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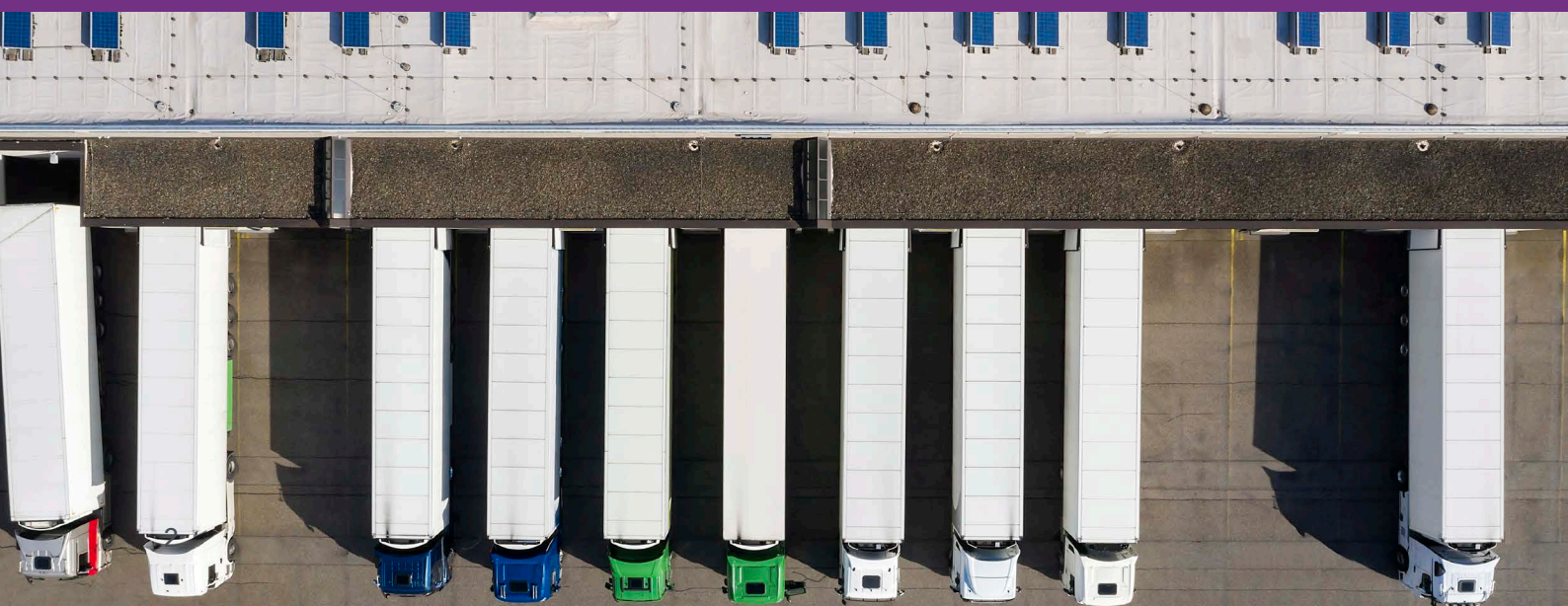
DIGITAL SUPPLY
CHAIN HUB

WMG
THE UNIVERSITY OF WARWICK

SUPPLY CHAIN RESILIENCE FRAMEWORK AND A METHODOLOGY FOR CREATING SUPPLY CHAIN RESILIENCE INDEX

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Executive summary

Project Title: Supply Chain Resilience for Manufacturing Supply Chains

Project timeline: Sep 2022 – Jan 2023

Summary: The Made Smarter innovation | Digital Supply Chain Hub programme, led by Digital Catapult commissioned this research to critically analyse the existing research and practices in supply chain resilience. This project has four key aims as follows: i) the development of a new definition of supply chain resilience in the new normal, ii) identification of practices and risk mitigation strategies to improve the end-to-end supply chain resilience in the manufacturing sector, iii) the development a practical supply chain resilience framework for evaluating and measuring supply chain resilience, and iv) developing the foundation and working method of a digital tool for the assessment of supply chain resilience within the manufacturing sector.

Research Design: The project explored existing research through a systematic literature review of the state-of-the-art research publication, industry practitioners' report and framework and tools developed by leading consulting firms. Two industry focused workshops were organised to engage UK's leading manufacturing companies and seek their input in developing strategies and frameworks. Furthermore, the developed framework was validated through feedback and validation sessions with senior supply chain executives from three manufacturing industry.

Stakeholder engagement: A series of activities were organised to engage with key stakeholders (fifty experts) and collect their feedback and data. The project outcome was disseminated at the Supply Chain in Practice (SCiP) events: the final Digital Supply Chain Hub event and Supply Chain Logistics Hub Industry event, in London. This project also created a community of practice with industry experts for the sustainability of the project.

Project Outcome: The outcome of the project is a comprehensive report detailing the following:

1. A systematic literature review report highlighting existing definitions of supply chain resilience, and the practices and strategies for managing resilience.
2. A list of existing frameworks and digital tools, methodologies for measuring supply chain resilience and discussing their limitations.
3. Provide a synthesised re-definition of supply chain resilience in the current normal.
4. A supply chain resilience framework that focuses on proactive and reactive approaches to managing and measuring supply chain resilience.
5. A methodology to build the foundation for supply chain resilience index and a digital supply chain resilience tool.
6. A visual demonstration of the supply chain resilience digital tool, its functioning and a visual roadmap for supply chain resilience measurement and improvement.
7. Engagement of fifty experts from across the UK's manufacturing sectors with a plan for the impact of research and ensuring the sustainability of the project.

Disclaimer: This report's findings are based on the authors' interpretation, and analysis of the evidence reviewed, including insights and data shared by the stakeholders who participated in the project workshops. Any mention of firm names or commercial products does not constitute an endorsement by the authors or their affiliated institutions. The copyright of all materials in this publication rests with the respective content authors and expert contributors. For further details, please contact: alok.choudhary@warwick.ac.uk.

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Industry engagement

The project activities involved 50 experts from 42 organisations, including 34 manufacturing/ services organisations and 8 Universities from across the UK. The organised activities include one online workshop, one face-to-face workshop, and three one-to-one feedback and validation sessions with relevant stakeholders from the industry. The following table lists the organisations which participated in the project activities.

Industry Participation			
RENISHAW plc	Jaguar Land Rover	Siemens plc	Ceva Logistics (Geffco)
William King Ltd	Resilinc	BAE Systems	QED Env Systems Ltd
Dnata	Goodfish group	Zoll Medical	Supply Vue
Authentise Ltd	Network Rail	DHL Parcel	KPMG
HVM Catapult	Estee Lauder	Linde BOC	Autentica Industrial Platforms Ltd
Prime Optimal Solutions	Kweevo	Epiphany Productions	Craft
Impression Technologies Ltd	Marchantcain	Tata Consumer Products	GTMA
Resgoring UK	Value Chain	HS2 Ltd	Hexagon consultants
Digital Supply Chain Hub	Syngenta		
Universities and Academic Institutions			
Cambridge University	Open University	Coventry University	University of Warwick
University of Leeds	University of Liverpool	EXCELIA GRIOP	Loughborough University

1. Context and Background Information

Over the past decade, global supply chains (SC) have been under severe stress. SCs have constantly struggled to cope with issues like trade wars, geo-political conflicts, crude oil prices, regulatory changes in maritime shipping, the downturn in the cargo shipping industry, amongst other issues. However, the advent of the Covid-19 pandemic followed by Ukraine-Russia crisis became a tipping point for the sector already facing headwinds and exposed the fragility and vulnerability of our global interconnected SCs. Faced with labour shortages, movement restrictions, and changing customer behaviours, many, if not all, SCs came to a complete standstill. The impacts were so far-reaching that even after three years of the initial Covid-19 impact, the aftereffects can still be seen across SC networks. Take, for instance, the considerable container backlog that plagued the US ports or the long lead times and delays that are still haunting the semiconductors, computer chips, and the automobile industry. During the pandemic it was interesting to observe that some SCs performed better under stress than the others, demonstrating their supply chain resilience. Additionally, consumer, shareholder and other stakeholders are increasingly concerned about sustainability-related practices, new forms of sustainability-related risk, including ESG risk, climate risk and modern slavery risks have emerged. Supply chain resilience (SCR) is about managing and adapting to the unknown across the whole spectrum of risk, from day-to-day operational risks to catastrophic supply chain disruption. Resilience necessitates both proactive and reactive approaches.

Traditional conceptualization of SCR focuses on the concept of flexibility, shock absorption capability, and adaptive capacity of SCs (Sheffi, 2005). It primarily refers to the degree of stress or abuse that a SC can sustain and the capability of a SC to recover or bounce back from a disruptive event (Christopher & Peck, 2004). Literature also acknowledges that system resilience can only be observed under perturbations, unfavorable events, signals, or inputs that may exceed or go beyond the normal design or operating conditions of the system (Punzo et al., 2020). However, none of the prominent and most cited research on SCR got to study resilience on the backdrop of a global catastrophe of the likes of the Covid-19 pandemic. Since the pandemic, our understanding of black swan events, such as low probability and extreme impact events, has evolved considerably. The availability of a considerable amount of data on the pandemic and the possibility to gather first-hand experience on the event provided an appropriate opportunity to evolve our understanding of SCR.

Deliverables

Drawn by the sudden explosion of research papers and contributions to the field of SCR research, it is relevant and timely to revisit our conceptualisation of SCR. With this report, we use post-pandemic research to evolve and update our understanding of SCR. The purpose of this report is to: i) understand the existing state-of-art literature on SCR and identify research gaps, ii) investigate and establish definitions of SCR, the quantification and measurement of resilience and identify methodological limitations, iii) identify relevant stakeholders from industry to gain insight on their view of SCR and existing methodologies used, iv) develop a SCR framework for the new normal with an aim to creating a SCR index tool, and v) propose a mechanism for developing a SCR index, a new metrics to measure SCR in the new normal.

In doing this, as shown in Figure 1, we aim to synthesize a complete and commonly accepted definition for SCR and develop evidence-based framework for assessing SCR and identify appropriate mitigation strategies to improve end-to-end SCR. This will be inclusive of clarification of key terminology, identification of key measurements, identification of key methodologies and frameworks, and examples of leading practice.

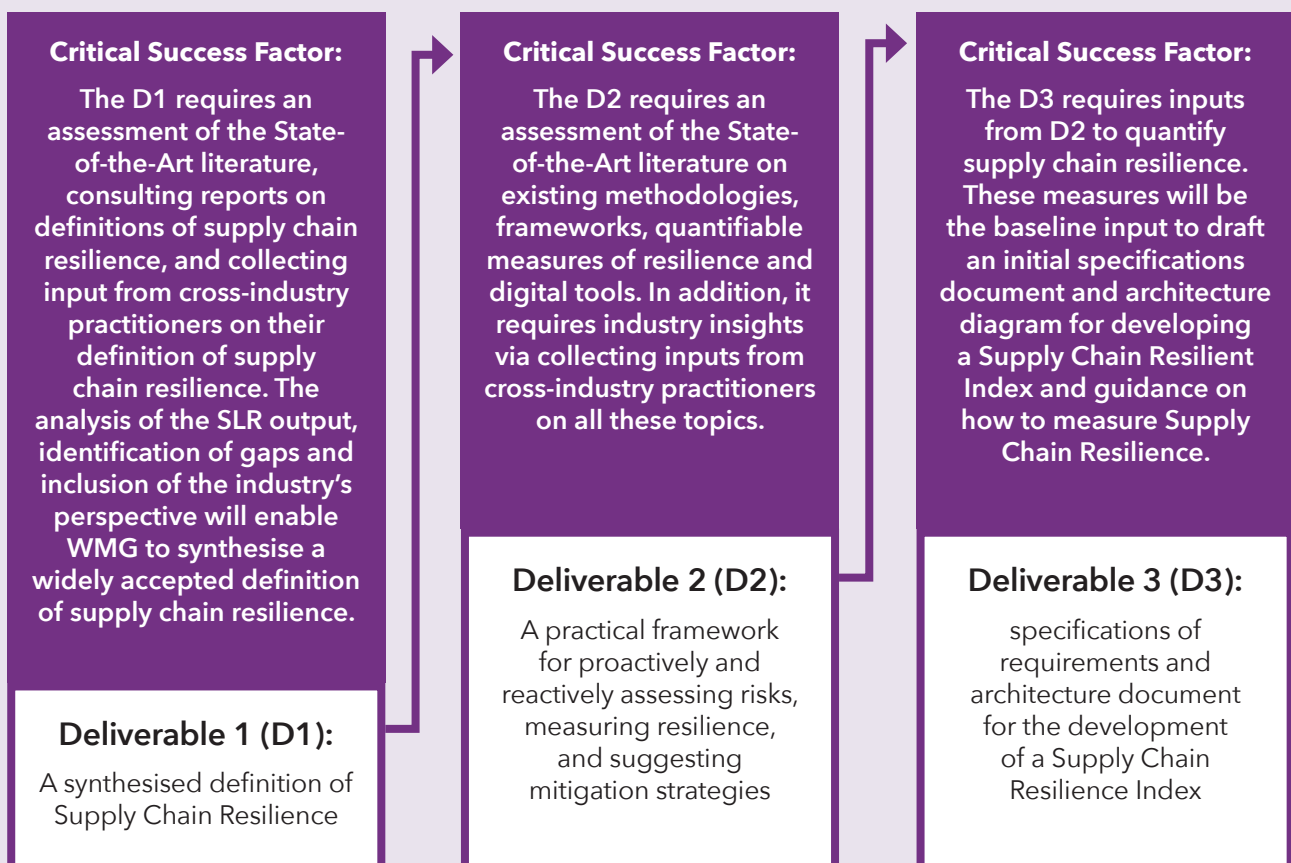


Figure 1. Deliverables of the first phase of the project.

Understanding the current knowledge on supply chain resilience

To provide a holistic overview of latest research on SCR, the WMG SC Research Group has conducted a systematic review of the available academic and industry literature, adopting the methodology as presented in Figure 2. Using this approach, we have developed understanding of the post-pandemic position on SCR in the literature, and sought to understand what the industry standard is, as published in the grey literature on SCR.

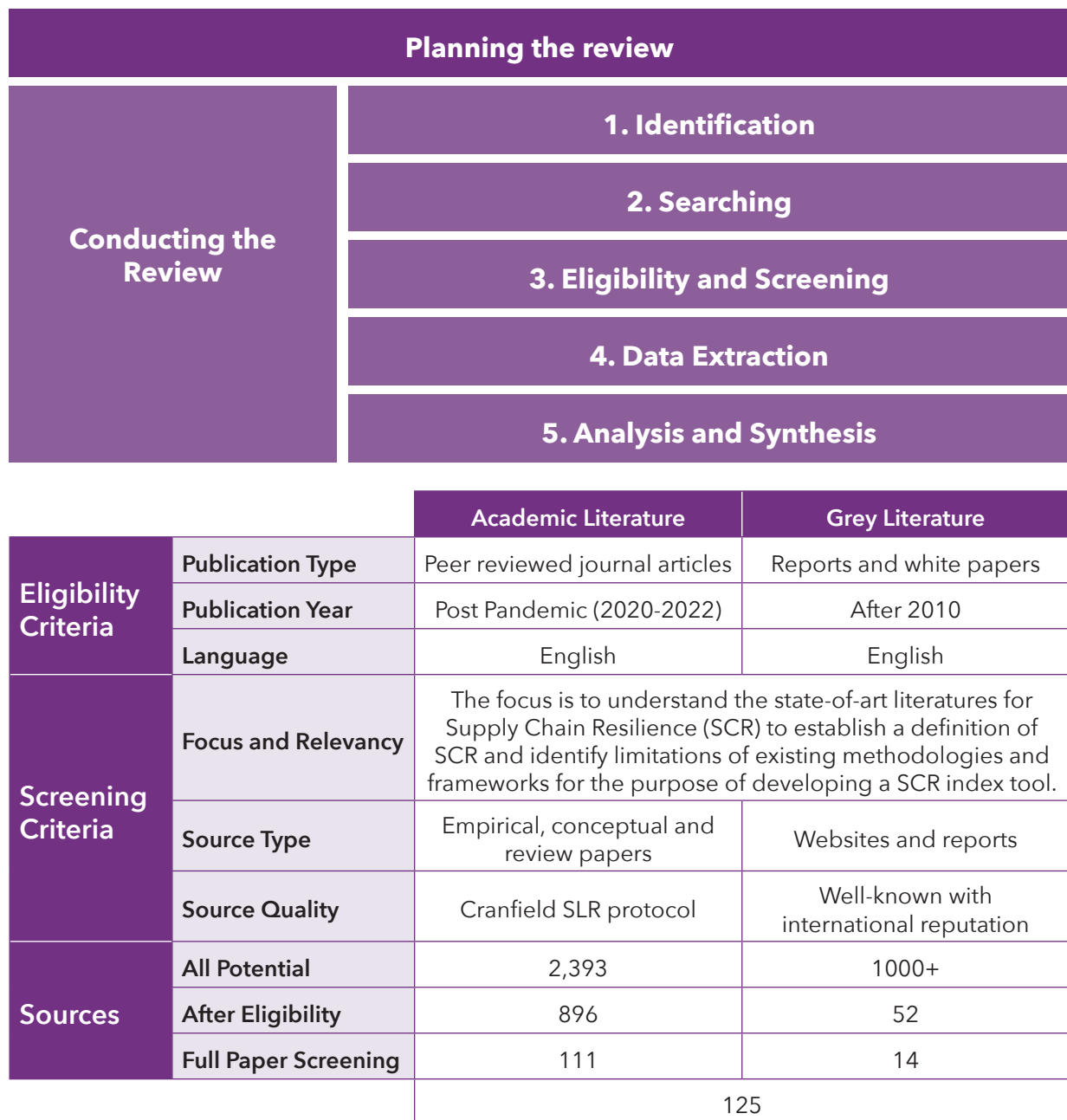


Figure 2. Systematic Literature Review Process.

From the systematic review adopted, the academic literature published fell into the categories as highlighted in Figure 3, which provides an overview including: the industrial sectors, methodologies, and country of origin for the academic literature investigated.

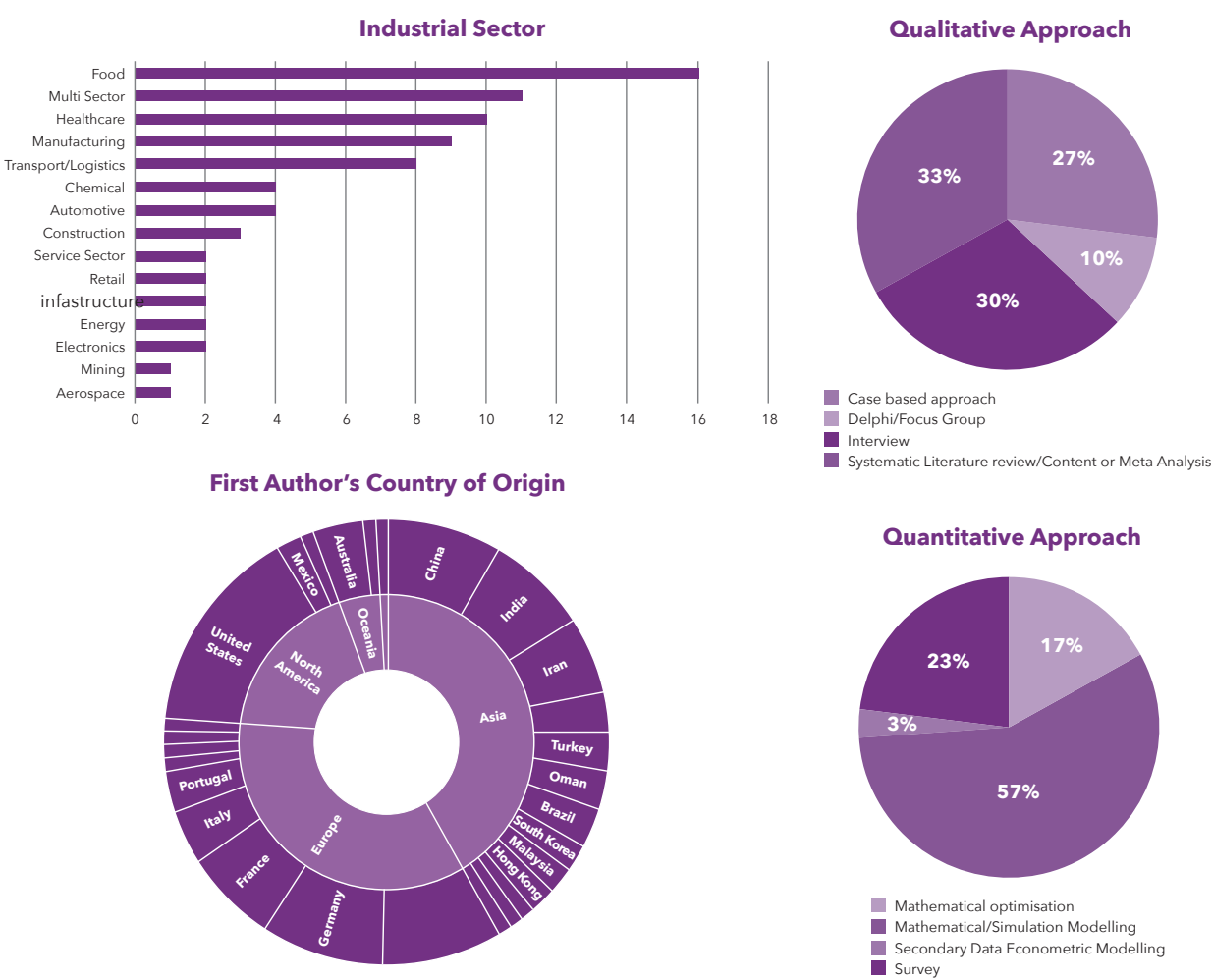


Figure 3. Descriptive Analysis of academic research since the pandemic.

Academic literature contributes to findings on two main basis points, those of academic resilience frameworks, and those of resilience strategies listed. Details of the frameworks and their contributing themes are presented alongside the presentation of the SCR framework, in the appendices. Appendix A provides details of industry framework and tools used for assessing supply chain resilience. Appendix B details frameworks and quantification tools derived from academic literature. Also, there is a direct comparison for both academic and industry frameworks, as presented in Table 10 and Table 11. On strategies, the frameworks had considerable overlap with the strategies listed, and so some repetition between frameworks and strategies is to be expected. Strategies were frequently mentioned in the literature outside the context of resilience frameworks, and these strategies are listed in Table 1. Only high-level strategies were retained, as an exhaustive list of strategies would not have been valuable for the purposes of developing the revised framework within this report, and the resilience measurement tool.

SC resilience strategies and practices	Authors
Information sharing (knowledge and risks)	Carvalho et al., 2022; Hohenstein et al., 2015; Jain et al., 2017; Scholten et al., 2014; Spieske et al., 2022; Vanany et al., 2021
Information management	Chowdhury & Quaddus, 2015; Scholten, Scott, & Fynes, 2014; Vanany, Ali, Tan, Kumar, & Siswanto, 2021
Risk sharing	Carvalho et al., 2022; Ekanayake, Shen, Kumaraswamy, Shen, & Kumaraswamy, 2021c; Jain, Shao, & Shin, 2017
Adapting production	Carvalho et al., 2022; Spieske, Gebhardt, & Kopyto, 2022
Resource relocation	Carvalho et al., 2022
Increasing visibility	Carvalho et al., 2022; Ekanayake, Shen, Kumaraswamy, Shen, & Kumaraswamy, 2021b; Jain, Kumar, Soni, & Chandra, 2017; T. Pettit, Fiksel, & Croxton, 2010; Raj, Anjan, Beatriz, Sousa, & Srivastava, 2022; Spieske et al., 2022; Tukamuhabwa, Stevenson, & Busby, 2017
Alternative supplier / strategic Sourcing	Carvalho et al., 2022; Chowdhury & Quaddus, 2015; Ekanayake et al., 2021c; Raj et al., 2022
Multi-sourcing	Chowdhury & Quaddus, 2015; Ekanayake et al., 2021c; Gebhardt, Spieske, Kopyto, & Birkel, 2022b; Hohenstein, Feisel, Hartmann, & Giunipero, 2015; Llaguno, Mula, & Campuzano-Bolarin, 2022; Namdar, Li, Sawhney, & Pradhan, 2018
Product substitution	Carvalho et al., 2022; Llaguno et al., 2022; Raj et al., 2022; Urciuoli, Mohanty, Hintsa, & Boekesteijn, 2014
Inventory managing	Carvalho et al., 2022; Costa et al., 2022; Gebhardt et al., 2022b; Hohenstein et al., 2015; Tukamuhabwa et al., 2017; Urciuoli et al., 2014
Backup transportation	Chowdhury & Quaddus, 2015; Gebhardt et al., 2022a
Standardisation	Gebhardt et al., 2022b; Moosavi & Hosseini, 2021; Spieske et al., 2022
Distribution network flexibility	Chowdhury & Quaddus, 2015; Ekanayake et al., 2021b; Gebhardt et al., 2022a; Hittle & Leonard, 2011; T. Pettit et al., 2010; Raj et al., 2022; Spieske et al., 2022; Tukamuhabwa et al., 2017; Urciuoli et al., 2014
SC partner collaboration	Chowdhury & Quaddus, 2015; Costa et al., 2022; Ekanayake et al., 2021c; Gebhardt et al., 2022a; Jain et al., 2017; Namdar et al., 2018; T. Pettit et al., 2010; Raj et al., 2022; Scholten et al., 2014; Spieske & Birkel, 2021; Spieske et al.,
SC partner development / Management	Costa et al., 2022; Gunasekaran, Subramanian, & Rahman, 2015; Spieske et al., 2022
Situating to market proximity	Gebhardt et al., 2022
Risk identification / monitoring	Ekanayake et al., 2021c; Moosavi & Hosseini, 2021; Raj et al., 2022; Spieske et al., 2022; Vanany et al., 2021
Outsourcing	Raj et al., 2022

Table 1. SC Resilience high level strategies and practices identified in the academic literature.

SC resilience strategies and practices	Authors
Redundancy (stock, products, facilities, supply network, etc.)	<i>Blackhurst, Dunn, & Craighead, 2011; Chowdhury & Quaddus, 2015; Ekanayake et al., 2021c; Hohenstein et al., 2015; Raj et al., 2022; Urciuoli et al., 2014</i>
Continuity / contingency planning	<i>Blackhurst et al., 2011; Raj et al., 2022; Spieske et al., 2022</i>
Digital technologies utilisation	<i>Blackhurst et al., 2011; Raj et al., 2022; Spieske & Birkel, 2021</i>
Postponement	<i>Llaguno et al., 2022; Moosavi & Hosseini, 2021</i>
Stakeholder management	<i>Chowdhury & Quaddus, 2015; Hohenstein et al., 2015</i>
Security system improvement	<i>Chowdhury & Quaddus, 2015; Tukamuhabwa et al., 2017</i>
Forecasting	<i>Chowdhury & Quaddus, 2015; Taghizadeh, Venkatachalam, & Chinnam, 2021; Tseng, Bui, Lim, Fujii, & Mishra, 2022</i>
Sustainability compliance	<i>Chowdhury & Quaddus, 2015; V. Jain et al., 2017; Tukamuhabwa et al., 2017</i>
Latest technology	<i>Chowdhury & Quaddus, 2015; Tukamuhabwa et al., 2017</i>
Learning	<i>Stone & Rahimifard, 2018</i>
Product modularity / interchangeability	<i>Costa et al., 2022; Spieske et al., 2022</i>
SC Revenue sharing	<i>Jain et al., 2017</i>

Table 1 (continued). SC Resilience high level strategies and practices identified in the academic literature

From the list of strategies identified and presented from the academic literature, several themes were identified. These themes comprise of: i) proactive and reactive time-based themes, ii) themes of dynamic capability, whereby the firms are able to respond through the adoption of SC practices, iii) themes of structural capability, whereby the SC network can reconfigure and adapt in response to changes in supply and demand, iv) strategies inclusive of SC planning, visibility, collaboration, buffer management, supply flexibility, and adaptability, v) pillars of SCR, whereby the foundation of the framework is based upon the qualities of: visibility, responsiveness and flexibility, integration and collaboration, and control, vi) firm orientation, as in firms consideration of, people, processes, technology, products and location, vii) the use of the framework as a measurement tool, ix) whether the framework considers sources of risk as part of the framework, x) the inclusion of digital technologies within the framework, xi) the consideration of sustainability as an element of resilience, and finally xii) the inclusion of financial resilience within the framework.

Gaps in research and practice

From exploration of both academic and grey literature, the following research gaps have been established:

- The existing academic research is fragmented, theoretical and lacks elements of practical relevance and applicability.
- Academic research tends to focus on a niche aspect of resilience, e.g., flexibility or agility and granularity of each practice, whereas grey literature focuses more on overarching components of SCR.
- Most of the research, including the one conducted by MIT and Cambridge (both discussed in appendix), focusses on measuring resilience in a reactive way, i.e., once a disruption has occurred. A proactive approach to assess and measure resilience is missing.
- The existing practical framework from industries and consulting firms are more tailored to their core competencies and service offering, limiting their coverage of SC practices and strategies.
- There is lack of research for post-pandemic SCR academic frameworks and therefore learning from post pandemic is missing in the existing frameworks.
- Frameworks presented across both industry and academia fail to incorporate a holistic approach, particularly in the context of SCR as an assessment tool.
- Whilst industry is concerned with strategies, this is rarely recognised in their frameworks, with broad concept themes applying.
- Despite the growing importance and relevance of sustainability and SC leadership in navigating the SC crisis, the existing frameworks have ignored the elements of sustainability, leadership, and resource efficiency.
- Academic frameworks are highly tailored for specific aspects of resilience following pandemic.

Later in this report, Table 10 and Table 11 present comparative findings of existing frameworks both from academia and industry, highlighting their limitations in comparison to the proposed framework.



2. Workshops and one-to-one sessions

Upon the development of a preliminary framework, we organised two workshops. The workshop was promoted through various university channels, social media including LinkedIn and to the companies partnering with WMG through its Supply Chain in Practice forum. An online workshop was organised first followed by a face-to-face workshop after a week. As shown in Figure 4, industry experts and practitioners were presented with the rationale and aims of the workshop. The research was explained, and breakout sessions were utilised to drive in discussion and receive feedback. To increase chances of getting valuable critical feedback from workshop participants, we took different approaches to the online based workshop, and the face-to-face workshop. In the online based workshop, all information around strategies and KPIs was provided, with participants invited to give comments. In the face-to-face workshop, information was selectively hidden to see where conversation from experts, and practitioners would focus, and to confirm if these aligned with our initial framework proposal.

Workshop Type	Online	Face-to-Face	Rationale/Aims/Outcomes
Number of participants	20	30	
Organisations represented	18	24	
Industry participants	12	22	
University experts	8	8	
Supply chain experience of participants	10-20 yrs	5-25 yrs	

- Evaluation of the results
- Co-creation for the definition of SCR and SCR framework
- Brainstorming proactive and reactive strategies
- Identification and capturing feedbacks for improvement

Figure 4. Workshop design and participant profile.

Re-defining supply chain resilience

Resilience has multidisciplinary and multidimensional elements, and with the concept crossing multiple fields, there are numerous definitions pertaining to SCR, highlighting the lack of consensus around the definition (e.g., Mensah & Merkuriev, 2014; Spiegler, Naim, & Wikner, 2012). This adds to the complexity of retaining a single concept of SCR for the purposes of this project. One of the most cited definitions in the literature defines SCR as the capability of SCs to prepare for unexpected events, respond to disruptions, and recover from them by maintaining continuity of operations at the desired level (Ponomarov & Holcomb, 2009). SCR is therefore seen as an approach to manage and improve SC performance when facing different types of disruptions (e.g., internal, external, and environmental) (Karl, Micheluzzi, Leite, & Pereira, 2018; Werner, 2020), and to develop reactive and proactive actions to effectively adapt operations to unexpected changes (Kamalahmadi & Mellat-Parast, 2016). Definitions have been offered up by both academic and industrial practitioners in the resources retrieved, Table 2 highlights the themes contained within each of the definitions provided.

Supply chain resilience definition themes	Authors
Recover from mishaps / disruption	Carvalho, Naghshineh, Govindan, & Cruz-machado, 2022; Datta et al., 2007; Gaonkar & Viswanadham, 2007; Gebhardt, Spieske, Kopyto, & Birkel, 2022a; Modgil, 2021; Ponomarov & Holcomb, 2009, APICS, 2016
Proactive, adaptive capability / establishing contingencies to cope with unforeseen events	Carvalho et al., 2022; Datta et al., 2007; Gaonkar & Viswanadham, 2007; Gebhardt et al., 2022a; Modgil, 2021; Ponomarov & Holcomb, 2009; McKinsey, 2021
Reduce probability of disruption	Cook, 2014
Reduce consequences of disruption	Cook, 2014; Xu, Zhang, Feng, & Yang, 2020
Reduce time to recovery following disruption	Adel, Vries, & Donk, 2022; Cook, 2014; Modgil, 2021; Spieske & Birkel, 2021; Interos, 2022
Continuity of operations, and connectivity and control of operations / maintain supply chain objectives / resist interruption	Costa et al., 2022; Manupati, Schoenherr, Ramkumar, Panigrahi, & Sharma, 2022; Modgil, 2021; Ponomarov & Holcomb, 2009; APICS, 2016; Crowe Horwath: Elks, 2020; Interos, 2022
Readiness (proactive pre-disruption), response, recovery (reactive post-disruption)	Ash, Diallo, Venkatadri, & Vanberkel, 2022; Costa et al., 2022; Gebhardt et al., 2022a; Crowe Horwath: Elks, 2020; Chatham House: Schneider-Petsinger, 2021; Interos, 2022
Recovering beyond prior level / better state of function (bounce back) following disruption	Spieske & Birkel, 2021; Xu et al., 2020
Redundancy, flexibility	Munir et al., 2022; McKinsey, 2021
Responsiveness, collaboration	Munir et al., 2022
Visible, agile	Munir et al., 2022; Chatham House: Schneider-Petsinger, 2021
Sustainable	Chatham House: Schneider-Petsinger, 2021
Adapting to new situations / opportunities	Ash et al., 2022; Fiksel, 2003, 2006; Iyengar, 2021; T. J. Pettit, Fiksel, & Croxton, 2010; Crowe Horwath: Elks, 2020; Interos, 2022

Table 2. SC resilience definition themes present in academic and industry literature. Authors highlighted in bold are industry sources, else sources are from academic literature.

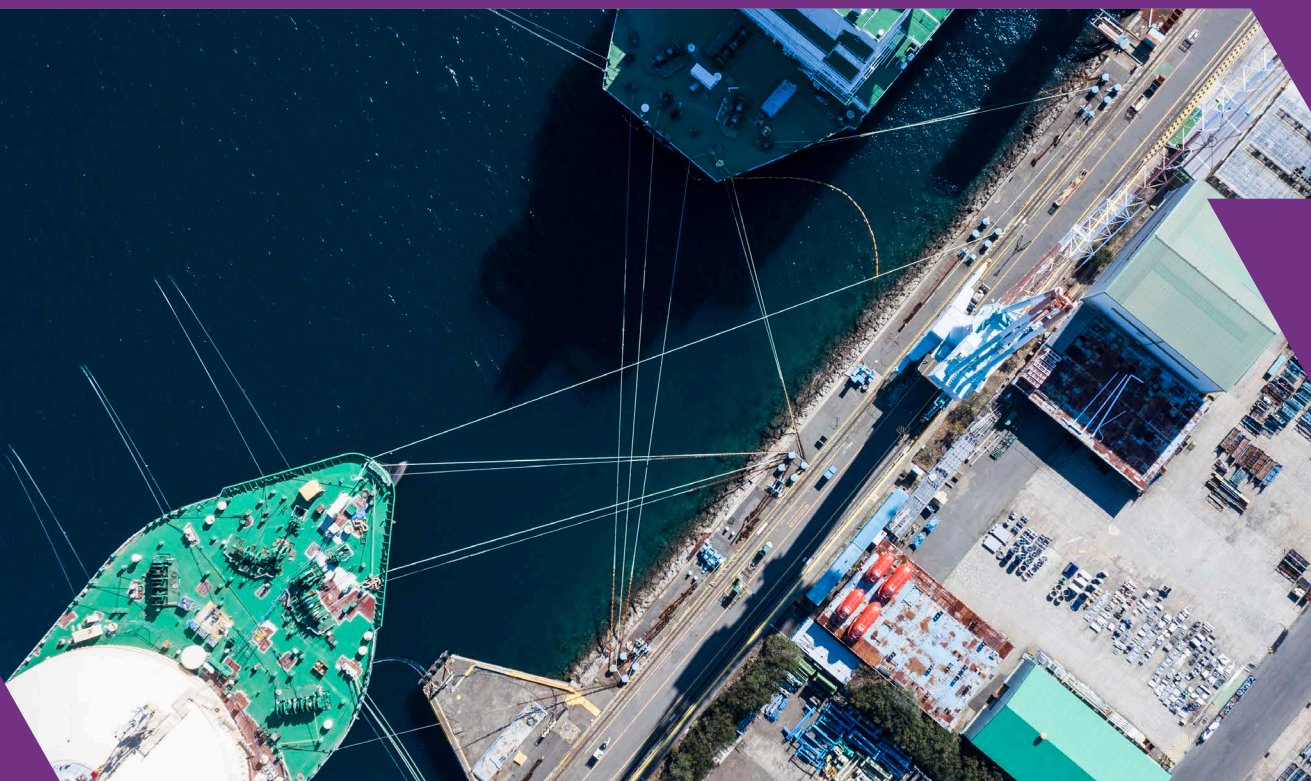
As seen from Table 2, whilst there are similarities among the existing definitions for SCR, there is still a broad range of interpretations of what constitutes SCR. The main themes which SCR fall under in accordance with the academic and grey literature are: i) continuity of operations and resisting disruptions, ii) being ready for, able to respond to, and being able to recover from a disruption, iii) establishing capabilities to handle unforeseen events, iv) the ability to recover from unforeseen events (with some authors noting that resilience requires returning to a better state than before or adapting to new situations), and v) reducing the time to recovery following a disruption. In amalgamation of these concepts, we have devised the following conception of resilience, and define it within the context of:

- Three phases - SCR covers the moments of pre-disruption, during-disruption, and post-disruption with a focus on readiness, responsiveness, and recovery/ growth, respectively.
- Two time-based strategies - Proactive and reactive strategies are adopted in the different phases to help organisations build up SCR.
- Three core considerations - Sustainability (ESG), Leadership, and Strategic Alignment are three core considerations, necessary to achieve SCR for the long term.
- Seven supporting SC capabilities - SC planning, visibility, collaboration, resource management, supply flexibility, learning, and adaptability are seven SC capabilities to support the SC resilience strategies (extended from (Zhang, Wu, Huang, & Zhang, 2021)).

We therefore define SCR as:

The ability of a supply chain to effectively prepare for, respond to, responsibly recover, bounce forward from an unexpected disruption, grow sustainably by utilising natural and social resources responsibly, and learn to adapt to future disruptions.

SCR is achieved through the deployment of pre-disruption capabilities of supply chain planning and visibility, during-disruption capabilities of collaboration, resource management, and supply flexibility, and post-disruption capabilities of learning and adaptation. These capabilities require three core considerations including ESG sustainability, leadership, and strategic alignment.



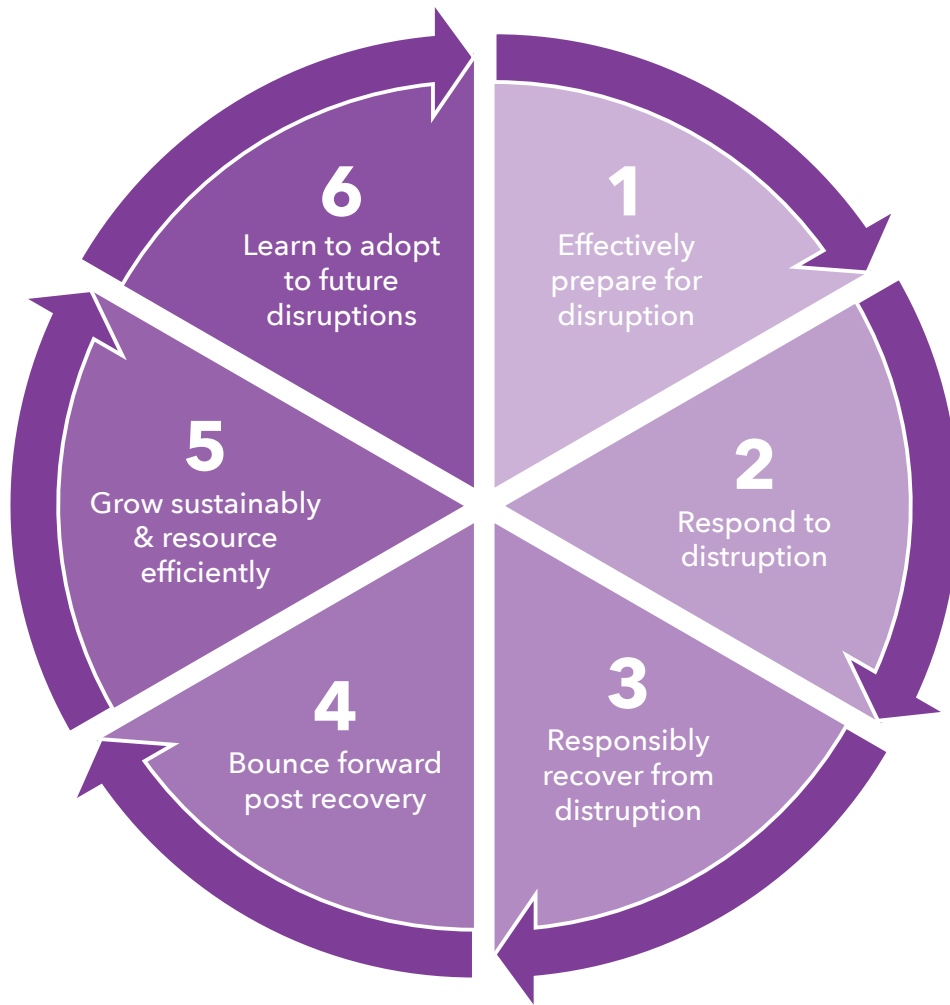


Figure 5. Six steps of supply chain resilience.

Figure 5 demonstrates the six steps to supply chain resilience. Historically, resilience was associated with the first three steps: 1) Effectively preparing for a disruption, 2) responding to a disruption, and 3) responsibly recovery from a disruption.

Following the pandemic, and the resulting greater global attention and direction towards sustainability in parallel with resilience, the new normal dictates that three further steps must be utilised to achieve supply chain resilience. These are: 4) Bouncing forward post recovery, 5) growing sustainably and resource efficiently, and 6) learning to adapt to future disruptions.

3. Development of a supply chain resilience framework

Approach

Using the online web-based package 'Mural', several academic experts brought in key learning points from both grey and academic literature to construct a new framework, incorporating the missing elements observed from prior frameworks. The framework was designed with the capability of being used as a resilience assessment tool. We collaborated through connecting ideas on a digital whiteboard, opting to enhance the prior WMG framework which incorporated many of the elements needed to construct this resilience framework, and to overcome the pre-existing limitations. The approach taken during the meeting was open-ended and collaborative, systematically going through each idea, such as strategies and arrangements, and discussing the merits and drawbacks, regularly consulting back to academic and grey literature sources in the context of the purpose of this framework. The initial framework was extensively discussed with the industry experts through the workshop sessions for further development, refinement, and addition of missing elements.

Supply chain resilience framework

As part of an ongoing iterative process, we developed a conceptual framework to complement the development of the SCR index. Figure 6 presents the recommended conceptual framework, finalised following incorporation of themes from industry, academia, and the workshops. This framework updates and builds on the original WMG framework, now expanded and incorporating specific strategies under each component. The final framework was validated with three industry experts through one-to-one validation and consultation sessions.

SC disruption resilience generally occurs within three separate phases, captured by this framework, and as represented extensively in academic and industry frameworks. The stage prior to the disruption, the readiness phase, is where proactive strategies designed to effectively prepare for an unexpected disruption, are implemented. Next, the responsiveness phase, where the SC manages the disruption in real time but may utilise these prepared strategies both in preparation and in response to the disruption. Finally, the recovery and growth phase, whereby reactive strategies are deployed, incorporate learnt experiences, and adapting the SC for future disruptions. It is vital to ensure that supply chains do not compromise their sustainability practices and that they responsibly use its natural and social resources to avoid any ESG risk. Due to the requirement for SCR to incorporate learning from past disruption and to realise these learning opportunities through adaptation for future disruptions, these stages are arranged circularly.

As the response to the disruption progresses through the three stages, actions are taken clockwise. There is no specific order to the readiness phase strategies, or the responsiveness stage strategies, as these strategies can be taken in any order, or simultaneously. However, during the growth and recovery phase, SCs must first learn from the experiences they have had, prior to deploying their adaptability strategies (which comprise of strategies situated within the prior five readiness and response categories). Once the adaptability stage has been actioned and the resilience of the SC has been improved, the cycle repeats. The focus is now on the readiness stage, incorporating the lessons learnt and adaptations from the previous disruption, and preparing for the next disruption.

At the centre of the framework are the core considerations which must be taken and incorporated throughout the stages. There are three elements here:

- Firstly, an overarching theme is whether the firm, through managing their SC disruption resilience, is incorporating sustainability (ESG) within their decision-making processes. Thereby reducing the likelihood of future legal, operational, or strategic challenges which may be present from a lack of consideration of sustainability within the core operating model of how the SC functions. ESG must be included at every step, particularly in the recovery and growth stages, to ensure that any specific recovery does not undermine natural or social resources. Exclusion would undermine the firm's resilience as this would increase the likelihood of unexpected announcements, through eroding the firm's reputation, and by diminishing the SCs limited social and natural capital.
- Secondly, is 'Leadership', whereby leadership must be utilised at every stage of the management of a resilient SC. Leadership is necessary for the: i) effective implementation of proactive and reactive strategies, ii) allocation of necessary resources to support supply chain resilience initiatives, iii) promoting of communication and collaboration amongst stakeholders, iv) managing of events when something goes wrong, v) fostering of the correct culture within the team, and vi) ultimately ensuring that the overall resilience strategy is cohesive and robust. This reduces the likelihood of unexpected events disrupting the firm any more than is minimally necessary and enables rapid recovery and future growth.
- Thirdly, is strategic alignment. The concept of strategic alignment in the development of a congruent business strategy is fundamental to profitable growth. Market opportunities are identified by understanding the competitive environment and translating this into a customer value proposition through the product and marketing strategy. Competitive advantage is then achieved if the SC can develop a strategy to deliver the value proposition at the lowest possible cost. SC alignment is achieved when there is congruence between the SC strategy, the infrastructure (the physical SC and its assets) and the operating model (the way the physical SC will be managed).

To present the following framework, the following over-arching themes corresponding to readiness (SC planning and visibility), responsiveness (collaboration, resource management, supply flexibility), and recovery/growth (learning and adaptability) whereby strategies are situated is described.

SC Planning concerns the ability of firms to coordinate business activities based on present and historical data, comprising of the capability to identify, sense, prepare and design the SC network. Visibility allows SC entities to securely connect and identify any significant issues in the end-to-end SC and make predictions and therefore decisions based on real time transparent data. Collaboration, another term for integration, concerns considerate management, cooperation, and consideration of stakeholder interests with decision making and information sharing within and across SC entities. Resource Management enables firms to efficiently optimise and organise their materials, information, time, finances, and other assets to respond to disruption. Supply Flexibility can be achieved through establishing multiple sourcing options in the SC network, retain a balance between sourcing efficiency and redundancy, and ensure that systems are easily replicable, scalable, and flexible. Learning from the disruption requires capability to collect, retain and disseminate knowledge about the disruption event and introduce new ideas for methods and approaches to handling future disruption. This is where finally, adaptability follows on. Adaptability is all about utilising the experience and learning from disruption to transform the SC to meet new dynamic demands.



1. SC Planning

1. Risk Identification
2. Sensing/trend monitoring
3. Supply & demand planning & forecasting
4. Production planning
5. SC network design

2. Visibility

1. End-to-end SC mapping
2. Prediction - exploding data to improve forecast and segmentation
3. Connectivity - collecting real-time data throughout the E2E SC
4. Transparency: tracking and traceability

3. Collaboration

1. Stakeholder management
2. Contract management
3. Information sharing
4. Partnerships
5. Aligning risk appetite between suppliers-focal firm

4. Resource Management

1. Cash management finance management
2. Product management
3. Information & technology management
4. Material management
5. Asset maintenance

5. Supply Flexibility

1. Single vs. Multi-sourcing
2. Diversified sourcing
3. Process standardisation
4. Contingency transport and capacity management
5. Global, regional and local sourcing

6. Learning

1. Capturing lessons learnt internally and introducing new KPIs
2. Managing knowledge mobility internally and externally
3. Training and education package
4. Ownership of risks and control KPIs
5. Transilience = the ability to simultaneously restore process and change - often radically

7. Adaptability

As a result of a disruption, learning from this disruption must revise all steps below:

1. SC Planning
2. Visibility
3. Collaboration
4. Resource Management
5. Supply Flexibility

Figure 6. Supply Chain Resilience Conceptual Framework.

Framework strategies

The following tables provide the definitions and indicative KPIs of each strategy relevant to the framework presented. Each table of strategy descriptions and indicative KPIs corresponds to the title of each meta-strategy box in the framework of SC Planning (Table 3), Visibility (Table 4), Collaboration (Table 5), Resource Management (Table 6), Supply Flexibility (Table 7), Learning (Table 8), and Adaptability (Table 9).

Readiness: Proactive

SC Planning		
Strategy	Description	Indicative KPIs
Risk identification	Process of locating and evaluating current potential risks to the SC and firms' operations and keeping track of how those risks may change in location, intensity, and nature and updated based on changing factors such as stakeholder relationships, operating environment, and policy.	<i>Number of risks identified over time, frequency of risk assessment, cost of risk assessment, percentage of process areas involved in risk assessments, supplier risk evaluation.</i>
Sensing / trend monitoring	Actively keeping up to date with short- and long-term industry, environmental, and consumer trends to scope where future potential risk may occur, with the intension of identifying new risks.	<i>Industry 4.0 reediness assessment, digitisation readiness assessment, scoping out future trends and technologies, technology benchmarking, dedicated R&D team and budget, Hackathon events</i>
Supply & demand planning & forecasting	Keeping track of consumer demand, raw resource and parts availability and factors influencing these, as well as projecting what future demand may look like, and planning for alternatives should supply or demand fail.	<i>Forecasted vs. actual sales (forecast error), adherence to Sales and Operation Planning (S&OP) processes inventory turnover, order fill rate, perfect order rate, reasons for return</i>
Production planning (Factory Planning & Scheduling (FP&S), Inventory Planning and Optimisation (IP&O), Master Planning (MP))	Planning facilities, materials, and human resources to be optimised and scheduled, balancing between optimal efficiency and redundancy.	<i>On-time delivery, total cycle time, capacity use, changeover time, planned maintenance percentage</i>
SC network design (facilities location, centralisation)	Identifying best location for facilities including suppliers, manufacturing warehouses, distribution centres and logistics networks based on supply and demand availability and distance to locate centre of operations, with alternative logistics routes available.	<i>Number of nodes in SC, centre of gravity, Ease of doing business index, Proximity to suppliers and customers, SCOPE 3 emission monitoring (e.g., carbon accounting)</i>

Table 3. SC Planning category strategies, strategy description, and respective indicative KPIs.

Visibility		
Strategy	Description	Indicative KPIs
End-to-end SC mapping	Identifying all critical suppliers and customers within all tiers, along with their location and function within the SC.	<i>Number of tiers identified, percentages of BOM match with suppliers, frequency of mapping process, value stream mapping</i>
Prediction - exploiting data to improve forecast and segmentation (e.g., Machine learning, Digital twin).	Using and exploiting data, machine learning, digital SC twin, and other tools to improve forecast of SC operations, effects of disruptions, and potential recovery strategy.	<i>Data quality/accuracy, investment in new technologies</i>
Connectivity - collecting real-time data throughout the E2E SC (e.g., IoT, Platforms, Virtual reality).	Connecting with systems to obtain real-time data so that it is possible to track materials, parts, and products through the SC using sensors, so that real time stock levels and locations can be determined.	<i>Cross-organisation system integration, automatic data collection, inter-organisation communication and interoperability, percentage of real-time data, connectivity assessment</i>
Security - securing data and flows (e.g., Block chain and Cybersecurity)	The encryption of all data pertaining to operations of focal firm and all critical SC partners, with security of materials, parts, and products secured.	<i>Cross-organisation system integration, automatic data collection, inter-organisation communication and interoperability, percentage of real-time data, connectivity assessment</i>
Transparency: tracking and traceability (e.g., Identifying resource flow)	Capability to identify where products have been after point of sale, as well as identify where materials, parts and products are within the SC.	<i>Data visibility and information availability, time to access right information</i>

Table 4. Visibility category strategies, strategy description, and respective indicative KPIs.

Responsiveness: Proactive and Reactive

Collaboration		
Strategy	Description	Indicative KPIs
Stakeholder management (e.g., suppliers, employees, customers management)	Engaging with stakeholders, providing training and development, outreach, communicating relevant aspects of business, operations, and decisions. Keeping stakeholders informed and being transparent.	<i>Stakeholder identification/ mapping/clustering, stakeholder empowerment, stakeholder engagement, co-development of products/services, (e.g., Retention rate, Lifetime value, Turnover rate, Edelman Relationship Index (trust, mutuality of control, commitment, satisfaction), external relations, community impact)</i>

Contract management (IP, data Ownership)	Ensuring contracts are fair, and in the interest of all parties whilst retaining relevant rights over data and intellectual property.	<i>Smart contract, compliance rate, and risk and reward sharing</i>
Information sharing	Sharing relevant and critical information with stakeholders at the right time and right format.	<i>NDA's, IP, data governance</i>
Partnerships (Long/ short term/ strategic suppliers)	Ensuring to engage in a right partnership with appropriate length is critical to corporate aims, strategic, and in the best interests of stakeholders, including suppliers.	<i>Number of projects in place for supplier/business development, number of strategic partnerships</i>
Aligning risk appetite between suppliers and focal firm	Ensuring any risk undertaken which impacts suppliers, or that risks undertaken by suppliers matches the capability and willingness of the other party to manage the consequences of this risk.	<i>Risk appetite assessment survey</i>

Table 5. Collaboration category strategies, strategy description, and respective indicative KPIs.

Resource Management		
Strategy	Description	Indicative KPIs
Cash Management Finance management (Vulnerability, SC financing)	Ensuring efficiency and redundancy in cash management, minimising financial vulnerability, and optimising financing for focal firm and SC partners. Not dismissing supplier based on poor performance now if they are critical and have future potential. Explore various SC financing e.g., reverse factoring	<i>Leverage ratio, Liquidity ratio, Cash to Cash Cycle Time, Backlog costs, Gross Margin Return on Investment</i>
Product Management (Buffer management, inventory spare capacity, time)	Exploring three potential mechanism, inventory spare capacity, time, to build buffer against any disruptions. Balancing stock redundancy and efficiency for aims of SC and current operating environment (i.e., geopolitics).	<i>Inventory Velocity, Stock level, Lead time; Order cycle time rate; Time to recovery</i>
Information & Technology Management	Ensuring that all information and technology is up to date, in a right format, best available and appropriately tailored to needs of SC.	<i>Data visibility and information availability, time to access right information</i>

Material Management (e.g., supply dependencies)	Based on the SC mapping, ensuring any criticalities in raw materials or parts dependencies are minimised and alternatives sources on supply are sought.	<i>Supply dependency analysis for critical component</i>
Asset maintenance (e.g., using technology for predictive maintenance)	Running scheduled downtime to minimise overall downtime so that necessary repairs, upkeep, and maintenance can be conducted for logistics and manufacturing networks, IT, buildings, and other critical infrastructure.	<i>Current cost of maintenance, investment in technologies for maintenance</i>

Table 6. Resource Management category strategies, strategy description, and respective indicative KPIs.

Supply Flexibility		
Strategy	Description	Indicative KPIs
Single vs. Multi-sourcing	Balancing benefits of single sourced, highly developed relationships with multi-sourced, redundant, and agile relationships.	<i>Number of suppliers, compliance rate, supplier availability, vendor rejection rate and cost, supplier defect rate, rate of emergency purchases, supplier lead time</i>
Diversified sourcing	Sourcing resources, parts, components, and products from a variety of different sources to ensure that there is limited vulnerability. Diversified product offering for business continuity planning.	<i>Number of suppliers in the network, geographic disparity of supplier, Number of nodes in SC, centre of gravity</i>
Process standardization	Simplified production and manufacturing with modular and easily repeatable SC design, simplifying complexity. Applies to machinery, personnel training, policy, human resources.	<i>homogeneity of internal SC processes, integration with other SC actors, integrated logistics systems</i>
Contingency transport and capacity management	Ensuring alternative availability in transportation options as well as maintaining capacity for peak demand in warehouses and logistics networks.	<i>Number of logistics partners</i>
Global, regional, and local sourcing	Balancing risks of globalised, regionalised, and localised sourcing so that the risks from all three are minimised.	<i>Number of regional/local/global suppliers in the network</i>

Table 7. Supply Flexibility category strategies, strategy description, and respective indicative KPIs.

Response / Growth: Reactive

Learning (Based on disruption experience)		
Strategy	Description	Indicative KPIs
Capturing lessons learnt internally and introducing new KPIs	Capability to record mistakes and convert them into opportunities for learning, and new targets to avoid prior issues reoccurring in the future.	<i>Mechanism to systematically capture lessons learnt</i>
Managing knowledge mobility internally and externally	Capability to readily share and provide knowledge to relevant internal and external stakeholders on the experience of the disruption.	<i>Mechanism to ensure accessibility and sharing lesson learnt</i>
Training and educational package	Capability to deliver learning points into training packages for key relevant stakeholders.	<i>Number of training and educational programs for risk management</i>
Ownership of risks and control KPIs	Capability to onboard experience of disruption and develop new KPIs to mitigate impacts for future disruption.	<i>Number of new KPIs introduced in response to disruption</i>
transilience = the ability to simultaneously restore some processes and change—often radically— others	Capability to restore prior functioning and adapt to new situations simultaneously by having regular touch points across various functions. This will ensure strategic alignment between the three core business strategies: Marketing/ commercial strategy, new product development strategy and SC strategy.	<i>Number of cross-functional meeting to ensure strategic alignment, and number and regularity of S&OP meetings.</i>

Table 8. Learning category strategies, strategy description, and respective indicative KPIs.

Adaptability		
Strategy	Description	Indicative KPIs
SC Planning	As a result of a disruption learning, all strategy steps must be revised.	<i>See Table 2</i>
Visibility		<i>See Table 3</i>
Collaboration		<i>See Table 4</i>
Resource Management		<i>See Table 5</i>
Supply flexibility		<i>See Table 6</i>

Table 9. Adaptability category strategies, strategy description, and respective indicative KPIs.

Framework comparison in context of existing frameworks

Frameworks from both industry and academia were explored and used to ascertain the most recent and best available practice for SCR. Our investigation found that academic frameworks, were less broad in conceptual development than the industry frameworks, the reasoning for this, is that the academic frameworks had a particular perspective or use case in mind in the development of these frameworks. In synthesising the grey literature frameworks selected for their contribution to this synthesis and development of SCR, Table 10 has been produced to demonstrate the presence of associated SCR frameworks inclusion components and their use in other frameworks. These components are either directly included, or otherwise implied in the wording, characterisation or intend in the application of the framework by the owning organisation. This table compares existing frameworks with the new proposed WMG framework, whereby most of the factors considered in this table are covered by this approach.

When comparing our proposed framework with the existing academic frameworks, it was noticed that the academic works tend to focus on nuanced aspects of resilience, such as flexibility or agility. Therefore, making it difficult to compare the grey and academic frameworks collectively. Academic literature focuses on granularity of each practice, whereas grey literature focuses more on overarching components of SCR.

Table 11 provides a cross-comparison between the proposed framework and several h frameworks in the academic literature. The WMG (new) framework provides a series of disadvantage over the other frameworks in literature.

Grey Literature Framework themes		Archilles	BCG	Crowe	Deloitte	Accenture	ASCM	WEF	IfM	McKinsey	WMG
Proactive / reactive time-based responses											
Dynamic capability of firms to respond through adoption of SC practices											
Structural capability of SC network reconfiguration to adapt in response to supply and demand changes											
Strategies	SC planning										
	Visibility										
	Collaboration										
	Buffer mgmt.										
	Supply flex.										
	Adaptability										
Pillars of Res SC	Visibility										
	Responsiveness / flexibility										
	Integration / collaboration										
	Control										
Orientation	People										
	Process										
	Technology										
	Product										
	Location										
Used as measurement tool											
Considers risk sources											
Inclusion of digital technologies											
ESG / Sustainability											
Financial resilience											

Included
 Implied

Table 10. Summary of themes of resilience included in resilience frameworks published in grey literature.

Academic Literature Framework themes		Costa et al., 2022	Moosavi & Hosseini, 2021	Spieske & Birkel, 2021	León-Mateos, Sartal, López-Manuel, & Quintás, 2021	Vanany et al., 2021	Ekanayake, Shen, Kumaraswamy, Shen, & Kumaraswamy, 2021a	Llaguno et al., 2022	Razak, Hendry, Stevenson, Hendry, & Stevenson, 2021	WMG
Resilience phases	Readiness									
	Response									
	Recovery/ Growth									
Redundancy										
Flexibility										
Visibility										
SC reengineering										
Adaptability										
Agility / responsiveness										
Integration / Collaboration										
Communication										
Knowledge management										
Information sharing										
Leadership										
Security										
SCRM / SCRM culture										
Financial health										
Considers risk sources										

■ Included ■ Implied

Table 11. Summary of themes of resilience included in resilience frameworks published in academic literature.

4. Development of a supply chain resilience Index & Assessment Tool

The strategies and KPIs associated with the SCR Framework form the basis for developing the SCR assessment tool. The aim of the assessment tool is to provide a supply chain resiliency index score. The score is calculated based on data provided in the responses of the questionnaire, as presented in Appendix C. A multi-criteria decision making TOPSIS model presented in appendix D is used to calculate the score.

Significance of SC Resiliency Index: The SCR index has the following significance:

- SCR assessment tool and index could be pro-actively used by SC managers to stress test their supply chain.
- It will assess the supply chain practices to identifying areas of vulnerability and enable the company to improve the resiliency of their supply chain by practices.
- It can enable a company to enhance its sourcing process (by having greater understanding of a potential suppliers' resiliency).
- It can be used as a communication tool to provide a capability to communicate internally to leadership regarding the status of their overall program and areas for further improvement, which are top of mind questions for BOD, CEO/CFO, Underwriters, etc.
- The SCR Index Offers a benchmarking tool which could be used to compare the performance against industry average, competitors, industry peers and best in class companies and over time, show progress on continuous improvement.

Questionnaire development: The SCR framework, associated strategies and KPIs were used as the basis point for the development of the questionnaire as the foundation of the assessment tool. Within the framework, there are seven practices making up the sections of the SCR index questionnaire, and within each of these are five guiding practices which questions were framed around. In addition to "not applicable" options, there are up to five response levels representing no capabilities (score of 1) and maximum capabilities (score of 5). The development of questionnaire has gone through several iterations to ensure its applicability in manufacturing industries and to make it compatible with the algorithmic approach used in this research. A detailed questionnaire is presented in Appendix C. The responses of the questionnaire are analysed using multi-criteria decision making methods. While the WMG team has developed a proprietary methodology to develop a Resilience Index considering weights of each strategy areas, and a group decision making approach, in the context of this project and for a simple illustration, we use a generic methodology widely used in research to calculate index based on multi-criteria.

Application of TOPSIS method to calculate Index: Based upon the inputs of industrial experts and the survey of resilience literature, we present a methodology to express a Firm's resilience capabilities as a unified Resilience Score. The score draws upon the inputs from stakeholders on various dimensions of a firm's resilience capabilities. It uses TOPSIS (Technique for Order Preference by Similarity to Ideal Solution), a Multi-criteria decision-making (MCDM) mathematical model, to mathematically analyse these inputs and generate a unified resilience score. The TOPSIS method combines the scores for all questions within a practice area and obtains an area score. A weighting is applied to each practice area based on the questions answered. Where not applicable has been selected, the area's weight for the total score is recalculated based on the number of questions answered for each area. A weighted sum for the TOPSIS scores for each area is then calculated to quantify the overall resiliency index score.

Outputs from the assessment tool: The output includes the resiliency index score, the practice area scores, and recommendations. The resiliency index score is the overall score pertaining to the performance of the firms SC resiliency capabilities. This helps determine if strategic and company c- suite involvement is required to sanction budgets and approve hires for enhancing the overall SC resiliency of the organisation. The practice area scores, show scores pertaining to the capabilities of the organisation in a particular SC area. These scores determine which practice areas within the organisation are lacking and in need of improvement, to help fine tune a firm’s resiliency capability for each practice area.

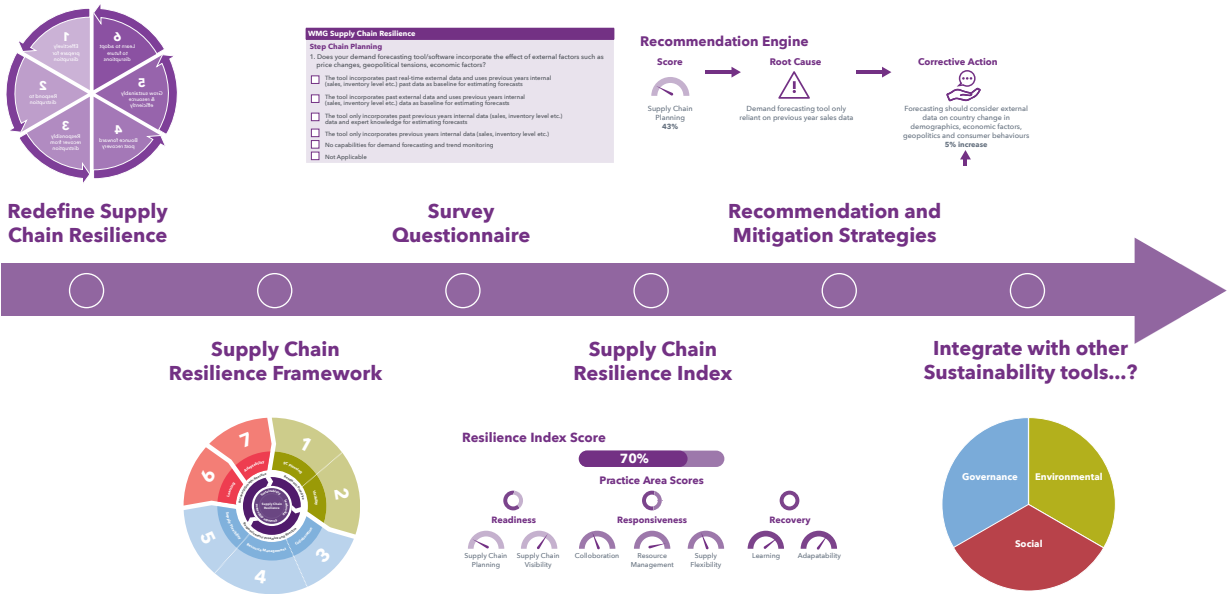


Figure 7. Step by step process of developing the SCR tool.

Visual demonstration of the supply chain resilience assessment tool

Figure 6 shows our systematic flow of developing SCR. The process starts from re-defining the SCR for the new normal, followed by the development of a practical capability driven framework, which feeds to the development of KPIs and related questionnaire. The resilience index module further analyses data and applies TOPSIS method to calculate score for each practice area as well as overall score.

This section visually demonstrates and presents a visual roadmap of the SCR tool development. The following figures demonstrate how the visual presentation of the SCR assessment tool would appear. Starting with Figure 8, a step-by-step guide for the SCR assessment tool is provided.

Supply Chain Resiliency Tool

Step 1: User fills in the survey, which is the input module of the tool
Step 2: The resiliency index module gives scores
Step 3: The diagnosis module gives root causes for low scores
Step 4: The recommendation module gives corrective actions to increase scores

Figure 8. Step by step guide to using Resiliency tool

Figure 9 presents an example of the appearance of the questionnaire, users will be able to select a single option per question as they progress through the questionnaire, with area subheading provided.

WMG Supply Chain Resilience

Supply Chain Planning

1. Does your demand forecasting tool/software incorporate the effect of external factors such as price changes, geopolitical tensions, economic factors?

- ☐ The tool incorporates past real-time external data and uses previous years internal (sales, inventory level etc.) past data as baseline for estimating forecasts
- ☐ The tool incorporates past external data and uses previous years internal (sales, inventory level etc.) data as baseline for estimating forecasts
- ☐ The tool only incorporates past previous years internal data (sales, inventory level etc.) data and expert knowledge for estimating forecasts
- ☐ The tool only incorporates previous years internal data (sales, inventory level etc.)
- ☐ No capabilities for demand forecasting and trend monitoring
- ☐ Not Applicable

Figure 9. Example presentation of questionnaire appearance.

Figure 10 presents the use of intelligence to inform the output of the questionnaire for the user, consulting industry workshop review and expert opinion, the latest in the extant academic literature with a post-pandemic focus as well as the best standards currently presented and available for review from industry, and with the survey calculating using TOPIS methodology for score calculation.

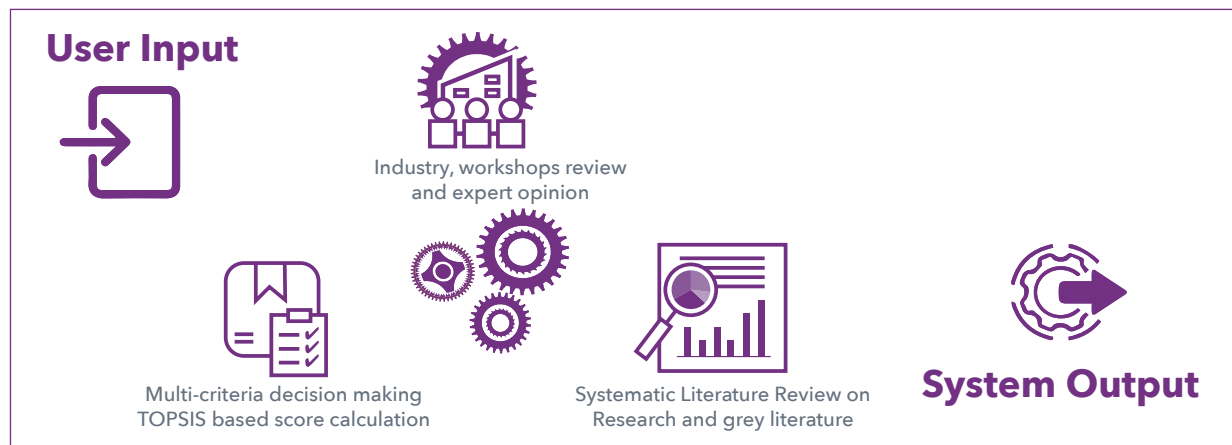


Figure 10. Overview of tool development methods and user questionnaire input output transformation.

Figure 11 demonstrates the flow of information from user input, through the modules to produce the respective outputs.

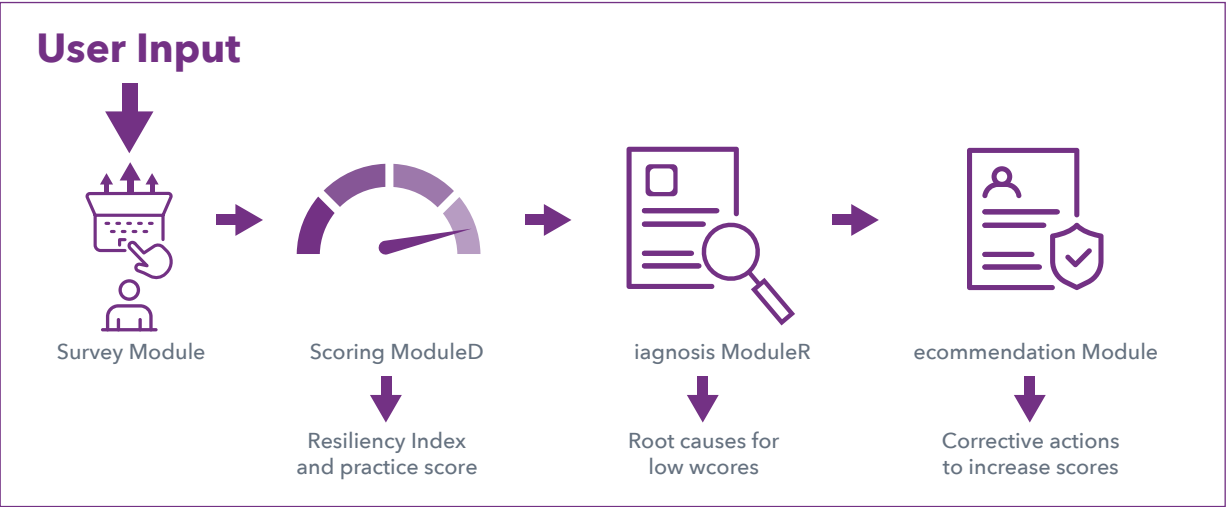


Figure 12 presents the visualisation of the score following completion of the survey.

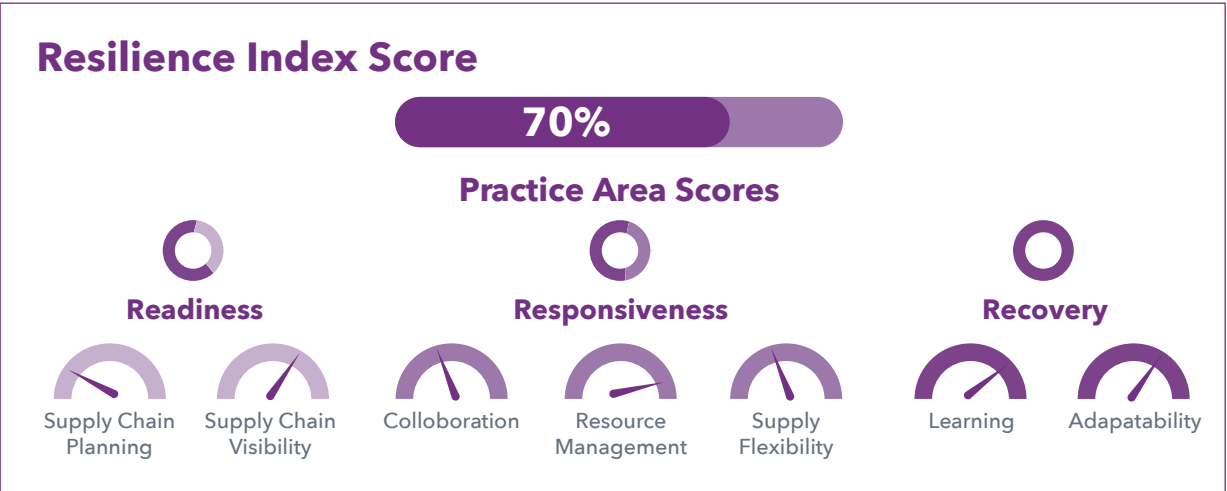
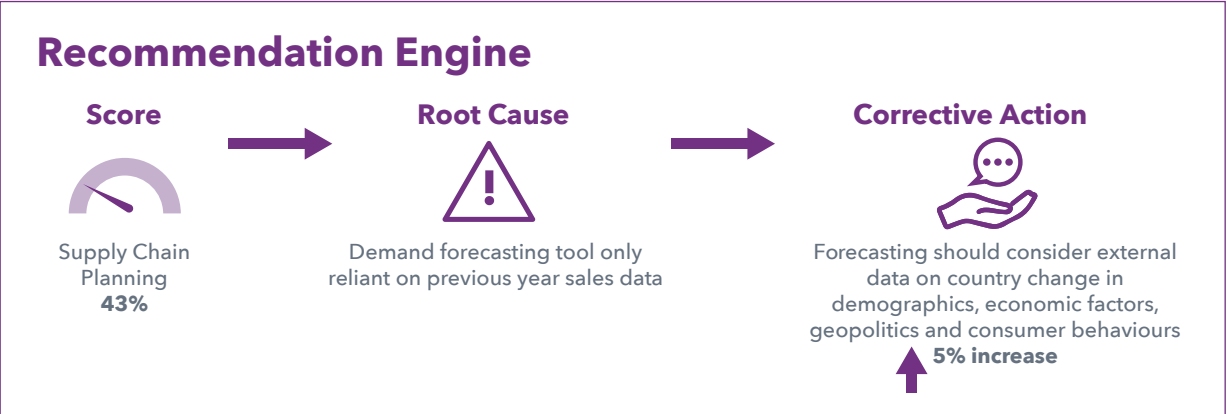


Figure 13 is a demonstration of the view for recommendation following the completion of the survey, and the user querying a particular score for reasoning of issues identified and suggested corrective action.



5. Concluding remarks

Managing supply chains has never been easy due to its complex nature. Covid-19 and recent geopolitical tensions across the globe have rung a bell that supply chain disruptions will always be unavoidable risks for businesses in the UK and elsewhere. To unleash the future potential, manufacturing firms must improve how they manage their supply chains, which, if done effectively, will make them more resilient when confronting any future crisis. To help firms with this, this project starts with redefining the supply chain resilience that better serves the post pandemic business environment. Based on the new definition, we constructed a theoretically informed framework for pre, during and post disruption, focusing on both proactive and reactive strategies. The framework provides a generic blueprint for supply chain resilience, whilst having leadership, strategic alignment and ESG sustainability as core considerations. Then the framework provides the backbone to our questionnaire for calculation of SCR index. This tool can provide a snapshot of an organisation's resilience capabilities and highlight the shortcomings and areas where further investments are required. We encourage firms to consider the feasibility of all the solutions together, as adopting only one of them may not be as impactful. This, ultimately, makes the supply chains antifragile to any future crisis.

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