

An integrated model of supply chain resilience and its impact on supply chain performance under disruption

Supply chain
resilience and
performance

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Abstract

Purpose – This study aims to explore the relationships among the five components of supply chain (SC) resilience (SCRES): visibility, velocity, flexibility, robustness and collaboration and their impacts on the SC performance under disruption (SCPUD).

Design/methodology/approach – Five SCRES components are identified from the literature review and data are collected using a web survey from 113 manufacturing companies in Taiwan. The data are analyzed by structured equation modeling with the partial least square solution. Two-stage least-squares (2SLS) regression was used to test the potential endogeneity of SC collaboration (SCC).

Findings – The results reveal that SCC is an exogenous driver of SCRES; it directly affects visibility, velocity, flexibility, robustness and SCPUD. Furthermore, SC flexibility is the only component of SC agility that directly affects SCPUD; it is influenced directly by SC velocity and indirectly by SC visibility through SC velocity. SC visibility is a vital agility component that positively influences SC velocity and SC robustness.

Research limitations/implications – The data in this study are cross-sectional and the sample size of 113 is relatively small. The relationship between SC robustness and SCPUD needs a longer observation period to reveal. The logistic issue in the shortage of carriers caused by the pandemic has been overlooked.

Practical implications – A firm should enhance its collaboration and flexibility in the SC as they both are the critical antecedents of SC performance (SCP) during the disruption period.

Originality/value – This study integrates visibility, velocity, flexibility, robustness and collaboration into a complete framework of SCRES. The dependent variable, SCPUD, measures SC performance (SCP) under the

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disruption caused by the COVID-19 pandemic. It is the first study to investigate the associations of the six constructs in a research model.

Keywords Supply chain resilience, Agility, Collaboration, Flexibility, Robustness, Performance under disruption

Paper type Research paper

1. Introduction

Owing to the outbreak of COVID-19 in 2020, many countries locked down cities and borders, impeding the movement of people and goods by air, land or water. Corporate offices and factories must shut down temporarily because of the lack of workforce, causing disruptions in 86% of global supply chains (SCs) (Van Hoek, 2020). These disruptions make SC resilience (SCRES) a critical strategy of sustainability (Ivanov, 2021).

Before the pandemic, many scholars have paid attention to SCRES and have extensively studied it from different perspectives. A scrutiny of the extant literature reveals that the significant disparity in the formative elements needed to secure the adaptive capability of resilience (Jüttner and Maklan, 2011; Petitt *et al.*, 2010). According to Scholten *et al.* (2014), SC (re-)engineering, collaboration, agility, risk awareness and knowledge management are the formative elements of SCRES. Furthermore, characteristics such as flexibility, velocity, visibility and collaboration may be considered as SCRES antecedents, rather than formative elements (e.g. Mandal *et al.*, 2016). Ali *et al.* (2017) indicate a lack of clarity on the relationships between these elements of SCRES. Our research aims to fill these research gaps.

This study proposes an integrated research model incorporating the concept of SCRES. Previously, many scholars have considered visibility, velocity, flexibility, robustness and collaboration as the five most common components of SCRES (Christopher and Peck, 2004; Ponomarov and Holcomb, 2009; Jüttner and Maklan, 2011; Wieland and Wallenburg, 2013). Among them, visibility, velocity and flexibility are identified as agility components (Jüttner and Maklan, 2011). Mackay *et al.* (2020) distinguish robustness and flexibility as proactive absorptive capabilities and reactive adaptive capabilities, respectively. While robustness can resist or avoid changes, flexibility can reconfigure SC operations and adapt to changes.

Regarding the impact of SCRES on performance, several studies confirm that SC agility (Chan *et al.*, 2017), collaboration (Wu *et al.*, 2014; Pradabwong *et al.*, 2017) and robustness (Wieland and Wallenburg, 2012) positively affect a firm's business performance. Besides these studies, the extant literature is scarce, especially regarding how SCRES affects SC's performance during pandemic disruptions. As such, this study aims to fill this gap by integrating the five common components (i.e. visibility, velocity, flexibility, robustness and collaboration) as a surrogate of SCRES and exploring their relationships with each other and with the SC performance under disruption (SCPUD). The study contributes to the extant knowledge of SCRES and how to build SCRES capabilities to achieve better SCPUD, especially in the pandemic disruption caused by COVID-19. On the one hand, knowing the interplay between the formative components of SCRES can realize their roles in SCRES, thus helping practitioners increase the comprehensive SCRES capabilities. On the other hand, understanding the effects of the formative components of SCRES on SCPUD can illustrate which component(s) can increase SCPUD. This study helps firms facing pandemic risks understand the way some resilient practices may improve SC performance (SCP).

The remainder of this paper is organized as follows. The next sections introduce the literature review in Section 2 and hypotheses development in Section 3, followed by the research method in Section 4. The results of data analyses and discussion are described in Section 5. Finally, Section 6 presents theoretical contributions, practical implications, research limitations and future work.

2. Literature review

2.1 Supply chain disruption

SC disruptions are unplanned and unanticipated events that disrupt the normal flow of goods and materials within an SC and expose firms to operational and financial risks (Craighead *et al.*, 2007). SC disruptions can be classified as random events of natural disasters (e.g. Gunesse *et al.*, 2018) or pandemic (e.g. Queiroz *et al.*, 2020), accidents (e.g. machine breakdown or fire) or intentional disruptions (such as acts of terrorism or sabotage). Sheffi and Rice (2005) note that the vulnerability to a specific risk varies considerably from company to company. Vulnerabilities in SC often lead to SC disruptions (Jüttner and Maklan, 2011). The four basic reasons causing the impact of disruption on SC execution (Dolgui *et al.*, 2018) include sourcing strategy (e.g. single sourcing), production planning (e.g. 100% capacity utilization), inventory management (e.g. low safety stocks) and control (e.g. no contingency plans). Regarding the consequence of SC disruptions, Zsidisin *et al.* (2016) confirm that SC glitches can decrease shareholder wealth. Dolgui *et al.* (2018), based on literature analysis, identifies the ripple effect of SC disruption on SC performance (SCP). Furthermore, scholars have proposed many means or strategies to reduce, mitigate or manage SC disruptive risk or uncertainty (Kleindorfer and Saad, 2005; Simangunsong *et al.*, 2012). Most of them agree that building an SCRES is crucial to recover from a negative impact of a disruption (Christopher and Peck, 2004; Jüttner and Maklan, 2011; Dolgui *et al.*, 2018). This study focuses on SC disruptions caused by the COVID-19 pandemic.

2.2 Supply chain resilience (SCRES)

SCRES is “the characteristics of a well-designed SC network with proactive and reactive capabilities, which enables the SC members to reduce the probability of disruptive events (or to reduce their impact) to take the organization to a stronger and more sustainable state” (Chowdhury and Quaddus, 2017, p. 188). Its focus is on the system’s adaptive capability to address temporary disruptive events (Jain *et al.*, 2017). A resilient system should absorb perturbation, given the system’s uncertainty and unpredictability (Asokan *et al.*, 2017). Strategically, Wieland and Wallenburg (2013) conceptualize resilience as reactive and proactive capacities, corresponding to two dimensions: agility and robustness. Another critical factor for building resilience is collaboration inside the SC (Christopher and Peck, 2004; Jüttner and Maklan, 2011), which aggregates SC resources to provide a survival capability and sustainability (Camarinha-Matos, 2014).

2.2.1 *Agility.* Swafford *et al.* (2006) define SC agility as an SC’s capability to adapt or respond quickly to a dynamic and unpredictable business environment. Agility is related to the ability to match supply more closely with demand, and the key to agility is speed (Christopher and Lee, 2004). Agility implies synchronization from one end of the pipeline to the other; all the SC players are “marching in step” (Christopher and Lee, 2004, p. 395). For example, synchronous supply requires transparency of demand and inventory as close to real-time as possible (Christopher and Lee, 2004). Jüttner and Maklan (2011) identify three components of agility: flexibility, velocity and visibility. These components are explained as follows:

- (1) *Flexibility* is the capability to adapt to new, different or changing requirements (Skipper and Hanna, 2009). It permits an organization to continuously improve customer satisfaction by leveraging routine performance to high non-routine compliance levels (Bowersox *et al.*, 1992). Factors that enable flexibility in the SC include strong SC relationships, contracts allowing modifications in delivery schedules, manufacturing facilities to produce multiple products, redundancy with slack or unused resources and a multi-skilled workforce (Johnson *et al.*, 2013). Supply chain flexibility (SCF) directly affects a customer and is the shared responsibility of two or more functions along the SC members (Vickery *et al.*, 1999). The dimensions of SCF include product flexibility (or customization), volume flexibility, launch

flexibility (i.e. new product introduction), access flexibility (i.e. widespread distribution) and responsiveness to target markets (Vickery *et al.*, 1999).

- (2) *Velocity* is the speed of SC activities that are critical to sustaining competitive advantages (Fisher *et al.*, 2000), such as customer response speed (Chiang *et al.*, 2015), purchase decision-making speed (Kaufmann and Gaeckler, 2015) and product launch speed (Vickery *et al.*, 2015). Furthermore, the SC speed can be improved by streamlined processes, reduced in-bound lead-times and reduced non-value-added time (Christopher and Peck, 2004). Chan *et al.* (2017) note that the speed of a firm's response to key measures of SC performance (SCP) helps the firm reduce manufacturing lead-times, increase new product introductions and improve customer service.
- (3) *Visibility* is the extent to which actors can access information that they consider critical or useful to their operations and beneficial mutually within an SC (Papert *et al.*, 2016). The information includes the identity, location and status of entities transiting the SC (Francis, 2008). SC visibility is the outcome of sharing useful or high-quality information (Williams *et al.*, 2013). Scholars argue that an automatic system and closer relationships among the SC partners are the critical factors accelerating SC visibility (Christopher and Lee, 2004). With information and communication technologies (ICTs) (Brandon-Jones *et al.*, 2014), electronic data interchange (EDI) (Barratt and Oke, 2007) and automatic identification technologies (Papert *et al.*, 2016), SC's connectivity can be increased (Dubey *et al.*, 2018a), gathering and sharing information. Namely, SC connectivity can facilitate information sharing and improve SC visibility (Dubey *et al.*, 2018a).

2.2.2 Collaboration. Collaboration is the state that inter-organizational partners are willing to work together to understand each other's viewpoints by sharing information and resources to achieve collective goals (Stank *et al.*, 2001). A business can deal with emergent problems through SC collaborative (SCC) innovation and problem-solving (Ramezani and Camarinha-Matos, 2020). Seven components of SCC have been identified: *information sharing, decision synchronization, incentive alignment, goal congruence, resource sharing, collaborative communication and joint knowledge creation* (Cao and Zhang, 2011). Among them, information sharing serves as a glue that integrates all other elements of collaboration into a whole, which triggers the productive behavior to attain collaborative objectives. This study considers the above components and adapts five collaborative processes from Wu *et al.* (2014): market development, collaborative communication, product/process design, process implementation and problem-solving.

2.2.3 Robustness. SC robustness is SC's ability to resist changes without adjusting its initial stable configuration (Wieland and Wallenburg, 2013). It usually involves redundancy, e.g. reserves or backup options (Durach *et al.*, 2015). Wieland and Wallenburg (2013) indicate that an SC member's anticipation and preparedness are necessary for maintaining robustness. The former is the forecast of possible future changes; the latter is the resistance to forecasted changes. Mackay *et al.* (2020) suggest that robustness leads to resilience; it is an absorptive capacity consisting of two dimensions, *resistance* and *avoidance*, through which a robust SC does not experience notable performance degradation in response to a disruption.

3. Hypotheses development

3.1 Relationships of SCC with SC agility

3.1.1 SCC and SC visibility. SC visibility generally addresses information about various entities and activities regarding end-to-end orders, inventory, forecasting, logistics, transportation, distribution, retailing and other unpredictable actions in the dynamic

environment (Wei and Wang, 2010). Its strength is determined by the amount of useful information shared across the SC network (Papert *et al.*, 2016). To share information, organizations should create linkages among the SC members via information technologies to enhance their SC visibility (Brandon-Jones *et al.*, 2014). Creating linkages among the SC members means enforcing SCC through the interoperability of information systems. The achievement of SC visibility is based on close collaboration with suppliers and customers and internal integration within the business (Christopher and Peck, 2004). Previous case studies have confirmed that SCC influences SC visibility (Scholten and Schilder, 2015). Therefore, we hypothesize as follows:

H1. SCC positively affects SC visibility.

3.1.2 SCC and SC velocity. Velocity emphasizes the efficiency of SC's response and recovery (Jüttner and Maklan, 2011). Higher SC velocity leads to quicker responses to market changes or SC disruptions (Christopher and Peck, 2004). SCC mechanisms such as collaborative communication, joint relationship effort and jointly created knowledge can increase SC velocity (Scholten and Schilder, 2015). With SCC efforts such as "joint creativity capacities, joint organizational learning, knowledge sharing, joint problem solving between supply chain partners, firms can improve absorptive capacity and thus introduce new products and services fast and frequently" (Cao and Zhang, 2011, p. 167). Moreover, SCC enables its members to adopt a common information system that can provide more demand information from customers through the information systems interoperability, thus supporting the correct forecasting of customer demand. For example, the apparel retailers of the same brand can search for the amount of inventory from each other with a common information system. This ability, in turn, accelerates the speed of manufacturing and distribution.

Another example is Taiwan's companies in the industry manufacturing electrical-automobile components. Some large companies, e.g. Taiwan Semiconductor Manufacturing Co. (TSMC) and Quanta Computer, plan to build or have factories in the USA to provide just-in-time supply service for their local collaborative customers (e.g. Tesla). This strategy is called "glocalization" that can speed up logistics, increasing SC velocity. Hence, we can postulate as follows:

H2. SCC positively affects SC velocity.

3.1.3 SCC and SCF. Collaboration offers benefits for SC members, including lower resource duplication, greater relevance to customer needs and more flexibility in response to changes in customer needs and the environment (Stank *et al.*, 2001). With a common information system, retailers and manufacturers can collaborate to respond to customer needs by considering each product's detail and providing more accurate sales data to forecast demand (Fisher *et al.*, 2000). Thus, SCC can facilitate SCF through information systems and enable SC partners to market appropriate products to the right customer at the right time. Collaboration encourages sharing information rather than holding them internally. Different information-sharing outcomes have been reported, including improved coordination for faster response, increased agility and flexibility, lowered the costs of inventory, transportation and manufacturing, and they have reduced the bullwhip effect (Prajogo and Olhager, 2012). The bullwhip effect refers to increasing swings in inventory due to the changing consumer demands as one moves up from consumers to suppliers in the SC (Forrester, 1961). Moreover, inter-organizational collaboration and resource alignment in the contingency planning process is positively related to flexibility (Skipper and Hanna, 2009). Previous case studies also confirm that SCC improves SCF (Scholten and Schilder, 2015). Hence, we postulate as follows:

H3. SCC positively affects SCF.

3.2 SCC and SC robustness

The advantage of collaboration comes from relational rent accrued by collaborative partners through combination, exchange and co-development of idiosyncratic resources (Dyer and Singh, 1998). Resource sharing relies on the long-term relationship between SC partners and the appropriate SC architecture for supporting collaborative planning and execution (Sheu *et al.*, 2006); it involves investing in and leveraging capabilities and assets with SC partners (Cao and Zhang, 2011). Furthermore, incentive alignment is another crucial driver for collaboration among partners. With sufficient incentives, they may engage in additional investment, share complementary resources and bear the potential risk within the process of SCC. Besides, with greater information sharing of upstream and downstream risk profiles, a high level of “supply chain intelligence” can be created (Christopher and Peck, 2004). This SC intelligence tracks the process of using knowledge generated and shared by partners and helps identify the sources of risk/uncertainty at each SC node and link. Thus, the SC intelligence in SCC could help improve SC robustness, and it is logical to hypothesize as follows:

H4. SCC positively affects SC robustness.

3.3 Relationships within SC agility

3.3.1 SC visibility and SC velocity. Christopher (2000) notes that a significant problem in SC is the limited visibility of real demand. The bullwhip effect had shown that SC members tend to forecast inventory levels based on their historical records and inventory policies but not on the real demand (Christopher, 2000). One way of solving the bullwhip effect is to create material and information decoupling points (Christopher and Towill, 2001). Material decoupling moves the flow of finished products downward to the customers along the SC pipeline with a postponement strategy of keeping inventory in semi-finished goods, rather than finished goods or raw materials (Christopher, 2000). Information decoupling moves the actual order and inventory information upward to the manufacturer using information systems (Mason-Jones and Towill, 1999). For example, an information system that is used for forecasting and planning demand/supply can measure the impact of a shortened lead-time and better match supply with demand (Fisher *et al.*, 2000). Clear information about supply and demand enables better SC visibility, leading to faster information exchange and better coordination among SC partners, which, in turn, accelerates SC operations (Fisher, 1997). An effective information system can provide data analysis and information sharing to increase velocity (Scholten and Schilder, 2015). Thus, we hypothesize as follows:

H5. SC visibility positively affects SC velocity.

3.3.2 SC velocity and SCF. SC velocity is most critical to products with short lifetimes (Fisher *et al.*, 2000). Due to customers' various preferences, many apparel retailers adopt a postponement strategy to stock more semi-finished goods than finished products, because customer demand is difficult to forecast beyond previous sale patterns. Retailers can manufacture the products in demand from semi-finished goods at any time according to customers' preferences to satisfy customer demand. This practice can speed up the SC process and enhance SCF (Fisher *et al.*, 2000). Billington and Amaral (1999) have noted that the effect of delayed configuration through postponement can significantly improve responsiveness.

Another strategy to cope with the uncertain demand for innovative products is to reduce or avoid uncertainties. The former is to have different products that share common components so that the demand for components becomes more predictable. The latter is to cut lead time so that firms can produce to order or at least manufacture the product at a time closer to when the demand materializes (Fisher, 1997). Thus, these strategies of production

postponement, shared components and cutting lead times speed up the production process and increase SCF, and we hypothesize as follows:

H6. SC velocity positively affects SCF.

3.4 Relationship of SC visibility and SC robustness

Scholars have noted that visibility in SC seems to enhance SC robustness (Durach *et al.*, 2015) and further empirically confirmed this relation (Brandon-Jones *et al.*, 2014). The end-to-end visibility provides timely, accurate data about demand, inventory and capacity to enable SC partners with confidence in making decisions on SC strategies to reduce risk and ensure continuity of operations, thus increasing SC robustness (Christopher and Lee, 2004). Hence, we propose as follows:

H7. SC visibility positively affects SC robustness.

3.5 Relationships of SCRES components and SCPUD

3.5.1 SCC and SCPUD. The benefit of collaboration of SC members is usually higher than the performance achieved by individual members (Jap, 1999). Based on the resource-based view, a firm could differentiate its performance from others by accumulating resources and capabilities that are rare, difficult to imitate and have no direct substitutes, enabling the firm to seize opportunities or avoid threats (Um and Kim, 2019). Moreover, a firm can gain competitive advantages by creating specialized assets in collaboration with SC partners through idiosyncratic investments, knowledge exchange, complementary competencies and more effective governance mechanisms (Dyer and Singh, 1998; Teece, 1987). Specifically, some scholars have demonstrated the significant effect of SCC on SCP (Pradabwong *et al.*, 2017; Wu *et al.*, 2014). During the period of the COVID-19 pandemic, a shortage of material is common in all industries, but in some sectors (e.g. 5G, semiconductor and computer), the shortage is severe because the demand is surging. This situation cannot be avoided unless an SC has a large collaborative network for sourcing materials or components. The demand surge leads to a price hike across the whole SC in the industry, including wafer foundry, integrated circuit (IC) design, IC package and testing and final goods, leading to increased SCPUD. Therefore, we posit the hypothesis as follows:

H8. SCC positively affects SCPUD.

3.5.2 SC visibility and SCPUD. Barratt and Oke (2007) demonstrate that visibility can lead to SC's improved operational performance. Christopher and Lee (2004) suggest that one key element to mitigate SC risks and improve SCP is the "end-to-end" visibility of the SC pipeline. SC members usually cope with SC uncertainty by buffering the SC interfaces with inventory, thus elongating the end-to-end pipeline and obscuring SC visibility. Generally speaking, information sharing between SC members significantly increases the SC's power. That is, an "information-enriched" SC performs significantly better than those not being able to access information beyond their corporate boundaries (Christopher and Lee, 2004). Asymmetric information and poor understanding between SC partners usually result in SCC failure causing the degradation of SCP.

To examine the effects of visibility factors on four measures of perceived firm performance (competitive position, market share, return on assets and customer service levels), Holcomb *et al.* (2011) identify 16 factors from three sources (customer, firm and supplier) in two geographical regions. They find that only the firm's raw material inventory level significantly affects the competitive position, market share and return on assets in the domestic North American group. Moreover, the firm's finished-product inventory level at the plant and the inbound shipments of supplier's supplier significantly affect the return on

assets in the international European Economic Area group. Finally, [Blackhurst et al. \(2005\)](#) confirm that visibility is a core factor mitigating the SC risk and loss. Thus, we posit as follows:

H9. SC visibility positively affects SCPUD.

3.5.3 SC velocity and SCPUD. [Christopher \(2000\)](#) indicates that the key to survival in turbulent and volatile markets is creating a responsive SC. Being responsive to the needs of the market requires a higher speed of action. [Narasimhan et al. \(2006\)](#) find that velocity is a strategic focus in the mature stage of a firm's SC management strategy. As a firm's focus shifts from short-term to long-term, the core measures of success should evolve from customer satisfaction to market and financial performance. In the long run, the firm's SC management strategy should focus on velocity-oriented initiatives such as electronic linkage with suppliers, just in time and customer-oriented logistics. [Kessler and Chakrabarti \(1996\)](#) further indicate that innovation speed may facilitate a new product's commercial success, especially in a competitive dynamic environment with a short product life cycle. [Miles et al. \(1978\)](#) regard fast product development as a "fit" between external conditions and internal action. Time-based competition, which permeates all facets of an organization, has thus emerged as a way to increase profits and market share while simultaneously containing costs and market risk ([Page, 1993](#)). Some scholars (e.g. [Gupta et al., 1992](#); [Murmman, 1994](#)) have claimed that the theoretical relationship between development speed and cost is a U-shaped function. On the left side of the minimum, shortening development time increases cost due to additional coordination and overtime work expenses. On the opposite side, lengthening development time raises the costs because of losing know-how and motivation and additional set-up costs ([Murmman, 1994](#)). In SC disruption, SC partners are under the pressure of short development time for contingency projects. They have to commit more resources and efforts (i.e. more costs) to complete the projects and sustain their operations, leading to higher costs and lower SCPUD. As such, we posit as follows:

H10. SC velocity negatively affects SCPUD.

3.5.4 SCF and SCPUD. SCF may improve a firm's efficiency ([Sanchez and Perez, 2005](#)) and effectively adapt to unforeseen changes ([Tummala et al., 2006](#)). Flexibility facilitates coordination processes and enables organizations to deal with high uncertainty ([Scholten and Schilder, 2015](#)). Under uncertain environments, firms can develop a competitive advantage by using flexibility to handle uncertainty better than their rivals ([Rojo et al., 2018](#)). Sanchez and Perez categorize SCF into three groups: basic flexibility (at the shop floor level), system flexibility (at the company level) and aggregate flexibility (at the SC level). They find that market share and return on sales (ROS) are affected only by system flexibility. The other SCP measures, including return on investment (ROI), return on investment (ROI) growth, market share growth and return on sales (ROS) growth, are significantly affected by all three flexibilities. [Vickery et al. \(1999\)](#) confirm that firms with stronger SCF — yield better business performance. In general, flexibility is confirmed to affect firm performance significantly. Thus, we hypothesize as follows:

H11. SCF positively affects SCPUD.

3.5.5 SC robustness and SCPUD. Building a robust SC often requires extra financial investments ([Wieland and Wallenburg, 2012](#)), because SC robustness incorporates redundancy such as multiple suppliers and slack resources in production or transport capacity ([Hohenstein et al., 2015](#)). These investments incur additional costs to improve business performance ([Wieland and Wallenburg, 2012](#)). A robust SC is designed to hedge the firm's performance against the worst contingencies regarding uncertain factors over a planning horizon ([Kouvelis et al., 2006](#)). Robustness is a proactive management strategy for

preventing SC glitches from occurring, which, in turn, helps to avoid deteriorating business performance (Wieland and Wallenburg, 2012). To avoid the possible impact of an adverse event, the cost incurred from maintaining “just-in-case” slack resources is inevitable (Christopher and Peck, 2004), resulting in lower SCPUD in the short term. Hence, we propose as follows:

H12. SC robustness negatively affects SCPUD in the short term.

3.6 Control variables

This study includes several control variables, including industry type and last year’s annual revenue, to limit extraneous effects that might offer an alternative explanation of SCPUD. Some studies suggest that industry type is an important control variable for SCP (Wu et al., 2014). Annual revenue in the prior year is also regarded as the other SCPUD control variable. The higher the annual revenue last year, the more resources to cope with the disruption this year, rendering less loss from the disruptive situation.

Given the above discourse, the research model with hypotheses is depicted in Figure 1.

4. Research methods

4.1 Subjects

Many industries in Taiwan are multi-national corporations with increasing international connections and have formed an industrial cluster of ICTs to supply key components and sub-contract work for their international customers. In the context of SC, manufacturing firms are more appropriate as the subjects. In the pilot test stage, the invitation e-mail containing a hyperlink to the web questionnaire was sent to a social media group in an accredited business school to solicit voluntary respondents. Two weeks later, 34 volunteers replied, but 4 were deleted because their companies are not in the manufacturing sector.

In the formal survey stage, a total of 698 manufacturing firms were obtained from the public companies listed by the Taiwan Stock Exchange Corporation in 2019. Furthermore, a

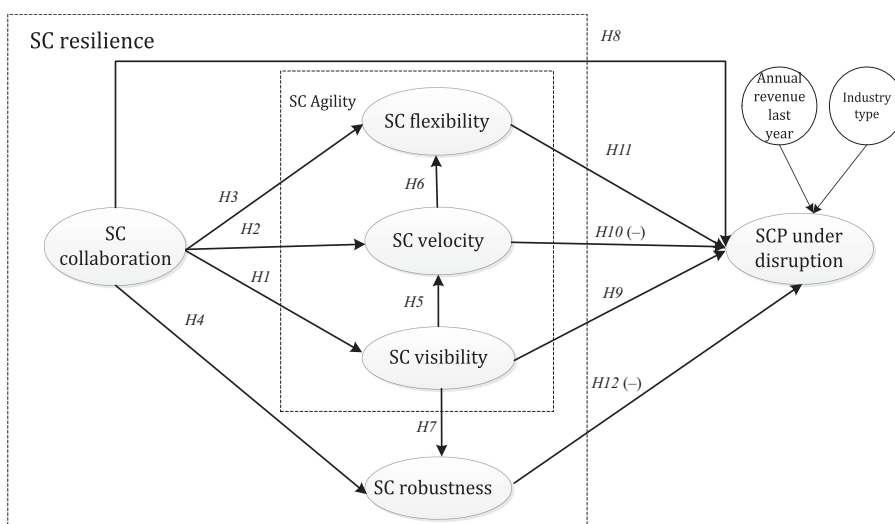


Figure 1. The research model

total of 627 over-the-counter (OTC) manufacturing companies were obtained from the over-the-counter (OTC) exchange website. The same invitation e-mail in the pilot test stage was sent to these 1,325 companies. A total of 604 public companies and 521 over-the-counter (OTC) companies received the e-mails, while the e-mail systems of the other companies rejected the unsolicited invitations. Consequently, the total sample available for the survey was 1,125 companies. A follow-up e-mail reminding them to reply was sent to these companies once a week. After three months from October 1 to December 31, 2020, 92 complete responses were obtained from these manufacturing firms, giving a response rate of 8.2%. After removing 9 careless respondents giving the same score to all questionnaire items, 83 useable samples remained. In total, 113 responses were available for analysis, 30 from the pilot test and 83 from the formal survey. The demographic profile of the firms is shown in Table 1. This low response rate may be attributed to the survey process being unsolicited. Besides, a few non-responding firms, inquired by follow-up phone calls, indicated that they did not participate because of lacking time or unwillingness to reveal confidential information. According to Cohen (1992), our research model contains 5 independent variables and desires a medium effect size, which requires 91 samples at a significant level of 0.05. Thus, our sample size of 113 satisfies this requirement.

Characteristic	Category	N	%
Industry type	High-tech manufacturing	78	69.03%
	Traditional manufacturing	35	30.97%
Annual revenue (NT\$) last year	Under 100m	5	4.43%
	100m–1bn	31	27.43%
	1bn–10bn	55	48.67%
	Greater than 10bn	22	19.97%
No. of employees	Under 1,000	71	62.83%
	1,000–5,000	23	20.36%
	5,000–10,000	13	11.5%
	Greater than 10,000	6	5.31%
No. of suppliers	Under 100	47	41.59%
	100–300	37	32.74%
	300–500	14	12.39%
	Greater than 500	15	13.28%
Tenure	Under 5 years	10	8.85%
	5–10 years	13	11.51%
	10–20 years	43	38.05%
	Greater than 20 years	47	41.59%
Educational level	Post-secondary	1	0.89%
	Bachelor	54	47.79%
	Master	53	46.9%
	Doctorate	5	4.42%
Gender	Male	77	68.14%
	Female	36	31.86%
Job title	Chairman	1	0.9%
	President (or general manager)	10	8.8%
	Vice president (or vice general manager)	28	24.8%
	Manager	33	29.2%
	Vice/Assistant manager	13	11.5%
	Director	16	14.2%
	Special assistant	5	4.42%
	Others	7	6.18%

Table 1.
Demographic profile of
the firms ($N = 113$)

4.2 Measurement items

The questionnaire has two parts. The first part is the necessary data about firms and informants. The second part uses a 7-point Likert scale (ranging from 1 = strongly disagree to 7 = strongly agree) to measure six constructs: SC's visibility, velocity, flexibility, robustness, collaboration and SCPUD. For SCF, the scale items are adapted from [Rojo *et al.* \(2018\)](#). The scale items of SC visibility are adapted from [Dubey *et al.* \(2018a\)](#) and [Barratt and Oke \(2007\)](#). SC velocity is conceptualized from [Chiang *et al.* \(2015\)](#), [Kaipia \(2008\)](#) and [Kaufmann and Gaeckler \(2015\)](#). The scale items of SCC are adapted from [Wu *et al.* \(2014\)](#), [Simatupang and Sridharan \(2008\)](#) and [Cao and Zhang \(2011\)](#). The scale items of SC robustness are self-developed from [Hohenstein *et al.* \(2015\)](#) and operationalized from the redundancy concept. SCPUD adapts scale items from [Sanchez and Perez \(2005\)](#) and [Wu *et al.* \(2014\)](#).

[Podsakoff *et al.* \(2003\)](#) note that common method bias comes from the measurement method rather than the construct. In the forerunning preface of the questionnaire, the informants were assured of anonymity and that the response data would be used only for analysis. They were not required to reveal their e-mail address before answering the web questionnaire. As this study used the same informant to evaluate all questionnaire items, there was a possible common method bias. The post-hoc Harman's single-factor test ([Podsakoff *et al.*, 2003](#)) was conducted by running exploratory factor analysis with the unrotated solution for all items included. The results show that three factors were extracted and accounted for 75.65 percent of the total variance. Because a single factor did not emerge from the un-rotated solution, the bias was not a significant issue.

4.3 Research procedure

The survey contains three stages, including the pre-test, pilot test and formal survey. In the pre-test stage, a total of five university professors and three senior managers from manufacturing industries evaluated the questionnaire's face validity. The purpose is to ensure the questionnaire's correctness, ease of understanding and contextual relevance. In the pilot test stage, a total of 30 survey samples were asked to fill out the questionnaires and give their opinions on the questionnaire's content. The responses from the 30 informants were used for analysis in the pilot test. We select the scale item with the highest factor loading from each of the four SCF sub-constructs ([Rojo *et al.*, 2018](#)) to measure SCF, but one of them is insignificant and subsequently deleted. We also select the scale item for SC velocity having the highest factor loading from purchasing decision-making speed ([Kaufmann and Gaeckler, 2015](#)) and customer response speed ([Chiang *et al.*, 2015](#)). The third item is selected from the three items related to SC speed in [Kaipia \(2008\)](#). The analysis shows that all constructs have Cronbach's α exceeding 0.7, supporting the final questionnaire's reliability. The final questionnaire containing 21 items is shown in [Table 2](#). All these constructs are reflective with their indicators; thus, the measurement and structural models are reflective. Using this web questionnaire, we collected the required data through a formal survey on Taiwan's manufacturing industries. The informants are asked to fill in all items on the web questionnaire before it can be submitted. Therefore, there is no possibility of missing data.

4.4 Potential endogeneity

Before the structural model's data analysis, it is necessary to examine whether the potential issues of endogeneity exist. Endogeneity refers to a situation in which an independent variable correlates with the structural error term (or "residual") in a model ([Lu *et al.*, 2018](#)). Endogeneity may come from the effect of the respective independent variable on the dependent variable and the effects of all unobserved factors that correlate with the independent variable and explain the dependent variable, making the interpretation problematic or even useless ([Ketokivi and McIntosh, 2017](#)).

Constructs and scale items	Sources
<i>Supply chain robustness</i>	
ROB1: Our SC has multiple transportation modes	Hohenstein <i>et al.</i> (2015), Christopher and Peck (2004)
ROB2: Our SC has multiple suppliers that provide major materials/components/products	
<i>Supply chain agility</i>	
Supply chain flexibility	
SCF1: Our SC can adjust manufacturing facilities and processes	Rojo <i>et al.</i> (2018)
SCF2: The information systems of our SC can support transportation and distribution management	
SCF3: Our SC can change delivery modes	
Supply chain visibility	
VIS1: Inventory levels are visible throughout the SC.	Dubey <i>et al.</i> (2018a)
VIS2: Demand levels are visible throughout the SC.	Barratt and Oke (2007)
VIS3: My firm and SC partners have frequent communications	
Supply chain velocity	
VEL1: Our SC reacts faster to make SC decisions	Kaufmann and Gaeckler (2015)
VEL2: Our SC can quickly launch new products to meet customers' demands	Vickery <i>et al.</i> (2015)
VEL3: Our SC can quickly deliver products to customers before the due date	Kaipia (2008), Chiang <i>et al.</i> (2015)
<i>Supply chain collaboration</i>	
COL1: My firm and SC partners collaborate in developing new market and customer response	Simatupang and Sridharan (2008), Cao and Zhang (2011)
COL2: My firm and SC partners set up a communication plan for action *	
COL3: My firm and SC partners collaborate in designing their processes or products	
COL4: My firm and SC partners collaborate in implementing their operational processes*	
COL5: My firm and SC partners have frequent interaction while problems occur	
<i>Supply chain performance under disruption</i>	
SCPUD1: Our SC can improve return on assets under the risk of SC disruption	Sanchez and Perez (2005)
SCPUD2: Our SC can improve the return on investment under the risk of SC disruption	Li <i>et al.</i> (2006)
SCPUD3: Our SC can improve sales growth under the risk of SC disruption*	Wu <i>et al.</i> (2014)
SCPUD4: Our SC can improve market share under the risk of SC disruption*	
SCPUD5: Our SC can improve production and inventory costs under the risk of SC disruption	
Note(s): * indicates the item is eliminated due to high collinearity value (VIF > 10)	

Table 2.
The survey
questionnaire

This study uses a two-stage least-squares (2SLS) regression on two instrumental variables to examine the endogeneity (Wooldridge, 2010) of the exogenous variable, i.e. SCC. Firm size and the number of suppliers were selected as two instrumental variables for SCC, because they are identified as the key drivers determining the adoption of certain collaboration practices (Caniato *et al.*, 2015; Aral *et al.*, 2018). In the first stage of the two-stage least-squares (2SLS) regression using STATA 16.1, SCC was regressed on the two instrumental variables and two control variables, as shown in Table 3 Model 1a. The results show that firm size ($\beta = 0.244$, $p > 0.1$) and the number of suppliers ($\beta = 0.072$, $p > 0.1$) do not significantly affect SCC.

Model 1a First stage: SCC	Model 1b Second stage: SC visibility	Model 1c second stage: SC velocity	Model 1d second stage: SCF	Model 1e Second stage: SC robustness	Model 1f Second stage: SCPUD
Industry type ^a	0.199	0.070	0.221 [†]	0.124	0.205
Annual revenue last year ^a	0.047	0.084	0.007	-0.034	0.053
No. of suppliers ^b	-	-	-	-	-
Firm size ^b	-	-	-	-	-
SCC	0.652*	0.916**	0.592*	0.975***	1.127*
(instrumented)					
R ²	65.5%	69.75%	74.86%	83.13%	50.9%
Durbin-Wu-	$F(1,108) = 0.025$;	$F(1,108) = 0.000$;	$F(1,108) = 0.362$;	$F(1,108) = 0.071$;	$F(1,108) = 0.271$;
Hausman test	$p = 0.8759$	$p = 0.9919$	$p = 0.5487$	$p = 0.7902$	$p = 0.6039$
Note(s):	^a control variable, ^b instrumental variable and *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, $\dagger p < 0.1$				

Table 3.
2SLS model

Subsequently, the predicted value for the assumed endogenous SCC is calculated based on Model 1a and applied to evaluate the relationships between SC visibility, SC velocity, SCF, SC robustness and SCPUD with the assumed endogenous SCC, along with the control variables. As shown in Model 1b to Model 1f in Table 3, the results indicate that all the relationships above are positive and significant at $p < 0.05$. The Durbin–Wu–Hausman endogeneity test was conducted to test the validity of two instrumental variables and determine if the exogenous variable, SCC, is endogenous. The result fails to reject SCC's exogenous structure with all $F(1,108)$ statistics insignificant at $p > 0.1$ level, suggesting the insignificant difference between the instrumented and the non-instrumented models. Thus, the endogeneity of SCC does not appear to be of significant concern in this study.

5. Results of analysis and discussions

5.1 Measurement model

Before undertaking statistical analyses, the test of potential non-response bias is required. A series of chi-square tests were performed between the earlier and later groups of 41 respondents each. The results showed no significant difference in any response between the two groups, indicating that the non-response bias is not significant. Next, the tests for collinearity and normality were performed. The estimation of path coefficients on the structural models is based on ordinary least squares (OLS) regressions of each endogenous latent variable on its corresponding predecessor constructs (Hair *et al.*, 2017). These path coefficients might be biased if the estimation involves critical levels of collinearity among the predictor constructs. To ensure collinearity is not an issue, the variance inflation factor (VIF) values of the items of all constructs should be less than 10 (Hair *et al.*, 2006); this results in dropping two items of SCC and two items of SCPUD (see Table 2). Finally, a total of 17 items of all constructs entered the final analysis. Structural equation modeling with SmartPLS 3.3.3 was performed to estimate the model because one of this study's purposes is to predict the influence of five components of SCRES on SCPUD and the sample size is relatively small (113 cases). The normality assessment is through the statistics of skewness and kurtosis (Cohen *et al.*, 2003). The maximum absolute values of skewness (0.854) and kurtosis (1.386) of the dataset were much lower than the threshold values of skewness < 2 , kurtosis < 7 recommended by Dubey *et al.* (2018b).

Next, the adequacy of the measurement model was evaluated based on the criteria of reliability and validity. All constructs in this study have composite reliability values ranging from 0.899 to 0.967, which are above the threshold value of 0.7 (Hair *et al.*, 2017), indicating high internal consistency. Scale validation proceeds with the analyses of convergent and discriminant validities. The scale's convergent validity was verified using two criteria suggested by Fornell and Larcker (1981): all factor loadings should exceed 0.7 and average variance extracted (AVE) by each construct should exceed 0.5. As shown in Table 4, all factor loadings of construct items range from 0.821 to 0.963, and all average variance extracted (AVE) values range from 0.779 to 0.907; thereby, the convergent validity meets the criteria.

The discriminant validity of the constructs is assessed according to the criterion suggested by Fornell and Larcker (1981) that the square root of average variance extracted (AVE) for each construct should be greater than its correlations with all other constructs. Table 5 shows that this pattern is confirmed. Hence, discriminant validity meets the criterion.

5.2 Structural model

To examine the structural model, we analyze the standardized path coefficients to test the hypotheses.

All the path coefficients in the model are reported and interpreted. The results in Figure 2 indicate that SCC has significant and positive effects on SC visibility ($\beta = 0.723$; $p < 0.001$) and

Supply chain resilience and performance

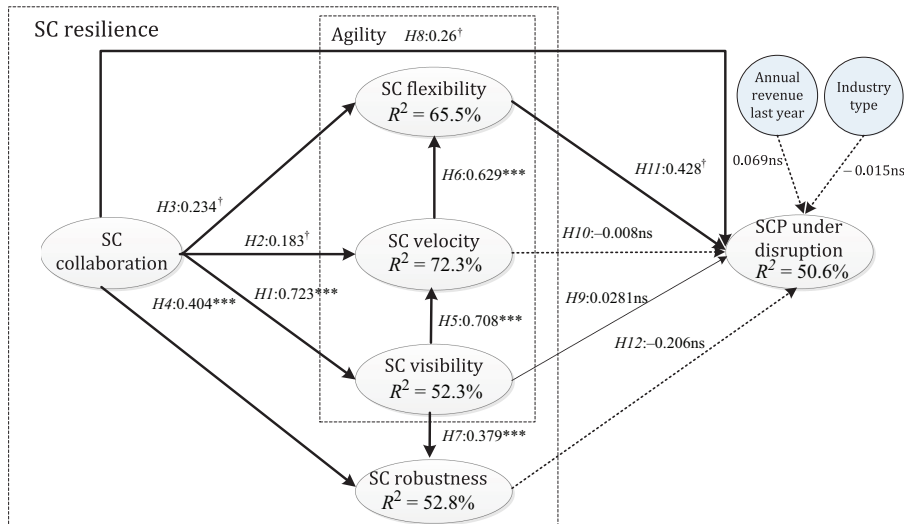
Construct	No. of items	Mean	Standard deviation	Item loadings	VIF	AVE	Composite reliability	Cronbach's alpha
SCF	3	4.944	1.673	0.873–0.924	2.191–3.010	0.812	0.928	0.884
SC visibility	3	4.773	1.403	0.854–0.951	1.972–6.102	0.837	0.939	0.901
SC velocity	3	4.938	1.241	0.821–0.935	1.747–3.698	0.797	0.922	0.872
SC robustness	2	5.292	1.201	0.880–0.927	1.686	0.817	0.899	0.779
SCC	3	4.926	1.313	0.859–0.919	1.855–2.938	0.779	0.913	0.859
SCPUD	3	4.401	1.455	0.934–0.963	3.749–6.780	0.907	0.967	0.949

Table 4. Measurement model

	SCF	SC visibility	SC velocity	SC robustness	SCC	SCPUD
SCF	<i>0.901</i>					
SC visibility	0.742	<i>0.915</i>				
SC velocity	0.792	0.841	<i>0.893</i>			
SC robustness	0.875	0.671	0.728	<i>0.904</i>		
SCC	0.671	0.723	0.695	0.678	<i>0.882</i>	
SCPUD	0.627	0.649	0.609	0.531	0.615	<i>0.953</i>

Note(s): Diagonal elements (in italics) are the square root values of the average variance extracted (AVE)

Table 5. Discriminant validity



Note(s): Bold line: Significant effect $p < 0.1$

Dotted line: Non-significant effect

$^\dagger p < 0.10$, $*p < 0.05$, $**p < 0.01$, $***p < 0.001$

Figure 2. The structural model with PLS results

SC robustness ($\beta = 0.404; p < 0.001$), supporting [H1](#) and [H4](#), respectively. Likewise, SC visibility has significant and positive effects on SC velocity ($\beta = 0.708; p < 0.001$) and SC robustness ($\beta = 0.379; p < 0.001$), supporting [H5](#) and [H7](#). Moreover, SC velocity has a significant and positive impact on SCF ($\beta = 0.629; p < 0.001$), supporting [H6](#). The relations between SCC and SC velocity ($\beta = 0.183; p < 0.1$) and between SCC and SCF ($\beta = 0.234; p < 0.1$) are also significant, supporting [H2](#) and [H3](#), respectively. The variances explained (R^2) are all acceptable at 52.3% (SC visibility), 52.8% (SC robustness), 65.5% (SCF) and 72.3% (SC velocity).

For the dependent variable of SCPUD, SCC ($\beta = 0.26; p < 0.1$) and SCF ($\beta = 0.428; p < 0.1$) both have significant and positive effects on it, supporting [H8](#) and [H11](#), respectively. The hypotheses of the negative relations between SC velocity with SCPUD ($\beta = -0.008; p > 0.1$) and between SC robustness with SCPUD ($\beta = -0.206; p > 0.1$), as well as that of the positive relation between SC visibility with SCPUD ($\beta = 0.281; p > 0.1$), are insignificant and [H9](#), [H10](#) and [H12](#), respectively, are not supported. It is worth noticing that the signs of the relations are consistent with the theoretical directions. All five SCRES components jointly explain 50.6% of the variance (R^2) of SCPUD. Finally, annual revenue last year ($\beta = 0.069; p > 0.1$) and industry type ($\beta = -0.015; p > 0.1$) have insignificant effects on SCPUD.

5.3 Mediating effects (indirect effects)

As shown in [Figure 2](#), three simple significant mediating effects exist in the research model. SC visibility partially mediates the relationships from SCC to SC velocity and SC robustness because that all direct effects among these three variables are significant at $p < 0.1$ level. Likewise, SC velocity partially mediates the relationships from SCC to SCF. Moreover, because the effects of SC visibility on SC velocity and SC velocity on SCF are both significant, the effect of SC visibility on SCF has to be examined. The analysis result shows that its effect is insignificant. Therefore, SC velocity has a full mediating relationship between SC visibility and SCF. [Table 6](#) identifies the significant mediating effects of these mediators: SC visibility and SC velocity. One specific indirect effect of exogenous construct on the endogenous construct via two serial mediators is identified. [Table 7](#) indicates that the specific indirect effect from exogenous constructs (i.e. SCC) to the endogenous construct (i.e. SCF) via two

Table 6.
Mediating effects with
a single mediator

Mediating variable (<i>M</i>)	Independent variable (<i>I</i>)	Dependent variable (<i>D</i>)	The direct effect of <i>I</i> on <i>M</i>	The direct effect of <i>M</i> on <i>D</i>	The direct effect of <i>I</i> on <i>D</i>	Indirect effect	Mediation
SC visibility	SCC	SC velocity	0.723***	0.708***	0.183 [†]	0.512***	Partial
	SCC	SC robustness	0.723***	0.379***	0.404***	0.274***	Partial
SC velocity	SCC	SCF	0.183 [†]	0.629***	0.234 [†]	0.115 [†]	Partial
	SC visibility	SCF	0.708***	0.516***	0.173	0.366**	Full

Note(s): *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, [†] $p < 0.10$

Table 7.
The indirect effects
with two serial
mediators

Path	Hypothesis	Indirect effect	The direct effect of <i>I</i> to <i>D</i>	Mediation
SCC→SC visibility→SC velocity→SCF	H1 → H5 → H6	$0.723 \times 0.708 \times 0.629 = 0.322***$	0.234 [†]	Partial

Note(s): *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, [†] $p < 0.10$

serial mediators (i.e. SC visibility and SC velocity) is significant. In addition to the direct and indirect effects, the total effect of each antecedent construct (independent variable) on the criterion construct (dependent variable) needs to be interpreted. The total effects of all antecedent constructs on the criterion constructs are exhibited in Table 8. As shown in Table 8, SCC's total effects on all the other constructs are highly significant at $p < 0.001$. Specifically, its total effect on SCPUD (0.605) is much higher than its direct effect (0.26) (see Figure 2).

5.4 Discussions

Firstly, the analyses support that SCC is a very important variable in SCRES; it directly and significantly influences other components of SCRES (i.e. visibility, velocity, flexibility and robustness). Therefore, SCC is the driver of SCRES, supporting H1, H2, H3 and H4. Brandon-Jones *et al.* (2014) confirm that information sharing, an SCC component, is the determinant of SC visibility. Scholten and Schilder (2015) also confirm that SCC increases SC visibility, SC velocity and SCF. When a disruptive event occurs, a firm can exert SCC partners' resources and exploit the collective intelligence among long-term collaborating partners to prevent or minimize the potential damage. SCC can share complete and useful information on inventories and sales among SC members to provide more accurate forecasting and faster response to customer demands.

Moreover, the empirical results support the impact of SCC on SCPUD, i.e. H8. SC partners with a collaborative relationship can increase SCPUD, because they understand and trust each other. TSMC and other Taiwan firms are among the world's most sophisticated chipmakers and produce a significant portion of the semi-conductors used in everything from vehicles to laptops (Oung, 2021c). Government officials and industry leaders in the USA and Taiwan pushed for closer cooperation on semi-conductor SCs between the two nations through a virtual meeting in February 2021 (Oung, 2021b).

Second, SCF is a very important component of SC agility. It connects SC visibility and SC velocity to form SC agility. SC visibility and velocity cannot directly influence SCPUD, only through SCF, which is the only component of SC agility that directly affects SCPUD, thus supporting H11. For example, from the beginning of 2021, the global economy is recovering from the COVID-19 pandemic. Domestic travels are increasingly popular, which prompts the demand for automobiles and related products. However, many major automakers in the USA, Japan and Germany lack materials such as automobile chips, causing production stoppages worldwide. Through official requests from the above foreign governments, Taiwan's leading chipmakers promised to squeeze out more chips for the global automobile industry with process flexibility to support the global automotive industry (Oung, 2021a). This strategic flexibility allows the firms to price up the rush orders of automobile chips, thus increasing SCPUD.

Independent Variable	Dependent Variable					
	SCF	SC visibility	SC velocity	SC robustness	SCC	SCPUD
SCF	–	–	–	–	–	0.428 [†]
SC visibility	0.445***	–	0.708***	0.379***	–	0.388*
SC velocity	0.629***	–	–	–	–	0.261
SC robustness	–	–	–	–	–	–0.206
SCC	0.671***	0.723***	0.695***	0.678***	–	0.605***

Note(s): – indicates not applicable, ⊙ indicates no indirect effect, and *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, [†] $p < 0.10$

Table 8.
The total effects of dependent variables

Third, this study identifies the fully-mediated relationships among the three components of agility: SC visibility, SC velocity and SCF. SC velocity fully mediates the relationship from SC visibility to SCF, namely, SC visibility directly and positively affects SC velocity and SC velocity significantly and positively affects SCF, supporting H5 and H6, respectively. Given that the extant studies (e.g. Fisher, 1997; Fisher *et al.*, 2000) only discuss the relationships among the three agility components without empirical evidence, this study fills this void; it sheds light on these relationships and provides insights into how the agility capability is formed. In the situation of disruption, SC agility is a critical capability to sustain the operation of SC.

For example, at the beginning of COVID-19, Taiwan's Government implemented a centralized policy about the supply of medical masks. The Government set up a national team to produce masks for its citizens; no other company could legally make and sell any mask. The Government imported mask-producing machines and assembled and distributed them to the members of the national team. It also provided the critical material of masks (i.e. melt-blown non-woven cloth) to these members and utilized drugstores and later expanded to convenient stores to channel the finished masks. Furthermore, the price and available amount of masks each citizen can buy every week are restricted to balance the supply and demand in the initial period of the pandemic. Every machine's capacity is fixed so that the demand for machines, materials and workforce can be estimated. Thus, this centralized manufacturing policy can increase the speed of production and control the amount of supply. Besides, citizens can search the available amount of masks at each store with a mask map system and buy masks at their convenient time to avoid lining up in advance. Thus, the centralized supply of masks accelerates the speed of producing masks. The visibility of the information on the *mask map system* makes the citizens convenient and easy to buy masks.

Fourth, SC visibility is the other focus of SCRES. This study empirically confirms that SC visibility has a significant and positive effect on SC robustness, supporting H7. This finding is consistent with that of Brandon-Jones *et al.* (2014). SC visibility enables SC members to identify vulnerabilities in the pipeline and know where the disruption could be before it occurs. This knowledge enables a firm to prepare for damage avoidance and recovery and achieves SC robustness.

In Taiwan's case, the Government recruited credible machinery manufacturers to assemble and customize the imported machines and distribute them to the national team to produce the needed masks. This way the government can avoid competition in the market and mitigate citizen's panic about masks. Moreover, this policy can coordinate the production amount and distribute the needed materials of masks to every team member, fostering SC robustness. Finally, SC robustness cannot influence SCPUD and other components of SCRES. Although SC robustness can be increased by both SCC and SC visibility, it is a consequence rather than an antecedent of SCRES. Because the pandemic occurs unexpectedly, firms have difficulties in preparing robustness in advance.

6. Conclusion

The empirical results show that every hypothesis in SCRES is significant; thus, this model is theoretically robust. Meanwhile, only the effects of both SCC and SCF on SCPUD are significant; hence, SCC and SCF are more important than the other components of SCRES.

6.1 Theoretical contributions

This study offers five theoretical contributions. First, it integrates five components (visibility, velocity, flexibility, robustness and collaboration) into a complete framework of SCRES for SC management based on the extant literature (Jüttner and Maklan, 2011; Wieland and

Wallenburg, 2013). It further defines SCRES as a dynamic capability consisting of proactive and reactive capabilities. This framework seems theoretically holistic and parsimonious. It is the first to operationalize SCPUD, which is different from SCP in the extant literature.

Second, there is a scarcity of studies exploring how the black box of SCRES functions. In this study, the relationships among the five components of SCRES and their influences on SCPUD are identified. Our analysis shows that two components of SCRES (SC velocity and SCC) converge on SCF and that SCF and SCC are the bridges between resilience and SCPUD. Third, this study reveals that SCC is the most crucial component of SCRES as it directly influences all other components of SCRES.

Fourth, the study confirms that SC visibility and SC velocity are the serial mediators between SCC and SCF. SC visibility is a mediator between SCC and SC velocity and between SCC and SC robustness. Likewise, SC velocity is a mediator between SCC and SCF and between SC visibility and SCF. Finally, SCC can affect SCPUD directly but SCPUD indirectly through three serial mediators (i.e. SC visibility, SC velocity and SCF).

6.2 Practical implications

This study sheds light on how to adapt SC to the situation of disruption. First, SC partners should establish SCC and SCF before they encounter disruptive events. Once these two capabilities are in place, they could sustain their performance when facing a disruptive event.

Second, SCF is a strategic advantage of a firm in the situation of disruption. As the useable resources are more limited under disruption, focal firms should exploit the extant resources and reduce unnecessary redundancies or slacks. SCF represents the ability to restructure existing capabilities and resources (Mackay *et al.*, 2020). For example, due to border closure and quarantine policy under the COVID-19 pandemic, many international passenger flights are grounded while the demand for cargo logistics increases drastically. Thus, many airlines converted passenger planes to transport light-weight packages, serving as a redundant resource for cargo carrying operators to mitigate the financial loss from the pandemic. Moreover, many countries' border closure results in the relocalization of strategic manufacturing operations adopted by multi-national enterprises or repositioning value chain activities to optimal locations overseas (Liu *et al.*, 2020). Moreover, when the losses caused by COVID-19 exceed the financial burden, industry corporations, including international airlines, are forced to lay off or give no-pay leaves to many redundant employees, keeping only the critical workforce to maintain the operations.

Third, SCC improves SCPUD. This study reveals that the close collaborative relationship among SC members is a mechanism for developing agility and robustness capabilities. This finding implies that SCC engenders high-level collaborative innovation and capabilities to enable joined problem-solving. Managers should pay more attention to SCC and adopt appropriate collaboration plans or strategies to act on the common goal and vision within SC members. Thus, they could cope with SC disruption, minimize cost, maximize revenue and sustain competitive advantages. Examples include contingency plan, supplier selection, SC design, relationship investment, vendor-managed inventory, collaborative planning, forecasting and replenishments (Rajesh, 2017). As no one in SCs can have sufficient information to identify and manage risks comprehensively, partners should expand their interests beyond their own companies and broaden their view of the whole SC (Zeng and Yen, 2017). Thus, building a collaborative culture in SCRES within SC partners is necessary.

Fourth, SCRES sustains SC. Resilience in SC levers losses from disruption back to a normal and acceptable situation. Business managers should deploy proactive strategies for long-term plans and reactive strategies for immediate actions during the recovery process. Only companies with mature SCRES capabilities can implement multiple risk management practices to address SC disruption (Rajesh, 2017). It is highly recommended that a firm should

monitor and improve as many SCRES components (capabilities) as possible to combat potential disruptive events in its SC operations.

Fifth, the appropriate investment in visibility is required for addressing or hedging the risk of disruption. The expense to facilitate SC partners' connectivity, such as investment in ICTs infrastructure, EDI and information systems interoperability, is essential for enabling SC visibility. Even decision support systems and automation with artificial intelligence and internet of things (IoT) (i.e. Industry 4.0) can be adopted. An establishment of Industry 4.0 systems could engender process flexibility, streamline optimization and information integration and improve production efficiency visibility, thus building an intelligent plant. Coupled with Industry 4.0, blockchain technology and cloud computing, a firm could achieve high SCRES by tracing the roots of disruptions, observing disruption propagation and responding with proper actions to stabilize SC operations.

6.3 Limitations and future research

There are some limitations to this study. First, the sample size of 113 in this study is relatively small. Further research may be conducted and collect more data from the same population. Second, this study analyzes cross-sectional data collected by a web questionnaire. As the association strength among variables in the research model might change over time, future research can conduct a longitudinal study with the data from the same informants to gain insight into what and how the associations of SCRES and SCPUD evolve.

Third, the negative impact of robustness on SCPUD being insignificant in this study might be due to the time-lag effect. Building SC robustness requires investment in additional resources and capacities in advance. The analysis result shows that SC robustness does not significantly decrease SCPUD in the short run. Future research can further examine the relationship between SC robustness and SCPUD with a longer observation period (Wieland and Wallenburg, 2012). Fourth, this study overlooks the logistic issue in the shortage of carriers caused by the pandemic. Future researchers could probe into optimizing transportation schedules to mitigate the shipment delay and increase SC logistics' resilience.

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