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ORIGINAL RESEARCH

Design of resilient and viable sourcing strategies in intertwined circular supply networks

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Abstract
This study examines the effects of intertwining and circularity on the design of resilient and viable sourcing and recovery strategies in supply chains. We first construct a case study where the supply chains of three industries (i.e., automotive, healthcare, and electronics) frame an intertwined supply network (ISN). Through a discrete-event simulation model developed in anyLogistix, we examine the impact of disruptions in supply and demand on the performance of individual supply chains and the ISN as a whole. We test the performance of several sourcing strategies and their combinations. A special focus is directed toward shared reverse flows. The results show that disruption impact and recovery processes in the Circular ISN do not always follow conventional patterns known from the resilience of individual supply chains due to intertwining and circularity effects. We offer some managerial recommendations for the design of resilient sourcing strategies in the ISN context that are triangulated around collaborative sourcing practices, coordinated production planning, shared reverse flows, and visibility in inventory management.

Keywords Sourcing strategy · Intertwined supply network · Resilience · Circular economy, Simulation · anyLogistix

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1 Introduction

The COVID-19 pandemic crisis has had major impacts on supply chains (Brusset et al., 2023; El Baz & Ruel, 2021; Ivanov, 2020; Sodhi et al., 2023). Travel and manufacturing constraints have been imposed, adversely impacting the possibilities to meet customer demands (Cherrafi et al., 2022). Material shortages and delivery delays caused by the virus outbreak reduced the performance, service levels, and productivity of supply chains for a long period (Choi, 2021). While demand for some products (e.g., masks and hand sanitiser) has increased, supply has not always been capable to respond adequately (Shen et al., 2021; Wang & Yao, 2021). In this setting, the research community called for the development of new methods for designing resilient and viable sourcing strategies in supply chains (Babai et al., 2023; Dolgui et al., 2020; Ivanov, 2022a).

One particular challenge in designing resilient and viable sourcing strategies stems from the dynamic interconnections and intersections of supply chains in different sectors (Feizabadi et al., 2023; Lotfi et al., 2022), forming intertwined supply networks (ISNs). The notion of the ISN was pioneered by Ivanov and Dolgui, (2020) as an integrity of interconnected supply chains that ensure the provision of goods and services to society and the market. In the ISNs, multi-directional links lead to changing roles of the supplier–buyer (Dolgui et al., 2020). In this case, sourcing differs from traditional linear supply chains because a supplier can be a customer and a factory can feed other factories. In the same line, distribution centres can receive final products and provide reused material or spare parts. In crisis periods, it is difficult to identify the critical supply chain because many essential manufacturers share the same sourcing provider (Hägele et al., 2023; Ivanov & Das, 2020; Li et al., 2023). Hence, designing an efficient and resilient sourcing strategy in the ISN is more complex, since the goal is ensuring the viability of the whole system. This complexity is more intense when an unexpected event occurs for a long period (Ivanov, 2023a). Liu et al. (2022) compared a short disturbance to a disease that attacks a specific organ and a long-term disruptive event to “bleeding or freezing to death”.

Additionally, collaboration among intertwined enterprises, including rerouting, capacity sharing, and expansion, leads to a more resilient network (Ghanei et al., 2023). Therefore, these collaborative practices in the ISN may positively affect the sourcing process and help cope with raw material shortages. Technologically, ISNs are based on collaborative platforms, which allow for visibility and digital supply chain mapping (Ivanov, 2023a; MacCarthy & Ivanov, 2022; MacCarthy et al., 2022; Zhang et al., 2022). While the intertwining of supply chains in the ISN has received growing attention, one missing element in this research is consideration of circular flows in supply chains (Ivanov & Keskin, 2023; Ivanov, 2021a, 2023a; Sardesai & Klingebiel, 2023; Sawik, 2023), which were proven to be an important but underexplored part of supply chain resilience (Ivanov, 2021b; Kennedy & Linnenluecke, 2022; Park et al., 2022).

Sustainability and circular supply chains gained an increased attention in literature (Brandenburg & Rebs, 2015; Govindan, 2020; Govindan et al., 2015; Homayouni et al., 2023; Kannan et al., 2023; Meier et al., 2023; Nag et al., 2021, 2021). Recent research pointed to multiple intersections of resilience and sustainability (Dolgui et al., 2020; Ivanov, 2022b, 2023b; Pavlov et al., 2019). Gaustad et al. (2018) stated that the implementation of circular economy principles has the potential to mitigate the material supply shortage during disruptions. As circular economy practices recover products and expand their life (Kalmykova et al., 2018), the supply of critical material can be ensured through a reverse flow. During the COVID-19 crisis, recycling and loop-closing initiatives have proven their effectiveness to address urgent shortages (Wuyts et al., 2020). Therefore, circularity can be considered an important and novel lens in designing resilient supply chains. Ivanov, (2022c)proposed a viable supply chain model, which integrates resilience and sustainability perspectives in the settings of long-term crisis. Combining circularity and intertwining may result in novel impacts on sourcing performance and customer behaviours (Kerber et al., 2021; Mina et al., 2021).

The viability of ISN is a novel and promising field of resilience research. However, the existing literature lacks insights evaluating the impacts of intertwining and circularity on sourcing performance under disruptions. Despite the great interest devoted to risk management strategies, little is known about the opportunities and challenges stemming from intertwining effects in managing the availability of materials. Moreover, only a few works have investigated the role of the circular economy in enhancing the resilience of sourcing practices. To the best of our knowledge, our study is the first to connect circular economy and supply chain viability. In order to examine these impacts, the present study addresses two research questions:

RQ1 ***How does the intertwining of supply chains impact performance during supply and demand disruptions?***
The purpose of this question is to analyse the ISN impact on recovery strategies during sourcing and demand disruptions, considering single, dual, and backup sourcing practices.

RQ2 ***How can circularity in the intertwining context help improve sourcing performance during supply and demand disruptions?***
This question aims to identify the contribution of circularity to ISN performance during sourcing and demand disruptions. More precisely, the CISN benefits while sharing the reverse flows will be investigated. We aim to identify the circular economy's ability to enhance the availability of raw materials during supplier closures and demand increases. To that end, CISN performance is analysed, considering single, dual, and backup sourcing practices.

Our study contributes to the literature by advancing knowledge about supply chain resilience and viability by combining intertwined and circular effects in the CISN. In the first stage, intertwining effects during a crisis are analysed and highlighted. Subsequently, circularity advantages are integrated to strengthen the viability of the overall network. A simulation approach is adopted to study the behaviour of three intertwined supply chains (i.e., automotive, electronics, and medical) during disruption periods, positioning the problem in the setting of a semiconductor shortage. We study the possible practices under intertwining to prevent shortages of raw materials during disruptions (Ivanov & Dolgui, 2022).We analyse sourcing strategies to provide generalised recommendations for the design of resilient and efficient sourcing practices. This study highlights the importance of collaboration and circular practices in ensuring the availability of materials during a long-term disruption period.

The remainder of this paper is organised as follows. A literature review on sourcing strategies, circular intertwined supply networks, and the semiconductor shortage problem is conducted in Sect. 2. The case study is presented in Sect. 3. Simulation logic, input data and scenarios are explained in Sect. 4, followed by experiments in Sect. 5. Our results are discussed in Sect. 6, followed by associated managerial insights. Section 7 summarises the major outcomes of this study and outlines some future research perspectives.

2 Literature review

In this section, a literature review is conducted. First, we review the studies on sourcing strategies available in the literature. Then, research on ISNs is presented, linking the discussion to the circular economy.

2.1 Sourcing strategies under disruptions

Sourcing strategies refer to a set of procurement decisions aiming to ensure long-term supply continuity (Martin, 2021). In the literature, different strategies are proposed. Single sourcing (working with one supplier) minimises production costs, reduces inventories, increases quality, strengthens relationships, and secures information sharing. However, this mode increases risks (Namdar et al., 2018; Ray & Jenamani, 2016). Multiple sourcing (working with diverse suppliers) reduces risks during disruption times (Aldrighetti et al., 2021) and maintains competitiveness between suppliers (Heese, 2015; Shan et al., 2023). Nevertheless, managing more than one supplier increases costs and complexity (Burke et al., 2007). Structures of dual sourcing may be symmetric (sourcing equal quantities from suppliers) or asymmetric (sourcing unequal quantities) (Jain & Hazra, 2017). Backup sourcing is used when a disruption occurs to the primary supplier in order to feed the factory; however, this source is characterised by higher costs and slower response times (Schmitt & Tomlin, 2012).

The long-term crises triggered by the pandemic raised novel questions about the effectiveness of the existing resilience mechanisms to ensure supply chains' survivability (Ivanov & Dolgui, 2020). According to Kumar et al. (2018), sourcing is a key strategy for mitigating risks and disruptions. Sourcing decisions are of vital importance, as they ensure the availability of material for the production process. One challenge for decision-makers is to strengthen sourcing practices by adopting powerful strategies dealing with negative and positive changes in the business environment. As an example, the semiconductor shortage turned automotive manufacturers' attention toward securing their sourcing strategies (Ramani et al., 2022).

In the literature, single, dual, multiple, contingent, outsourcing, and backup sourcing have been the subject of many studies (He et al., 2020; Ivanov, 2017; Li et al., 2017, 2021; Namdar et al., 2018; Niu et al., 2019; Thomas & Mahanty, 2020; Wang & Yu, 2020). Each strategy has strengths and weaknesses in terms of cost, lead time, and resilience (Aldrighetti et al., 2023). Sourcing strategies under disruption have also been the subject of different studies in the literature. Appendix 1 summarises the main findings of the works related to sourcing in supply chains under disruptions.

2.2 Circular-intertwined supply networks

ISNs are seen as complex systems which encompass many supply chains with dynamic structures, roles, and behaviours (Ivanov & Dolgui, 2020). ISNs are characterised by three properties: open system, structural dynamics, and integrity (Wang & Yao, 2021). In other words, ISNs interconnect different industrial sectors, securing the provision of society and markets with goods or services (Ivanov & Keskin, 2023; Ivanov, 2023b). The dynamic structures refer to the ability to change the roles of suppliers and buyers (Feizabadi et al., 2023).

Studies on ISNs under disruption are in their infancy stage. The most recent analysis of supply chain viability and ISNs can be found in Ivanov et al., (2023). In their seminal work, Ivanov and Dolgui, (2020) defined the term "ISN" and proposed a biological system model for ISN viability, extending the analysis from the supply chain to the ecosystem level. They illustrated the viability of ISN under disruption using game theoretical models. Wang and Yao (2021) proposed a model to design an ISN network, select supply routes, and assign customers under a facility and transportation disruption. The optimisation approach captured the trade-off between cost and viability performance in the medical sector.

Feizabadi et al., (2023) elaborated on a novel lens of ISN analysis, namely jury-rigging behaviour. Drawing on complex adaptive systems and Ashby's law of requisite variety, they developed a simulation model to examine complex behaviours combining parts and components in a manner that is not pre-specified to solve a problem encountering unknown unknowns. They studied jury-rigging search behaviour to manage the interdependencies across the supply chains as adaptive mechanisms. Dolgui et al. (2023) and (Chervenkova & Ivanov, 2023) studied intertwining strategies for automotive industry repurposing for production of healthcare product through intertwining of commercial and healthcare supply chains.

Yue et al., (2023) used network simulation to identify hidden risky sources in TFT-LCD supply networks, considering risk propagation. Their approach allows the detection of hidden risky interfirm cooperation. Liu et al. (2022) adapted an underload cascading failure model to evaluate a network's viability and adaptability against the disturbance caused by the COVID-19 pandemic. Ghanei et al. (2023) studied a two-stage stochastic network design problem that incorporated three different resilience strategies to design ISNs under a fair co-operation.

Since ISNs are interconnected supply chains, the circular intertwined supply network (CISN) is an ISN where supply chains share the reverse flow and recover common materials. The characteristics of the ISN strengthen links and ease the material flow, which is consistent with circular economy principles. Figure 1 illustrates the material flow in the CISN.

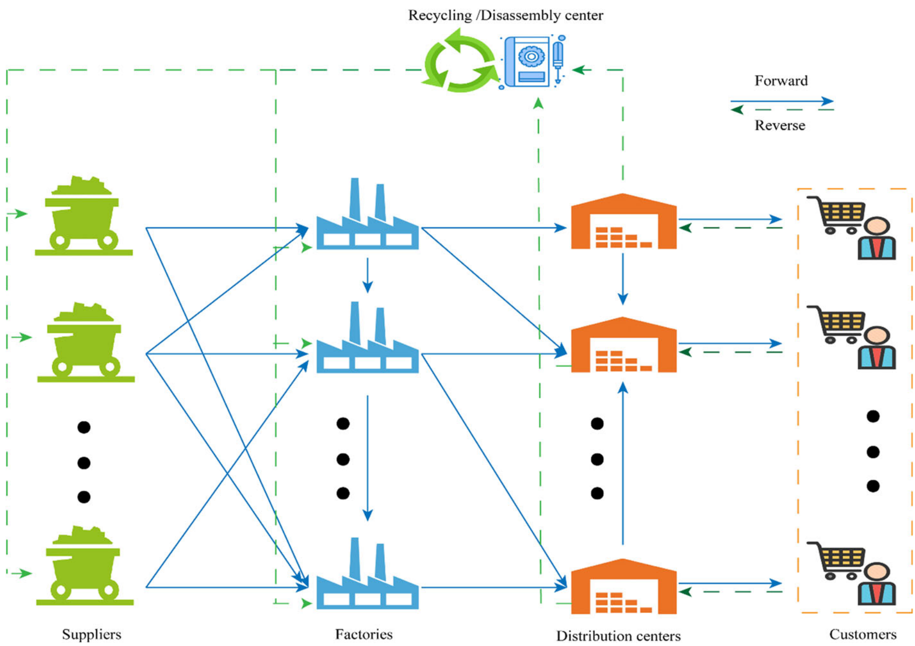

Fig. 1 CISN structure

3 Problem statement, case study, and methodology

3.1 Generalised problem statement

We study a problem where several supply chains of different industries intersect, sharing common suppliers, components, and warehouses. We name the integrity of these supply chains an ISN. When disruption hits a common supplier, the inventories and production capacities of some supply chains can be used to mitigate shortages in the others. In addition, the companies share some reverse flows. The reused materials can help to cope with material shortages due to a supplier disruption. Our objective is to examine the effects of intertwining and circularity on supply chain resilience and propose managerial guidelines on how to improve resilience through the usage of intertwining and circularity effects.

3.2 Semiconductor shortage and circular economy

In the wake of the COVID-19 pandemic, industries have experienced a semiconductor shortage (Ramani et al., 2022). The complex semiconductor production system serves several markets and ecosystems, e.g., the automobile production and mobility ecosystem (Srivastava et al., 2022). Chip manufacturers oriented their final products to fulfil the pressing demands of medical, remote work, and distance learning (Chang et al., 2022). While sales of chips to the vehicle industry collapsed during the lockdown, the demand for electronic devices (e.g., computers and phones) increased (Attinasi et al., 2021). Vehicle manufacturers reported that production was constrained by an insufficient quantity of semiconductors, which increased new car prices and reduced inventories (Krolikowski & Naggert, 2021). The transition toward 5G technology, self-driving cars, and the integration of Industry 4.0 tools had already increased the demand for chips before COVID-19 (Voas et al., 2021).

Leading suppliers, generally located in Taiwan and South Korea, account globally for 83% of worldwide chip production (McAleese, 2021). In this setting, innovative practices are required to minimise organisations' dependence on a few chip providers (Marinova & Bitri, 2021). One of these options is localisation of chip production through investing in new plants. However, this practice is expensive, imposing a long ramp-up time. As stated by Frieske and Stieler (2022), possible measures for rapid adaptation include short-term work and adjustment of production processes and inventories. Possible long-term practices include maximising stocks of critical components, strengthening a multiple-sourcing strategy, and supporting local chip manufacturing.

In addition to COVID-19 disruptions and geopolitical issues, semiconductor (SMC) supply chain complexity is one of the reasons behind this shortage (Mohammad et al., 2022). The average cycle time is about 10–15 weeks, fabrication is costly (Mönch et al., 2018), and facilities are distributed across continents. Therefore, building a resilient SMC supply chain is a challenging task. In this context, a circular economy may be effective to deal with shortages during a crisis because of its role in enhancing the availability of materials. To that end, an innovative design for disassembly is required to enable the recovery and reuse of microchips (Schröder, 2022). As examples of circular initiatives, Nikon purchases semiconductor lithography systems in end-of-life, collects the usable parts, and assembles them into new systems for reuse as replacements. Retronix has developed a process to recover and refurbish these components to enable reuse.

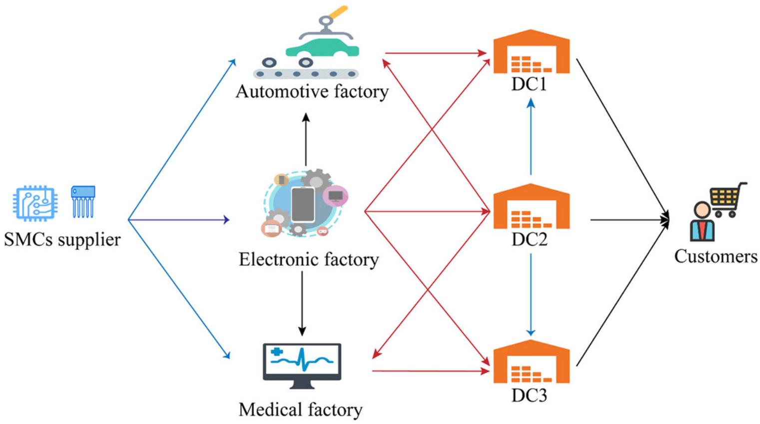

Fig. 2 The ISN design

3.3 Case study

We now introduce a case study which will be used for simulation analysis. The case study is based on three intertwined supply chains, which frame an ISN as presented in Fig. 2.

The ISN as a whole secures the provision of society with mobility, communication, and medical equipment. The ISN consists of four layers, including suppliers, focal firms, distribution centres, and customer zones. The primary supplier, the backup supplier, and the electronics and medical factories are located in Asia, while the automotive factory and the second supplier are in Europe. The electronics factory produces smartphones (SPs) and touch screens (TSs). The automotive parts factory produces car dashboards (CDs), and the medical factory produces medical equipment (e.g., blood pressure monitors (BPMs)). TSs are produced by the electronics factory and purchased by the other companies. There are three interconnected distribution centres. DC2 provides TSs (supplied by the electronics factory) to the focal firms and DCs. Customers are dispersed worldwide.

During the COVID-19 pandemic, the three factories suffer from the semiconductor shortage, since the production plants rely on the same supplier and the global capacity of this necessary component is limited. The managers of the three supply chains should design viable sourcing strategies. They propose to improve their sourcing strategies through supplier diversification, enhanced collaboration resulting from intertwining, and implementing circular economy practices through a shared reverse flow. The scope of this study is to analyse the impact of intertwining and circularity during supply and demand disruptions while adopting different sourcing strategies. We examine the proposed sourcing practices in the ISN through simulations.

3.4 Methodology

The present study adopts the simulation methodology proposed in the literature (Aldrighetti et al., 2019; Burgos & Ivanov, 2021; Gianesello et al., 2017; Ivanov, 2017, 2019, 2020). Compared to analytical models, simulation can handle complex problems with situational behaviour over time (Ivanov, 2019). Simulation models virtually present real-world problems through different scenarios (Sun et al., 2021). The logic of this study is shown in Fig. 3.

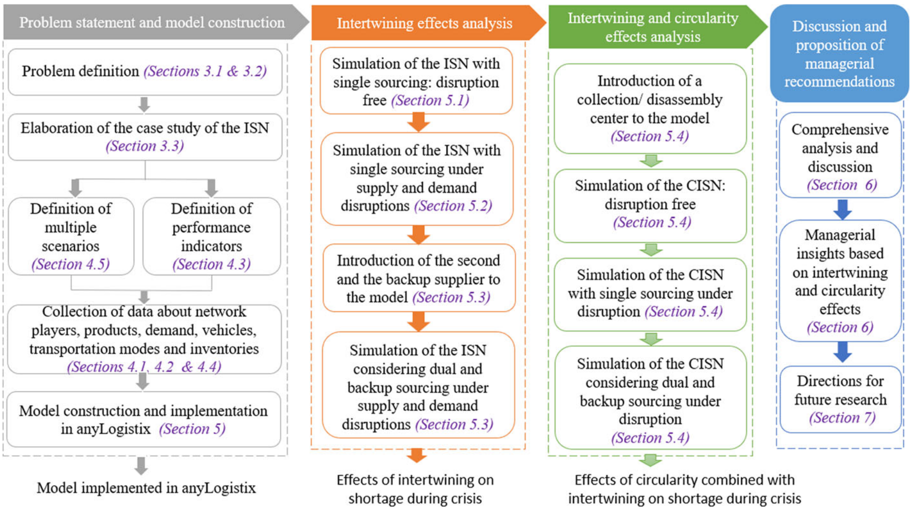

Fig. 3 Research process

First, the current ISN is simulated with the help of anyLogistix software. The performance indicators are calculated to be used for comparison. Then, the ISN is simulated with the introduction of supply and demand disruption. In the third step, we consider backup and dual sourcing to mitigate the impacts of disruptions. Fourth, a novel collection/disassembly centre is introduced to recover SMCs from obsolete products for reuse in the CISN. anyLogistix is a software developed by the AnyLogic Company. The software is easy for researchers to use to create and analyse supply chain models (Miscevic et al., 2018; Vitorino et al., 2022) and perform network optimization and simulation (Stewart & Ivanov, 2022). It is used to solve problems including supply chain design, risk assessment, inventory and sourcing, transportation and production planning, and bullwhip effect quantification.

4 Simulation model

4.1 Simulation model logic

Figure 4 shows the simulation model design. Customer demand for products (CDs, BPMs, and SPs) generates orders at the DCs. Demand for all TSs generates orders at DC2, demand for TS3 creates an order at DC1, and demand for TS2 creates an order at DC3. According to the customers' inventory policies and expected lead times, these DCs place orders at the factories. Orders of CDs and BPMs at the automotive and medical factories create orders of TS3 and TS2 at the electronics factory. The used products create a flow from customers towards the collection/disassembly centre. Factories can order semiconductors from this centre or from the primary supplier located in Taiwan. Reused semiconductors are cheaper than new ones.

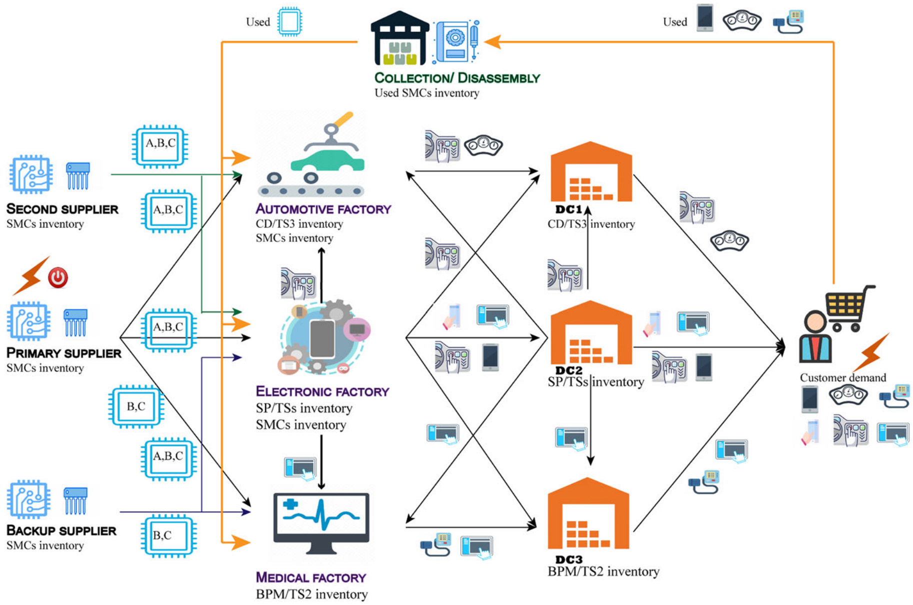

Fig. 4 Simulation model setup

4.2 Input data

The simulation system comprises three suppliers, three factories, three distribution centres, 20 customers and a collection/disassembly centre. We consider facility cost, carrying cost and production cost. In the ISN. The electronics factory produces three types of TSs, "TS3" is for CD, TS2 is for BPM, and "TS1" for SP. Table 1 summarises the costs and prices of these products. Prices are collected from the website www.made-in-china.com. We used the

Table 1 Product details

Product		Cost ($)	Price ($)
Semiconductor (SMC)	A	6	9
	B	3.4	5
	C	0.7	1
Touch screen (TS)	3	26.7	40
	2	13.3	20
	1	6.7	10
Smartphone (SP)		200	300
Car dashboard (CD)		666.7	1000
Blood pressure monitor (BPM)		166.7	250

cost-based price method to calculate cost considering a profit markup of 50% as follows (1):

$$Cost(i) = \frac{Price(i)}{1.5} \tag{1}$$

The demand generated in the model is presented in Table 2.

We consider three types of vehicles: trucks, lorries, and aeroplanes. For deliveries from the primary and the backup suppliers to factories, an aeroplane with a capacity of 600 m^3 is used. For deliveries between factories and DCs, a truck with a capacity of 22 m^3 is used. For transportation from the DCs to customers, for product return from customers, and from the second supplier to the automotive factory, we use a lorry with a capacity of 12 m^3. We consider a less-than-truckload (LTL) transportation policy. The air transportation cost is \$0.0006/kg/km and the land transportation cost is \$0.00015/kg/km.

A continuous review policy with a re-order point and variable order quantity (MIN–MAX policy) with safety stock (SS) is used for final products. The parameters of the policy can be defined as follows (Aldrighetti et al., 2019; Gianesello et al., 2017):

$$s = d * (LT) + SS \tag{2}$$

$$S = 2 * s \tag{3}$$

Table 2 Customer demand

Customers	Car dashboards	Touch screens			Smartphones	Blood pressure monitors
		TS1	TS2	TS3		
Customer 1	200			130		30
Customer 2					600	
Customer 3	50					
Customer 4		250			1500	50
Customer 5	100					200
Customer 6		200			3500	
Customer 7	100			400		
Customer 8						230
Customer 9		200			290	
Customer 10			340			
Customer 11	150					
Customer 12	160					170
Customer 13					390	
Customer 14		180			200	
Customer 15			200			2600
Customer 16	240				300	620
Customer 17	450			250		
Customer 18		130			455	
Customer 19	400					70
Customer 20						1000
Total	1850	980	540	780	7235	5020

where s is the re-order point, S is the target level, d is the demand, and LT is the lead time.

A continuous review policy with a re-order point and fixed order quantity (R-Q) is employed for raw materials (SMCs) and semi-final products (TSs). The initial stock at the beginning of the simulation has been set equal to the target inventory (i.e., the MAX level).

4.3 Indicators of performance

In this study, three indicators are used to evaluate the performance in each scenario as proposed by Aldrighetti et al. (2019).

- Financial performance measured by revenue and cost involving facility, carrying, production, and transport costs. These elements are chosen because of their ability to assess the economic health and efficiency of an organisation. They allow to understand the impacts of a disruption on sales and overall profitability.
- Customer performance measured by **(1)** the expected lead time (ELT) service for customers, equal to 1 if the product is delivered on time, i.e., in accordance with the customer's ELT (Burgos & Ivanov, 2021); **(2)** the service level, which represents the ratio between the number of orders fulfilled immediately from inventory-on-hand and the total number of orders placed at the production plant (Aldrighetti et al., 2019). These indicators allow measuring the customer satisfaction and how the company is meeting the customer needs and expectations in a volatile environment. Through these metrics, decision-makers can evaluate the impact of resilience strategies on customer demand fulfilment during disruptions.
- Operational performance measured by the inventory dynamics, which indicate the availability of products at all the facilities, the demand backlog, and the difference between production requested and produced. The metrics are selected because of their ability to identify the imbalances between supply and demand and assess the effectiveness of the implemented strategies to reduce these imbalances manifestations. Inventory, purchase orders, production quantity and demand backlog data help explain and identify the reasons behind customer and financial indicators. Further, the nature the studied problem and scenarios require observing inventories and their ability to fulfill customer demands.

4.4 Model assumptions

The assumptions of the simulation model are described as follows:

- The proposed network involves a shared reverse flow through recovery of all products.
- We consider one raw material (SMCs). References to SMCs are simplified to SMC Type A, SMC Type B, and SMC Type C.
- We assume that the price of recovered products is about 50% of that of new products.
- The obsolete products are recovered from four main customers, which present 25% of CDs, 70% of SPs, and 53% of BPMs.
- We suppose that customers place orders once per week.
- The SS is equal to the mean weekly demand.
- The reorder point is half of the weekly demand.
- We suppose that the capacities of factories are unlimited to focus on shortage problem.
- The capacities of primary and second supplier are limited. However, the capacity of the backup supplier is unlimited and SMCs are sold at a higher price.
- Backlog processing is studied at factories and DCs levels.

- Obsolete products are recovered from four main customers, which present 25% of CDs, 70% of SPs, and 53% of BPMs.
- In dual sourcing, the quantities of raw material purchased from primary and second supplier follow a uniform split policy.
- The lead time at the backup supplier is 30 days.

4.5 Scenarios

The model simulates a one-year period from 1 January 2022 to 31 December 2022, considering four scenarios. Table 3 shows the experimental setup for the simulation scenarios.

The first scenario (baseline scenario) evaluates the performance of the ISN under business-as-usual conditions (disruption-free). The results are considered as a benchmark for comparing and analysing the ISN performance during supply and demand disruption. In the second scenario (disruptive scenario), three sub-scenarios are implemented. First, a 3-month shutdown at the primary supplier plant is simulated to analyse the impact of this closure on the whole ISN. Second, demand disruption scenarios are simulated to assess the ability of the ISN to manage the increase/decrease in demand. In the third scenario (disruptive scenarios with contingent sourcing strategies), intertwining and sourcing strategies are combined and evaluated to measure their effects on ISN performance. In the fourth scenario

Table 3 Scenarios' characteristics

Scenarios	Events	Characteristics
First	Baseline scenario	Business as usual without disruptions
Second	Primary supplier shutdown	From 1 April 2022 until 30 June 2022
	Demand increase for all products	From 1 April 2022 until 30 June 2022 Demand coefficient = 3
	Demand increase for SPs and BPMs and decrease for CDs	Demand coefficient = 0.2 for: CD: Customers 7, 11, 17, and 19 (60% of base demand) Demand coefficient = 3 for: SP: Customers 4 and 6 (70% of base demand) BPM: Customer 15 (52% of base demand) From 1 April 2022 until 30 June 2022
	All disruptions	All disruptions' characteristics mentioned earlier From 1 April 2022 until 30 June 2022
Third	Disruptions with dual and backup sourcing	The disruptive events of Scenario 2 are simulated with: Dual sourcing for the automotive factory Backup sourcing for the medical factory Both strategies for the electronics factory
Fourth	Disruptions-free	The factories share the reverse flow and the collection/disassembly centre in the CISN
	Combined disruptions	Disruptions in the CISN considering single sourcing
	Combined disruptions	Disruptions in the CISN considering dual and backup sourcing

(scenarios in the CISN), a novel shared collection/disassembly centre is open to feed the factories with used semiconductors. Disruptive events are simulated in the CISN subject to different sourcing strategies.

5 Experiments, results, and analysis

5.1 Baseline scenario: Normal Scenario (NS)

In the NS, the ISN operates under disruption-free conditions. It can be observed in Fig. 5 that the ELT service level and service level are equal to 1(a, b), which means that consumers receive the ordered products on time. The available inventory can satisfy customers' demand without any shortage or backlog (c, d, e, f). The financial performance indicators (Table 4) shows that the ISN is profitable.

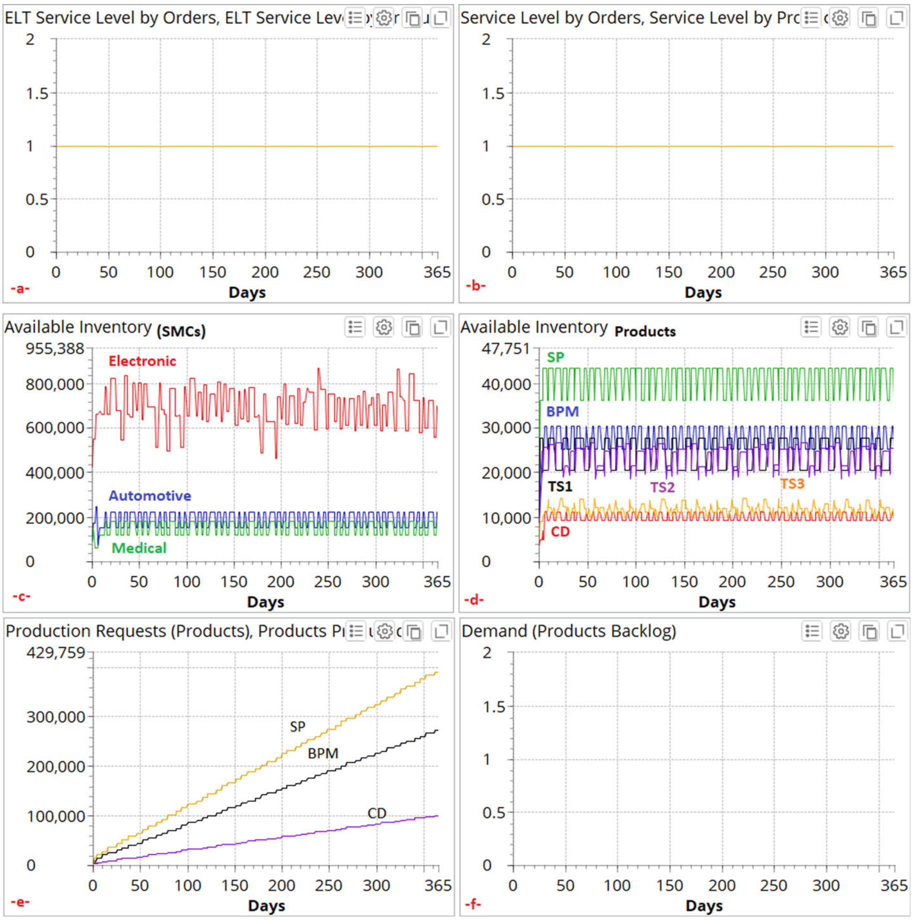

Fig. 5 Experiment results: NS

Table 4 Financial performance of the ISN in NS

Indicators	Automotive	Electronic	Medical
Costs	17.520.223,027	26.496.010,220	11.252.218,000
Revenue	98.057.000,000	115.036.508,000	66.515.700,000

5.2 Disruption scenarios

In the second scenario, the performance of the ISN is evaluated under disruption scenarios. Financial performance results are summarised in Table 5.

5.2.1 ISN under supply disruption (SUSD)

We simulate a shutdown at the primary supplier starting on 1 April 2022 and lasting until 30 June 2022. The results are depicted in Fig. 6. Table 5 shows that revenue and total cost decrease compared to NS. Customer performance indicators decrease as well (a, b). This can be explained by the reduction of the inventory levels of final products (d) resulting from the difference between the production requested and produced (e) during the crisis. The impacts are especially intense at the automotive and medical companies compared to the electronics one. This can be explained by the SMC inventory level at each factory (c). Since production shuts down at the automotive and medical factories, the electronics factory uses the SMC inventory supplied for TSs to produce SPs. However, the global inventory at the electronics factory is not sufficient to fulfil demand during the supplier shutdown, as highlighted by the increase in demand backlog (f). A shortage of SMC Type C stopped production at the electronics factory. This can explain the available inventory of SMCs and the demand backlog between days 118 and 180. This component appears in the bill of materials of all products. In contrast, a shortage of SMC Type A does not affect the production of BPMs, TS2, and TS1. In the post-disruption period, we observe higher inventories of TS2 and TS3 at the medical and automotive factories along with a shortage of SMCs and a backlog of BPMs and CDs. This can be explained by the disruption tails, an absence of adaptability between production and inventory policies during the transition toward the recovery period (Ivanov, 2019). However, the situation at the electronics factory is nearly disruption-tails-free. This means that the electronics factory's recovery is different from those of the automotive and medical factories. This is confirmed by the duration when the production requested is higher than that produced (e). Moreover, the inventory of SMCs at the electronics factory increased

Table 5 Financial performance of the ISN supply chains under disruptions

Scenarios	Automotive		Electronic		Medical	
	Cost (%)	Revenue (%)	Cost (%)	Revenue (%)	Cost (%)	Revenue (%)
SUSD	− 12.9	− 13.2	− 10.2	− 7.5	− 13.7	− 11.3
SUDD	11.2	10.2	16.2	26.5	6.5	11.6
SUDD'	− 9	− 11.6	19.4	32.6	6	11.8
SUSDD	− 12.3	− 11.7	− 9.8	− 7.9	− 12.6	− 11.1

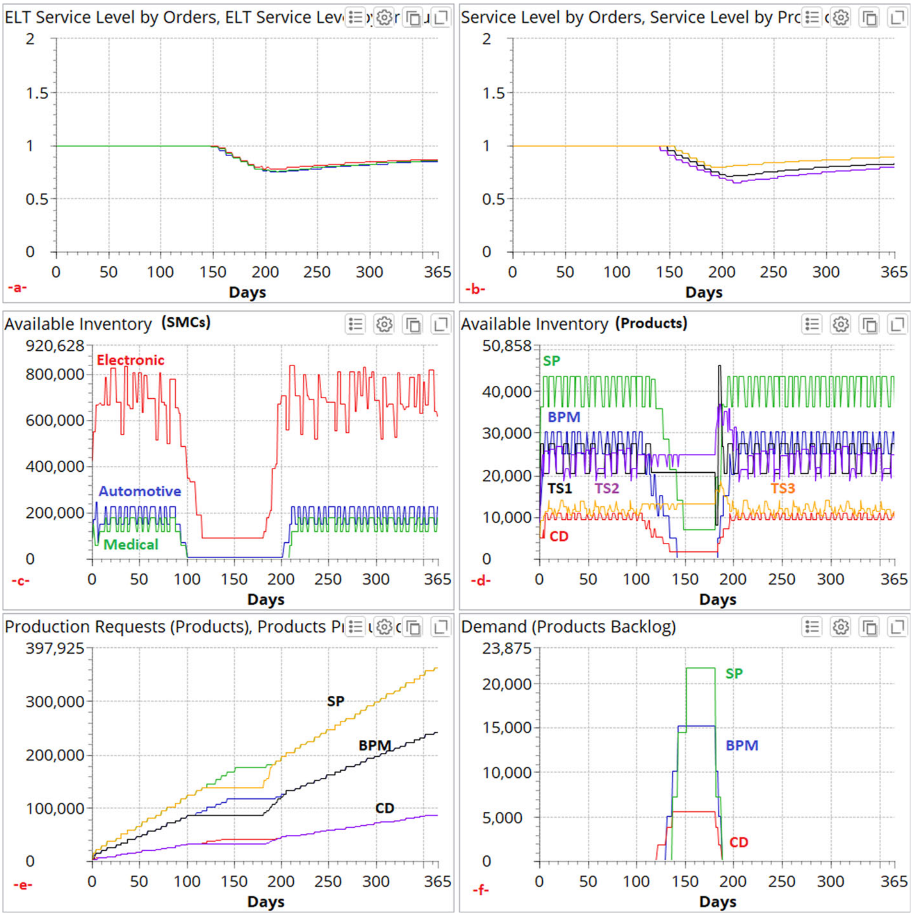

Fig. 6 Experiment results: Primary supplier shutdown (SUSD)

directly after the primary supplier reopened, while it started to increase from day 240 for the other factories (c).

5.2.2 ISN under demand increase (SUDD)

In this scenario, an increase in demand is simulated from 1 April 2022 until 30 June 2022. The impacts of network performance on an increase in demand for all products are shown in Fig. 7. The results of an increase in demand for SPs and BPMs and a decrease in that for CDs in the network are presented in Fig. 9.

When the demand for all products increases, the profit increases compared to the NS (Table 5). The ELT service level is between 0.98 and 1 because this metric does not consider orders that are not yet shipped, delayed or dropped. However, the service level decreases (b). This can be explained by the demand backlog of BPMs and CDs (f) resulting from incomplete orders. The inability to complete orders is not due to the SMC shortage but to TS inventory (Fig. 8a). The quantity of TSs purchased is not sufficient to fulfil the demand (d).

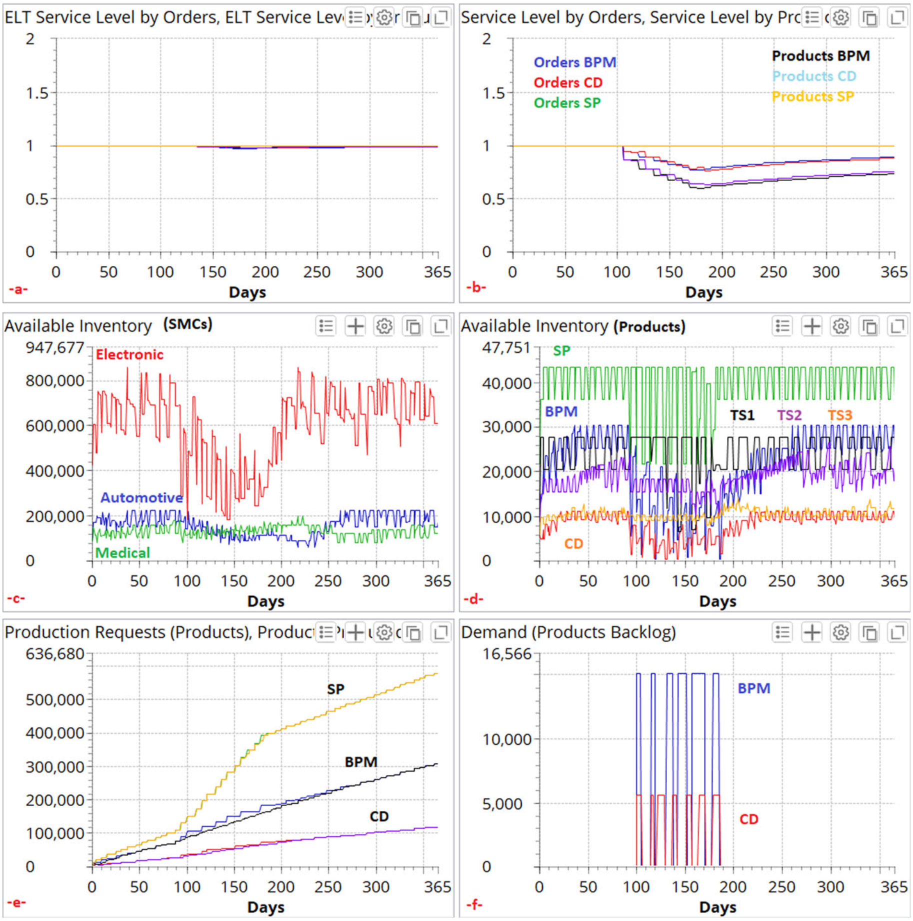

Fig. 7 Experiment results: All products demand increase (SUDD)

Fig. 8 Available inventory of TSs in factories

Actually, the normal provision of TSs is maintained. The electronics factory cannot increase TS1 and TS3 production due to the demand increase for SPs and the limited SMC inventory. The reason is to maintain the service level (b). Nevertheless, if the demand for SPs increases further, a backlog will be observed because of the global SMC inventory.

When the demand for SPs and BPMs increases and the demand for CDs decreases (Fig. 9), the results are similar to the previous scenarios. As expected, cost and revenue at the electronics and medical factories increase while the service level decreases. For the automotive factory, the service level is maintained, but the cost and revenue decrease. The demand decrease does not affect the service level because the placed orders are shipped on time. In this scenario, the production at the automotive factory decreases, which means that the demand for TS3 decreases and the electronics factory can re-allocate its SMC inventory to produce TS2 or TS1 (Fig. 8b). This reallocation strategy impacted positively the profitability of the electronics factory.

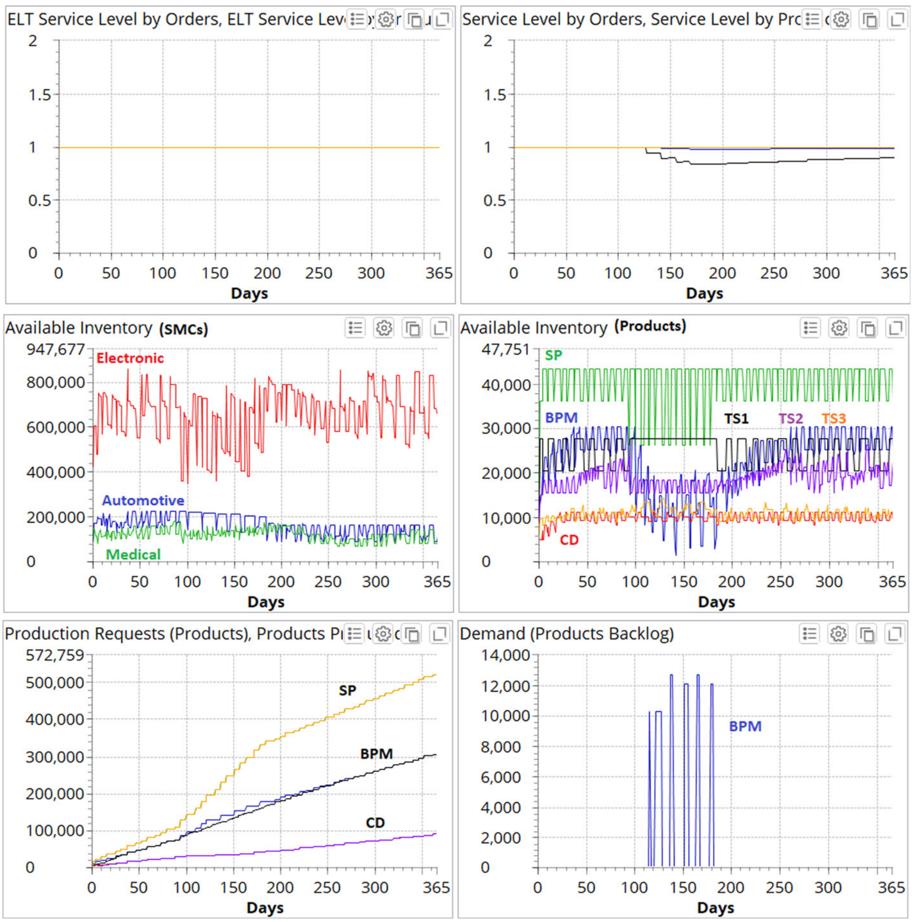

Fig. 9 Experiment results: BPM, SP demand increase and CD decrease (SUDD')

5.2.3 ISN under supply and demand disruption (SUSDD)

This scenario simulates a combination of the scenarios presented above: a shutdown at the supplier, demand increases for SPs and BPMs, and a demand decrease for CDs. Figure 10 shows the results of this experiment. As seen in Table 5, the financial performance decreases compared to NS due to a lack of final products' production and delivery. The service level by orders for CDs is equal to 1, 0.8 for SPs, and 0.813 for BPMs (a). The demand backlog of BPMs and SPs (f) shows that orders are not delivered to customers due to the lack of required products shown in (d). The inventory level of TS2 and TS3 increases at factories during the disruption, which increases the carrying cost. This indicates that there is no coordination in production planning between factories. Else, with the decrease in TS3 demand, the electronics factory can orient the available inventory of SMC to produce SPs, TS1, or TS2. A backlog of CDs is observed at the end of the disruption due to the decrease in CD inventory and the normal state of demand (d).

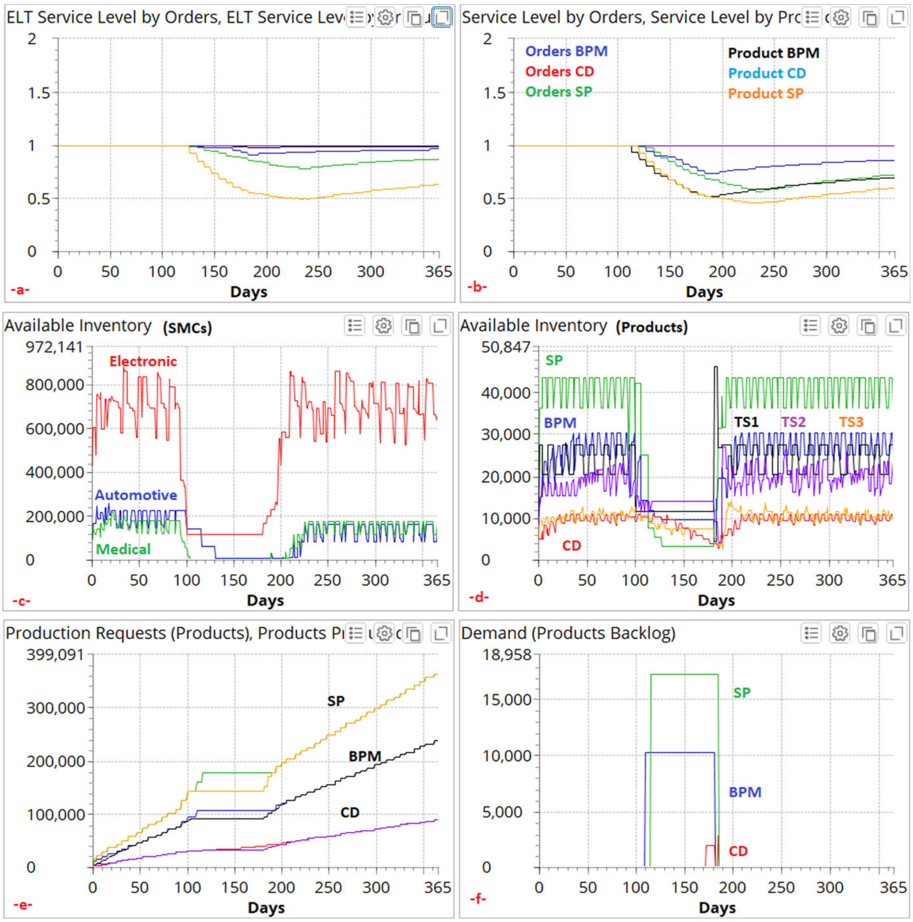

Fig. 10 Experiment results: Supplier shutdown, BPM, SP demand increase, and CD decrease (SUSDD)

5.3 Third scenario: Scenario with dual and backup sourcing

In the third scenario, multiple sourcing strategies are considered. Dual sourcing for the automotive factory, backup sourcing for the medical factory, and both strategies for the electronics factory are used. Indicators of financial performance results are compared in Table 6.

It can be observed in Table 6 that while considering dual and backup sourcing strategies cost decreases at the electronics and automotive factories and increases at the medical factory due to the sourcing mode comparing to NS with single sourcing. Collaborating with a local second supplier (dual sourcing) decreases the transportation cost for the automotive factory, while collaborating with an emergent supplier (backup sourcing) increases the cost for the medical factory. A combination of both strategies results in a slight cost reduction, as observed for the electronics factory.

During demand increase scenario (SS-DD), the revenue and the costs are higher for companies opting for backup sourcing comparing to dual sourcing. Figure 11 shows the experimental results of the demand increase scenario. An improvement in service level (b) is shown compared to Fig. 7. At the beginning of the disruption, the SMC inventory level at the electronics factory decreases during the lead time of the backup supplier (c). When the backup supplier starts feeding the factory, the inventory level increases (c), and the produced production meets the production requested (e). This ensures the availability of SPs at the DCs (d) and prevents an SP demand backlog (f). Moreover, the factory maintains the production of TSs (Fig. 12a). The demand backlog of CDs and BPMs (f) is reduced compared to Fig. 7.

When demand increases, the SMC inventory at the medical factory decreases (c), generating a reduction of BPMs at DC3 (d), hence creating a backlog of demand and a decrease in the service level. After receiving the SMCs from the backup supplier, the BPM inventory level increases at DC3, and the customers receive their demand (no demand backlog). At the end of the disruption, a demand BPM backlog is observed parallel to an increase in TS2 inventory at the medical factory. The increasing demand for BPMs increases the demand for TS2 at the electronics factory, which creates pressure on the backup supplier. As for CDs, the demand backlog is observed during the disruption; this can be explained by the level of SMCs at factories supplied by the primary and secondary suppliers. In contrast to the medical factory, which receives an extra quantity of SMCs from the backup supplier, the automotive factory receives the same quantity as purchased, as under normal conditions.

Figure 13 shows the experimental results of the supplier shutdown and demand increase (SS-SDD). Cost and revenue increase at all factories. However, customer performance decreases compared to the previous scenario (a, b). The closure of the primary supplier turns

Table 6 Financial performance of the ISN with multiple sourcing under disruptions

Scenarios	Automotive		Electronics		Medical	
	Cost (%)	Revenue (%)	Cost (%)	Revenue (%)	Cost (%)	Revenue (%)
SS-NS*	− 1.46	0.00	− 0.12	0.00	2.02	0.00
SS-DD	5.3	10.2	16	30	9.2	27.3
SS-SDD	11.2	9.3	24.5	35.5	16.9	23.7
SS-SDD’	− 3.1	− 11.7	20.28	32.7	19.26	29.22

*SS-NS: Normal scenario with dual and backup sourcing

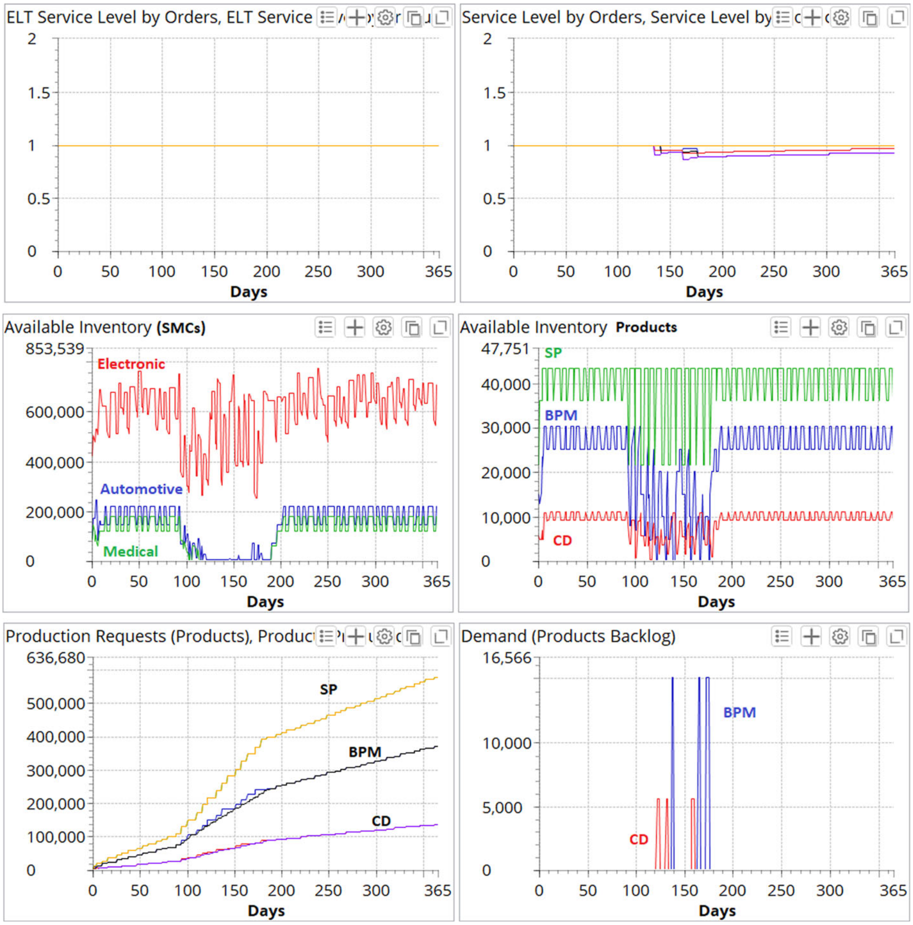

Fig. 11 Experiment results: Demand increase for all products in (SS-DD)

Fig. 12 Available inventories of TSs at factories

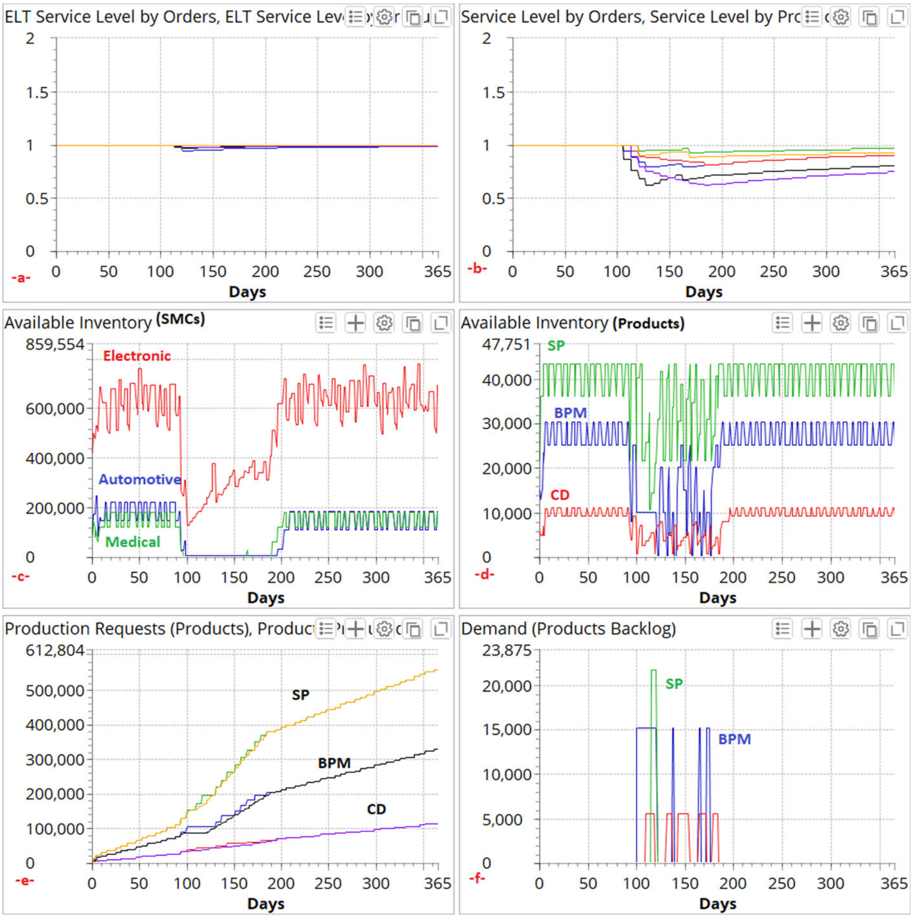

Fig. 13 Experiment results: Primary supplier shutdown and demand increase (SS-SDD)

the automotive factory's sourcing strategy into single sourcing, which creates a demand backlog for CDs (f) resulting from the decrease of products at DC1 (d). A decrease in BPMs at DC3 is observed after the primary supplier closes due to the backup supplier's lead time (d). Despite SMC delivery, the BPM backlog persists (f). A demand backlog for SPs is also observed at the beginning of the disruptions, explained by the backup supplier's lead time. Then, the factory operates with dual sourcing (Supplier 2 and backup supplier). In this situation, the backup supplier feeds the factories by a ratio due to the limited SMC capacity. As seen in (Fig. 12b), the inventory level of TS2 and TS3 at factories increases. This means that the electronics factory responds to the increased demand for BPMs and CDs, while the medical and automotive factories cannot deliver the product due to a lack of SMCs.

Figure 14 shows the results when the supplier shutdown occurs parallel to the SP and BPM demand increase and the CD demand decrease (SS-SDD'). ELT service level and service level are improved compared to the previous scenarios (a, b). A BPM demand backlog is observed. In contrast to the scenario with a supplier shutdown and demand increase, there is no backlog in SP and CD demand. This can explain the customer performance indicators improvement.

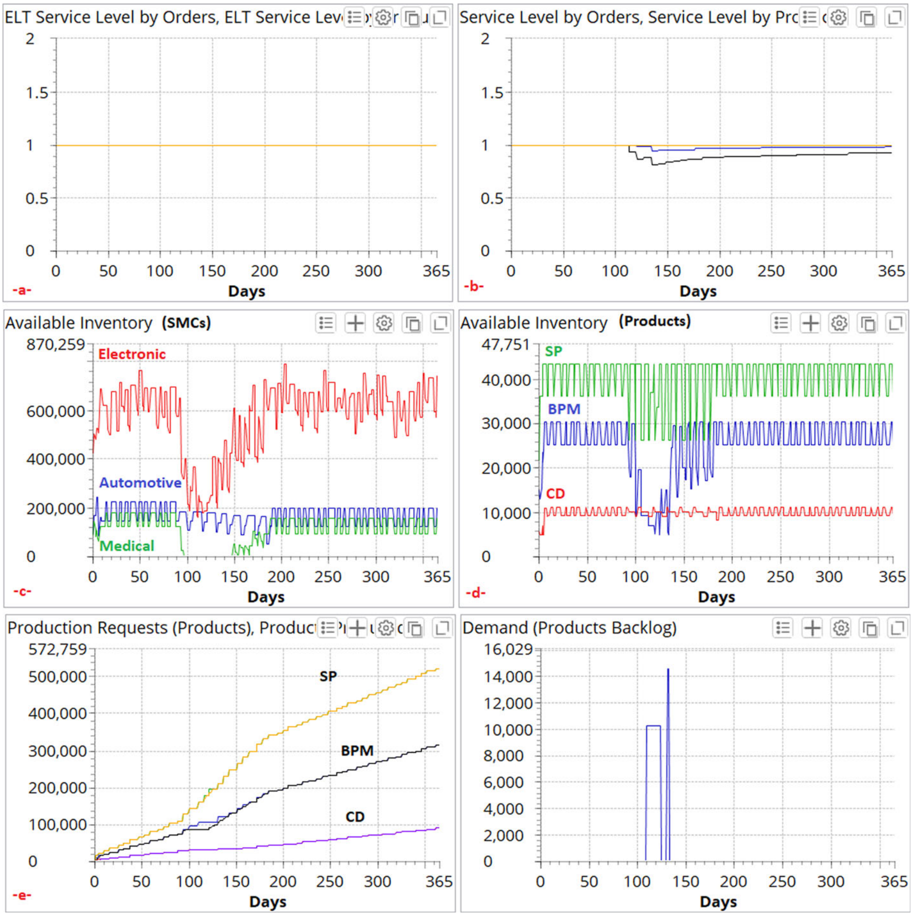

Fig. 14 Experiment results: Primary supplier shutdown, SP and BPM demand increase, and CD decrease (SS-SDD')

The automotive factory purchases SMCs from the secondary supplier (c), and this quantity is sufficient to feed the reduced production resulting from the demand decrease. This decrease is advantageous for the electronics factory because the quantity purchased from the second supplier increases and covers the period of the backup supplier's lead time (d). The pressure on the backup supplier is hence minimised, and no BPM demand backlog appears at the end of the disruption (d, f). The electronic factory maintains the production of the semi-products TSs (Fig. 12c).

5.4 Fourth scenario: disruptions in the CISN with different sourcing strategies.

In this scenario, a CISN is operating under disruption free conditions, disruptions with single, dual, and backup sourcing. Table 7 shows the financial performance indicators of the CISN. Figure 15 present the experimental results of the CISN in normal conditions (C-NS). Outcomes related to customer and operational performance are similar to the NS. However,

Table 7 Financial performance of the CISN

Scenarios	Automotive		Electronics		Medical	
	Cost (%)	Revenue (%)	Cost (%)	Revenue (%)	Cost (%)	Revenue (%)
C-NS	− 10.6	0.00	− 20.7	0.00	− 17.2	0.00
C-SDD	− 25.3	− 11.7	− 24.4	32.3	− 13.1	25.4
C-SS-SDD	− 5.13	− 11.7	18.28	50.7	19.26	35.22

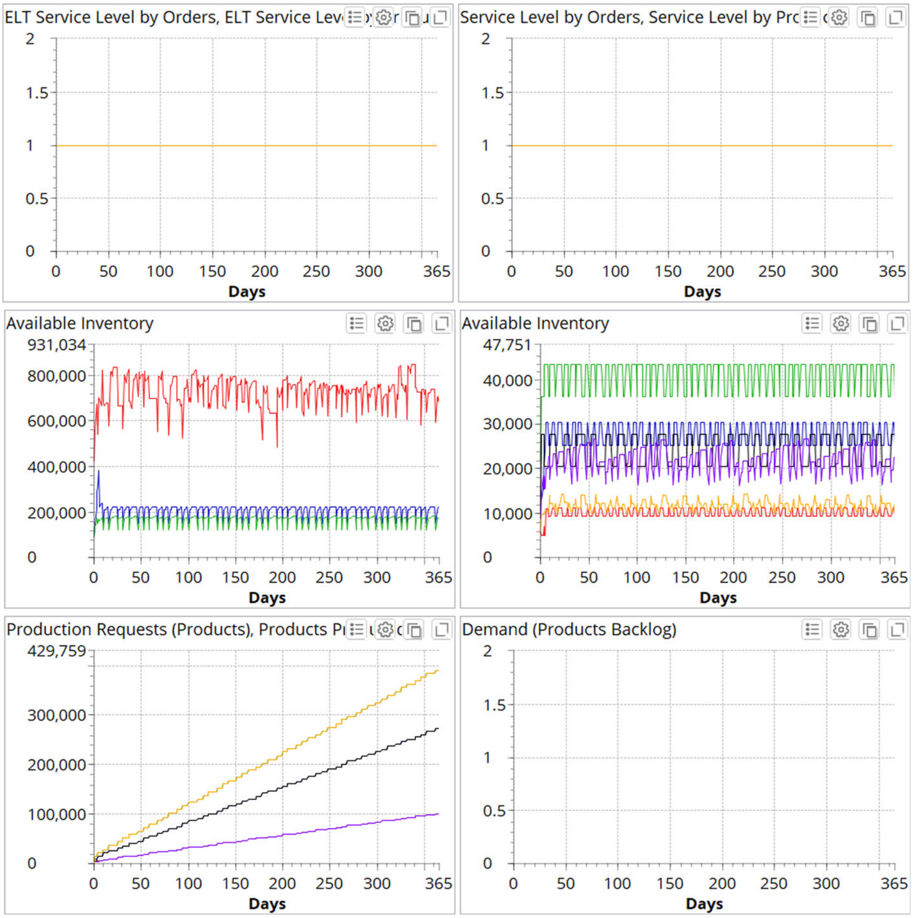

Fig. 15 Experimental results: CISN under disruptions-free conditions (C-NS)

the economic performance is improved due to the minimization of raw materials cost. Cost of the electronics factory are reduced most significantly because 70% of the SP are recovered. Figure 16 shows the experimental results of the primary supplier shutdown, SP and BPM demand increase, and CD demand decrease, considering a single supplier in the CISN (C-SDD). The integration of circular practices with single sourcing improves the global service level from 0.665 to 0.96. The consumption of the reused SMCs at the end of the disruption generates a decrease in BPMs at DC3, creating a backlog in demand. This is explained by the SMC shortage observed in the medical factory after day 130 (Fig. 17). It can be seen that there is no demand backlog and no shortage at the electronics factory. This means that this factory exploits the most inventory of reused SMCs which impacted its economic profitability.

Figure 18 shows the experimental results of the primary supplier shutdown, SP and BPM demand increase, and CD demand decrease, considering dual and backup sourcing in the CISN. An improvement in the service level is observed (0.99), there is no demand backlog, and the available inventory at DCs satisfies customers' demand. At the beginning of the

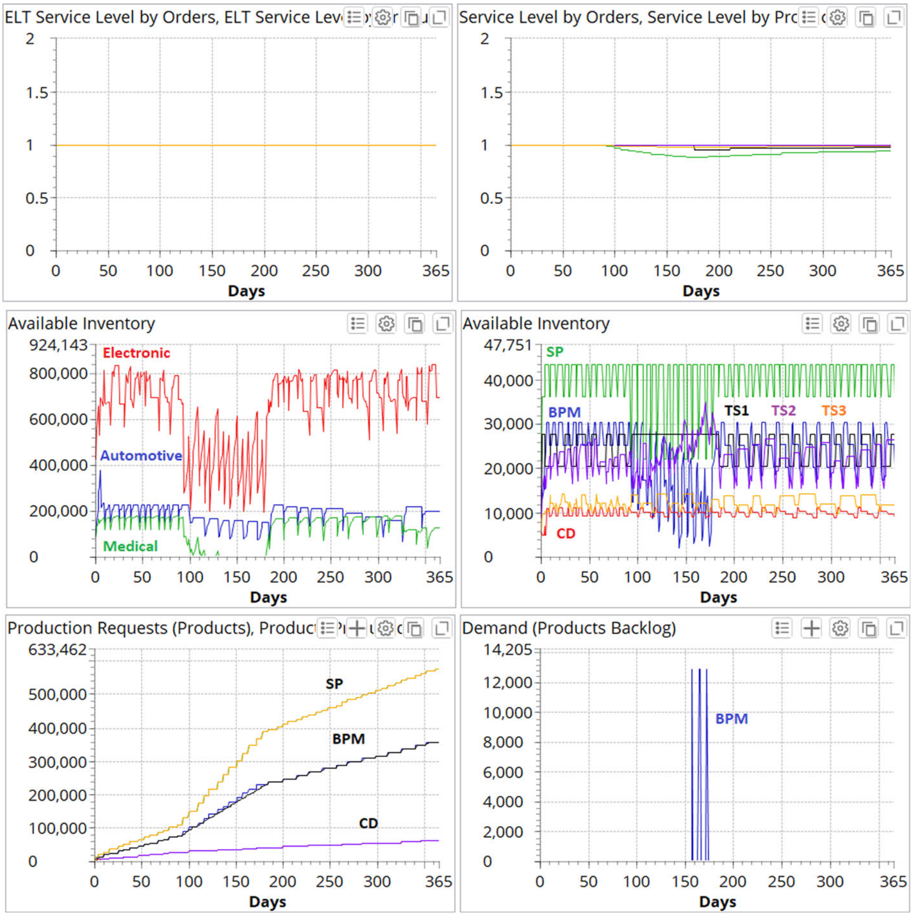

Fig. 16 Experiment results: Primary supplier shutdown, SP and BPM demand increase, and CD decrease in the CISN (C-SDD)

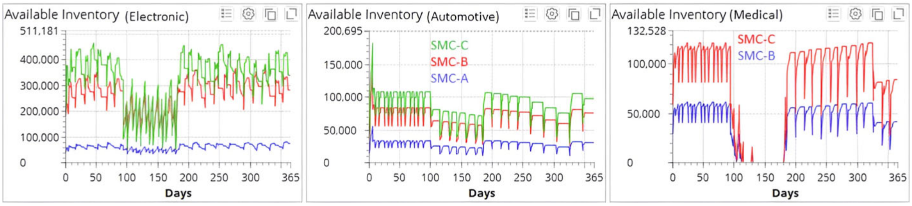

Fig. 17 Available SMCs inventories at factories

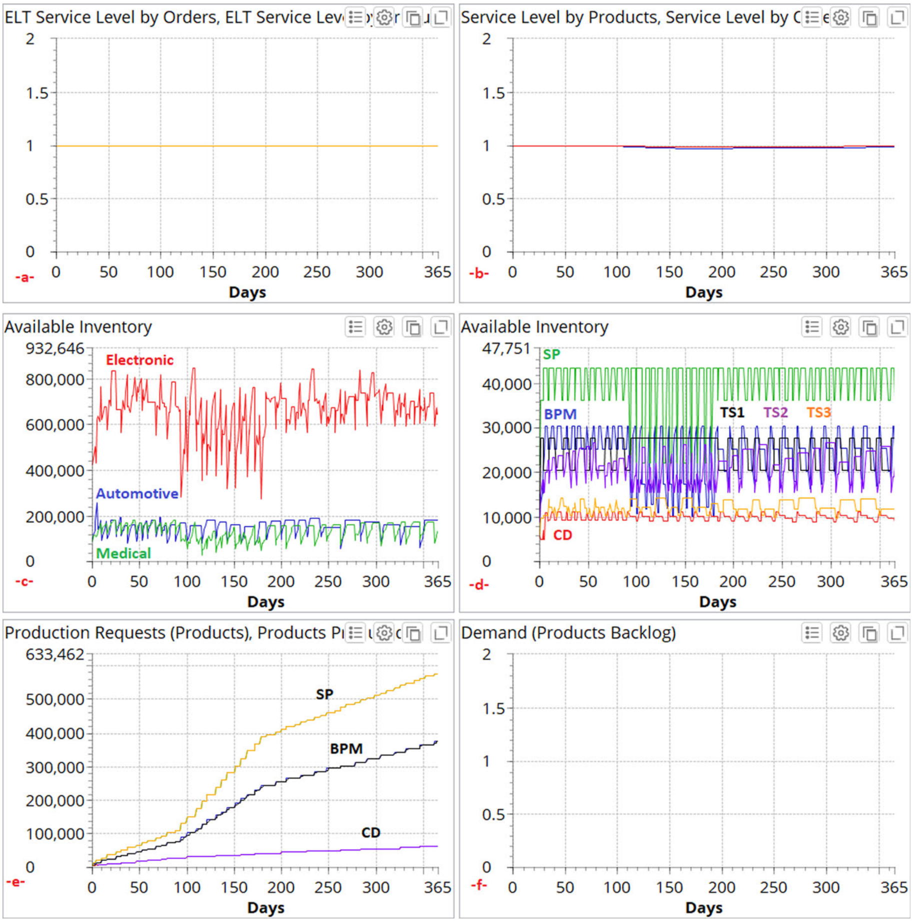

Fig. 18 Experiment results: Primary supplier shutdown, SP and BPM demand increase, and CD decrease in CISN with dual and backup sourcing (C-SS-SDD)

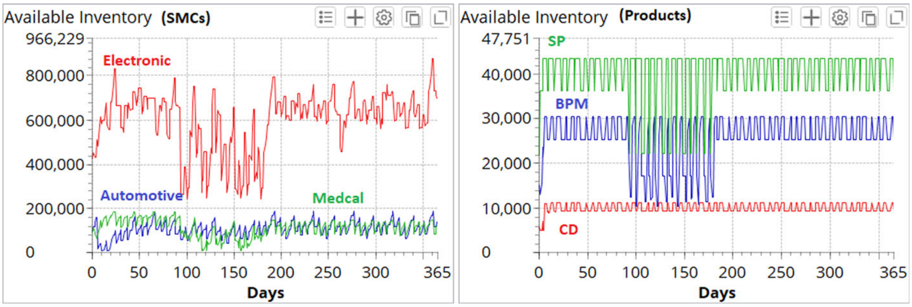

Fig. 19 Inventory levels: Primary supplier shutdown and demand increase in the CISN

disruption, recovered and purchased SMCs from the second supplier are used to satisfy the demand for SPs and TSs. The recovered SMCs prevent an inventory shortage at the medical factory during the backup supplier's lead time. When the demand for CDs increases, the level of SMCs at factories will decrease, but the level of product availability at the DCs still allows the customers' demand to be satisfied, as illustrated in Fig. 19. Compared to the same scenario without circularity, electronics and medical factories are more profitable. In addition to benefit from CD demand decrease and a reduced pressure on suppliers, the two factories employed the reused materials to fulfil more customers' demands.

6 Discussion and managerial insights

In this section, we discuss the impacts of intertwining and circularity, considering different sourcing strategies under supply and demand disruptions. We observe that the effects of disruptive events on ISN performance are different from those on the classical supply chains. Table 8 summarises major experimental outcomes, their explanation from intertwining and circularity perspectives, and associated managerial insights.

First, intertwining offers the possibility to share inventories. For instance, the inventory at the automotive factory during a demand decrease can be redirected to the electronics and medical factories to avoid shortages. This observation is in line with literature arguing that sharing inventories can be profitable (Zhang et al., 2019) and allow better matching of supply and demand (Villa & Castañeda, 2018). Somarin et al. (2023) affirmed that stock reallocation ensures the availability of materials and avoids backorder situations. Paul and Chowdhury (2020) stated that collaborating and sharing resources among manufacturers increases the service level. However, when this mechanism is based on individual profit and loss, supply chain partners can share fake information (Xu et al., 2020). Therefore, this strategy cannot be implemented in the absence of a high level of trust.

Second, intertwining offers the possibility to prepare collaborative production planning. This strategy is effective in reducing the effect of disruptions (Duong & Chong, 2020; Zeng & Yen, 2017). The nature of the ISN involves collaboration between companies for long-term resilience to disruptions (Ghanei et al., 2023). Collaborative planning leads to coordinated activities (Hill et al., 2018). According to the environmental conditions (e.g., facility shutdowns and demand disruptions), supply chain managers can establish collaborative planning for production for the optimal use of raw materials without an increase in inventories. In the studied ISN, collaborative production planning considering the demand decrease of CDs

Table 8 Managerial insights

Experimental observations	Effects of intertwining	Effects of circularity	Managerial recommendations
With contingent sourcing strategies, inventory dynamics at the electronics factory are close to disruption-free operations (Fig. 11). A part of this inventory can be redirected to automotive and medical producers to avoid shortages	Through intertwining, sharing of inventory across different producers becomes possible Dual/backup sourcing practices for similar materials used in different supply chains of the ISN can help mitigate the disruption's impact on performance		Development of inventory visibility systems and supplier collaboration portals Development of collaborative response practices by reallocation of inventories and supply across different supply chains in the ISN
At the beginning of the disruptions, recovered SMCs can be used to avoid shortages (Fig. 18)	Intertwining offers the possibility to share the inventory of recovered SMCs	Circularity offers the ability to collect obsolete products and recover SMCs through the disassembly process	A coordinated system is needed to manage the shared inventory of reused SMCs Companies opting for backup sourcing should define their inventory policy according to the lead time of the backup supplier
The CD demand decreases during the SP and BPM demand increases minimise pressure on the electronics factory and the supplier (Fig. 14)	Intertwining offers the possibility to transfer the quantity of SMCs supplied by the supplier to the electronics and medical factories		Develop a financial compensation system for exchange of inventories Introduce new clauses in the supplier's contract to re-orient the SMCs toward the other factories at the same price if the demand decreases
The electronics factory produces TSs despite the shortage of SMCs at the medical and automotive factories (Fig. 10)	Through intertwining, the three companies can adjust their production based on the available inventories to mitigate financial performance impacts		Increase real-time information-sharing between companies Develop sensing strategies for optimal production planning Develop collaborative management of the supplier relationship

Table 8 (continued)

Experimental observations	Effects of intertwining	Effects of circularity	Managerial recommendations
During the primary supplier shutdown, production stopped due to shortage of SMC Type C (Fig. 6)	Through intertwining, companies can share information about their inventories to reallocate potential sources of components and raw materials	Through total recovery of SMCs and optimal product design, producers can maintain production and satisfy demand during short-term disruptions	During product development, the minimum necessary number of SMCs should be used Develop specific product designs for disruption periods
The second supplier is unable to fulfil the increasing demand for SMCs due to its limited capacity (Fig. 13)		Recovered SMCs can be recycled, and materials can be sold to the secondary supplier. This can reduce cost and cycle time	Open a recycling plant in the supplier zone Analyse the impacts of using recycled material on the supplier's lead time
During the demand increase, the electronics factory used the most available inventory of the reused SMCs (Figs. 16 and 17)	Intertwining allows to increase the number of recovered raw materials in the network		Define regulations to specify the percentage of reused raw materials for each factory
With contingent sourcing strategies and the recovered SMCs, no demand backlog and no shortages are observed (Figs. 18 and 19)	Intertwining allows to reassign sources between companies according to the demand	Circularity of raw materials supports dual and backup sourcing by covering their weakness	Build a dynamic collaborative sourcing strategy for the whole ISN incorporating all sources of raw materials (both new and reused ones). The strategy should be flexible to be adjusted according to the disruption and recovery dynamics

makes it possible to decrease TS3 production and produce SPs, BPMs, TS1, and TS2 based on the available inventory of SMCs in the whole ISN.

Third, intertwining allows the definition of a collaborative sourcing strategy. Paul and Chowdhury (2020) suggest that during a crisis, all manufacturers should share their information to locate all available emergency sources in the context of "collective emergency sourcing". In the ISN, securing provisions for the most critical node (i.e., the electronics factory) helps indirectly secure a part of the provisions for the other factories. The pressure on the backup supplier during the demand increase period, the shortage of SMCs during the lead time, and the second supplier's inability to increase the purchased quantity of SMCs during the primary supplier's closure are evidence of the necessity to define a collaborative sourcing strategy. The intertwined companies should adopt a collaborative sourcing strategy. As an example, during the primary supplier's shutdown, the three companies should define a strategy for optimal procurement of SMCs from the backup and secondary suppliers. This will lead to synchronous production aiming to fulfil the maximum of customers' demand.

As for supply chain sourcing strategies, in dual sourcing, the second supplier can maintain a percentage of sourcing according to the ratio of quantity splitting during the shutdown of the primary supplier plant. However, dual sourcing with limited supplier capacity has no effect when demand increases. The shorter the lead time at the backup supplier, the higher the effectiveness of this strategy during a supply disruption. This finding is in line with Li et al. (2021), who indicated that time and cost affect this sourcing strategy. Aldrighetti et al. (2019) showed that having a backup supplier is effective to mitigate long-term disruptions. However, knowing the great cycle time of semiconductors, adopting this strategy could lead to shortages, and a combination of dual and backup sourcing strategies is more effective. When demand increases, the electronics factory's inventory has nearly disruption-free performance using the secondary source and the backup supplier. During the primary supplier shutdown, the impacts on this factory were lower than those on the two other factories. The results support Li et al.'s (2021) recommendation to adopt combined strategies during long-term disruptions.

The results of this study indicate that the reused SMCs can cover the shortage at the beginning of a disruption if single sourcing is used. This means that circularity of raw materials is effective during short-term disruptions. Additionally, when an unexpected event occurs, the inventory of reused raw materials can be considered as an emergency inventory. Recovered raw materials can compensate for the drawbacks of contingent sourcing strategies (i.e., the lead time of the backup supplier and the limited capacity of the secondary supplier). Therefore, circularity of raw materials can be considered as a support to sourcing strategies. Nevertheless, three related issues should be considered. First, the impact of customer behaviour on the return rate (van Loon & Van Wassenhove, 2020) and the product's life duration play an important role. For instance, the first use of a CD is longer compared to an SP, but the quantity of SMCs in a CD is higher. As a result, a conflict can be created during a crisis. This can be resolved in the context of intertwining through collaborative regulations. Second, the location of the collection/disassembly centre should be considered. As the intertwined companies and their customers are geographically dispersed, it would be difficult to find an optimal location for all. In this situation, the DCs can play the role of collection/disassembly centres. Since each DC is managed by a company (e.g., DC1 is managed by the automotive factory), a virtual collection/disassembly centre can be created to ensure the visibility of SMCs' movements. In this context, artificial intelligence has proved its efficiency in managing collaborative platforms in emerging situations (Zhang et al., 2022). Third, the ability to disassemble obsolete products is important. Product designers should be aware of the end-of-life strategy to ease and unify the disassembly process among the products of the ISN.

Based on the experimental results, some specific implications can be derived. The CISN should be supported by digital technology, especially adopting Internet-of-Thing and blockchain technologies by all partners in order to manage real time information. A non-digitalized SC within the network could not collaborate and coordinate activities effectively with other partners (Dolgui and Dubey et al., 2023; Dolgui and Ivanov, 2023; Ivanov, 2023a, 2023b). Further, the intertwined companies should be able to repurpose their production and operation according to customers' behaviour. For instance, when the demand decreased for CD, the automotive factory should repurpose activities in coordination with factories with demand increase to survive. Moreover, when intertwined producers are sharing the same raw material, the process of supplier selection should consider other factors rather than traditional criteria such us the supply reliability during a crisis and the ability of the supplier to collaborate with intertwined partners. Lastly, when establishing an outsourcing relationship, both players should be aware of the consequences of disruptions and elaborate adequate regulations.

7 Conclusion

The objective of this study was to examine the impacts of intertwining and circularity on sourcing performance in supply chains during supply and demand disruptions, considering single, dual, and backup sourcing practices. We studied the problem of an SMC shortage in an ISN comprising three supply chains from the electronics, automotive, and medical sectors. With the help of anyLogistix software, a simulation of several scenarios was implemented.

Our proposed model not only can be used directly in industry to stress-test the supply chain's viability with consideration of intertwining and circularity effects but also provides a number of interesting conceptual insights. The results indicate that intertwining offers the possibility to increase collaboration by sharing information, transferring inventories, establishing coordinated production planning, and defining a collaborative sourcing strategy (RQ1). Moreover, a circular economy supports sourcing performance during a crisis. In case of short-term disruptions, reused raw materials can feed manufacturing plants. If considering a long-term crisis, circular practices and contingent sourcing strategies can ensure the availability of raw materials. Operating as a CISN increases the effectiveness of circular practices in dealing with the drawbacks of dual and backup sourcing (RQ2).

The proposed managerial recommendations identified four directions for future research: (1) elaborating novel methods to define how contingent sources should be managed to achieve synchronous production, (2) defining policies to structure the collaboration between intertwined companies, (3) proposing methods to shift from local sourcing (reused raw material) to external sourcing (suppliers), and (4) developing a method to manage the shared reverse flows.

Future research can examine other circular economy practices and other forms of interconnections in the ISN. In this context, future studies can analyse an ISN where one of the supply chains uses the waste of the others as a principal raw material. For instance, the sugar and paper supply chains can be intertwined. A by-product of sugar factories is the bagasse which is used in paper production. Scholars can simulate disruptions with demand uncertainty, other inventory policies, other sourcing strategies, and other mitigating strategies. A conceptual framework can be developed to formalise the supply of reused and new semiconductors. Other case studies can be simulated to validate our results and shed light on other aspects of the ISN and CISN.

The considered case study has some limitations. The profit markup is estimated at 50%. This value may differ across industries, but it does not influence our particular modelling settings because it is only used to define the products cost and the purpose is the compare these costs among different scenarios. We only consider facility, carrying, transport and production cost. As there are other costs to consider, the total cost can be influenced. It is assumed that a fixed percentage of products is collected from each product. However, in real life this returned products ratio is uncertain. The capacities of facilities are considered unlimited to highlight and focus on the shortage problem. If capacities are constrained, there will be other strategies to implement such as capacities reallocation. The limitations point to several way to extend the results of our study in future. In particular, real-life use cases can be examined with real data sets. Different constraints (e.g., capacities) can be included into model formulations.

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Declarations

Conflict of interest No conflict of interest has to be declared.

Appendix 1

Sourcing strategies under disruptions (See Table 9).

Table 9 Previous works on sourcing strategies analysis under disruption

References	Sourcing strategies	Method	Main findings
(Gupta et al., 2021)	Two suppliers	Game theory	The price leadership defines the order quantity. It increases when the supplier is the leader The non-disrupted supplier can increase the price before receiving orders
(Li et al., 2021)	Standalone and combined strategies	Control theory	Cost and time affect sourcing strategies Standalone strategies can address shortages in short-term disruptions For long-term disruptions, it is recommended to adopt combined strategies
(Wang & Yu, 2020)	Contingent sourcing and dual sourcing	Game theory	Contingent sourcing and responsive pricing can substitute dual sourcing if the emergency cost and lost sales costs are lower If the disrupted capacity increases, the probability of a substitution relationship increases as well

Table 9 (continued)

References	Sourcing strategies	Method	Main findings
(He et al., 2020)	Dynamic contingent sourcing	Quantitative model	Demand and inventory are related to the time of employing contingent sourcing in addition to customer behaviour and demand recovery For long disruptions, dynamic contingent sourcing strategies can be ineffective when operations are recovered during production downtime For a short disturbance, the effectiveness of dynamic contingent sourcing strategies is related to the demand recovery time, the intensity of competition, and customer behaviours
(Thomas & Mahanty, 2020)	Emergency backup supplier	Dynamic simulation approach	In a short-term scenario, there is a trade-off between enhancing the service level and profitability impacted by the cost, response time, and spare capacity of the backup supplier In a long-term scenario, a trade-off between readiness and recovery practices exists

Table 9 (continued)

References	Sourcing strategies	Method	Main findings
(Aldrighetti et al., 2019)	Increasing the inventory levels; lateral transshipment; backup supplier	Simulation	For short-term disturbances, lateral transshipment is favourable to mitigate the negative effects of disruptions with a slight increase in costs. Collaborating with a backup supplier is the most effective mitigation strategy for long-term disruption
(Namdar et al., 2018)	Single and multiple sourcing, backup supplier contracts, spot purchasing, and resilient strategies	Two-stage stochastic programming	Compared to single sourcing, a multiple-sourcing strategy increases the service level if decision-makers are risk-aware and their ability to detect early warning signals is higher. This capability is pivotal for supply chain resilience
(Ivanov, 2017)	Single and dual sourcing	Simulation approach	Dual sourcing is recommended when the level of inventory is low and demand is high Single sourcing is recommended (1) when both inventory level and demand are low, (2) when inventory level is high and demand is low with production smoothing, and (3) when demand and inventory level are high with capacity flexibility

Table 9 (continued)

References	Sourcing strategies	Method	Main findings
(Zhu, 2015)	Dual sourcing (2 suppliers: local and overseas)	Stochastic dynamic programming	Disruption at the local source is costlier than overseas Data about the local source is more relevant than overseas data When both sources are considered, the disruption information is precious and leads to cost savings
(Gupta et al., 2015)	Contingent, dual, and sole sourcing strategy	Game theory	A buyer operating under supply disturbance should be aware of the supply state and the competitor's time to place an order when working with an unreliable supplier
(Fang et al., 2013)	Single, dual, multiple, and contingent sourcing	Stochastic optimisation	The marginal benefits of collaboration with three or more suppliers are much lower Dual sourcing is more favoured than having a backup supplier, even with zero lead time

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