Front. Eng. Manag. 2023, 10(1): 143–157
https://doi.org/10.1007/s42524-022-0236-y

RESEARCH ARTICLE

Jiaguo LIU, Yumeng XI, Junjin WANG

Resilience strategies for sustainable supply chains under budget constraints in the post COVID-19 era

Abstract The COVID-19 outbreak has caused uncertainty risk surges, increased sustainable supply chain vulnerabilities, and challenges to sustainable supply chain resilience (SSCR) management. Therefore, improving SSCR is necessary to alleviate vulnerabilities, and SSCR management must generate large capital investments. However, the economic downturn brought about by the COVID-19 epidemic has made some companies have limited budgets that can be used to improve SSCR. Therefore, the design of resilience solutions needs to fully consider the constraints of budgetary costs. Most of the existing related literature only discusses optimal resilience solutions under certain cost constraints, so such resilience solutions cannot be applied to most enterprises. In this study, we set the cost constraint as a variable quantity, using resilience efficiency and customer satisfaction as indicators, to determine the changing laws of optimal resilience strategies when cost constraints change. These rules can be applied to enterprises with different budgeted costs. Our findings suggest that companies should prioritize sacrificing resilience measures (RMs) related to adaptive capacity when budget costs gradually decline, and RMs related to absorptive capacity are indispensable at all budget levels. Furthermore, the pursuit of environmental and social sustainability cannot be abandoned, no matter how limited the flexible budget may be.

Keywords sustainable supply chain, customer requirement, resilience efficiency, customer satisfaction, budget constraint

Received April 30, 2022; accepted October 18, 2022

Jiaguo LIU, Yumeng XI, Junjin WANG (✉)
School of Maritime Economics and Management, Dalian Maritime University, Dalian 116026, China
E-mail: 1204703207@qq.com

This research was supported by the Social Science Fund of Liaoning Province (Grant No. L21CGL004).

1 Introduction

Since the COVID-19 outbreak, companies have faced problems such as labor shortages, increased costs, tight cash flows, and increased supply chain uncertainties due to the advancement of various epidemic prevention measures, such as isolation and delayed rework (Song, 2020). The normalization of the epidemic not only directly affects supply chain liquidity but also indirectly amplifies the competition of trade rules and geopolitics, which increases the risks of uncertainties and instabilities. Close collaborations among stakeholders of sustainable supply chain management (SSCM) may also exacerbate the spread of negative impacts of risk factors (RFs) throughout supply chains, thereby compromising sustainable supply chain (SSC) performance (He et al., 2021). Therefore, designing optimal SSC resilience strategies to mitigate risks is crucial for SSCM. The improvement of supply chain elasticity is definitely accompanied by a large amount of resource investments (Wang et al., 2017). However, under the impact of the COVID-19 epidemic, production shutdowns have caused sharp drops in the incomes of some companies, and investments that can be used to improve the elasticity are limited. Therefore, the design of resilience strategies must tradeoff between elasticity and cost, which is the purpose of this study. Among them, the resilience strategy mentioned here refers to several resilience measures (RMs) that can be freely combined.

The concept of portfolio approach mentioned in the article by Pettit et al. (2013) is similar to the resilience strategy in this study, and this portfolio approach has been applied by many authors (Wasserman, 1993; Park and Kim, 1998; Chowdhury and Quaddus, 2015; He et al., 2021) for the design of SSC resilience solutions. These authors tend to employ a specific metric to find the optimal combination, and resilience efficiency (RE) and customer satisfaction (CS) are useful metrics to measure the performances of resilience solutions. Moreover, these authors realize the importance of cost considerations when designing SSC resilience solutions. These papers use mathematical programming models to find resilience solutions with CS (RE) maximization as the objective function and a certain budget cost as the constraint. However, these papers only solve optimal resilience strategies under certain cost constraints. Budgeted costs vary across firms of different sizes, and given that resource constraints vary over the long term, the conclusions of these articles are less applicable. To draw a research conclusion that can be applied to most enterprises, the present study sets cost limitation as a variable and discrete quantity and uses two indicators, RE and CS, to determine the changing laws of optimal resilience strategies when budget costs change. To the best of our knowledge, few articles have conducted such an investigation.

Several approaches can be taken to achieve the research goals, but the quality function deployment (QFD) model has been chosen for this research. The QFD model enables SSC to proactively mitigate vulnerabilities, rather than react passively, and it is a mature technology suitable for designing SSC resilience strategies in the COVID-19 era where uncertainties and risks are frequent (Faisal, 2013). This study uses the QFD model to analyze RMs, which can improve SSC elasticity from the customer requirement (CR) perspective, and adopts the 0–1 nonlinear programming model, which has been proven to be an effective way to generate efficient solutions (Chowdhury and Quaddus, 2015) to find the best RM combination strategy. The 0–1 nonlinear programming is adopted to simplify the calculation, as this study assumes that a certain RM can only be implemented or not implemented, and no situation of implementing one-half exists. For a further analysis of CR and CS, we use the Kano model in QFD for data analysis. Methodologically, the following are our contributions. We set the cost limitation as a variable quantity, and through multiple nonlinear programming analyses, we find a regularity that can be applied to most firms.

The remainder of the paper is arranged as follows. Section 2 mainly conducts a literature review related to CR, RF, and RM, including an integrated introduction and review of QFD and Kano models. Section 3 details the various methods and processes used in this research. Section 4 analyzes the relationships among CR, RF, and RM in detail, combined with the impact of the COVID-19 epidemic, and applies and discusses the methods introduced in Section 3. Section 5 summarizes the research and puts forward its limitations.

2 Literature review

2.1 SSC CR

With the continuous growth of CRs in the global supply chain competition, correctly identifying CRs and providing appropriate products or services to improve CS have become important strategies to enhance the competitiveness of enterprises. The consideration of CRs also provides ideas for the design of SSC resilience solutions: The priority of RMs is established by their ability to satisfy CRs and the importance of CRs themselves. Therefore, the correct identification of CRs is a critical step and an important part of this research.

As supply chain customers and other stakeholders pay increasing attention to supply chain performance in terms of environmental issues, social responsibilities, and economic benefits, SSC has developed three sustainability requirements, namely, economic, environmental, and social requirements (Büyüközkan and Berkol, 2011; Büyüközkan and Çifçi, 2013). Therefore, many articles related to sustainable supply chain resilience management (SSCRM) use SSC sustainability requirements when considering CRs and divide CRs into three categories, i.e., economic, environmental, and social requirements. According to the relevant literature summary, economic requirements mainly include cost and price competitiveness, high product quality, on-time delivery, professional customer service, and efficient inventory management; environmental requirements mainly comprise efficient resource utilization, pollution reduction, and green safety and health; and social requirements mainly include compliance with social laws and respect for local cultures (Büyüközkan and Berkol, 2011; Büyüközkan and Çifçi, 2013; Zhang and Awasthi, 2014; Yazdani et al., 2020; He et al., 2021; Xie et al., 2022). The above research on CRs is shown in Table 1, where "●" indicates the top CRs considered in the study.

Evidently, "professional customer service" and "pollution reduction" are critical CRs that get the most attention in these articles. However, issues such as large-scale factory shutdowns, extended public holidays, and adjustments in the transportation industry caused by the COVID-19 outbreak may make some relatively non-critical CRs (e.g., "cost and price competitiveness" and "on-time delivery") get relatively more attention than ever.

2.2 Supply chain resilience vulnerabilities

Svensson (2000) was the first to propose supply chain vulnerabilities and believed that vulnerabilities mean the existence of random disturbances, which cause factors or raw materials in supply chains to deviate from the normal, expected, and planned state, thereby affecting manufacturers and their collaborators in supply chains. However, Svensson (2000) did not distinguish between supply chain fragility and risk. Jüttner et al. (2003) differentiated the two concepts of supply chain risks and supply chain vulnerabilities and defined supply chain vulnerabilities as "the propensity of risk sources and risk drivers to outweigh risk mitigating strategies, thus causing adverse

Table 1 Major SSC CR projects

		Zhang and Awasthi (2014)	He et al. (2021)	Büyüközkan and Berkol (2011)	Xie et al. (2022)	Büyüközkan and Çifçi (2013)	Yazdani et al. (2020)
Economic requirements	Competitive cost and price	√	√	●	√	√	√
	Improved quality		√		√	√	
	On-time delivery	√	●		●		
	Enhanced customer service	●	●		√	●	●
	Efficient inventory management			●			
Environmental requirements	Efficient resource utilization		√	√	√	●	●
	Pollution reduction		●	●	●	●	●
	Health and safety	●	√		●	√	√
Social requirements	Legislation compliance	●	√	√	√	√	
	Respect for local culture		√				

supply chain consequences”. We will analyze the supply chain RFs from the perspective of risk drivers in the concept of supply chain vulnerability. Supply chain vulnerabilities can be driven by many factors, such as delays during transportation, port disruptions, frequent natural disaster occurrences, weak communications, supply shortages, demand volatilities, quality issues, operational issues, and terrorism attacks (Kleindorfer and Saad, 2005; Blackhurst et al., 2008; Colicchia et al., 2010). Kleindorfer and Saad (2005) identified three main vulnerability sources: First, operational factors, including equipment and system failures, sudden supply interruptions, and strikes; second, natural disasters, including earthquakes, hurricanes, and storms; and third, terrorism or political instability. Blos et al. (2009) proposed four main sources of supply chain vulnerabilities, i.e., financial, strategic, hazard, and operational vulnerabilities. Wagner and Bode (2006) believed that the driving factors of supply chain vulnerabilities can be understood from three aspects: Demand-driven, supply-driven, and global outsourcing. Among them, global outsourcing is embodied in the aspects of product variety, outsourcing quantity, and member quantity. Subsequently, Liu et al. (2015) supplemented Wagner and Bode (2006)’s view and believed that environmental factors (including natural and social environments) are also important factors that cannot be ignored in supply chain vulnerabilities. Supply chain risk analysis is an important part of our research, which refers to Liu et al. (2015) to analyze RFs from four aspects: Demand, supply, global outsourcing, and environmental risks.

2.3 SSC RMs

Holling (1973) was one of the pioneers in conceptualizing resilience as “the ability of a system to absorb change”. Many subsequent articles have also endorsed this resilience concept, which is the ability of a system to recover and return to its original state (Mitroff and Alpaslan, 2003; Christopher and Peck, 2004; Ponomarov and Holcomb, 2009). However, Heckmann et al. (2015) and Liu et al. (2015) mentioned that supply chain resilience must have the ability to “overcome supply chain fragility and reduce supply chain risk”. Chowdhury and Quaddus (2015) defined this capability as the ability of supply chains to reduce the impacts of disruptions caused by vulnerabilities by developing the required preparation level, quick response capacity, and recovery capacity. Fennell and Alexander (1987) and Bode et al. (2011) argued that the two basic resilience capabilities are buffering and bridging, and that all RMs are related to these two capabilities. Among them, buffering is external to current relationships, which attempts to achieve stability by establishing protection measures, which, in turn, protects companies from interferences caused by transaction relationships; and bridging is internal to current relationships, which seeks to prevent uncertainties by gaining information about looming supply chain disruptions and their consequences. Pettit et al. (2013) and Liu et al. (2015) defined resilience as absorptive, recovery, and adaptive capacities. Among them, absorptive capacity refers to the ability of supply chains to prepare for unexpected risk events, respond quickly to disruptions, and reduce their impacts (Chowdhury and Quaddus, 2016); recovery capacity means the ability of supply chains to maintain control over their structures and functions to respond to emergencies and return to their original states within acceptable periods (Pires Ribeiro and Barbosa-Povoa, 2018); and adaptability refers to the ability of supply chains to dynamically evolve (Chowdhury and Quaddus, 2017). Our study follows the view of Liu et al. (2015), that is, the resilience capacity is divided into three types: Absorptive, recovery, and adaptive capacities. A review of RMs corresponding to these three resilience capabilities is shown in Table 2.

However, under the influence of the COVID-19 epidemic, some RMs cannot be well implemented in reality. For example, “high transportation efficiency” cannot be implemented due to strict traffic control and regional blockade. At the same time, some previously unnoticed

Table 2 Key items for SSC RMs

		Büyüközkan and Berkol (2011)	Chowdhury and Quaddus (2015)	He et al. (2021)	Büyüközkan and Çifçi (2013)	Yazdani et al. (2020)	Zhang and Awasthi (2014)
Absorptive capacity	Supply chain relationship management	√	√	√	√	√	√
	Forecasting and predictive analysis			√	√		
	Inventory management	√	√	√	√	√	
	Advanced information technology (IT) system	√		√	√	√	√
	Workflow optimization	√			√		√
	High transportation efficiency	√	√		√	√	
Recovery capacity	Multiple supply sources		√	√			
	Market development			√			
	Labor skills training	√	√	√	√	√	
Adaptive capacity	Product modularity and multiple material uses	√	√	√			√
	New technology integration	√			√		
	Product and process improvement	√	√	√	√		√
	Life cycle management			√	√		

RMs may become necessary in the post-COVID-19 era, such as the risk of market share loss caused by trade rules and geopolitical competitions, making RMs, such as “market development”, important. Therefore, in the post-COVID-19 era facing a new risk structure, the RM selection also needs to keep pace with the times.

2.4 QFD

QFD is a customer-driven product development methodology for identifying and solving problems involving product, service, and strategy delivery to improve CS (González et al., 2004). Therefore, it is considered as one of the effective methods to quantitatively incorporate CRs into strategic and operational management. QFD methods have been applied to product development (Cristiano et al., 2001; Chan and Wu, 2002), service design (Zheng and Pulli, 2012), and supply chain management (Haq and Boddu, 2017). QFD has also been successfully applied to SSCRM (Chowdhury and Quaddus, 2015; Lam and Bai, 2016; Qazi et al., 2018; Nooraie et al., 2020). Furthermore, Carnevalli and Miguel (2008) stated in their review on QFD that QFD plays a role in various research methods, from theoretical modeling to experiments.

However, QFD has certain limitations. For example, in a customer-oriented market where product or service development starts with CRs, if decision makers fail to correctly prioritize CRs, the model conclusions would deviate from reality. Fortunately, the Kano model has great potential for an in-depth analysis of CRs, as it can classify and prioritize CRs on the basis of how they contribute to CS. Therefore, the Kano model is a suitable method to compensate for the QFD limitations in the CR analysis. In addition to being able to perform CR priority analysis well, the Kano model can also quantify CS according to the CR fulfillment degree. Therefore, the Kano model can integrate the qualitative results of the CR analysis and the quantitative results of the CS analysis into the QFD model, providing a mathematical programming model for the optimal design of a product (He et al., 2021).

3 Methodology

As illustrated in Fig. 1, the proposed approach begins with CR analysis based on the Kano model to determine the weight and CS for each CR. Then, the first House of Quality (HoQ) is constructed to identify the relationship between CRs and RFs and to determine the relative importance of RFs. Next, the second HoQ is built to model the relationship between RFs and RMs and determine the weight of each RM. Finally, on the basis of the above analysis, the nonlinear optimization model is established to find the optimal elastic policy under the corresponding budget level.

3.1 CR analysis

3.1.1 CR identification

The consideration of CRs is critical in the design of SSC resilience strategies. In a customer-oriented market, SSC performance is largely determined by CS (Zhang and Awasthi, 2014). To improve CS, companies must correctly identify CRs and provide suitable products or services. The CRs that must be identified in this study are the SSC requirements. The main goals of SSCs include economic, environmental, and social sustainability, so the

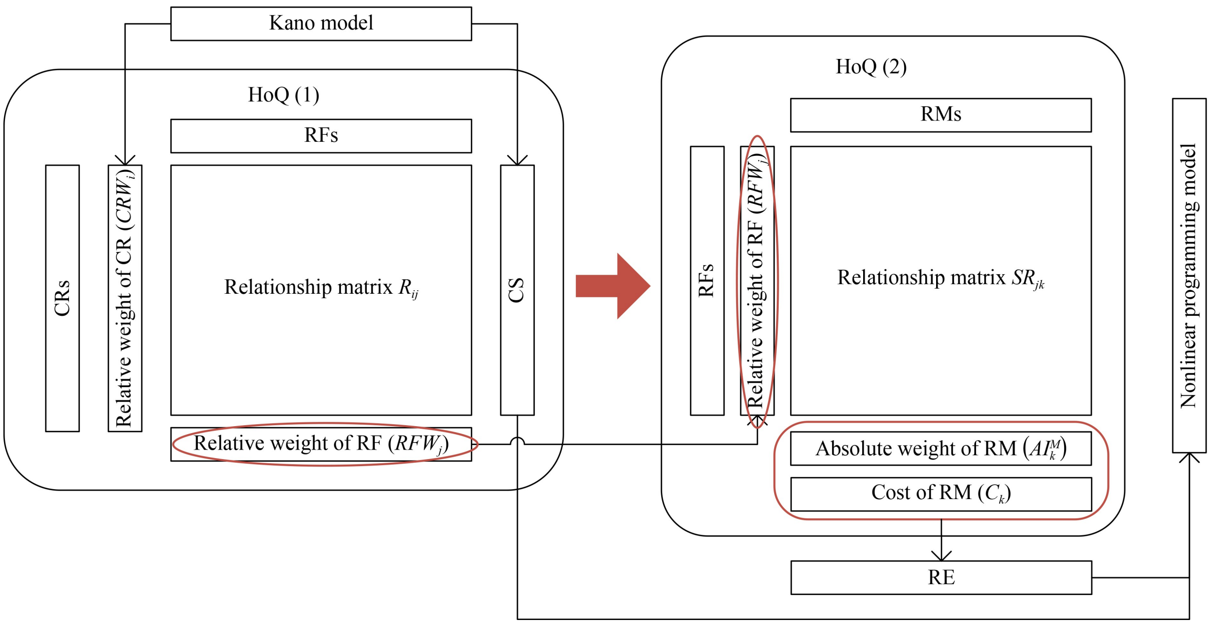

Fig. 1 Structure of the approach.

corresponding CRs can be classified into three categories: Economic, environmental, and social requirements (Büyüközkan and Berkol, 2011; Bastas and Liyanage, 2018). According to these three categories, literature survey, expert interview, and personal interview methods can be used to collect CRs.

We first summarize CRs by reviewing previous research results. Then, we invite eight experts in the supply chain field to form a judging panel and use the Delphi method to consult them. We distribute anonymous questionnaires to the eight experts in the first round. If an expert believes that a CR should be selected, then its score is recorded as 1; if the expert believes that a CR should not be selected, then its score is recorded as 0. In the first round of the survey, CRs with a score of 2 or less are not selected, whereas CRs with a score of 6 or more are selected. CRs with a score between 2 and 6 proceed to the next round of scoring. Through analogy, the appropriate CRs are finally collected.

3.1.2 Importance analysis of CRs based on the Kano model

CR analysis is an important work of SSCRM. In this section, the Kano model is used to determine the importance ranking of each CR. The Kano model, proposed by Kano et al. (1984), is a useful tool for classifying and ranking CRs. The Kano categories include must-be quality (M), one-dimensional quality (O), attractive quality (A), indifference quality (I), and reverse quality (R). Based on the Kano questionnaire table (Table 3) and the Kano evaluation table (Table 4), the importance weight of each CR_i can be obtained using Eqs. (1)–(4) (Berger et al., 1993).

Table 3 Kano questionnaire

Kano question	Answer
Functional question (e.g., if the design solution fulfills this CR, how do you feel?)	1. I like it that way
	2. It must be that way
	3. I am neutral
	4. I can live with it
	5. I dislike it that way
Dysfunctional question (e.g., if the design solution does not fulfill this CR, how do you feel?)	1. I like it that way
	2. It must be that way
	3. I am neutral
	4. I can live with it
	5. I dislike it that way

Table 4 Kano evaluation table (source by Berger et al. (1993))

Functional	Dysfunctional				
	Like	Must-be	Neutral	Live-with	Dislike
Like		A	A	A	O
Must-be	R	I	I	I	M
Neutral	R	I	I	I	M
Live-with	R	I	I	I	M
Dislike	R	R	R	R	

$$d_i^+ = \frac{A_i + O_i - R_i}{A_i + O_i + M_i + R_i + I_i}, \tag{1}$$

$$d_i^- = -\frac{O_i + M_i - R_i}{A_i + O_i + M_i + R_i + I_i}, \tag{2}$$

$$G_i = d_i^+ - d_i^-, \tag{3}$$

$$CRW_i = \frac{G_i}{\sum G_i}, \tag{4}$$

where A_i, O_i, M_i, R_i and I_i represent the distribution ratios of their respective Kano categories, d_i^+ refers to the positive joy of CR_i, and d_i^- represents the negative disgust of CR_i. CRW_i is the relative importance weight of CR_i, determined by the normalized value of its range, G_i, which is measured by positive delight minus negative disgust.

3.2 RF analysis

3.2.1 RF identification

According to March and Shapira (1987), risk is the change in the probability distribution of an outcome and the change in the probability and subjective value. Combined with the viewpoints of Jüttner et al. (2003) and Liu et al. (2015), our study divides RFs into: Demand, supply, environmental, and global outsourcing risks. Subsequently, combined with the impact of the COVID-19 epidemic, our research discusses RFs in detail in Section 4.2.

3.2.2 HoQ construction for CRs and RFs

The first HoQ links CRs and RFs. Its purpose is to identify the absolute and relative weights of RFs on the basis of the strength of each RF impact on individual CRs. In line with QFD literature (Chan and Wu, 2002; Nyoman Pujawan and Geraldin, 2009; Faisal, 2013), we measure R_{ij} (the relationship between CR_i and RF_j) using the scale of 9 (strong mitigation), 3 (moderate mitigation), 1 (little mitigation), and 0 (no mitigation), which is presented in Table 5. Then, the importance weights of RFs are calculated from CRW_i and R_{ij}. According to Lam and Bai (2016), the relative weights of RFs serve as the starting point for establishing the second HoQ.

According to CRW_i and R_{ij}, the absolute weight (AI_j^F) and relative weight (RFW_j) of RF_j are calculated by Eqs. (5) and (6), respectively.

$$AI_j^F = \sum_{i=1}^{n} CRW_i R_{ij}, \tag{5}$$

$$RFW_j = \frac{AI_j^F}{\sum_{j=1}^{m} AI_j^F}. \tag{6}$$

3.3 RM analysis

3.3.1 RM identification

According to Jüttner et al. (2003), the tendency of risk sources and drivers to outweigh risk mitigation strategies leads to supply chain vulnerabilities. Therefore, the right risk response can reduce such vulnerabilities. According to the research conclusions of Pettit et al. (2010; 2013) and Liu et al. (2015), three major supply chain resilience capabilities match supply chain vulnerabilities: Absorptive, recovery, and adaptive capacities. Absorptive capacity refers to the direct bearing capacity of supply chains themselves to external shocks, including the bearing magnitude and frequency. Recovery capacity means the repair ability of supply chains after emergency shocks, including the recovery degree and speed. Adaptive capacity is the ability of supply chains to adjust and adapt according to changes in the external environment, generally defined as an inevitability, that is, to accept changes and establish a system that can adapt to new conditions and orders. This section finds RMs related to these three ability categories through literature survey, expert interview, and personal interview.

Table 5 Linguist terms for evaluation

Number	Linguistics term	Corresponding score (R_{ij})
1	Strong	9
2	Moderate	3
3	Little	1
4	No	0

3.3.2 HoQ construction for RFs and RMs

As described in Section 3.2.2, the second HoQ establishes the connection between RFs and RMs starting from the relative weights of RFs. Experts are invited to score the relationship between RF_j and RM_k through the scale in Table 5. The scoring result is recorded as SR_{jk}, which represents the mitigating effect of RM_k on RF_j.

Similar to Section 3.2.2, the absolute weight (AI_k^M) and relative weight (RMW_k) of RM_k are calculated by Eqs. (7) and (8), respectively.

$$AI_k^M = \sum_{j=1}^{m} RFW_j SR_{jk}, \tag{7}$$

$$RMW_k = \frac{AI_k^M}{\sum_{k=1}^{l} AI_k^M}. \tag{8}$$

3.4 Optimization model

3.4.1 RM cost analysis

The cost of each RM is also estimated by experts. The specific process is as follows: The h-th expert gives a most likely cost (C_{km}^h), a positive cost (C_{ko}^h), and a negative cost (C_{kp}^h) for RM_k. Using Eq. (9), the cost assessment result (C_{ke}^h) of RM_k by the h-th expert is obtained. The final cost of RM_k (C_k) is given by Eq. (10).

$$C_{ke}^h = \left(4 * C_{km}^h + C_{ko}^h + C_{kp}^h\right)/6, \quad \forall k = 1, 2, ..., l, \ \ h = 1, 2, ..., q, \tag{9}$$

$$C_k = \sum_{h=1}^{q} C_{ke}^{h}/q,\ \forall k = 1, 2, ..., l. \tag{10}$$

3.4.2 RE of RM

According to Vugrin et al. (2011), we define RE as the ratio of the absolute weight of an RM to its cost (Eq. (11)).

$$RE_k = \frac{AI_k^M}{C_k},\ \forall k = 1, 2, ..., l. \tag{11}$$

3.4.3 Synergies among RMs

Following Chowdhury and Quaddus (2015), we use matrix $\boldsymbol{S}$ (Eq. (12)) to represent the synergistic effect among various RMs. Among them, matrix element S_{kr} ($S_{kr} = S_{rk}$) represents the cost that can be saved when RM_k and RM_r are used simultaneously (Park and Kim, 1998). S_{kr} is obtained through expert evaluation, and the specific process of expert evaluation refers to Eqs. (9) and (10).

$$\boldsymbol{S} = \begin{bmatrix} 0 & 10 & 0 & 10 & 20 & 0 & 0 & 0 & 0 & 0 & 0 \\ 10 & 0 & 20 & 25 & 0 & 10 & 0 & 0 & 0 & 0 & 20 \\ 0 & 20 & 0 & 10 & 10 & 0 & 0 & 0 & 0 & 0 & 0 \\ 10 & 25 & 10 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 20 & 0 & 10 & 0 & 0 & 10 & 0 & 0 & 0 & 0 & 0 \\ 0 & 10 & 0 & 0 & 10 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 20 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 20 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 20 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}. \tag{12}$$

3.4.4 RE maximization under budget constraints

Taking RE maximization as the objective function and the elastic shaping cost as the constraint condition, this study establishes a 0–1 nonlinear programming model, as shown in Eqs. (13) and (14). When $x_k = 1$, RM_k is adopted; and when $x_k = 0$, RM_k will not be adopted by the manager. In addition, B respects to the budget constraint.

$$\max f(x) = \sum_{k=1}^{l} RE_k x_k, \tag{13}$$

$$\sum_{k=1}^{l} C_k x_k - \sum_{k=1}^{l} \sum_{r>k}^{l} S_{kr} x_k x_r \leqslant B,\ x = \{0, 1\}. \tag{14}$$

3.4.5 CS maximization under budget constraints

Similar to Section 3.4.4, this section adopts a 0–1 nonlinear programming model with CS maximization as the objective function and budget cost as the constraint. Considering the scenarios in which firms are likely to focus on economic requirements at the expense of environmental and social requirements, this study discusses resilience strategies for maximizing CS in three scenarios (in different scenarios, economic, environmental, and social requirements are given with different weights).

In this study, the Kano model is used to quantify CS. The approximation function proposed by Florez-Lopez and Ramon-Jeronimo (2012) (Eq. (15)) can quantify CS_i according to the Kano category and fulfillment level (y_i) of CR_i. The relationship between CS_i and y_i is illustrated in Fig. 2.

$$CS_i = CS(y_i) = \begin{cases} 0.5y_i^2 + 0.5 & \text{(attractive CRs)} \\ y_i & \text{(one-dimensional CRs)} \\ -0.5y_i^2 + y_i & \text{(must-be CRs)} \\ 0.5 & \text{(indifferent CRs)} \end{cases}. \tag{15}$$

RFL_j represents the reduction value of RF_j, and $RFL_{j\max}$ refers to the reduction value of RF_j when $x_k = 1$ ($\forall k = 1, 2, ..., l$). f_i represents the fulfillment degree of CR_i, and $f_{i\max}$ represents the fulfillment degree of CR_i when $x_k = 1$ ($\forall k = 1, 2, ..., l$). The specific calculation process of y_i is shown in Eqs. (16)–(20).

$$RFL_j = \sum_{k=1}^{l} x_k SR_{jk}, \tag{16}$$

$$f_i = \sum_{j=1}^{m} RFL_j R_{ij}, \tag{17}$$

$$RFL_{j\max} = \sum_{k=1}^{l} SR_{jk}, \tag{18}$$

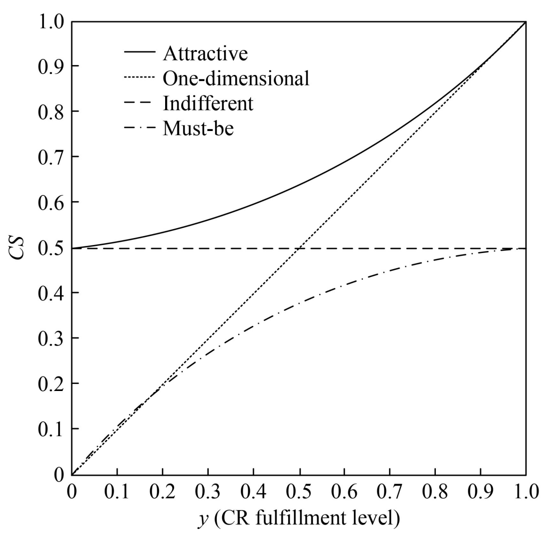

Fig. 2 CR's CS based on the Kano model.

$$f_{i\max} = \sum_{j=1}^{m} RFL_{j\max} R_{ij}, \tag{19}$$

$$y_i = \frac{f_i}{f_{i\max}}. \tag{20}$$

Scenario 1: Give equal weight to economic, environmental, and social requirements.

This research defines the total CS as the sum of the satisfaction of each CR, and the constraints follow the budget constraints in Section 3.4.4. The specific model is displayed in Eqs. (21) and (22).

$$\max g_1(X) = \sum_{i=1}^{n} CS_i, \tag{21}$$

$$\sum_{k=1}^{l} C_k x_k - \sum_{k=1}^{l} \sum_{r>k}^{l} S_{kr} x_k x_r \leqslant B,\ x = \{0,\ 1\}. \tag{22}$$

Scenario 2: Determine the satisfaction weights of various requirements according to the CRW_i of CR_i.

For example, CR_1, CR_2, and CR_3 belong to economic requirements, then the satisfaction weight related to economic requirements is the sum of CRW_1, CRW_2, and CRW_3 to calculate the satisfaction weight related to environmental and social requirements. The specific model is shown in Eqs. (23) and (24).

$$\max g_2(X) = \sum_{i=1}^{n} CRW_i CS_i, \tag{23}$$

$$\sum_{k=1}^{l} C_k x_k - \sum_{k=1}^{l} \sum_{r>k}^{l} S_{kr} x_k x_r \leqslant B,\ x = \{0,\ 1\}. \tag{24}$$

Scenario 3: Maximize satisfaction related to economic requirements.

In this scenario, the objective function only includes satisfaction related to economic requirements. For example, if some polluting companies struggle to maintain normal economic performance under the influence of the COVID-19 epidemic, then these companies may not have the energy to consider sustainability factors, and focus more on economic performance. When establishing the model, this study chooses the most extreme assumption, that is, an enterprise only considers economic benefits and completely sacrifices environmental and social benefits. The specific model is presented in Eqs. (25) and (26).

$$\max g_3(X) = \sum_{i=1}^{3} CS_i, \tag{25}$$

$$\sum_{k=1}^{l} C_k x_k - \sum_{k=1}^{l} \sum_{r>k}^{l} S_{kr} x_k x_r \leqslant B,\ x = \{0,\ 1\}. \tag{26}$$

4 Results and discussion

4.1 CR analysis

Step 1.1: CR identification

Through literature review and social research, CRs are finally determined as: Cost and price competitiveness (CR_1), on-time delivery (CR_2), professional customer service (CR_3), efficient resource utilization (CR_4), environmental pollution reduction (CR_5), green safety and health (CR_6), and enhanced social welfare (CR_7). As shown in Table 6.

Step 1.2: CR analysis based on the Kano model

As presented in Section 3.1.2, to analyze CR priority, this study designs the Kano questionnaire table (Table 3) to distribute to the respondents and finally obtains 200 valid questionnaires. Combined with the questionnaire results and the Kano evaluation table (Table 4), the Kano category of each CR is obtained. Then, the importance weight of each CR is obtained using Eqs. (1)–(4). The analysis results are shown in Table 7. Given that the opinions of respondents on the Kano types of CRs are not uniform, when calculating CS using Eq. (15), we measure CS according to the proportion of Kano types of CRs. For example, the survey on CR_1 shows that 27% of the respondents believe that CR_1 is of type A, 47% of respondents believe that CR_1 is of type O, and 26% of respondents believe that CR_1 is of type M. Then, the calculation process of CS_1 is shown in Eq. (27).

$$CS_1 = 0.27 * (0.5y_1^2 + 0.5) + 0.47 * y_1 + 0.26 * (-0.5y_1^2 + y_1). \tag{27}$$

As can be seen from Table 7, supply chain customers are interested in supply chains for CR_2 (on-time delivery), CR_1 (cost and price competitiveness), CR_3 (professional customer service), and CR_4 (efficient resource utilization). Subsequently, they focus on factors such as CR_5 (environmental pollution reduction), CR_6 (green safety and health), and CR_7 (improve social welfare).

Under the influence of the COVID-19 epidemic, the concern of supply chain customers for CR_2 (on-time delivery) is obvious. Epidemic prevention measures, such as road blockades and goods sterilization, have seriously affected logistics and transportation efficiency. The delay of a batch of goods often affects the operation of the entire downstream supply chain. For certain perishables, such as temperature-sensitive goods, the importance of on-time delivery is even more prominent.

Cost and price competitiveness is an important source of enterprise competitive advantage, so CR_1 (cost and

Table 6 CRs

Notation	CR
CR_1	Cost and price competitiveness
CR_2	On-time delivery
CR_3	Professional customer service
CR_4	Efficient resource utilization
CR_5	Environmental pollution reduction
CR_6	Green safety and health
CR_7	Social welfare improvement

Table 7 Experimental results through the Kano model

	A_i	O_i	M_i	I_i	R_i	d_i^+	d_i^-	G_i	CRW_i
CR_1	27.00%	47.00%	26.00%	0	0	0.74	−0.73	1.47	0.1551
CR_2	30.00%	50.00%	20.00%	0	0	0.80	−0.70	1.50	0.1582
CR_3	43.00%	40.00%	17.00%	0	0	0.83	−0.57	1.40	0.1477
CR_4	29.00%	41.00%	26.00%	4.00%	0	0.70	−0.67	1.37	0.1445
CR_5	41.00%	33.00%	26.00%	0	0	0.74	−0.59	1.33	0.1403
CR_6	26.00%	27.00%	47.00%	0	0	0.53	−0.74	1.27	0.1340
CR_7	44.00%	28.00%	14.00%	14.00%	0	0.72	−0.42	1.14	0.1202

price competitiveness) is the focus of customers at any time. However, several articles prove that supply chain customers are willing to pay extra to ensure that goods arrive on time, even at the expense of a certain price competitiveness. Thus, CR_2 is slightly more weighted than CR_1.

Customer service levels have always been a source of competitive advantage for companies because supply chain customers pay attention to service quality. High-quality customer services can greatly improve satisfaction and help form long-term relationships with customers.

Efficient resource utilization means an increase in the input–output production resource efficiency, which not only helps save raw materials but also means high environmental and social benefits. In addition, due to the shortage of resources caused by the COVID-19 outbreak and the implementation of the green sustainability concept, supply chain customers have also paid increasingly attention to CR_4 (efficient resource utilization).

4.2 RF analysis

Step 2.1: SSC RF identification

Following Jüttner et al. (2003) and Liu et al. (2015), this study divides supply chain risks into four types: Demand, supply, environmental, and global outsourcing risks.

(i) Demand risk

Supply chains refer to network chain structures formed by upstream and downstream enterprises involved in the activities of providing products or services to end customers during the production and circulation process. Reasons such as man-made and natural disasters cause supply and demand uncertainties in supply chain systems. Such uncertainties propagate up supply chains, creating high losses and disruption risks.

Since December 2019, the COVID-19 epidemic has gradually spread globally on a large scale, and almost all manufacturing companies have been affected by it. The specific manifestation is the surge in market demand for certain product types, resulting in general difficulties in raw material supply. This effect propagates upstream and downstream along supply chains.

(ii) Supply risk

Various epidemic prevention policies, such as road blockades and goods sterilization in medium- and high-risk areas, have been strictly implemented. Logistics inefficiency caused by transportation interruption has become a major difficulty in raw material, finished, semi-finished, and other goods supplies for manufacturing enterprises. Coupled with the “zero inventory” management concept that the manufacturing industry has always implemented, the original company production plan has been seriously disrupted. Furthermore, huge demand and material supply uncertainties have brought difficulties to the new production plan.

The COVID-19 epidemic not only directly affects supply chain liquidity but also indirectly leads to international conflict escalation. The technological blockade of China by Western countries has forced the interruption of the Chinese manufacturing industry’s technology supply chain, and production technology shortage has become prominent.

In addition, the abundant, low-cost, and high-quality labor force has always been an important source of international competitive advantage for the Chinese manufacturing industry. However, with the gradual reduction of the industry’s demographic dividend, labor costs continue to increase. Coupled with the rising prices of upstream raw materials, the Chinese manufacturing industry is facing unprecedented pressure. Furthermore, due to the outbreak and continued spread of the epidemic, a large number of employees cannot return to daily work, further weakening the advantage of the Chinese manufacturing labor force.

(iii) Environmental risk

The environment refers to the natural and social environment in which supply chains survive, and a stable natural and social environment is the basis for the normal operation of enterprises. Therefore, environmental risk is one of the risks faced by enterprises, which can be divided into natural and social environmental risks. Natural environment risk refers to the risk of heavy fines for companies releasing pollutants into the air or disposing industrial wastes on lands or in waterways. Social environmental risk refers to the legal, social, political, and economic risks that enterprises encounter from their operating environments. For example, the COVID-19 outbreak has intensified geopolitical competition, resulting in a shrinking market share of some industries in China, such as electronic communication equipment. The "black swan event" of the COVID-19 epidemic has also caused changes in the exchange rates among currencies of various countries, affecting the import and export of the Chinese manufacturing industry.

(iv) Global outsourcing risk

Outsourcing refers to the activities in which companies delegate noncore businesses to third parties, which specialize in operations. With the economic globalization development, outsourcing services have also developed from domestic outsourcing to global outsourcing. However, outsourcing activities bring risks related to information sharing.

Information-sharing risks mainly include information asymmetry and leakage risks. Specifically, information asymmetry occurs in outsourced processes where real-time monitoring is difficult. Outsourcing service providers may take advantage of enterprises' information disadvantage, hide some real information, and even use false information to mislead enterprises to achieve the purpose of concluding outsourcing contracts with enterprises. Meanwhile, the information leakage risk often occurs in the IT industry.

According to the above analysis, RFs are shown in Table 8.

Step 2.2: HoQ construction for CRs and RFs

After the RFs are determined, the HoQ for CRs and RFs is displayed in Table 9. The absolute and relative weights of RFs are presented at the bottom of the HoQ.

4.3 RM analysis

Step 3.1: RM identification

Referring to the three major capabilities of supply chain resilience and a review of related literature, this study identifies 11 RMs, as shown in Table 10.

Step 3.2: HoQ construction for RFs and RMs

Similar to Step 2.2, the HoQ for RFs and RMs is shown in Table 11 (the output of HoQ (1), i.e., the relative weight of supply chain risk (RFW_j), is used as input to HoQ (2) to obtain the risk mitigation capability of each RM). The absolute and relative weights of each RM are shown at the bottom of the HoQ. The cost and RE of each RM are also listed at the bottom of the HoQ.

Table 8 RFs

Risk type	RF
Demand risk	Supply and demand uncertainty (RF_1)
Supply risk	Production planning problem (RF_2)
	Transportation interruption (RF_3)
	Production technology shortage (RF_4)
	Labor force advantage weakening (RF_5)
Global outsourcing risk	Information sharing risk (RF_6)
Environmental risk	Emergency risk (RF_7)
	Exchange rate and price change (RF_8)
	Reduced market share (RF_9)
	Environmental pollution (RF_{10})

4.4 Optimal resilience strategies to maximize RE under budget constraints

The supply chain of the Chinese manufacturing industry is highly complex and faces various threats. Policymakers have a range of resilience strategies to choose from, which, if implemented one by one, can theoretically maximize supply chain resilience. However, the budget applied to supply chain resilience management is limited. Therefore, on the basis of fully considering the synergistic effect, a reasonable combination of different strategies can maximize RE under a limited cost.

This study takes RE maximization as the objective function and the limited resilience shaping cost as the constraint condition. It also uses the 0–1 nonlinear programming model to calculate optimal resilience strategies under budget constraints, as shown in Eqs. (13) and (14).

Table 9 HoQ (1)

RF_j		RF_1	RF_2	RF_3	RF_4	RF_5	RF_6	RF_7	RF_8	RF_9	RF_{10}
CR_i	CRW_i	Relationship matrix between CRs and RFs									
CR_1	0.1551	3	1	0	0	9	1	1	9	3	0
CR_2	0.1582	3	3	9	3	0	3	9	0	1	0
CR_3	0.1477	0	1	1	1	0	1	3	1	1	0
CR_4	0.1445	3	3	0	9	0	3	0	0	0	0
CR_5	0.1403	0	3	0	1	0	1	1	0	0	9
CR_6	0.1340	0	1	0	9	0	1	9	0	0	1
CR_7	0.1202	1	0	0	0	0	3	3	0	0	9
AI_j^F		1.494	1.766	1.572	3.269	1.396	1.846	3.729	1.543	0.771	2.479
RFW_j		0.075	0.089	0.079	0.164	0.070	0.093	0.188	0.078	0.039	0.125

Table 10 RM

Ability	RM
Absorptive capacity	Supply chain relationship management (RM_1)
	Prediction and predictive analysis (RM_2)
	Inventory management (RM_3)
	Advanced IT system (RM_4)
Recovery capacity	Multisource supply (RM_5)
	Market development (RM_6)
	Labor skill training (RM_7)
Adaptive capacity	Modular product and multiple material use (RM_8)
	Product and process improvement (RM_9)
	Product differentiation and customization (RM_{10})
	Safety warning and maintenance (RM_{11})

According to Eqs. (13) and (14), this study uses the excel solver to calculate optimal resilience strategies when cost constraint B is set to 600, 500, 400, 300, 250, 225, 200, 190, and 180, respectively. The specific results are presented in Table 12.

As presented above, the following conclusions can be drawn: (i) When the elastic budget is sufficient, the maximum RE that an enterprise chooses to implement all resilience strategies one by one is about 0.445. (ii) When the elastic budget gradually declines, sacrificing a certain adaptive capacity can save a large part of the cost while still maintaining a high resilience level. For example, compared with implementing each RM one by one, when the budget is 300, the system achieves a resilience level of 93.89%, whereas the actual cost is only 275, which is equivalent to sacrificing 6.11% of the resilience level and saving 36.78% of the resilience shaping cost. When the budget is 400, the resilience level is sacrificed by less than 1%, and the resilience shaping cost is saved by 18.39%.

4.5 Optimal resilience strategies to maximize CS under budget constraints

The idea of CS emerged in the mid-1980s. This idea advocates that all business activities of an enterprise should be based on CS and analyze CRs from the perspective of customers and their viewpoints, rather than a company's own interests and viewpoints. Transforming the business concept of improving CS into a feasible business mode has become a market competition strategy respected by domestic and foreign enterprises (Kapranos and Young, 1998).

We use the Kano model to quantify CS, and a 0–1 nonlinear programming model is used to calculate resilience strategies that maximize CS. As shown in Section 3.4.5, we discuss CS maximization in three scenarios. In the first scenario, we assign equal weights to economic, environmental, and social requirements and use a nonlinear programming model to calculate resilience strategies that maximize CS. In the second scenario, we assign the importance weights of various requirements according to CRW_i and calculate resilience strategies that maximize CS. In the third case, we only consider economic sustainability requirement-related satisfaction maximization to find optimal resilience strategies.

Scenario 1: Give equal weights to economic, environmental, and social requirements.

According to Eqs. (21) and (22), optimal resilient policies are calculated when B is equal to 600, 500, 400, 300, 250,

Table 11 HoQ (2)

RM_k		RM_1	RM_2	RM_3	RM_4	RM_5	RM_6	RM_7	RM_8	RM_9	RM_{10}	RM_{11}
RF_j	RFW_j	Relationship matrix between RFs and RMs										
RF_1	0.075	3	9	3	1	1	1	0	0	1	0	0
RF_2	0.089	0	1	0	1	1	0	1	3	9	1	1
RF_3	0.079	3	0	1	0	9	0	0	0	0	0	9
RF_4	0.164	0	0	0	0	0	0	9	3	1	0	0
RF_5	0.070	0	0	0	0	1	0	9	0	0	0	0
RF_6	0.093	3	3	1	9	0	0	0	0	0	0	3
RF_7	0.188	3	9	9	0	9	0	0	3	0	0	9
RF_8	0.078	1	9	9	0	3	0	0	3	0	0	1
RF_9	0.039	0	3	0	0	0	9	0	1	3	3	0
RF_{10}	0.125	0	0	0	0	0	0	1	3	3	0	9
AI_k^M		1.383	3.550	2.786	1.001	2.869	0.425	2.327	1.970	1.531	0.205	3.970
RMW_k		0.063	0.161	0.127	0.045	0.130	0.019	0.106	0.090	0.070	0.009	0.180
C_k		30	50	40	50	70	40	30	80	60	80	70
RE_k		0.046	0.071	0.070	0.020	0.041	0.011	0.078	0.025	0.026	0.003	0.057

Table 12 Optimal combination of flexible strategies under limited budgets

B	Absorptive capacity				Recovery capacity			Adaptive capacity				Total RE	Resilience level	Actual cost
	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}			
600	1	1	1	1	1	1	1	1	1	1	1	0.445	100.00%	435
500	1	1	1	1	1	1	1	1	1	1	1	0.445	100.00%	435
400	1	1	1	1	1	1	1	1	1	0	1	0.443	99.42%	355
300	1	1	1	1	1	1	1	0	1	0	1	0.418	93.89%	275
250	1	1	1	1	1	1	1	0	0	0	1	0.393	88.17%	235
225	1	1	1	1	1	0	1	0	0	0	1	0.382	85.78%	215
200	1	1	1	1	0	0	1	0	0	0	1	0.341	76.58%	175
190	1	1	1	1	0	0	1	0	0	0	1	0.341	76.58%	175
180	1	1	1	1	1	0	1	0	0	0	0	0.325	73.05%	165

225, 200, 190, 180, and 170, respectively. The calculation results are presented in Table 13.

Scenario 2: Determine the satisfaction weights of various requirements according to the CRW_i of CR_i.

According to Eqs. (23) and (24), calculate optimal resilient policies when B is equal to 600, 500, 400, 300, 250, 225, 200, 190, 180, and 170, respectively. The calculation results are displayed in Table 14.

Scenario 3: Maximize satisfaction related to economic requirements.

According to Eqs. (25) and (26), calculate optimal resilient policies when B is equal to 600, 500, 400, 300, 250, 225, 200, 190, 180, and 170, respectively. The calculation results are provided in Table 15.

Comparing Tables 13–15, on the premise that the three resilience capacities (i.e., absorptive, recovery, and adaptive capacities) are all non-zero, the CS of an optimal resilience strategy under each budget constraint is a value from 4 to 6. To obtain a certain level of market competitiveness, achieving at least five or more CS is necessary, that is, enterprises must prepare a flexible budget of at least 250.

When the COVID-19 epidemic leads to sluggish corporate revenues and flexible budgets below 250, many companies may choose to focus their limited funds on economic requirements (Scenario 3). However, comparing Tables 14 and 15, under the same budget level, the CS of Scenario 3 is always less than or equal to that of Scenario 2. Interestingly, when the budget is 180, Scenario 2 spends less actual cost but achieves higher CS than Scenario 3. Thus, this study infers that no matter how limited the budget is, the pursuit of environmental and social sustainability cannot be abandoned.

In addition, through the comparison of Tables 12 and 15, the nine RMs, namely, RM_1, RM_2, RM_3, RM_4, RM_5, RM_6, RM_7, RM_9, and RM_{11}, are important to obtain market competitiveness (CS greater than 5). In any case, the absorptive capacity (RM_1, RM_2, RM_3, RM_4) is the most indispensable resilience capacity.

5 Conclusions

Supply chain resilience is the ability of supply chains to respond to emergencies and system structures to maintain this ability. The higher the supply chain resilience, the

Table 13 Calculation results for Scenario 1

B	Absorptive capacity				Recovery capacity			Adaptive capacity				Total RE	Resilience level	Actual cost	CS
	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}				
600	1	1	1	1	1	1	1	1	1	1	1	0.445	100.00%	435	6.030
500	1	1	1	1	1	1	1	1	1	1	1	0.445	100.00%	435	6.030
400	1	1	1	1	1	1	1	1	1	0	1	0.443	99.42%	355	5.980
300	1	1	1	1	1	1	1	0	1	0	1	0.418	93.89%	275	5.486
250	1	1	1	0	1	0	1	0	1	0	1	0.388	87.02%	250	5.132
225	1	1	1	1	1	0	1	0	0	0	1	0.382	85.78%	215	4.972
200	1	1	1	1	0	0	1	0	0	0	1	0.341	76.58%	175	4.430
190	1	1	1	1	0	0	1	0	0	0	1	0.341	76.58%	175	4.430
180	1	1	1	1	0	0	1	0	0	0	1	0.341	76.58%	175	4.430
170	1	1	1	0	0	0	1	0	0	0	1	0.321	72.09%	170	4.179

Table 14 Calculation results for Scenario 2

B	Absorptive capacity				Recovery capacity			Adaptive capacity				Total RE	Resilience level	Actual cost	CS
	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}				
600	1	1	1	1	1	1	1	1	1	1	1	0.445	100.00%	435	6.030
500	1	1	1	1	1	1	1	1	1	1	1	0.445	100.00%	435	6.030
400	1	1	1	1	1	1	1	1	1	0	1	0.443	99.42%	355	5.980
300	1	1	1	1	1	1	1	0	1	0	1	0.418	93.89%	275	5.486
250	1	1	1	0	1	0	1	0	1	0	1	0.388	87.02%	250	5.132
225	1	1	1	1	1	0	1	0	0	0	1	0.382	85.78%	215	4.972
200	1	1	1	1	1	0	0	0	0	0	1	0.305	68.36%	185	4.434
190	1	1	1	1	1	0	0	0	0	0	1	0.305	68.36%	185	4.434
180	1	1	1	1	0	0	1	0	0	0	1	0.341	76.58%	175	4.430
170	1	1	1	1	1	0	1	0	0	0	0	0.325	73.05%	165	4.076

Table 15 Calculation results for Scenario 3

B	Absorptive capacity				Recovery capacity			Adaptive capacity				Total RE	Resilience level	Actual cost	CS
	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}				
600	1	1	1	1	1	1	1	1	1	1	1	0.445	100.00%	435	6.030
500	1	1	1	1	1	1	1	1	1	1	1	0.445	100.00%	435	6.030
400	1	1	1	1	1	1	1	1	1	0	1	0.443	99.42%	355	5.980
300	1	1	1	1	1	1	1	0	1	0	1	0.418	93.89%	275	5.486
250	1	1	1	1	1	1	1	0	0	0	1	0.393	88.17%	235	5.065
225	1	1	1	1	1	0	1	0	0	0	1	0.382	85.78%	215	4.972
200	1	1	1	1	1	0	0	0	0	0	1	0.305	68.36%	185	4.434
190	1	1	1	1	1	0	0	0	0	0	1	0.305	68.36%	185	4.434
180	1	1	1	0	1	0	0	0	0	0	1	0.284	63.87%	180	4.181
170	1	1	1	1	1	0	1	0	0	0	0	0.325	73.05%	165	4.076

better the performance in the face of disturbances. However, the implementation of an efficient resilience strategy is costly, and not all companies can spend such an amount of money. Compared with large-scale enterprises, small- and medium-sized enterprises have limited flexibility budgets, so emphasizing the tradeoff between flexibility level and flexibility cost is necessary. Supply chain resilience performance is not only related to the resilience level but also depends on CS, so introducing CS quantification to find optimal resilience strategies is necessary. In addition, when designing resilience strategies, the cooperative relationship among RMs should be fully considered to achieve the effect of 1 + 1 > 2.

This study combines QFD and Kano models to calculate the importance weights of RFs and RMs from the importance ranking of CRs. Then, it uses the absolute weight and implementation cost of RMs to calculate their REs. Subsequently, it calculates the CS of CRs using the Kano type and the fulfillment levels of CRs. For the calculation of optimal strategies, this research adopts the 0–1 nonlinear programming model. Taking the budget cost as the constraint condition, this study calculates optimal resilience strategies with RE and CS maximization as the objective function, respectively.

Comparing resilience strategies that maximize RE under different budget constraints (Table 12), this research infers that when budgets are limited, firms can prioritize sacrificing RMs related to adaptive capacity, namely, RM_8 (product modularity and multiple material use), RM_9 (product and process improvement), and RM_{10} (product differentiation and customization). To maintain high resilience levels against risks, RM_{11} (safety warning and maintenance) in adaptive capacity is indispensable. When CS maximization is taken as the objective function, considering that in reality, companies may ignore sustainable requirements, such as environmental and social requirements due to insufficient funds, this study sets up a model of similar scenarios for comparison and discussion. Comparing Scenarios 2 (Table 14) and 3 (Table 15), we find that even if a company budget is low, it cannot abandon the pursuit of environmental and social sustainability. Comparing Tables 12 and 15, we observe that in any case, absorptive capacity (RM_1, RM_2, RM_3, and RM_4) is the most indispensable resilience capacity.

This work can be extended in several directions. It uses the mathematical programming model to calculate the highest RE corresponding to each budget level and determines the changing laws of optimal resilience strategies when budget levels change. Another probable future research direction is to understand how SSC managers choose appropriate budget levels for moderate flexibility. Future researchers can characterize risk levels using methods such as mathematical modeling and find ways to map these risk levels to RE. Such research can help managers choose budget levels that can achieve RE that matches the risk levels faced by SSCs. In this way, a modest elasticity, which matches risks to resource investments, can be achieved. Therefore, risk level quantification deserves further research attention.

References

Bastas A, Liyanage K (2018). Sustainable supply chain quality management: A systematic review. Journal of Cleaner Production, 181: 726–744

Berger C, Blauth R, Boger D (1993). Kano's methods for understanding customer-defined quality. Center for Quality Management Journal, 2(4): 3–35

Blackhurst J V, Scheibe K P, Johnson D J (2008). Supplier risk assessment and monitoring for the automotive industry. International Journal of Physical Distribution & Logistics Management, 38(2): 143–165

Blos M F, Quaddus M, Wee H M, Watanabe K (2009). Supply chain risk management (SCRM): A case study on the automotive and electronic industries in Brazil. Supply Chain Management, 14(4): 247–252

Bode C, Wagner S M, Petersen K J, Ellram L M (2011). Understanding responses to supply chain disruptions: Insights from information processing and resource dependence perspectives. Academy of Management Journal, 54(4): 833–856

Büyüközkan G, Berkol Ç (2011). Designing a sustainable supply chain using an integrated analytic network process and goal programming approach in quality function deployment. Expert Systems with Applications, 38(11): 13731–13748

Büyüközkan G, Çifçi G (2013). An integrated QFD framework with multiple formatted and incomplete preferences: A sustainable supply chain application. Applied Soft Computing, 13(9): 3931–3941

Carnevalli J A, Miguel P C (2008). Review, analysis and classification of the literature on QFD: Types of research, difficulties and benefits. International Journal of Production Economics, 114(2): 737–754

Chan L K, Wu M L (2002). Quality function deployment: A literature review. European Journal of Operational Research, 143(3): 463–497

Chowdhury M M H, Quaddus M (2016). Supply chain readiness, response and recovery for resilience. Supply Chain Management, 21(6): 709–731

Chowdhury M M H, Quaddus M (2017). Supply chain resilience: Conceptualization and scale development using dynamic capability theory. International Journal of Production Economics, 188: 185–204

Chowdhury M M H, Quaddus M A (2015). A multiple objective optimization based QFD approach for efficient resilient strategies to mitigate supply chain vulnerabilities: The case of garment industry of Bangladesh. Omega, 57: 5–21

Christopher M, Peck H (2004). Building the resilient supply chain. International Journal of Logistics Management, 15(2): 1–14

Colicchia C, Dallari F, Melacini M (2010). Increasing supply chain resilience in a global sourcing context. Production Planning and Control, 21(7): 680–694

Cristiano J J, Liker J K, White III C C (2001). Key factors in the successful application of quality function deployment (QFD). IEEE Transactions on Engineering Management, 48(1): 81–95

Faisal M N (2013). Managing risk in small and medium enterprises (SMEs) supply chains' using quality function deployment (QFD) approach. International Journal of Operations Research and Information Systems, 4(1): 64–83

Fennell M L, Alexander J A (1987). Organizational boundary spanning in institutionalized environments. Academy of Management Journal, 30(3): 456–476

Florez-Lopez R, Ramon-Jeronimo J M (2012). Managing logistics customer service under uncertainty: An integrative fuzzy Kano framework. Information Sciences, 202: 41–57

González M E, Quesada G, Picado F, Eckelman C A (2004). Customer satisfaction using QFD: An e-banking case. Managing Service Quality, 14(4): 317–330

Haq A N, Boddu V (2017). Analysis of enablers for the implementation of leagile supply chain management using an integrated fuzzy QFD approach. Journal of Intelligent Manufacturing, 28(1): 1–12

He L, Wu Z, Xiang W, Goh M, Xu Z, Song W, Ming X, Wu X (2021). A novel Kano-QFD-DEMATEL approach to optimise the risk resilience solution for sustainable supply chain. International Journal of Production Research, 59(6): 1714–1735

Heckmann I, Comes T, Nickel S (2015). A critical review on supply chain risk: Definition, measure and modeling. Omega, 52: 119–132

Holling C S (1973). Resilience and stability of ecological systems. Annual Review of Ecology and Systematics, 4(1): 1–23

Jüttner U, Peck H, Christopher M (2003). Supply chain risk management: Outlining an agenda for future research. International Journal of Logistics Research and Applications, 6(4): 197–210

Kano N, Seraku N, Takahashi F, Tsuji S (1984). Attractive quality and must-be quality. Journal of the Japanese Society for Quality Control, 14(2): 147–156

Kapranos P, Young K P (1998). Manufacturing for value-customer satisfaction. Metallurgia, 65(1): 23–27

Kleindorfer P R, Saad G H (2005). Managing disruption risks in supply chains. Production and Operations Management, 14(1): 53–68

Lam J S L, Bai X (2016). A quality function deployment approach to improve maritime supply chain resilience. Transportation Research Part E: Logistics and Transportation Review, 92: 16–27

Liu J G, Jiang X H, Zhao J L (2015). Resilience of the supply chain system based on interpretative structural modeling. Journal of Systems & Management, 24(4): 617–623 (in Chinese)

March J G, Shapira Z (1987). Managerial perspectives on risk and risk taking. Management Science, 33(11): 1404–1418

Mitroff I I, Alpaslan M C (2003). Preparing for evil. Harvard Business Review, 81(4): 109–115

Nooraie V, Fathi M, Narenji M, Parast M M, Pardalos P M, Stanfield P M (2020). A multi-objective model for risk mitigating in supply chain design. International Journal of Production Research, 58(5): 1338–1361

Nyoman Pujawan I, Geraldin L H (2009). House of risk: A model for proactive supply chain risk management. Business Process Management Journal, 15(6): 953–967

Park T, Kim K J (1998). Determination of an optimal set of design requirements using house of quality. Journal of Operations Management, 16(5): 569–581

Pettit T J, Croxton K L, Fiksel J (2013). Ensuring supply chain resilience: Development and implementation of an assessment tool. Journal of Business Logistics, 34(1): 46–76

Pettit T J, Fiksel J, Croxton K L (2010). Ensuring supply chain resilience: Development of a conceptual framework. Journal of Business Logistics, 31(1): 1–21

Pires Ribeiro J, Barbosa-Povoa A (2018). Supply Chain Resilience: Definitions and quantitative modelling approaches, a literature review. Computers & Industrial Engineering, 115: 109–122

Ponomarov S Y, Holcomb M C (2009). Understanding the concept of supply chain resilience. International Journal of Logistics Management, 20(1): 124–143

Qazi A, Dickson A, Quigley J, Gaudenzi B (2018). Supply chain risk network management: A Bayesian belief network and expected utility based approach for managing supply chain risks. International Journal of Production Economics, 196: 24–42

Song H (2020). The implication of the novel coronavirus outbreak to supply chain flexibility management. China Business and Market, 34(3): 11–16 (in Chinese)

Svensson G (2000). A conceptual framework for the analysis of vulnerability in supply chains. International Journal of Physical Distribution & Logistics Management, 30(9): 731–750

Vugrin E D, Warren D E, Ehlen M A (2011). A resilience assessment framework for infrastructure and economic systems: Quantitative and qualitative resilience analysis of petrochemical supply chains to a hurricane. Process Safety Progress, 30(3): 280–290

Wagner S M, Bode C (2006). An empirical investigation into supply chain vulnerability. Journal of Purchasing and Supply Management, 12(6): 301–312

Wang Y Q, Gao Y, Teng C X (2017). Literature review and research prospects of supply chain resilience under disruption. Management Review, 29(12): 204–216 (in Chinese)

Wasserman G S (1993). On how to prioritize design requirements during the QFD planning process. IIE Transactions, 25(3): 59–65

Xie Y, He L, Xiang W, Peng Z, Ming X, Goh M (2022). Prioritizing risk factors in sustainable supply chain using fuzzy Kano and interval-valued intuitionistic fuzzy QFD. Kybernetes, in press, doi:10.1108/K-07-2021-0642

Yazdani M, Wang Z X, Chan F T (2020). A decision support model based on the combined structure of DEMATEL, QFD and fuzzy values. Soft Computing, 24(16): 12449–12468

Zhang Z, Awasthi A (2014). Modelling customer and technical requirements for sustainable supply chain planning. International Journal of Production Research, 52(17): 5131–5154

Zheng X, Pulli P (2012). Improving mobile services design: A QFD approach. Computing and Informatics, 26(4): 369–381