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RESEARCH ARTICLE

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# Modeling of the resilient supply chain system from a perspective of production design changes



**Abstract** Building an effective resilient supply chain system (RSCS) is critical and necessary to reduce the risk of supply chain disruptions in unexpected scenarios such as COVID-19 pandemic and trade wars. To overcome the impact of insufficient raw material supply on the supply chain in mass disruption scenarios, this study proposes a novel RSCS considering product design changes (PDC). An RSCS domain model is first developed from the perspective of PDC based on a general conceptual framework, i.e., function-context-behavior-principle-state-structure (FCBPSS), which can portray complex systems under unpredictable situations. Specifically, the interaction among the structure, state and behavior of the infrastructure system and substance system is captured, and then a quantitative analysis of the change impact process is presented to evaluate the resilience of both the product and supply chain. Next, a case study is conducted to demonstrate the PDC strategy and to validate the feasibility and effectiveness of the RSCS domain model. The results show that the restructured RSCS based on the proposed strategy and model can remedy the huge losses caused by the unavailability of raw materials.

**Keywords** resilient supply chain, supply chain disruption, domain modeling, product design changes

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## 1 Introduction

The COVID-19 pandemic has brought great disasters to people all over the world, affecting 227 countries and regions, resulting in more than 6.29 million deaths. Recently, an outbreak of a variant of the virus known as Omicron in Shanghai has forced the government to take lockdown measures. The implementation of these measures not only disrupts the normal life of Shanghai residents, but also brings huge disasters to many local physical supply chain industries. For example, the stocks of sportswear brands Adidas and Under Armour have fallen by 4% and 25% respectively during this period (Hetzner, 2022a). In addition, the chip business is also stretched to the breaking point. Microchip has a complex global supply chain, and its semiconductor chips are widely used in automobiles and industrial machines, and many key suppliers are in Shanghai. Therefore, most of products cannot be manufactured and used due to the epidemic, or existing products cannot be delivered in time (McGregor, 2022). Furthermore, the automobile industry has also been affected, especially Tesla, because the Shanghai manufacturing plant is not only the main domestic supply place, but also the export center of the European market (Hetzner, 2022b).

Due to complex and interrelated network structure of the global supply chain, the outbreak of the epidemic has seriously threatened the normal operation of the international supply chain (Paul and Chowdhury, 2021). Unlike other supply chain risks such as volcanic eruptions, strikes, and earthquakes, the epidemic spreads with the flow of people without visible signs. The blockade policy adopted due to the epidemic has interrupted many links among suppliers, factories, distributors and logistics (Ivanov, 2020). Shortage of raw materials can directly lead to production line stagnation and will affect the downstream distributors and logistics distribution. This kind of chain reaction of interruption leads to order backlog and delivery failure, paralyzes the supply chain, and ultimately brings incalculable economic losses.

The unprecedented supply chain disruptions triggered by pandemics have drawn the attention of scholars to the study and practice of supply chain resilience (SCR) (Ivanov and Dolgui, 2020; Shi et al., 2021). Traditional risk management measures of responding to partial supply chain disruptions by adding back-up suppliers as well as inventory and expanding new distribution channels have shown their inadequacy and limitations (Chopra and Sodhi, 2004; Torabi et al., 2015; Ivanov et al., 2017). A series of new supply chain risks, such as the instability of raw material supply, uncertainty in market demand (Paul and Chowdhury, 2021), the ripple effect caused by the impact of long-term epidemic, and the scale of unpredictable interruptions, have brought unprecedented challenges to the survival and development of physical manufacturing enterprises (Dolgui et al., 2018). Therefore, it is necessary to design resilient supply chains from a special perspective to improve the capability of enterprises to withstand risks (Rajesh, 2021).

The continuous production and supply of relevant parts is the key to ensure the normal operation of supply chain system (SCS). Therefore, examining the security of SCS from the perspective of product strategic management and discussing effective product flexibility design strategy are necessary for the resilient development of supply chain. Thus, it is necessary to carry out resilient product design and enhance the elastic supply capacity of components to maintain the resilience of the SCS, so that enterprises can still survive in the changing environment. This study constructs a resilient supply chain system (RSCS) based on product design changes (PDC) by combining with upstream suppliers and distributors from two design perspectives including resilient design of products and elastic supply of components. The construct of the model not only needs to systematically analyze the structure, function, behavior, and other characteristics of SCS, but also needs a proprietary tool to guide the management and reconstruction behavior. Then, based on function-context-behavior-principle-state-structure (FCBPSS) modeling tool, a novel domain model of RSCS is constructed, which helps us to guide operators to establish and manage SCS from different perspectives (Song and Wang, 2022).

The main contributions of this study are presented as follows: First, the supply chain model based on PDC provides a new perspective for the research of RSCS in the post epidemic era. Second, a novel domain model with FCBPSS is applied to the complex SCS, which provides a new idea and method for the management and reconstruction of RSCS.

The rest of this study is organized as follows. Section 2 presents a literature review regarding SCR, PDC and domain model. An RSCS framework considering PDC is described in Section 3. In Section 4, a novel FCBPSS domain model of RSCS is proposed, followed by an illustration of the application of domain model in Section 5. Conclusions and further discussions are provided in Section 6.

## 2 Literature review

### 2.1 Supply chain resilience

The concept of SCR was first proposed by Rice and Caniato (2003). After that, different scholars put forward different definitions of SCR, in which the most widely recognized definition of SCR is the adaptability of the supply chain to deal with emergencies, interruptions and recoveries (Ponomarov and Holcomb, 2009). In recent years, the world has become volatile, uncertain, complex, and ambiguous with the frequent occurrence of uncertain disruption events, such as COVID-19 (Gao et al., 2021). Therefore, a large number of scholars focus on the study of SCR, strategies for SCR improvement and the application of disruptive technologies to SCS (Wang et al., 2022).

The data during COVID-19 shows that the failure of a single supply chain connection or node may lead to a global supply chain crisis (Chowdhury et al., 2021). Chowdhury and Quaddus (2016) put forward many SCR strategies for the current vulnerability, which mainly focus on three dimensions, namely, preparation, response and recovery. In order to minimize the impact of the shortage of basic living resources, scholars put forward various countermeasures, such as resuming production as soon as possible or increasing the production of related products (Lozano-Diez et al., 2020). Managers can reallocate existing resources, such as redeploying resources from non-priority areas or redeploying employees from non-essential activities, to promote the normal production of basic living materials (Leite et al., 2021). During the epidemic, the improvement of production capacity can improve the SCR (Paul and Chowdhury, 2021). Removing non-essential production processes and establishing temporary production capacity can increase the resiliency and responsiveness of SCS. The regional decentralized manufacturing base with necessary logistics support were proposed by Shekarian and Mellat Parast (2021). In order to make the existing resources serve more customers, some scholars proposed to modify the basic characteristics such as product quality or size to improve the comprehensive production capacity (Paul and Chowdhury, 2020). In addition to improving production capacity, some scholars proposed resilient response strategies in response to the shortage of raw materials. It is recommended that diversifying suppliers in different regions and implementing emergency purchase to avoid failures of supply caused by the lockdown (Remko, 2020). In view of the large-scale destruction of the supply chain caused by the epidemic, it is particularly important to study the reorganization of the supply chain. The traditional efficiency-oriented production modes, such as centralized production and decentralized global procurement, are no longer suitable for the post epidemic era. Besides, some scholars proposed that adopting the nearest production mode and reducing the number of partners in the supply chain are effective measures to deal with supply chain disruption (de Paulo Farias and de Araújo, 2020; Ivanov and Das, 2020). Some researchers regarded the transformation of supply chain structure as a countermeasure. Critical resource sharing strategy were proposed to reduce the interdependency of a single-agency structured supply chain (Mehrotra et al., 2020).

In addition to traditional methods, many disruptive technologies such as digital twin technology, blockchain technology, additive manufacturing, and artificial intelligence smart system are being studied to improve the resilience and sustainability of SCS (Frederico, 2021). Digital twin technology can be used to improve attributes in terms of real-time data of disruption and end-to-end visibility (Ivanov and Dolgui, 2021). It is suggested that smart system and autonomous processes are able to generate more resilience and reconfigure supply chain to disruptions (Ralston and Blackhurst, 2020). Blockchain technology can promote distributed collaborative production, facilitate the sharing of industrial big data, as well as assist in collaboration and rapid trust, with promising applications in intelligent manufacturing and SCR (Dubey et al., 2020; Zhang et al., 2020). Additionally, several studies argued that the use of additive manufacturing method such as 3D printing technology can meet the extra demand for ventilators and personal protective equipment, and the use of artificial intelligence can help develop sustainable business model (Iyengar et al., 2020).

### 2.2 Product design changes

Local disruptions caused by the COVID-19 pandemic or geopolitical crisis propagate forward and backward through material flows and ultimately affect the entire SCS (Li et al., 2021; Park et al., 2022). In the face of large-scale disruption of the original suppliers and market demand fluctuations occurring simultaneously or sequentially (Ivanov, 2020), original product can no longer be produced, so that manufacturers must make design changes to existing products to mitigate the negative impacts on SCS (Chen et al., 2022). Existing studies about PDC are provided as follows.

To meet diversified customer needs and enhance the market competitiveness, continuous PDC requests run through the entire product life cycle (Chen et al., 2022). PDC refers to the modification or adjustment of the product or the components that make up the product to promote the improvement of its function (Chen et al., 2015). Due to the complex structure and function of the product, the design change of a component often leads to changes of related components and suppliers. Based on existing product design patterns, a multi-stage model was proposed to select and coordinate appropriate components and suppliers. The model can analyze the assembly relationships between various components and can consider constraints such as cost and product quality (Wang and Che, 2008). To control the impact of component changes on other parts, an attribute-based, object-oriented change impact analysis method was proposed by Chen et al. (2015) to perform the change impact analysis task. The complex dependencies between different components make it difficult to build an objective function that evaluates the optimal change path. To this end, an integrated simulation and optimization approach was introduced by Li et al. (2019) to identify the optimal change scheduling plans for renewable resource-constrained change propagation.

To the best of our knowledge, few scholars proposed response strategies from the perspective of product design in the existing research on SCR strategies. In addition, previous literature on PDC mainly focused on the impact of design change behavior on the product. However, the design, production and sourcing of product components are equally intertwined with SCS. The only way to improve the viability of SCS in the face of a fluctuating external environment is to create an RSCS through the resilient design of products. Implementing a PDC strategy to respond to market changes is a critical path to increasing the resilience and sustainability of SCS when the market changes dramatically or when material supply fails.

### 2.3 Domain model

To facilitate people to fully understand, communicate and manage the constructed RSCS, a domain modeling framework called FCBPSS was proposed; however, the function-behavior-state (FBS) domain model was originally proposed for the design of human–computer interface (Lin and Zhang, 2004). In recent years, some scholars have already applied domain modeling to enterprise information systems and financial systems. Wang et al. (2016) proposed a service system domain modeling framework for managing enterprise information systems and illustrated its application. Song and Wang (2022) proposed a domain modeling framework for financial systems and validated its effectiveness in financial system disruption recovery. As a general domain modeling tool, FCBPSS conceptual framework can also be applied to SCS, which will help us facilitate management activities such as reconfiguration, design, planning and control of SCS.

## 3 The proposed RSCS framework

SCS is a kind of service system because its characteristics are consistent with the definition of a service system (Wang et al., 2016). Based on this, there are three subsystems in an SCS, including the supply chain infrastructure system (SCIS), supply chain substance system (SCSS) and supply chain management system (SCMS). SCIS refers to all companies of SCS, including suppliers, manufacturers, and distributors, which is the premise and foundation for the realization of the function of SCS. SCSS consists of components, products, and design parameters. SCMS refers to an integrated system of people and management information system, which supports the management of SCIS and SCSS.

Based on above conceptions, a sample RSCS considering PDC is described in Fig. 1. SCIS consists of $m$ suppliers, one manufacturer and $m$ distributors. They are connected with orders and contracts. SCSS consists of $n$ components and a product. Each component corresponds to one supplier and there are alternative suppliers for key components. The manufacturer is responsible for the design of the product and provides the design parameters to suppliers. Different components produced by suppliers are assembled to form product which is delivered to various distributions.

PDC strategy is proposed to deal with the crisis of supply disruptions or demand changes caused by epidemic. To control the impact of design changes and improve the overall network resilience, the resilient design of components ($r$) and the resilient capacity design of suppliers ($R$) are planned simultaneously.

The resilience mechanism of SCS considering product design is shown in Fig. 2. Design change behaviors are generally initiated from feedback from suppliers or distributors. Figure 2 shows a manufacturer and several suppliers, where the status of manufacturer is terrible due to the unavailable of components and the status of new suppliers are healthy and available. Manufacturer can restructure SCS through the PDC strategy, which can provide the design framework of new components, match with available suppliers and initiate collaboration to produce new product $P'$. Thus, a novel RSCS is obtained by redesigning the product structure and changing the supplier network. Despite the simplicity of the principles of the proposed system, there are many practical difficulties in practice. In the next section, a general conceptual framework will be proposed to study this system.

## 4 Domain modeling of RSCS

Domain modeling is a good way to understand and study the complex system in unexpected circumstances such as COVID-19 epidemic. Based on a general conceptual framework, i.e., FCBPSS, a novel domain model of RSCS from the perspective of PDC is proposed in this section.

### 4.1 Structure of SCIS and SCSS

The system structure refers to the various subsystems that make up the system and the relationship among the subsystems. The basic structure of the sample network has been described in Section 3. To explore the impact of design change behaviors on the whole SCS, the structural features about supplier, components and distributors will be described in detail. As shown in Fig. 3, a three-layer network graph is proposed to analyze the structure of SCS. The circular nodes represent firms or components,

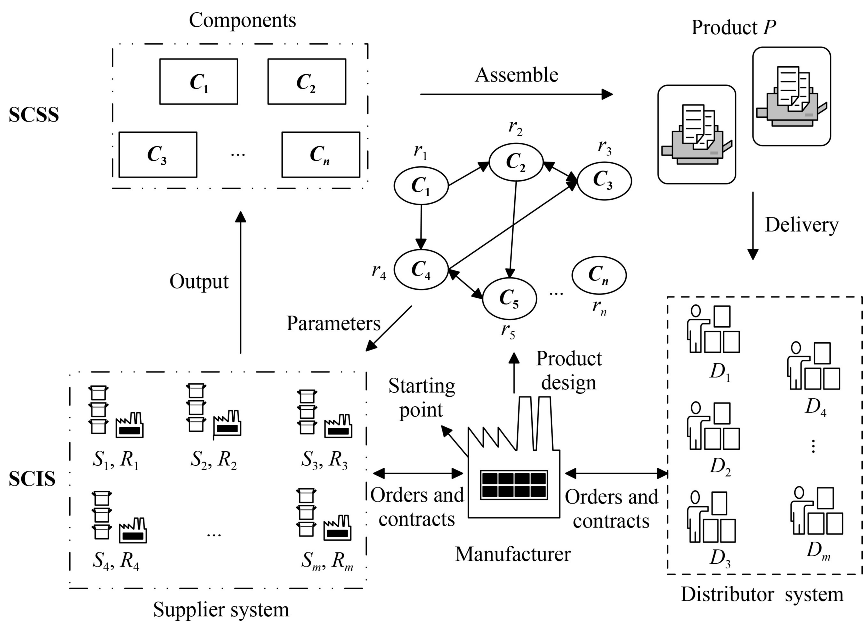


**Fig. 1** A sample RSCS considering PDC.

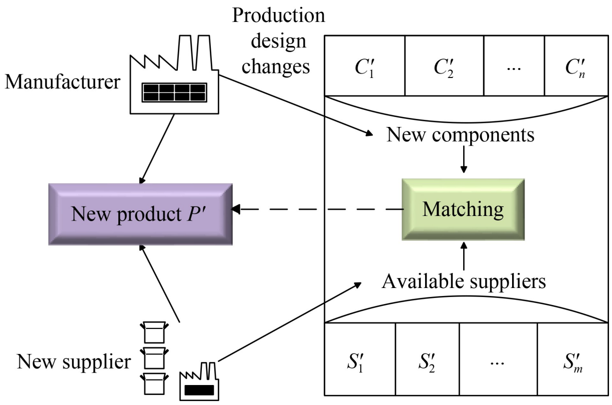


**Fig. 2** The mechanism of RSCS based on PDC.

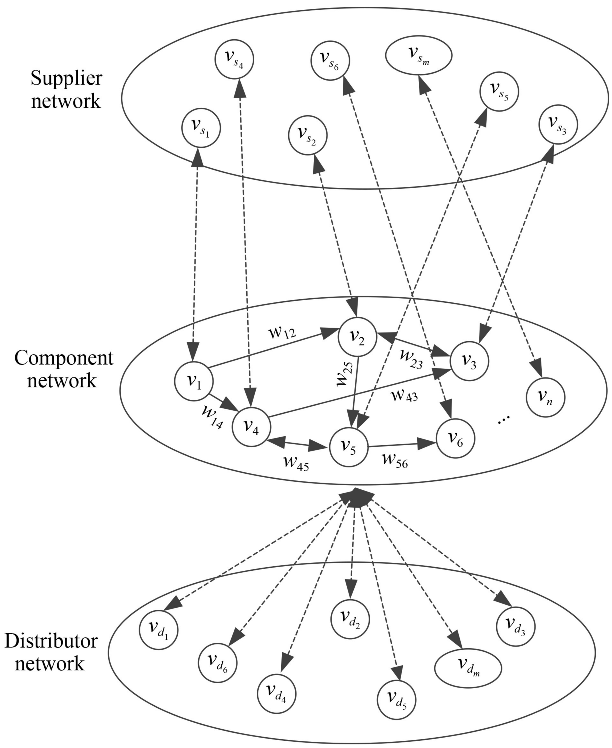


**Fig. 3** Supplier-component-distributor network model.

the dotted line represents supply and demand, and the solid line among components represents the correlation coefficient.

Different sub networks have different attributes, and the connection between nodes and layers in each sub network are also different. Since there is no business crossover between suppliers, each supplier supplies only one component to the manufacturer. Therefore, there is only one node set in the design structure matrix of the supplier network. Each supplier $v_{s_i}$ can be represented by a node, thus the supplier network model can be expressed as $G_s = (v_{s_1}, v_{s_2}, ..., v_{s_m})$.

The network structure of complex products is usually modeled by using the design structure matrix $G_c = (V, E, W)$. Each node represents a component, the directed edge represents the connection between nodes, and the $w_{ij}$ on the edge represents the correlation coefficient. The set of nodes is noted as $V = (v_1, v_2, ..., v_n)$, and the set of edges is noted as $E = \{e_{ij} | i \in n, j \in n\}$. If nodes $i$ and $j$ are connected, then $e_{ij} = 1$; otherwise, $e_{ij} = 0$. Besides, $W = \{w_{ij} | i \in n, j \in n\}$ denotes the correlation coefficient set of nodes. The correlation coefficient is accessed from components network adjacency matrix which is obtained by product design expert.

Similar to the supply network, there are no relationships among distributors. Therefore, there is only one node set in the design structure matrix of the distributor network. The distributor network model can be expressed as $G_d = G(V_d)$, where $V_d = (v_{d_1}, v_{d_2}, ..., v_{d_m})$.

### 4.2 Principles of the SCSS and SCIS

The principles of SCIS are used to restrict the behavior of economic entities and provide guidance for their operation. Taking suppliers as an example, suppliers can only work with limited equipment and resources, so their delivery rates are affected by production elasticity, maximum equipment load and other factors. In addition, all companies in SCS are supervised by the relevant authorities and they must comply with safe, legal, and regulated business rules.

The principles of SCSS guide the behaviors of components and products that flow within SCIS. The principles of SCSS refer to the elastic design of components and products to cope with unpredictable changes, such as retaining design redundancy or tolerance to improve the elasticity of products and the flexibility of SCS. It is necessary to maintain the features and functions of original products as much as possible and control the impact of change behaviors.

### 4.3 States and behaviors of SCSS and SCIS

#### 4.3.1 State and behavior of SCSS

The state of SCSS refers to properties of the materials that flow within SCIS. The state of product includes its composition and performance. The state of components refers to physical structure features as well as the coupling relationship ($w_{ij}$) among them. The behavior of SCSS will lead to changes of the value of state variables. Meanwhile, the behavior is also affected by state variables. The behavior of SCSS in this study refers to PDC. The changes of product design will directly lead to the changes of composition and physical features.

A complex product is a collection of components and their associations. Changes in one module will cause changes in other modules that connected with it. To describe design change behavior, change proportion function $C_i$ is proposed to describe the changes in structure ($\Delta S_i$) and function ($\Delta f_i$) of node $i$.

$$C_i = C(\Delta f_i, \Delta S_i). \quad (1)$$

The value of design tolerance $r_i$ determines whether the point needs to be changed. When the change proportion of the initial node is smaller than the design tolerance, the node will automatically absorb the change and will not propagate to its adjacent nodes. When the change proportion of the initial node exceeds the design tolerance, it absorbs some changes and continues to propagate to the next-level adjacent nodes. During the subsequent change transfer process, the propagation influence will gradually become smaller until being terminated under the effect of design tolerance $r_i$. Therefore, the change risk transfer function $T_{ij}$ is used to describe the change propagation impact in order to study the propagation impact of node $i$ change on node $j$. As shown in Fig. 4, the initial changed node is represented by $v_1'$, and the changes of $v_2$ and $v_4$ follow the change of $v_1$.

$$T_{ij} = C_j = \begin{cases} (C_i - r_i) w_{ij}, & C_i \geqslant r_i \\ 0, & C_i < r_i \end{cases}. \quad (2)$$

We define a binary integer variable $n_i$ to better observe the state of nodes to design changes. When $n_i = 1$, it means that the node is affected and needs to be changed; otherwise, $n_i = 0$, and it means the node is normal and does not need to be changed.

$$n_i = \begin{cases} 1, & C_i \geqslant r_i \\ 0, & C_i < r_i \end{cases}. \quad (3)$$

Product resilient index $R_p$ can be expressed as the proportion of healthy nodes, and the total number of components is denoted by $n$.

$$R_p = \frac{n - \sum_{i \in n} n_i}{n}. \quad (4)$$

### 4.3.2 State and behavior of SCIS

The state of SCIS mainly refers to the attributes of suppliers, manufacturers, and distributors. Taking suppliers as an example, the state refers to the type of output parts, the capacity range of flexible production, the location distribution, and the health status. The behavior of SCIS is the causal relationship among its state variables. Therefore, the behavior of a supplier refers to the changes of its numbers, location, structure, and health status.

The behavior of PDC of node $v_i$ will also influence the state and structure of suppliers. After receiving the design change information of component $v_i$, the supplier $v_{s_i}$ compares the range of product change with the production capacity. If it is within the flexible production range $R_i$, it can continue to produce and supply; otherwise, the manufacturer needs to choose a new alternative supplier. As shown in Fig. 4, the redesign of component $v_1$ causes the change of supplier $v_{s_1}$ to $v_{s_1}'$. Suppliers $v_{s_2}$ and $v_{s_4}$ can endure the changes of components $v_2$ and $v_4$, respectively. The change of supplier $V_{s_i}$ can be expressed as follows:

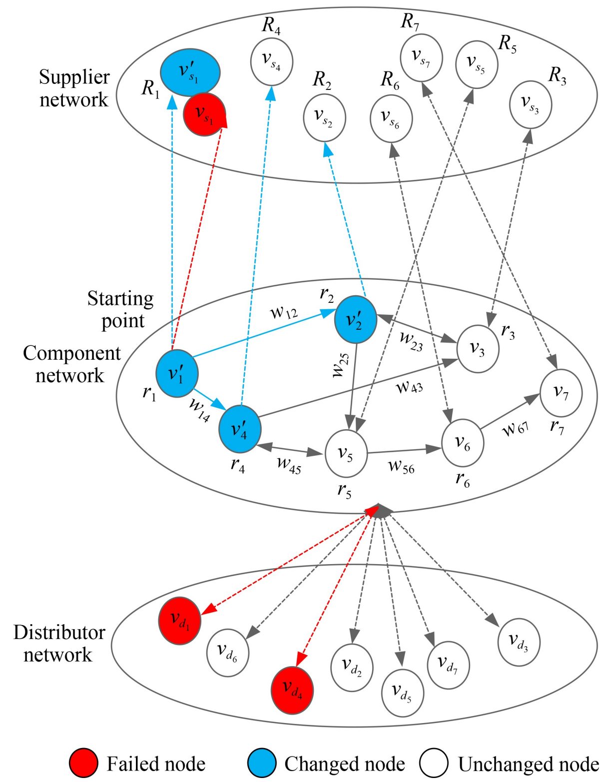


**Fig. 4** The impact of PDC on SCS.

$$V_{s_i} = \begin{cases} v_{s_i}, & C_i \leqslant R_i \\ v_{s_i}', & C_i > R_i \end{cases}. \quad (5)$$

The epidemic also disrupts some distribution centers, such as $v_{d_1}$ and $v_{d_4}$ in Fig. 4. The resilient index of SCS can be expressed as the ratio of the number of firms that returned to a healthy state after a design change to the total number of firms in SCS. Assuming that the total number of suppliers in the sample network is $Q_s$, the total number of distributors is $Q_d$, and the number of firms that cannot be recovered from the interruption is $Q^*$, the resilient index $R_s$ can be expressed as follows:

$$R_s = 1 - \frac{Q^*}{Q_s + Q_d}. \quad (6)$$

### 4.4 Contexts and functions of SCIS and SCSS

The context in the domain model of FCBPSS can be described as the enterprise living environment. The context of SCS can be divided into two categories, including normal and abnormal. The former refers to the conventional market environment without adverse fluctuations in SCS. In this situation, each enterprise in SCS has a stable working state and various functions can be realized successfully. The latter refers to an abnormal situation in which production activities are forced to come to a halt due to the inability of the company to maintain normal operations.

The context and function of SCIS are shown in Fig. 5. We take digital product mobile phones as an example. In normal context, suppliers have stable orders, which can provide sufficient supply of electronic components for manufacturer, such as patented technology, processors, and chips. The function of SCIS can be reflected by various good operational indicators, such as the steady growth of sales and good feedback from customers. However, under abnormal circumstances such as COVID-19 pandemic, downstream mobile phone manufacturers are unable to assemble their products due to the lack of raw materials such as semiconductors, which makes suppliers unable to deliver on time.

The context and function of SCSS are shown in Fig. 6. In the normal context, substances flow within SCS in an orderly and standardized manner. The features like type, structure, performance and price of products or components will not extensively change. In the abnormal context, due to the lack of necessary technical elements, the launch of new products will be delayed. Therefore, manufacturers must consider the changes of product design to improve the ability of enterprises to adapt to abnormal environment, or restructure SCS by adjusting product structural parameters and functional parameters and developing new products.

### 4.5 Model evaluation

First, the proposed domain model provides an integrated network design framework, which can guide the design of RSCS. It is easy for designers to have a comprehensive understanding of SCS because the model can derive the major domain-vocabulary needed for practical work (Wang et al., 2016; Song and Wang, 2022). For the design of SCIS, the entrepreneurs need to consider the number and distribution of suppliers or distributors as well as the maximum capacity of the plant which considers the structure and state. For the design of SCSS, the product attributes refer to structural and functional parameters as well as the design tolerance of the components need to be designed and defined carefully.

Second, the domain model can be used to guide the management of SCS. According to the FCBPSS domain model, the management of SCS mainly refers to its structure, behavior, function, and state. As shown in Fig. 7, when PDC is considered, the management of SCSS mainly refers to the planning of the product or component structure and the control of its behavior and state. For example, whether the change is within the tolerance of the component, how to make changes can have the least impact on the structure and function of other components. The management of SCIS mainly refers to plan new supply and demand relationship and restructure the infrastructure system. For example, if existing component suppliers cannot meet the additional demand within their

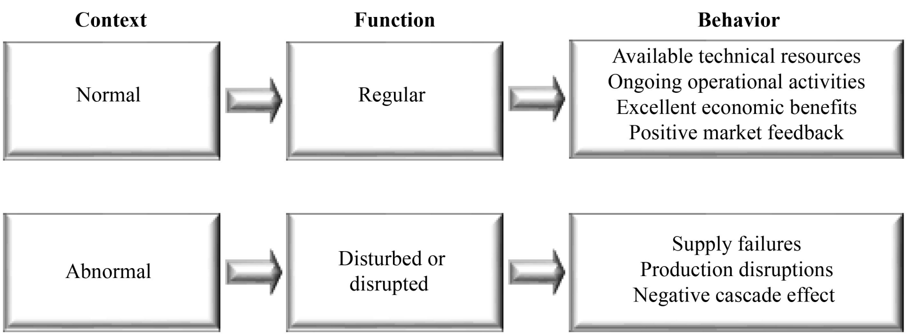


**Fig. 5** Context and function of SCIS.

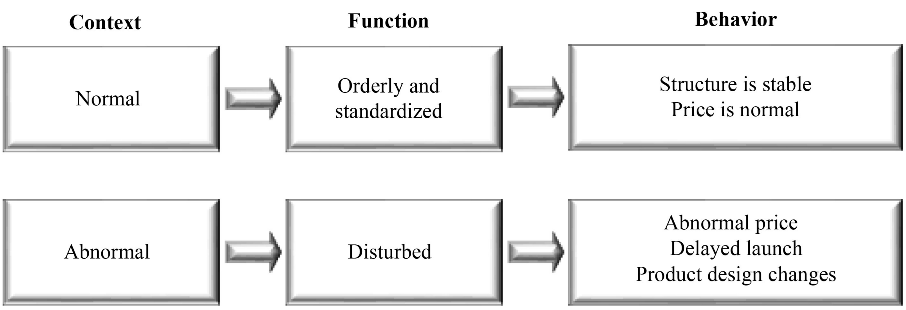


**Fig. 6** Context and function of SCSS.

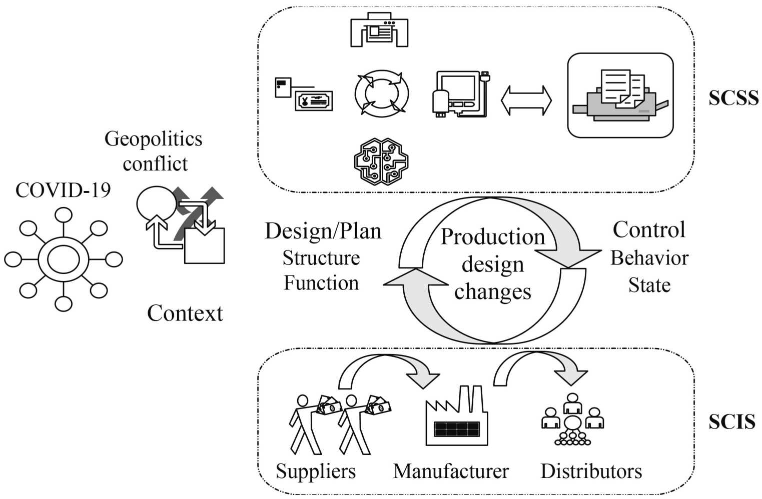


**Fig. 7** The management of PDC for SCS.

resilient supply range, managers must select a new supplier to replace the old one.

The plan of SCIS ensures the continuity of the structure. The control of the behavior and state of SCSS reduces the spread of change risk and enhances the resilient and robustness of SCS. Based on the FCBPSS domain model, the integrated management (such as design, plan and control) of SCIS and SCSS will effectively guarantee the resilience and sustainability of SCS in the process of PDC (Wang et al., 2016).

## 5 Case study

In 2021, a cell phone manufacturer, Company *H*, was on the verge of bankruptcy because components were not available due to the epidemic. Its suppliers are mainly in Asia, America, and Europe. The status of components, suppliers and distributors is shown in Table 1. Symbol *U* indicates that the component is not available, or the company is invalid. Symbol *A* means that the component is available, or the suppliers and distributors are healthy. The interruption of suppliers directly affects the production of product *P*, which ultimately causes the company *H* to suffer serious losses. The product structure diagram of *P* is presented in Fig. 8. Correlation coefficient $w_{ij}$ is illustrated in Table 2. To reduce the sales loss, the FCBPSS modeling tool will be used to guide the redesign of RSCS based on PDC and supplier network reconstruction.

### 5.1 PDC strategy evaluation

The domain model framework points out that adjusting the structure of SCIS and SCSS can effectively control the behavior and change the status of companies in the SCS. Company *H* can maintain market competitiveness by adjusting the composition of its products and redesigning a new product $P'$ with similar performance to product *P*. To enhance the resilience of $P'$ and reduce the risk of design change propagation, design tolerance ($r_i$) of $P'$ is considered in the design process. Table 3 shows the component design change parameters of product $P'$. The dependency matrix of $P'$ is presented in Table 4.

**Table 1** The states of components, suppliers, and distributors

| Component | A | B | C | D | E | F | G | | |
|---|---|---|---|---|---|---|---|---|---|
| State | *U* | *U* | *U* | *U* | *A* | *A* | *A* | | |
| Supplier | $S_1$ | $S_2$ | $S_3$ | $S_4$ | $S_5$ | $S_6$ | $S_7$ | | |
| State | *U* | *U* | *U* | *U* | *A* | *A* | *A* | | |
| Distributor | $D_1$ | $D_2$ | $D_3$ | $D_4$ | $D_5$ | $D_6$ | $D_7$ | $D_8$ | $D_9$ |
| State | *A* | *U* | *U* | *U* | *A* | *U* | *U* | *A* | *U* |

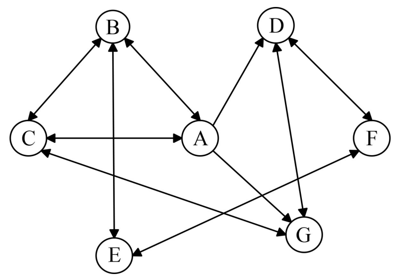


**Fig. 8** Component structure diagram of product *P*.

**Table 2** Component network adjacency matrix of product *P*

| $w_{ij}$ | A | B | C | D | E | F | G |
|---|---|---|---|---|---|---|---|
| A | | 0.5 | 0.3 | 0.4 | | 0.2 | 0.1 |
| B | 0.9 | | 0.5 | | 0.5 | | |
| C | 0.8 | 0.5 | | | | | 0.3 |
| D | 0.7 | | | | | 0.6 | 0.7 |
| E | | 0.7 | | | | 0.4 | |
| F | | | | 0.7 | 0.6 | | |
| G | 0.5 | | 0.6 | 0.7 | | | |

**Table 3** Component design change parameters of product $P'$

| Components | New components | Design tolerance ($r_i$) |
|---|---|---|
| A | a | 0.3 |
| B | b | 0.2 |
| C | c | 0.2 |
| D | d | 0.3 |
| E | e | 0.3 |
| F | f | 0.2 |
| G | g | 0.2 |

**Table 4** Component network adjacency matrix of product $P'$

| $w_{ij}$ | a | b | c | d | e | f | g |
|---|---|---|---|---|---|---|---|
| a | | 0.3 | 0.1 | 0.2 | | | |
| b | 0.7 | | 0.4 | | 0.5 | | |
| c | 0.6 | 0.4 | | | | | 0.3 |
| d | 0.6 | | | | | 0.4 | 0.6 |
| e | | 0.6 | | | | 0.4 | |
| f | | | | 0.5 | 0.6 | | |
| g | | | 0.3 | 0.6 | | | |

Next, we consider the impact on product when components B and b have the same proportion of design changes, $C_B = C_b = 0.62$. As shown in Fig. 9(a), the changes of node B are propagated to nodes D, G, and F through nodes A, C, and E, respectively. As shown in Fig. 9(b), the changes of node b propagate and terminate to nodes a, c, and e.

According to Eq. (4), product resilient index $R_p$ and $R_{p'}$ can be expressed as:

$$R_p = \frac{n - \sum_{i \in n} n_i}{n} = 0, \tag{7}$$

$$R_{p'} = \frac{n - \sum_{i \in n} n_i}{n} = 0.43. \tag{8}$$

The resilient index indicates that product $P'$ has higher resilience. On the one hand, changing the composition of ingredients re-engineers the product structure. On the other hand, controlling state parameters to ensure the behavior of components also reduces the impact of change propagation. The effectiveness of the domain model in guiding product flexibility design and improving product flexibility has been verified. By changing structural parameters, such as reducing the coupling correlation between components, the change propagation behavior can be effectively suppressed, and the nodes are kept in a healthy state.

### 5.2 Supplier network reconstruction

Redesigning infrastructure systems is the second way to build an RSCS based on PDC. According to the analysis of SCS using the domain model presented in Section 4, changing the structure of the infrastructure system, such as replanning the distribution of suppliers or manufacturers to facilitate flexible raw material procurement, is very important for the survival of companies in an unpredictable environment. Thus, company $H$ can cooperate with four domestic suppliers and construct a supplier network with elastic supply functions. If component's structure or function changes, the supplier still has the corresponding production capacity. The state of the new network is shown in Table 5. The rebuilding of the supplier network restores the failed components and suppliers to normal state. In addition, some distribution centers are still unavailable due to the lockdown policy, such as $D_2$, $D_3$ and $D_6$.

According to Eq. (6), the SCR index of product $P$ can be calculated as:

$$R_s = 1 - \frac{Q^*}{Q_s + Q_d} = 0.38. \tag{9}$$

The SCR index of product $P'$ can be calculated as:

$$R_{s'} = 1 - \frac{Q^*}{Q_s + Q_d} = 0.81. \tag{10}$$

Combining the product resilience index ($R_p$) with the SCR index ($R_s$), a composite resilience index $R_c$ can be expressed as follows, in which $\alpha$ represents the weight, and let $\alpha$ be 0.3.

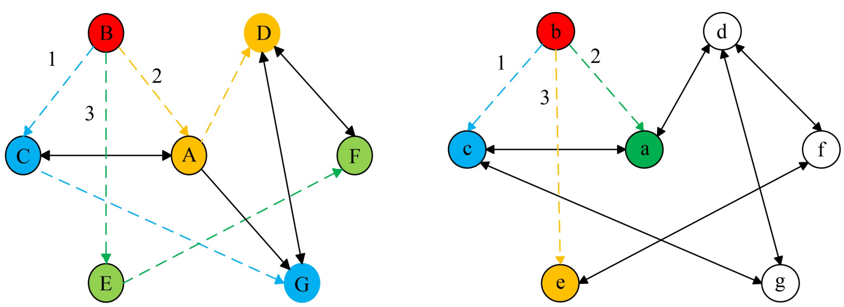


**Fig. 9** Design change propagation impact diagram.

**Table 5** State of components, suppliers, and distributors of the new network

| Component | a | b | c | d | e | f | g | | |
|---|---|---|---|---|---|---|---|---|---|
| State | $A$ | $A$ | $A$ | $A$ | $A$ | $A$ | $A$ | | |
| Supplier | $S'_1$ | $S'_2$ | $S'_3$ | $S'_4$ | $S_5$ | $S_6$ | $S_7$ | | |
| State | $A$ | $A$ | $A$ | $A$ | $A$ | $A$ | $A$ | | |
| Distributor | $D_1$ | $D_2$ | $D_3$ | $D_4$ | $D_5$ | $D_6$ | $D_7$ | $D_8$ | $D_9$ |
| State | $A$ | $U$ | $U$ | $A$ | $A$ | $U$ | $A$ | $A$ | $A$ |

$$R_c = \alpha R_P + (1-\alpha) R_s. \tag{11}$$

The composite resilience index of normal SCS (CRN), composite resilience index of disrupted SCS (CRD) and composite resilience index of the redesigned SCS (CRR) are shown in Fig. 10, assuming that the value of composite resilience index is 1 under the normal condition.

As shown in Fig. 10, the value of composite resilience index drops sharply to 0.27 under disruption, however, it increases to 0.7 after reconstruction. The results verify the effectiveness of the proposed domain model in guiding the construction of RSCS as well as demonstrate the effectiveness of the proposed PDC strategy in dealing with large-scale disruptions in the context of the epidemic. The proposed FCBPSS domain model not only promotes the holistic understanding of the constructed SCS, but also provides an effective management for building RSCS.

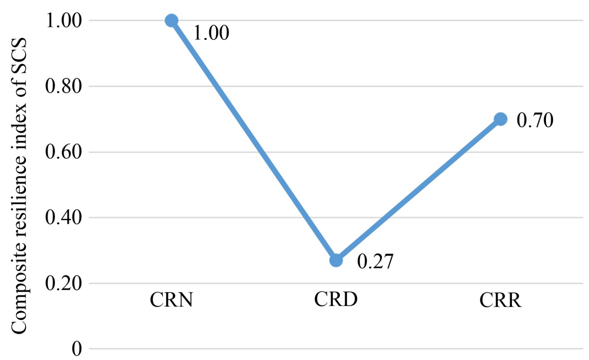


**Fig. 10** Composite resilience index of SCS.

## 6 Conclusions

This study constructed an RSCS considering PDC and analyzed its resilient mechanism. Based on the general conceptual framework FCBPSS, a novel RSCS domain model considering PDC was first established. The proposed RSCS domain model contributes to the systematic reconstruct and management of RSCS. Then, a case study was conducted to verify the effectiveness of the established model in guiding the construction of RSCS. Besides, the effectiveness of the proposed PDC strategy in dealing with large-scale disruptions in the context of the epidemic was demonstrated.

For the convenience of research, the proposed model assumes that one product corresponds to one major supplier, which is relatively harsh in real-world scenarios. In addition, due to the unstructured features of variables, this study does not have enough precise and quantitative indicators about the scope of design changes in the analysis, which will reduce the authenticity. Finally, the PDC strategy is mainly applicable to the electronic product industry because electronic products have greater design flexibility and faster update frequency, which is not suitable for traditional manufacturing such as steel and chemical industry.

In the future, more quantitative analysis can be applied to analyze the coupling relationship between product components. With the application of the domain model in SCS, more SCR indicators based on the product perspective are worth studying. Besides, a more efficient RSCS can be designed to better respond to future disruptive threats (Wang et al., 2016).

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