etc. Due to several historical events and over-industrialization, research on supply chain risks has attracted much attention in the past decades in addition to the above-mentioned traditional supply chain management (Nezamoddini et al., 2020). Supply chain risks include external and internal failures that may prevent the enterprise from normal operation and carbon emissions that may cause extreme weather and endanger human beings. According to the 2021 Taiwan CEO Survey, supply chain risk ranks first among the top five risks affecting Taiwanese enterprises. The National Science and Technology Council White Paper for 2023-2026 highlights the growing risk of supply chain disruptions due to highly uncertain futures and insufficient resilient infrastructure, exacerbated by global events like pandemics and wars. It also emphasizes sustainable production and consumption strategies.

This research investigates the impact of risk on the strategic and tactical planning of a supply chain. To propose a mitigating strategy, we must first identify the risk. External supply chain failures include natural disasters such as extreme weather (e.g., hurricanes), earthquakes, pandemics (e.g., COVID-19), and geopolitical conflicts (e.g., the Russia-Ukraine and Israel-Hamas wars). Internal failures include machine breakdown, workforce strikes, human resource unavailability, etc. This research examines external failure types and proposes applicable risk mitigation strategies to lessen the impact of such risks. Recent works on reliable facility design include Peng et al. (2011) and Snyder and Daskin (2005). They develop resilient SCNDs to mitigate the risk of supply disruption.

On the other hand, addressing climate change through energy-saving and carbon-reduction measures to achieve sustainable operations is also a pressing issue for industry today. It has attracted much attention (Nurjanni et al., 2017). While it is worthwhile to design robust supply chain networks that integrate sustainability and resilience, most existing literature approaches these issues from individual perspectives (Ahmadi-Javid and Hoseinpour, 2019; Baghalian et al., 2013; Gholami et al., 2019; Liu et al., 2020; Nayeri. et al., 2021). In recent years, a few works have emerged that considered integrated sustainable and resilient models (Fahimnia and Jabbarzadeh, 2016; Fahimnia et al., 2018; Zeng et al., 2023). However, the integrated models overlook the impact of supply chain risk on the tactical planning level of a supply chain. These tactical planning levels include production and inventory planning, among others. Thus, this study proposes an integrated SCND model that embeds production and inventory planning under a stochastic scenario (Wang, 2023). From the literature review, how to respond to supply chain disruption and maintain a sustainable network in an efficient way forms the research motivation of this study.

Considering the risks, we integrated strategic and tactical planning for a SCND problem. Unlike sequential planning, integrating tactical aspects like production and inventory into SCND at an early stage enables global optimization of supply chain management. The goal is to design a sustainable and resilient supply chain that considers the queueing effect. A queueing-inventory module is incorporated in the SCND to mitigate the impact of supply disruptions, less carbon emission, and less order waiting time, enabling more flexible and responsive systems. We model it as a stochastic mixed-integer nonlinear programming with recourse and use AMPL with Gurobi to solve it. The research objectives are to minimize the following: Costs related to facility setup, transportation, inventory holding and backorders subject to carbon emissions allowance. This study proposes a new integrated supply chain model that combines carbon emissions, resilience, and the order queueing effect. With embedded queueing-inventory modules as surrogates for production and inventory systems, we formulate the studied problem as a stochastic mixed-integer nonlinear programming (SMINLP). The trade-offs between setup cost, operating cost, transportation cost, and inventory related costs are explored to achieve the study's goal of sustainable and resilient supply chain network design considering agile responsiveness.

Planning of sustainable and resilient supply chains with agility

A schematic diagram of facility location under external failures is shown in Figure 1. In a given scenario, suppose a supplier or facility shuts down due to an unexpected event. The left side of Figure 1 displays the original raw material supplied by suppliers and the original facility locations and assignments. The right side shows how the affected locations are reassigned after disruption, with demands and raw material supplies absorbed by unaffected suppliers or facilities through an optimization process. Assume factories adopt (S-1, S) policies. Customer demand is assumed to arrive as a Poisson process. If stock is available upon order arrival, products are dispatched immediately. The system allows for backorders. When inventory drops one unit, a replenishment order of size one is triggered to raise the inventory to a target level S. When a facility is operating normally, it starts production (replenishment) whenever a new order comes. If the supply is open but is disrupted, it cannot perform replenishment. The goal is to find a robust optimal solution that attains the minimum expected operating costs, including facility operating, production, warehouse operating, transportation, inventory, and backorder costs across all scenarios while satisfying the carbon emission allowance quota each time period, say, one year. Assume supplier and demand point locations are known. Factories may shut down due to supply chain disruptions. This study adopts stochastic programming with recourse approach, where scenario-independent decision variables, including facility setup, production level, and warehouse level, are first determined, and all the others are scenario-dependent variables, including demand assignments, transportation mode, cumulated demand and traffic intensity at facilities under different scenarios are obtained as recourse.

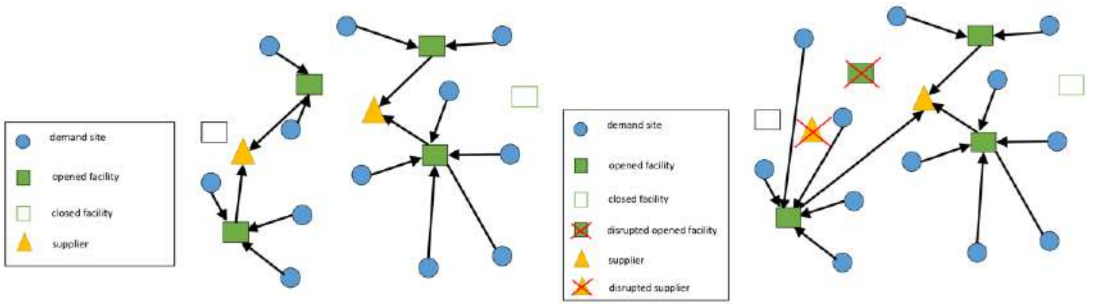

Figure 1 External disruption schematic — the left shows original facility locations and assignments; the right shows reassignment after disruption under a given scenario.

Sets and Indices

I	Set of potential facility locations, indexed by i
J	Set of demand points, indexed by j
M	Set of transportation modes, indexed by m
K	Set of scenarios, indexed by k, where k=0 represents the normal operation of the supply chain without external failures, k=1 represents supply chain failure

Notations and System Parameters

G	Cost objective value
f_i	Operating cost for facility i per unit time
λ_j	Demand size at demand point j
d_{ij}	Distance between facility i and demand point j
c_p	Unit production cost
c_s	Operating cost for warehouse per unit time
c_h	Holding cost per unit per unit time
c_b	Backorder cost per unit per unit time
c_{ijm}	Unit transportation cost from facility i to demand j using transportation mode m
e_i	Carbon emissions per unit of production at facility i
e_{ijm}	Carbon emissions per unit transported from facility i to demand point j using transportation mode m
$emit\_up$	Carbon emissions allowance level per unit time
$w_{i1}^k(\lambda_i^k, \mu_i, S_i)$	Average inventory level at facility i under scenario k
$w_{i2}^k(\lambda_i^k, \mu_i, S_i)$	Average backorder inventory level at facility i under scenario k
a_i^k	Equals 1 if facility I is affected and shut down in scenario k; 0 otherwise
p_k	Probability that scenario k happens

Decision Variables

First stage

x_i	Equals 1 if facility i is established; 0 otherwise
μ_i	Production rate (capacity) at facility i
S_i	Replenishment up to level at facility i

Second stage

y_{ijm}^k	Equals 1 if facility i supplies demand point j using transportation mode m under scenario k; 0 otherwise
λ_i^k	Cumulative demand at facility i under scenario k
ρ_i^k	Traffic intensity at facility i under scenario k

The mathematical model is as follows.

Min Total cos

$$G = \sum_{i=1}^{I}(f_i + c_p\mu_i + c_s S_i)x_i + \sum_{k=1}^{K} p_k \left(\sum_{i=1}^{I}\sum_{m=1}^{M}\sum_{j=1}^{J} c_{ijm}\,\lambda_j\, y_{ijm}^k + \sum_{i=1}^{I} c_h\, w_{i1}^k(\lambda_i^k, \mu_i, S_i) + \sum_{i=1}^{I} c_b\, w_{i2}^k(\lambda_i^k, \mu_i, S_i) \right) \quad (1)$$

Subject to

$$y_{ijm}^k \le (1 - a_i^k)x_i, \forall i \in I, \forall j \in J, \forall m \in M, \forall k \in K \quad (2)$$

$$\sum_{i=1}^{I}\sum_{m=1}^{M} y_{ijm}^k = 1, \forall j \in J, \forall k \in K \quad (3)$$

$$\sum_{j=1}^{J}\sum_{m=1}^{M} \lambda_j y_{ijm}^k = \lambda_i^k, \forall i \in I, \forall k \in K \quad (4)$$

$$\lambda_i^k < \mu_i \quad (5)$$

$$\sum_{i=1}^{I} e_i\lambda_i^k + \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{m=1}^{M} e_{ijm}\, d_{ij}\, y_{ijm}^k \le emit\_up, \forall k \in K \quad (6)$$

$$x_i,\ y_{ijm}^k = (0,1), S_i = \mathbb{Z}^+ \cup 0, \mu_i \ge 0, \forall i \in I, \forall j \in J, \forall m \in M, \forall k \in K \quad (7)$$

Equations (1) represent the objective function, and Term 1 represents the first stage decision on the production inventory system, including facility operating cost, machine operating cost, and warehouse operating cost. Term 2 represents the second stage recourse decision, including transportation cost, inventory holding cost, and backorder cost. Equation (2) ensures that transportation in disruption scenarios can only occur if a facility is open and not disrupted. Equation (3) ensures that each customer is assigned to exactly one facility using only one transportation mode under each scenario. Equation (4) ensures that in all scenarios, the total supply from a facility equals the sum of the demand assigned to it. Equation (5) guarantees system stability under each scenario. Equation (6) Equation enforces that carbon emissions per unit time cannot exceed the allowable emission level. Term 1 captures carbon emissions from production. Term 2 captures carbon emissions from transportation. (7) imposes integer and non-negativity constraints.

Assume the production facility can be treated as an M/M/1 queueing inventory system with a base stock replenishment policy. Inventory and backorder levels depend on the initial decision protection level, inventory level, and cumulative demand assignment under different scenarios. Thus, we obtain inventory-related measures as follows:

$$w_{i1}^k(\lambda_i^k, \mu_i, S_i) = S - \frac{\lambda_i^k/\mu_i \left(1 - \left(\lambda_i^k/\mu_i\right)^{S+1}\right)}{1 - \lambda_i^k/\mu_i}$$

$$w_{i2}^k(\lambda_i^k, \mu_i, S_i) = \frac{\left(\lambda_i^k/\mu_i\right)^{S+1}}{1 - \lambda_i^k/\mu_i}$$

Numerical Example

Assume five potential facilities, 10 demand points, two transportation modes, and three disruption scenarios. The data are simulated as in Table 1 for the operating cost at facilities. Assume carbon emissions per unit generated at the production facility and carbon emissions for transportation from the facility to the demand point using different transportation modes is the same. Actual implementation may use more realistic formulas to obtain these data. Table 2 lists disruption scenarios where scenario 0 means normal-as-usual condition. Scenario 1 and 2 mean supply chains are under disruption, where facilities 2 and 5 are affected in scenario one and facilities 3 and 5 are affected in scenario 2. We use AMPL with Gurobi 12 solver running on a Mac OS, iCore 7 2.6 GHz CPU, and 16GB RAM. The optimal solution objective is 1043.075403, Carbon emission is 180.55 for all scenarios. For this highly nonlinear problem, it takes about 10 minutes to find the optimum. Tables 3 and 4 show optimization results.

Table 1 Cost parameters for facilities

Cost Parameters	F1	F2	F3	F4	F5
Operation	100	120	90	110	60
Unit production	1	1.2	2.1	1.1	1.5
Ware-housing	3	2	2	1	3

Table 2 simulated scenarios and corresponding a_i^k

scenarios	Probabilities	F1	F2	F3	F4	F5
0	1/3	1	1	1	1	1
1	1/3	1	0	1	1	0
2	1/3	1	1	0	1	0

Table 3 Optimization results for production facilities

solutions	F1	F2	F3	F4	F5
Open?	yes	no	no	yes	no
Production Capacity	62.248	-	-	150	-
Warehouse Size	3	-	-	10	-
Cumulated demand	45	-	-	130	-
Traffic intensity	0.721867	-	-	0.866667	-
Inventory level	1.37668	-	-	5.05399	-
Backorder level	0.985682	-	-	1.55395	-

Table 4 Optimization results for demand assignments

scenarios	F1	F2	F3	F4	F5
0, 1, 2	D4, D5, D9	-	-	D1, D2, D3(M2) D6, D7, D8 D10	-

Conclusion and future research

In this study, we use a two-stage stochastic programming with a recourse model to solve a supply chain network design problem considering disruption and carbon emission risks. The proposed methodology not only considers the strategical level but also the tactical level, which may attain a global optimization compared to the traditional sequential approach. We use AMPL with Gurobi solver to solve the formulated MINLP problem. Our model gives businesses a more comprehensive framework to think comprehensively when designing a robust and sustainable supply chain with agile responsiveness in mind. Future research may extend the problem to a more realistic setting to show its applicability and investigate other solution alternatives to solve the problem efficiently.

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