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COMMENTS

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Balancing resilience and efficiency in supply chains: Roles of disruptive technologies under Industry 4.0

Abstract In the Industry 4.0 era, disruptive technologies such as big data analytics, blockchain, Internet-of-Things, and additive manufacturing have become major forces driving supply chain transformation. Under such circumstances, particular attention should be attached to balancing resilience and efficiency of the supply chain, especially in the presence of more turbulence. In this study, we first summarize the conflicts between supply chain efficiency and supply chain resilience regarding practices and objectives. Then, we discuss the positive effects of disruptive technologies in improving resilience and efficiency. Afterwards, we propose a research agenda that covers both the influence mechanism and trade-off mechanism of these technologies in terms of resilience and efficiency.

Keywords disruptive technologies, supply chain, resilience, efficiency, paradox, balance

1 Introduction

Global supply chain (SC) facilitates the flow and optimal allocation of production factors such as labor, capital, and information worldwide. The use of SC lean management concepts such as just-in-time (JIT) production, zero inventory management, and process reengineering provides theoretical support for improving efficiency and reducing costs in the global SC (Jayaram, 2016). However, the increasing complexity of SCs and unexpected disruptions such as the COVID-19 pandemic have exposed drawbacks of this approach, which may weaken the ability of companies and SCs to respond to unexpected risks (Ruiz-Benítez et al., 2018). The outbreaks of major global public health events are highly likely to lead to the disruption of a link in the SC, which will trigger domino effects and eventually paralyze the SC network. In this circumstance, the academia and business have recognized the importance of improving SC resilience (SCR) while pursuing SC efficiency (SCE). While SCs need to increase their resilience to reduce disruption risks, they also need to optimize business processes to improve operational efficiency. The simultaneous pursuits of SCE and SCR seem to be contradictory, as their practices and objectives clash (Ruiz-Benítez et al., 2018). For example, SCR tends to mitigate the adverse effects of SC disruption risk by building strategic inventories, creating redundancies, and using nearshore sourcing (Remko, 2020). By contrast, zero inventory, elimination of any potential redundancy, and global sourcing of low-cost suppliers are effective means of improving SCE. Nonetheless, achieving both SCR and SCE has become a necessity in this highly uncertain era. Disruptive technologies promise new opportunities to balance SCR and SCE. Jonathan Wright, a managing partner of global cognitive process reengineering and SC consulting at IBM services, believes that the application of technologies such as blockchain in business processes can improve end-to-end visibility, operational speed and SCR. The great potential of smart SCs supported by technologies has also been identified in practice. For example, applying blockchain to oil SC management not only increases the transparency of business processes, but also reduces transportation costs and time. In view of the necessity and contradiction of achieving the balance between SCR and SCE, we aim to develop a framework that trades off SCR and SCE based on disruptive technologies such as big data analytics (BDA), blockchain, Internet-of-Things (IoT), and additive manufacturing (AM) in the Industry 4.0 era.

Our research makes several contributions to the literature. First and foremost, although existing literature

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emphasizes the importance of SCR and SCE, the research regarding the synergistic development of these two dimensions is still insufficient. Therefore, this paper calls for researchers and practitioners to solve the conflict between SCR and SCE. Second, it has become a consensus that disruptive technologies drive SC reform (Ning et al., 2022; Wu et al., 2022), while how to use technological advantages to balance the contradiction between SCR and SCE is overlooked. Finally, we present some future research questions, including influence mechanism and trade-off mechanism of SCR and SCE supported by disruptive technologies. Answering these research questions will guide managers to make more appropriate SC decisions. In this paper, we first discuss the potential of disruptive technologies to balance SCR and SCE, which consists of two parts: the paradox of resilience and efficiency and the practical application of emerging technologies in the SCs. Then, we build a future research agenda. Finally, we conclude the paper. This paper is not a complete literature review but attempts to explore the mechanisms via which disruptive technologies balance resilience and efficiency by emphasizing the need for research.

2 Effect of disruptive technologies on balancing resilience and efficiency

2.1 Supply chain resilience and efficiency paradox

The trade-off between resilience and efficiency is one of the most contradictory issues in the SC management field (Roscoe and Blome, 2019; Belhadi et al., 2022). On the one hand, in recent decades, improving efficiency and reducing cost have become the goal pursued by SC practitioners, and lean management theory aiming at establishing an efficient production and operation system has also attracted extensive attention from scholars. Lean production originated from Toyota's production system and later extended to lean design, lean manufacturing, lean inventory, and other lean production management systems. Shah and Ward (2007) clarified the concept of lean production and proposed several dimensions of lean systems from both internal (related to the company) and external (related to stakeholders) perspectives. This system includes dimensions such as supplier feedback, JIT delivery by suppliers, supplier development, customer involvement, pull, continuous flow, set up time reduction, total productive/preventive maintenance, statistical process control, and employee involvement. Lean SC requires optimizing and transforming the whole SC link by eliminating non-value-added activities between upstream and downstream enterprises (Belhadi et al., 2018). According to SC lean management theory, SC members can improve overall operating efficiency and increase profits by reducing cost, improving quality, eliminating redundant activities, and maintaining low inventory levels (Sundar et al., 2014).

On the other hand, in recent years, unpredictable events such as COVID-19, natural disasters, and trade protectionism have brought challenges to the stability of SCs. SC practitioners have shifted their perspective to enhancing SCR to reduce the disruption risk of SC and maintain the continuity of business operations. Existing literature has extensively discussed the definition, dimensions, strategies, and capabilities of SCR, providing a theoretical basis for the establishment of SCR (Scholten et al., 2014; Chowdhury and Quaddus, 2017; Dong et al., 2022). SCR is the ability of the SC to recover the original state or a more ideal state after extraordinary disruptions, including two dimensions of robustness and agility (Wieland and Wallenburg, 2013). These two dimensions correspond to two strategies adopted by firms to reduce the adverse impacts of unexpected shocks, namely, proactive and reactive (Wieland and Wallenburg, 2013; Hosseini et al., 2019). Proactive strategies reflect the ability of SC to prevent and resist disruptions. Such strategy allows firms adequate time to consider a reasonable reaction, and their performance will not substantially deviate from targets even in the face of unpredictable major disasters. Reactive strategies reflect the responsiveness and restorability of the SC. Such strategy can immediately adjust production plans to new market conditions. SCR can be divided into absorptive capacity, adaptive capacity, and restorative capacity according to temporal attributes, which constitute three lines of defense against disruption risk (Hosseini et al., 2019). Table 1 shows the definitions and implementation mechanisms for these three capacities.

Simultaneously enhancing SCR and SCE seems to be in conflict, as these two objectives involve opposing strategies (Ruiz-Benítez et al., 2018). In practice, lean production systems that pursue zero inventory and JIT principles mean less redundancy, which impede the implementation of SCR strategies such as building safety inventory, determining alternative suppliers, and seeking multiple sources, ultimately reducing the ability of SC to absorb, adapt, and recover from disruptive events. In other words, the pursuit of resilience may come at the expense of some efficiency (Klimek et al., 2019).

Given that efficiency and resilience are applicable to different market environments, efficiency is especially applicable to stable market conditions and environments; meanwhile, resilience is conducive to maintaining the normal operations of firms in dynamic, complex, and chaotic environments (Markolf et al., 2022). Existing literature suggests reconciling efficiency and resilience rather than opposing them (Brede and de Vries, 2009). Several explorations have been attempted on the synergetic development of SCE and SCR. For instance, Chowdhury and Quaddus (2015) introduced the concept of SCR efficiency and explored how to select the optimal and effective resilience strategies in the case of uncertain environment

Table 1 Three capacities of SCR (Hosseini et al., 2019)

Capacity	Definition	Implementation mechanisms
Absorptive capacity	The ability of an SC system to absorb and withstand unpredictable disturbances and minimize the adverse consequences of disruptions with minimal input	Supplier segregation Multiple sourcing strategy Inventory management
Adaptive capacity	The degree to which the SC system can adapt to unpredictable disturbances without any recovery practices	Rerouting Backup supplier Communication
Restorative capacity	The ability of an SC system to quickly recover when the first two lines of defense are insufficient to support normal levels of performance	Facility restoration Manpower restoration Technology restoration

and limited resources. They established a multi-objective optimization model in which the resilience capability must be resource efficient, and the resilience strategy selection must be effective. Chopra et al. (2021) demonstrated that using commons can not only achieve SCE during normal times but also ensure SCR in the event of disruption.

2.2 Role of disruptive technologies in the supply chain

The application of disruptive technologies such as BDA, blockchain, IoT, and AM could help enhance SCR and SCE. Figure 1 shows the mechanisms by which disruptive technologies affect resilience and efficiency, and we will discuss in detail how these technologies affect resilience and efficiency. Notably, these technologies may have other factors to achieve resilience and efficiency which are not limited to those we discuss next.

Specifically, BDA is a technology that provides valuable insights into corporate decision making by collecting, cleaning, and analyzing structured, semi-structured, and unstructured data. The application of BDA in firms strengthens the identification of risk exposure in the planning stage and helps them implement proactive strategies. Specifically, BDA can not only identify possible threats and disruption risks, but also accurately predict future market demand, which has profound significance for improving the visibility of SCR (Shmueli and Koppius, 2011; Kache and Seuring, 2017). BDA is also seen as an effective tool to improve operational efficiency as its potential to optimize resource utilization and reduce total costs (Borgi et al., 2017). For example, Nambiar et al. (2013) provided insights into how BDA can drive a paradigm shift in the healthcare industry to better achieve operational efficiency.

Blockchain is a distributed shared ledger and database that is decentralized, immutable, traceable, and transparent. The application of blockchain technology, such as tracing product sources, improving SC security, transparency and visibility, ensuring data security, and realizing smart contract fulfillment, provides technical support for reducing SC security risks and improving SCR (Lohmer et al., 2020). For example, companies can use blockchain to track the root of SC disruptions, select short-term emergency actions, and formulate medium- and long-term recovery policies based on real-time analysis of available capacity and inventory both upstream and downstream of the SC (Ivanov et al., 2019). The application of blockchain in SC can also realize information sharing, simplify transaction process, improve information receiving speed, and ensure content accuracy, thus improving SCE (Li et al., 2022). For example, Hastig and Sodhi (2020) demonstrated that blockchain-based systems can achieve SCE by eliminating errors, simplifying processes, enhancing SC visibility, and improving order fulfillment.

IoT is a technology that connects products, machines,

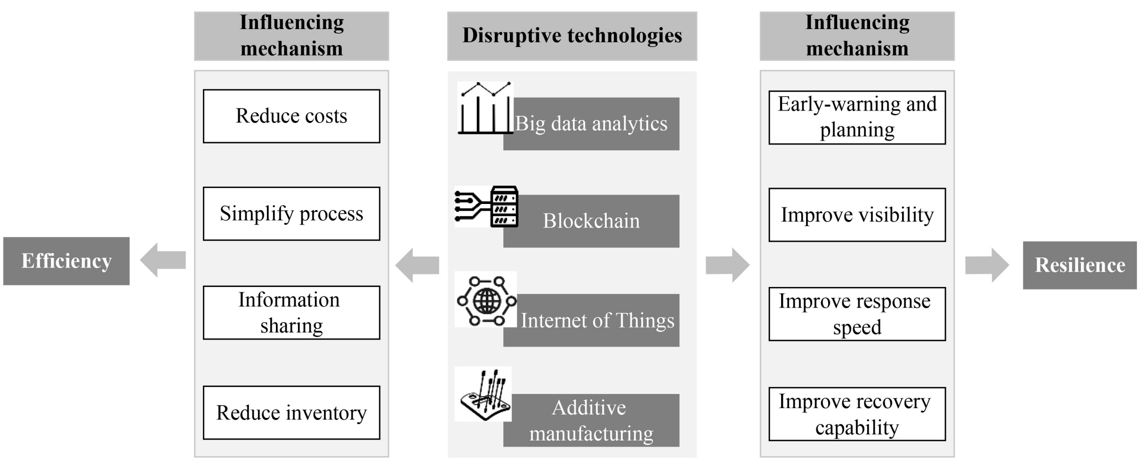

Fig. 1 Influence mechanism of disruptive technologies on balancing SCR and SCE.

and people through various information-sensing devices to realize the Internet of everything. The number of active IoT devices is expected to exceed 25.4 billion by 2030. Such commercial value contained in the IoT has attracted the attention of scholars and practitioners (Ben-Daya et al., 2019). The IoT has the potential to change the paradigm of SC management. Collecting and analyzing data returned from information-sensing devices can improve SC visibility and provide early warning of possible risks (Ben-Daya et al., 2019), which can improve SCR. Risk detection and timely response also largely improve SCE. In practice, approximately 83% of businesses using IoT technology have improved their efficiency.

AM is also known as 3D printing, rapid prototyping, and rapid manufacturing. Unlike traditional manufacturing methods that cut usable parts by subtracting large pieces of material, AM is a manufacturing technique that uses software and numerical control systems to construct three-dimensional objects layer by layer. The use of AM at all stages of the SC allows faster manufacturing and shorter delivery time, thus improving SC responsiveness (Ivanov et al., 2019), an important capability of SCR. This technology can also increase product personalization and reduce the overall inventory levels. According to statistics, AM can reduce waste and material costs by up to 90%, which can significantly improve SCE.

Table 2 shows the mechanisms of these technologies on SCR and SCE. From Table 2, we can clearly see that disruptive technologies can be viewed as powerful tools for implementing both SCR and SCE.

3 Future research agenda

We have discussed the potential of disruptive technologies in building SCR and SCE. Figure 2 shows the research typology in SC management, including targeted analysis and exploratory analysis. Targeted research is predefined and typically used to solve SC resource optimization problems. By contrast, exploratory analysis focuses on learning to develop new insights rather than determining optimal solutions (Swink et al., 2022). Based on this framework, we provide two broad agenda for future research: Influence mechanism research and trade-off mechanism research.

Regarding influence mechanism research, some important challenges are integrating various approaches and considering synergistic effects among different breakthrough technologies. First, more theory-based empirical and analytical research could have looked into the relevant

Table 2 Mechanisms of disruptive technologies on SCR and SCE

Technologies	Characteristics	Application areas	Benefits
BDA	Multi-source big data acquisition Data mining Analytical prediction Data visualization	Risk early-warning Demand forecasting SC planning Resource optimization SC network design	Risk control Cost optimization Improved efficiency Improved visibility
Blockchain	Disintermediation Immutability Transparency Irreversibility Smart contracts	Product traceability Information sharing Transaction process simplification Contract fulfillment	Improved transparency Data security assurance Improved speed and visibility Improved efficiency Strengthened collaboration
IoT	Perceiving objects Information transmission Intelligent processing	Risk early-warning Product traceability Dynamic tracking Inventory management Automatic scanning	Improved speed and visibility Improved responsiveness Strengthened collaboration Shortened trading hours Reduced transaction costs
AM	Flexible design High material utilization rate Customized product No mold required	Manufacturing Customization	Shortened delivery time Improved responsiveness Reduced inventory and manufacturing costs

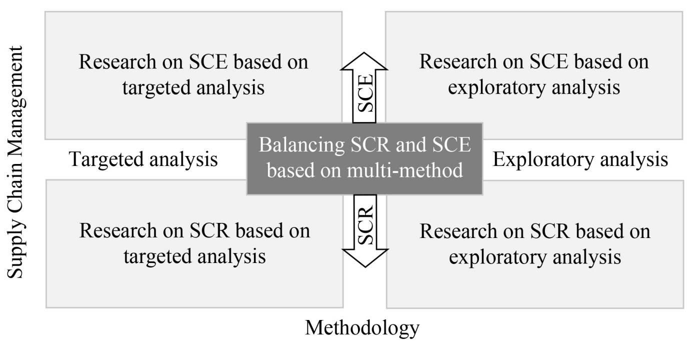

Fig. 2 Research typology of SC management.

Table 3 Future research questions of two mechanisms

Mechanisms	Questions	Methods
Influence mechanism	What is the relationship between disruptive technologies and SCR or SCE? How does a single disruptive technology contribute to SCR or SCE? How do disruptive technologies that consider synergies influence SCR or SCE? What factors influence the impact of disruptive technologies on SCR or SCE?	Experimental research Mathematical model Simulation method Conceptual model Empirical analysis Case study Multi-method
Trade-off mechanism	Can disruptive technologies balance SCR and SCE? How do disruptive technologies balance SCR and SCE? What factors influence the balance between disruptive technology-enabled SCR and SCE? How can one design an SC structure to balance SCR and SCE based on the characteristics of disruptive technologies?	

applications of disruptive technologies such as BDA, blockchain, IoT, and AM. For example, Dong et al. (2022) developed a theoretical model to explore how blockchain affects SC optimal risk mitigation and financial strategies. Using a game-theoretic approach, the authors found that blockchain-based systems help manufacturers make informed financing decisions, and the financing scheme used determines whether all SC members benefit. Second, existing literature discusses the impact of disruptive technologies on SCR and SCE based on a single method. A more comprehensive multi-method study combining empirical analysis and theoretical modeling is worth exploring. For example, Chen et al. (2022) combined literature review and semi-structured interview to explore the positive effects of IoT and blockchain on improving resilience, providing theoretical references for pharmaceutical SC members to formulate risk countermeasures. Finally, most of the existing studies have explored the positive effects of a single disruptive technology. In practice, in the Industry 4.0 era, SC typically deploys multiple technologies. Therefore, how the synergies among different technologies affect SCR and SCE to achieve the optimization of SC management needs further exploration. For example, Narwane et al. (2021) explored the combined role of blockchain and BDA in the field of SC risk management and provided a new approach in improving SCR. Gupta et al. (2022) used partial least squares based structural equation modeling (PLS-SEM) to explore the role of BDA and AM in improving SCR and reducing ripple effects. They found that BDA has a significant effect on risk intelligence, while AM improves preparedness and intelligent risk control.

Regarding trade-off mechanism research, SC researchers can explore paradox solutions based on the opportunities identified in the previous section. As mentioned above, researchers have demonstrated that technologies play a critical role in SC management, and their applications in SC have the potential to improve SCR and SCE. However, some persisting research gaps need further exploration. First, under what conditions can disruptive technologies simultaneously improve resilience and efficiency remains unclear. For example, Belhadi et al. (2022) adopted a hybrid approach to innovatively verify that AM technology can potentially achieve the coordination of resilience and efficiency at the SC level. They also demonstrated that factors such as SC collaboration, data-driven systems, and knowledge are critical to realizing the benefits of AM. Second, exploring how these technologies balance SCR and SCE has practical significance. For example, Ivanov et al. (2019) provided an initial framework for investigating mechanisms by which digital technologies enhance ripple effect control and reduce disruption risk. Last but not least, optimizing the SC structure according to different advantages of disruptive technologies to achieve the balance between SCR and SCE is a critical step from theoretical exploration to practical application. For example, Mohammaddust et al. (2017) developed a dual-objective model that considers lean and responsive strategies to explore the optimization of SC design and risk mitigation strategies. As shown in Table 3, we summarize some interesting questions and possible methods to help researchers develop some papers.

4 Concluding remarks

This paper provides an insight into how disruptive technologies balance SCR and SCE. Although some studies have revealed new insights into the impact of emerging technologies on resilience and efficiency, the exploration of how digital technologies can simultaneously build SCR and SCE remains vague. Moreover, how to optimize the application of different digital technologies to various links of SC according to their unique advantages also needs further discussion. In this paper, we simply provide a framework and identify some directions that can be used to guide future research. We hope that exploring these new questions can help scholars and practitioners gain some useful insights.

References

Belhadi A, Kamble S S, Venkatesh M, Chiappetta Jabbour C J, Benkhati I (2022). Building supply chain resilience and efficiency through additive manufacturing: An ambidextrous perspective on the dynamic capability view. International Journal of Production Economics, 249: 108516

Belhadi A, Touriki F E, El Fezazi S (2018). Benefits of adopting lean production on green performance of SMEs: A case study. Production Planning and Control, 29(11): 873–894

Ben-Daya M, Hassini E, Bahroun Z (2019). Internet of Things and supply chain management: A literature review. International Journal of Production Research, 57(15–16): 4719–4742

Borgi T, Zoghlami N, Abed M, Naceur M S (2017). Big data for operational efficiency of transport and logistics: A review. In: Proceedings of the 6th IEEE International Conference on Advanced Logistics and Transport (ICALT). Bali: IEEE, 113–120

Brede M, de Vries B J (2009). Networks that optimize a trade-off between efficiency and dynamical resilience. Physics Letters A, 373(43): 3910–3914

Chen X, He C, Chen Y, Xie Z (2022). Internet of Things (IoT)–blockchain-enabled pharmaceutical supply chain resilience in the post-pandemic era. Frontiers of Engineering Management, in press, doi:10.1007/s42524-022-0233-1

Chopra S, Sodhi M, Lücker F (2021). Achieving supply chain efficiency and resilience by using multi-level commons. Decision Sciences, 52(4): 817–832

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

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

Dong L, Qiu Y, Xu F (2022). Blockchain-enabled deep-tier supply chain finance. Manufacturing & Service Operations Management, in press, doi:10.1287/msom.2022.1123

Gupta S, Bag S, Modgil S, de Sousa Jabbour A B L, Kumar A (2022). Examining the influence of big data analytics and additive manufacturing on supply chain risk control and resilience: An empirical study. Computers & Industrial Engineering, 172: 108629

Hastig G M, Sodhi M S (2020). Blockchain for supply chain traceability: Business requirements and critical success factors. Production and Operations Management, 29(4): 935–954

Hosseini S, Ivanov D, Dolgui A (2019). Review of quantitative methods for supply chain resilience analysis. Transportation Research Part E: Logistics and Transportation Review, 125: 285–307

Ivanov D, Dolgui A, Sokolov B (2019). The impact of digital technology and Industry 4.0 on the ripple effect and supply chain risk analytics. International Journal of Production Research, 57(3): 829–846

Jayaram A (2016). Lean six sigma approach for global supply chain management using Industry 4.0 and IoT. In: Proceedings of the 2nd International Conference on Contemporary Computing and Informatics (IC3I). Greater Noida: IEEE, 89–94

Kache F, Seuring S (2017). Challenges and opportunities of digital information at the intersection of big data analytics and supply chain management. International Journal of Operations & Production Management, 37(1): 10–36

Klimek P, Varga J, Jovanovic A S, Székely Z (2019). Quantitative resilience assessment in emergency response reveals how organizations trade efficiency for redundancy. Safety Science, 113: 404–414

Li G, Xue J, Li N, Ivanov D (2022). Blockchain-supported business model design, supply chain resilience, and firm performance. Transportation Research Part E: Logistics and Transportation Review, 163: 102773

Lohmer J, Bugert N, Lasch R (2020). Analysis of resilience strategies and ripple effect in blockchain-coordinated supply chains: An agent-based simulation study. International Journal of Production Economics, 228: 107882

Markolf S A, Helmrich A, Kim Y, Hoff R, Chester M (2022). Balancing efficiency and resilience objectives in pursuit of sustainable infrastructure transformations. Current Opinion in Environmental Sustainability, 56: 101181

Mohammaddust F, Rezapour S, Farahani R Z, Mofidfar M, Hill A (2017). Developing lean and responsive supply chains: A robust model for alternative risk mitigation strategies in supply chain designs. International Journal of Production Economics, 183: 632–653

Nambiar R, Bhardwaj R, Sethi A, Vargheese R (2013). A look at challenges and opportunities of big data analytics in healthcare. In: Proceedings of the IEEE International Conference on Big Data. Silicon Valley, CA: IEEE, 17–22

Narwane V S, Raut R D, Mangla S K, Dora M, Narkhede B E (2021). Risks to big data analytics and blockchain technology adoption in supply chains. Annals of Operations Research, in press, doi: 10.1007/s10479-021-04396-3

Ning Y, Li L, Xu S X, Yang S (2022). How do digital technologies improve supply chain resilience in the COVID-19 pandemic? Evidence from Chinese manufacturing firms. Frontiers of Engineering Management, in press, doi:10.1007/s42524-022-0230-4

Remko V H (2020). Research opportunities for a more resilient post-COVID-19 supply chain: Closing the gap between research findings and industry practice. International Journal of Operations & Production Management, 40(4): 341–355

Roscoe S, Blome C (2019). Understanding the emergence of redistributed manufacturing: An ambidexterity perspective. Production Planning and Control, 30(7): 496–509

Ruiz-Benítez R, López C, Real J C (2018). The lean and resilient management of the supply chain and its impact on performance. International Journal of Production Economics, 203: 190–202

Scholten K, Sharkey Scott P, Fynes B (2014). Mitigation processes–antecedents for building supply chain resilience. Supply Chain Management, 19(2): 211–228

Shah R, Ward P T (2007). Defining and developing measures of lean production. Journal of Operations Management, 25(4): 785–805

Shmueli G, Koppius O R (2011). Predictive analytics in information systems research. Management Information Systems Quarterly, 35(3): 553–572

Sundar R, Balaji A N, Kumar R S (2014). A review on lean manufacturing implementation techniques. Procedia Engineering, 97: 1875–1885

Swink M, Hu K, Zhao X (2022). Analytics applications, limitations, and opportunities in restaurant supply chains. Production and Operations Management, 31(10): 3710–3726

Wieland A, Wallenburg C M (2013). The influence of relational competencies on supply chain resilience: A relational view. International Journal of Physical Distribution & Logistics Management, 43(4): 300–320

Wu L, Lu W, Xu J (2022). Blockchain-based smart contract for smart payment in construction: A focus on the payment freezing and disbursement cycle. Frontiers of Engineering Management, 9(2): 177–195