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Uncertainties of supply chain transition and integration for Industry 5.0: a review of operations management literature

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REVIEW ARTICLE

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Uncertainties of supply chain transition and integration for Industry 5.0: a review of operations management literature

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ABSTRACT

Unlike Industry 4.0, Industry 5.0 is a disruptive innovation and value-driven paradigm motivated by quests to achieve industry-wide human-centric, sustainable, resilient, and connected production systems. Uncertainty, due to an absence or ambiguity in information on the supply chain transition and integration needs of Industry 5.0 systems, makes the paradigm challenging for supply chain managers. This article explores the strategies and uncertainties of supply chain transition and integration for Industry 5.0. Using a systematic review methodology, the article identifies variabilities concerning human-centric and twin transition uncertainties alongside foundational and implemental integration uncertainties for Industry 5.0 architectures and assessments. The review also captures a triad of vulnerabilities involving disruption, tension, and competition uncertainties due to Industry 5.0. Taken together, these uncertainties require an embedded-extended logic for uncertainty management based on implementing *embedded strategies* that deal with variabilities and enacting *extended measures* to cope with crisis-related events and shocks due to vulnerabilities. Additionally, the review theorises on how technology-based variations induce a 'toss-up effect' or indecisiveness due to the wide range of strategic options (and their potential pitfalls) available to Industry 5.0 operators or Operator 5.0. Predicated on the review insights, future research proposed includes studies on Industry 5.0 intelligence, co-creation, affordances, and risks.

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Industry 5.0; supply chain uncertainty; digital transition; industrialisation; Industry 4.0; human–machine collaboration

1. Introduction

Industrialisation remains an essential ingredient for transforming nations into prosperous and developed economies (Hauge 2023) because industries create the systems, equipment, goods, and services that drive economic activities. Over the years, industries have been progressively transformed during three distinctive industrial revolutions that involved eras of mechanisation, electrification, and automation of industry, succeeded by a fourth industrial revolution, or Industry 4.0, which heralded the digitalisation and digital transformation of manufacturing and service operations (Alam, Forhad, and Ismail 2020; AlMalki and Durugbo 2023). Due to the progress achieved during these eras, industrialisation focus has logically and strategically *transitioned* from an accumulation of unprocessed agrarian and raw materials towards *integrated* production capabilities that support and boost manufacturing, services and intelligence. The fifth industrial revolution, or Industry 5.0, is an emerging industrialisation era inspired by visions of human – robot collaboration and bioeconomy (Narkhede et al. 2025); consolidating the major industrial progress made from previous eras, and championed by the European Commission (2021) along with multinational corporations like SAP, PwC, Ericsson, Nokia, Rothschild & Co, Micron, and ATOSS.

Although existing research on Industry 5.0 is relatively scant and still maturing (Leng et al. 2022; Kaswan et al. 2025), the outlook and opportunities for operations and supply chain management (OSCM) are mainly positive and prospective. In this regard, the 2023 special issue in the *International Journal of Production Research* on transitioning from Industry 4.0 to Industry 5.0 (Grosse et al. 2023) was timely and reflective of attempts to promote and accrue high-quality OSCM research on Industry 5.0. These attempts are crucial because the Industry 5.0 vision calls for concerted efforts to tackle disparities between future manufacturing requirements and societal needs for sustainable development and prosperity (Leng et al. 2022). The European Commission (2021) also observes that Industry 5.0 reflects the application of innovative technologies for wealth creation and the need for digital (and green) transitions, in industrial trends increasingly termed 'twin transitions' (Bianchini, Damioli, and Ghisetti 2023; Kovacic et al. 2024) or 'dual transitions' (Sgambati and Carvalho 2024). Yet, a core aspect of

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OSCM research is the nature of uncertainties associated with paradigms, phenomena and practices that advance OSCM. Uncertainties for OSCM are reflected by long-standing questions on the state of operational unknowns due to a paucity in pertinent information, but Industry 5.0 introduces unique task environments and operating models for smart and sustainable manufacturing systems (Caggiano, Semeraro, and Dassisti 2023; Peruzzini, Prati, and Pelicciari 2023; Sharma and Arya 2022). Thus, depth in understanding and sound practices for managing uncertainties are crucial to how OSCM professionals are decisive in implementing OSCM strategies for the Industry 5.0 era.

In efforts to advance high-quality OSCM scholarship on Industry 5.0, *this article aims* to explore the strategies and uncertainties of supply chain transition and integration for Industry 5.0 within the literature. While supply chain transition means migrating or switching from old to new forms of processes and production systems in steps and time horizons that are based on substantial changes to preexisting supply chain designs (Bejlegaard, Sarivan, and Waehrens 2021; Ye, Hung Lau, and Teo 2023), supply chain integration is 'the degree to which a company collaborates with its supply chain partners and collaboratively manages intra-organizational and interorganizational processes' (Tiwari 2021, 1464) – both concepts contribute to the industrial transformation and innovation of supply chains (Burke, Zhang, and Wang 2023; Ngo, Pham, and Nguyen 2023).

According to the UN Trade and Development (UN Trade and Development 2024), the Internet of Things (IoT) devices in circulation are expected to reach 39 billion by 2029, underscoring a growing trend in an important digital technology that underpins both Industry 4.0 and Industry 5.0. How supply chains strategically transition to and integrate these digital technologies is instrumental to industrial transformation and innovation. For supply chain managers, insights on the determining factors of Industry 5.0, such as uncertainty, aid in preparing for (Gladysz et al. 2023), influencing (Enang, Bashiri, and Jarvis 2023) and creating a systemic view (Grosse et al. 2023) of supply chain transition and integration. In furtherance of OSCM practice, this article reviews current OSCM research studies on Industry 5.0 and uses insights from these studies to propose a management model of OSCM strategy for coping with supply chain transition and integration uncertainties in the Industry 5.0 era.

For OSCM researchers (e.g. Roscoe et al. (2020), and de Lima, Seuring, and Sauer (2022)), uncertainties triggered by emerging paradigms cause a fundamental and in-depth rethinking of systems for production and sourcing strategies. Similarly, this article argues for a focus on OSCM strategy and uncertainties of the emerging Industry 5.0 paradigm. In the literature, several scholars present reviews on the Industry 5.0 concept with respect to characteristics (Leng et al. 2022) and maturity models (Hein-Pensel et al. 2023) as well as dedicated examinations of the paradigm with respect to sustainable manufacturing (Narkhede et al. 2025), flexible manufacturing (Destouet et al. 2023), and supply chain resilience (Agrawal et al. 2024). There are also recent reviews which explore the nature of supply chain uncertainty in the context of emerging paradigms such as the circular economy (de Lima, Seuring, and Sauer 2022) and closed-loop supply chain (Peng et al. 2020). However, what is lacking is a thoughtful examination and clear articulation of the supply chain variabilities and vulnerabilities of Industry 5.0 – the need to fill this void is the motivation for this review. In filling this void, the review also attempts to stimulate debate on uncertainty management for future supply chains and provides insights that target the community of OSCM researchers and practitioners with interests in industrialisation trends, challenges, and opportunities. In line with the aim and motivation of this article, the research questions confronted here are as follows:

- **R1.** What is the current state of OSCM literature on supply chain strategy for Industry 5.0?
- **R2.** What are the uncertainties (i.e. variabilities and vulnerabilities) of supply chain transition and integration for Industry 5.0?
- **R3.** How can OSCM practitioners improve uncertainty management for supply chain transition and integration in the Industry 5.0 era?

The rest of this review article proceeds as follows: §2 gives an overview of Industry 5.0 and uncertainties in supply chains, §3 outlines the review methodology, §4 details the findings, while §5 discusses the theoretical and managerial implications of the review findings along with review limitations and a set of research challenges for future OSCM studies.

2. Industry 5.0 and uncertainties in supply chains

In literature, Industry 5.0, championed by the European Commission (2021), is viewed as a disruptive innovation (Sharma and Arya 2022) and value-driven (Enang, Bashiri, and Jarvis 2023; Ivanov 2023; Dacre et al. 2024; Goujon et al. 2024; Leng et al. 2024) paradigm with potentials for enhanced production systems. Industry 5.0 complements and expands the vision of Industry 4.0 (Goujon et al. 2024; Rejeb et al. 2024) based on four interrelated principles of *human-centricity*, *sustainability*, *resiliency* (Xu et al. 2021), and *connectivity* (Huang et al.

2022), as shown by Figure 1. Human-centricity places human needs and welfare at the core of production by developing initiatives that improve work-life balance and employee well-being, and by emphasising safe, secure, diverse, and inclusive workspaces that lead to strengthened human rights, work-life balance, well-being, dignity, integrity and privacy. The focus of human-centricity also extends to skill development and catering to the needs of aging workforces. In parallel, sustainability positions respect for the environment at the heart of production and champions circular economy processes associated with secondary markets and product recovery, e.g. refurbishing, remanufacturing, and recycling. Resiliency puts system recovery at the centre of operations strategy and strives for organic capabilities that prevent, withstand and recover from disruptions and crisis situations. Connectivity supports multi-level integration of human-oriented tasks and technology-supported manufacturing via the use of digital technologies (Sahoo, Saraf, and Uchil 2024), ensuring seamless links between cyberspace and physical spaces (Huang et al. 2022). Thus, connectivity in an Industry 5.0 context situates digital technologies at the centre of production by laying emphasis on broad integration at human-machine, machine-machine, and human-human interfaces (Leng et al. 2022). Due to these principles, Industry 5.0 heralds the transitions of human operators from traditional workers into enhanced, intelligent, and skilful workers who are supported by digital technologies, leading to a new category of operatives dubbed 'Operator 5.0' (Destouet et al. 2023; Gladysz et al. 2023).

Although there are evident intersections between the foci of Industry 4.0 and Industry 5.0, as summarised by Table 1, Industry 5.0 is distinctive in setting and requiring a synergy of human-centricity, connectivity, sustainability and resiliency targets for production and solutions, e.g. energy-efficient bio-inspired systems and smart homes from recyclables that are powered by renewable energy sources. The table shows some key disruptive and enabling technologies that provide the bases for Industry 5.0 system architectures, and innovation (Orso et al. 2022; Gladysz et al. 2023; Peruzzini, Prati, and Pelicciari 2023; Horvat, Jäger, and Lerch 2024; Li, Sun, and Yu 2024) is central to these architectures, which require participatory design and innovation ecosystems for achieving human-automation symbiosis in collaborative designs for operations and supply chains.

Considering the core principles of Industry 5.0 draws attention to supply chain design for x-abilities in areas of traceability (Sarkar, Sharma, and Shardeo 2025), interoperability (Ordieres-Meré, Gutierrez, and Villalba-Díez 2023), visibility (Agrawal et al. 2024), adaptability (Leng et al. 2022; Ma, Yao, and Wang 2024), reliability (van Oudenhoven et al. 2023; Ghobakhloo et al. 2024), and leagility (Fani et al. 2024; Fernández-Miguel et al. 2024). Factoring customisation strategies (Huang et al. 2022; Narkhede et al. 2025) along with active and mutual learning (Rožanec et al. 2022) as part of human-machine collaboration additionally play key roles in converting flexible modularised production systems into autonomous learning production systems. For operators, enhanced production systems demand approaches for tackling multi-objective problems to reintegrate human, environmental, connectivity, and resiliency concerns during resource allocation (Ma, Yao, and Wang 2024) and production scheduling (Battini et al. 2022; Destouet et al. 2023; Bouaziz et al. 2024). Accordingly, the practical implementation of Industry 5.0 principles creates uncertainty in the supply chain (Chang, Jia, and Ren 2024; Kumar et al. 2024) and requires upskilling/reskilling of workers, review of ethics, significant investments, as well as enhanced data gathering and security, and interoperability measures (Fernández-Miguel et al. 2024; Narkhede et al. 2025).

Uncertainties perturb OSCM due to the inherent complex nature of supply networks and the differing objectives of entities within supply chains (Blackhurst, Wu, and O'Grady 2004), particularly in the context of a 'bull-whip' effect originating from demand fluctuations (Lee, Padmanabhan, and Whang 1997). Further exacerbating this effect is a continued intensification of industry competition and globalisation, which triggers further uncertainty with pressures to factor flexible delivery (Angkiriwang, Pujawan, and Santosa 2014; Flynn, Koufteros, and Lu 2016) and service operations (Durugbo and Erkoyuncu 2016). Uncertainty in this context means an 'individual's perceived inability to predict outcomes accurately in the general business environment because of insufficient information or the inability to discriminate between relevant and irrelevant data' (Milliken 1987, 136). Thus, uncertainty in supply chains relates to an absence or ambiguity in information for OSCM (Van Der Vorst and Beulens 2002) – stemming from a panoply of variabilities and vulnerabilities (Durugbo et al. 2020; Flynn, Koufteros, and Lu 2016; Sreedevi and Saranga 2017). Typically, OSCM responses to this uncertainty include: (i) strategies to control for total quality, design new products or redesign the supply chain (Davis 1993), (ii) reduction and coping strategies (Simangunsong, Hendry, and Stevenson 2012, 2016), (iii) buffering and redesign strategies (Angkiriwang, Pujawan, and Santosa 2014), and (iv) measures for resource deployment, network reconfiguration, and business environment alignment (Roscoe et al. 2020). Generally, these strategies tend to be reactive or proactive in support of the operational, tactical, and strategic decisions that aim to reduce or quash instances

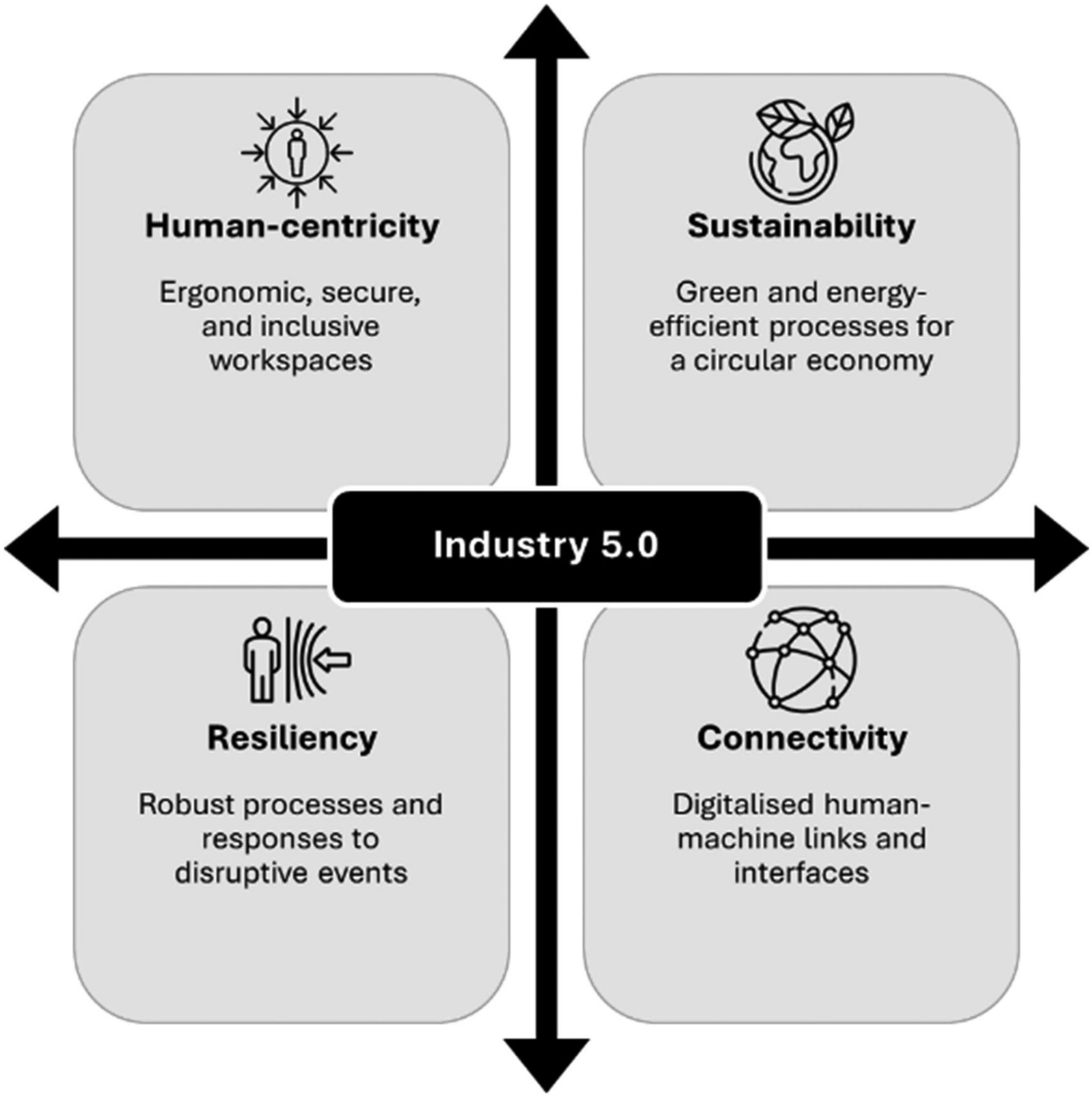

Figure 1. Main principles of Industry 5.0.

of disruptions and crisis events (Angkiriwang, Pujawan, and Santosa 2014; Roscoe et al. 2020).

Irrespective of the adopted strategy, there is somewhat of a consensus that effective planning and preparedness *a priori* decreases uncertainty (Durugbo et al. 2020) because 'without uncertainty, transactions would be fully predicted *ex-ante*' (Han, Trienekens, and (Onno) Omta 2011, 313), and as a result, awareness on potential sources of uncertainty is key to crafting OSCM strategy. Accordingly, OSCM literature offers several industrially-relevant, theoretically-grounded and empirically-supported categorisations of uncertainty sources. For a start, the pioneering work by Davis (1993) classifies uncertainty according to demand (customer), process (manufacturing), and supply (delivery) sources. Extending on this classification, Mason-Jones and Towill (1998) account for uncertainty due to control systems as part of an uncertainty circle model, and there have been further considerations for technology uncertainty that reflects technological advances (Chen and Paulraj 2004), transport uncertainty that signals complexities in supplier-carrier-customer links and flows (Sanchez-Rodrigues et al. 2008), and environmental uncertainty which triggers risk in demand, supply and processes within supply chains (Sreedevi and Saranga 2017). In contrast, Van Der Vorst and Beulens (2002) provide a typology based on uncertainty in quantities, quality, and timings within the supply chain, Flynn, Koufteros, and Lu (2016) offer a categorisation of micro-, meso- and macro-level supply chain uncertainty due to variability, lack of information and ambiguity, while Simangunsong et al. (2012, 2016) propose a classification of internal organisation, internal supply chain, and external uncertainties.

Table 1. Comparing the foci of Industry 4.0 and 5.0.

	Industry 4.0	Industry 5.0
Origin	2011 – from the Industrie 4.0 strategic initiative involving BITKOM, VDMA and ZVEI in Germany; alongside similar initiatives in Italy (Industria 4.0), Sweden (Produktion 2030), the USA (Industrial Internet Consortium), China (Made in China 2025), and Japan (Society 5.0) • Inspired by the rapid emergence and development of disruptive digital innovations such as social media, smartphones, and self-driving cars	2021 – from the European Commission; driven by virtual workshops convened by the Directorate-General Research and Innovation during July 2020 • Inspired by reflections on grand societal challenges, as reflected in policy initiatives like the Green Deal, and the socioeconomic impacts of COVID-19 pandemic
Technological focus	• Technology push • Digitalisation and digital transformation with focus on automation.	• Socio-technology pull • Digital transition and integration with focus on technologies re-oriented and re-designed for human-centricity, connectivity, sustainability and resiliency.
Technologies at the heart of supply chain transition and integration efforts	• Cyber Physical Systems (CPSs) that merge computational and physical functionalities with significant automation capabilities and support for human interactivity • additive manufacturing (3D printing) • advanced modelling and simulation, advanced robotics • augmented reality • artificial intelligence • big data analytics • blockchain • cloud computing • cognitive computing • cybersecurity • decentralised computing • digital shadows and twins • cyber-physical systems • edge computing • fin-tech • green computing • holography • industrial robots • Internet by and for people • Internet of contents and knowledge • Internet of things • Internet of everything • Internet of services • metaverse • mixed reality • recommender systems • renewable energy sources • sky computing • smart materials • social computing • virtual reality • unmanned aerial vehicles	• Re-oriented Industry 4.0 technologies in line with Industry 5.0 principles (e.g. social or human CPSs) • Industrial cobots that work with human operators in a safe, interactive and welfare-oriented manner using bio-inspired technologies like functional near-infrared spectroscopy • bionics • human digital twins
Supply chain and operations management focus	Automated designs that stress • mass production, • operational efficiency and • cost reduction from automated functions	• Inclusive and integrated designs that re-emphasise and give prominence to • mass customisation • operational productivity and creativity • worker well-being, human-automation symbiosis, planetary production boundaries, as well as • societal prosperity and equitable progress during routine, disruptive and crisis times
Production and human impact of paradigm	• Boosts in operating performance and profit • Increased automation of human tasks based on CPSs for production	• Enhanced socioeconomic prosperity for all stakeholders • Increased reintroduction of human operators displaced by Industry 4.0 through new roles like collaborative robots (cobots) designers

Recently, there has been renewed focus on uncertainty in supply chains due to an increase in the frequency of geopolitical and crisis events for individuals, organisations and regions (van Oudenhoven et al. 2023). Along these lines, global economies are currently undergoing transitions that increasingly render supply chains vulnerable as the future confronts a 'fragmented and multipolar world' (European Union 2023, 7). For OSCM, these events trigger a 'ripple effect' (Ivanov, Sokolov, and Dolgui 2014; Dolgui, Ivanov, and Sokolov 2018)

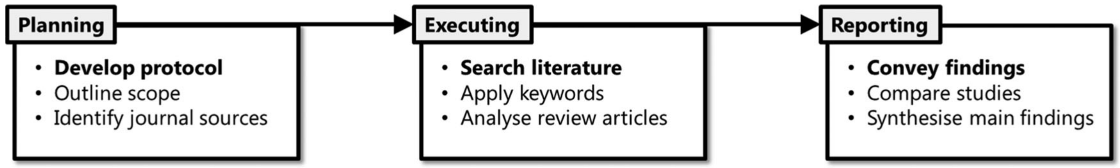

Figure 2. Outline of 3-step approach adopted for the systematic review (Durugbo 2020).

which disrupts supply networks, and due to the socioeconomic implications of this effect, OSCM studies have expanded in coverage to shed the spotlight on uncertainties and strategic choices for supply chain finance (Zhao, Liu, and Zhang 2024), innovation to operations (Souza et al. 2022), and production systems during supply chain disruptions, e.g. during the Coronavirus disease 2019 (COVID-19) pandemic (Kopytov et al. 2024) and geopolitical events, e.g. Brexit (Roscoe et al. 2020). Concurrently, mandates for eco-innovation and sustainable production causes reconsiderations of supply chains to account for sustainability uncertainties associated with closed-loop supply chains (Peng et al. 2020), circular supply chains (de Lima, Seuring, and Sauer 2022), and renewables for making energy management systems more sustainable (Iris and Lam 2021).

3. Research methodology

Using the systematic review methodology (Torgerson 2003; Tranfield, Denyer, and Smart 2003), this article seeks to provide and deepen knowledge on the nature of OSCM strategy and uncertainties for Industry 5.0. This approach is appropriate and suitable due to support for clear procedures which minimise bias via audit trails that follow the sourcing of publications through to the reporting of results. For this review, a 3-step approach recommended by Tranfield, Denyer, and Smart (2003) is adopted. The approach involves planning, executing and reporting, as summarised by Figure 2.

For the *planning* step, a review protocol (Torgerson 2003) outlining the main aspects of the review (i.e. purpose, search strategy, databases, screening, inclusion and exclusion criteria, and reliability and validity measures) was developed, as detailed by Table 2. To ensure the production of a focused and high quality review, an initial criterion was set to include peer-reviewed journal articles published within internationally-leading scientific publication outlets. Consequently, the review excludes conference proceedings, theses and dissertations, textbooks, and unpublished working papers. Here, planning the review involved choosing two scholarly abstract and citation databases: (i) Scopus (http://www.scopus.com) by Elsevier the Dutch publishing firm and (ii) Web of Science (WoS) (http://www.webofscience.com) by Clarivate Analytics the British-American analytics firm. These databases are leading sources for scholarly literature and are widely-accepted by academic communities due to their specialisation on scientific content and the quality of their collections. In added efforts to identify only high quality OSCM-themed research studies, an additional criterion was set for the inclusion of articles published by outlets contained within the OPS&TECH field of the 2021 Chartered Association of Business Schools (ABS) journal list and within the 3509 field of research (and OSCM-themed journals) on the 2022 Australian Business Deans Council (ABDC) journal list. Selecting sources from these lists ensures the review provides research insights from reputable and respectable OSCM journals (Durugbo et al. 2021). Furthermore, these journals are 'exemplars of excellence, most original, best executed, and highly regarded' (Bore et al. 2017, 67) and account for where OSCM 'research leadership (is) coming from' (Babbar et al. 2018, 350).

For the *executing* step, a simultaneous search of titles on Scopus and WoS was conducted using the '"Industry 5.0" OR "fifth industrial revolution"' search string, which represents the main terms related to this review. This initial search produced 1391 and 721 results on Scopus and WoS, respectively. Limiting the results to English language peer-reviewed journal articles, in accordance with the review protocol of Table 2, resulted in 533 and 543 results on Scopus and WoS, respectively. Limiting the results to journals on the OSCM-themed journals of the ABS and ABDC lists generated 48 and 61 results, respectively. Cross-referencing both lists for duplicates produced 62. Subsequently, searches using the '"Industry 5.0" OR "fifth industrial revolution"' search string on the OSCM-themed journals of the ABS and ABDC lists produced 10 additional publications, resulting in a total of **73** unique articles published between 2021 and 2024. Executing the review involved accessing electronic copies of the publications on the portals of the relevant outlets, e.g. ASCE Library, Elsevier Science Direct, Emerald Insight, IEEE Xplore, Sage Journals, Springer Link, and Taylor & Francis Online. Table 3 shows the distribution of articles according to publication outlets, indicating that the *Journal of Manufacturing Systems* and the *International Journal of Production*

Table 2. Systematic literature review protocol.

Review aspect	Description	Review focus
Purpose	Aim of the literature review	To explore strategies and uncertainties (i.e. variabilities and vulnerabilities) of supply chain transition and integration for Industry 5.0 in OSCM literature.
Search strategy	Approach that informs search for publications	Using key terms to scan scientific databases according to set inclusion and exclusion criteria
Search strings	Set of terms applied to source publications	'Industry 5.0' OR 'fifth industrial revolution'
Databases	Independent indexes and repositories of scientific per-reviewed publications	Scopus and Web of Science
Screening and inclusion criteria	Conditions to choose and include publications for the review	Empirical and conceptual peer-reviewed publications on the Association of Business Schools (ABS) and Australian Business Deans Council (ABDC) journal quality lists
Exclusion criteria	Conditions to leave out publications for the review	Duplicates of publications as well as conference proceedings, theses and dissertations, textbooks, and unpublished working papers
Reliability and validity	Measures to improve the credibility and confidence of the review	Focus on ABS and ABDC articles improves quality along with a review by two independent OSCM researchers

Table 3. Distribution of review articles according to publication outlets.

Journal Name	Grade*	Number of articles
Journal of Manufacturing Systems	1 (B)	16
International Journal of Production Research	3 (A)	15
Computers and Industrial Engineering	2 (A)	9
Computers in Industry	3 (N/A)	5
IEEE Transactions on Engineering Management	3 (A)	4
International Journal of Production Economics	3 (A)	4
International Journal of Computer Integrated Manufacturing	2 (B)	3
Total Quality Management and Business Excellence	2 (C)	2
Journal of Manufacturing Technology Management	1 (B)	2
Journal of Intelligent Manufacturing	1 (B)	2
Production Planning & Control	3 (A)	1
Supply Chain Management: An International Journal	3 (A)	1
Journal of Construction Engineering and Management	2 (A*)	1
International Journal of Quality & Reliability Management	2 (B)	1
Benchmarking	1 (B)	1
International Journal of Productivity and Performance Management	1 (B)	1
The TQM Journal	1 (B)	1
Operations Management Research	1 (C)	1
Flexible Services and Manufacturing Journal	1(C)	1
International Journal of Logistics Management	1 (N/A)	1
Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering	1 (N/A)	1
Total		**73**

*Grades are according to number rank on the Chartered Association of Business Schools (ABS) list and alphabet rank on the Australian Business Deans Council (ABDC) journal list.

Research are the most significant journals within our sample.

For the *reporting* step, an analysis and synthesis of the gathered articles was conducted to present findings. In line with the systematic review methodology (Jesson, Matheson, and Lacey 2011; Gough, Oliver, and Thomas 2012), a thematic analysis (Guest, MacQueen, and Namey 2012; Nowell et al. 2017) facilitates the scrutiny and clustering of articles. Scrutiny from reading through articles aids in achieving data familiarity and identifying key concepts which are then reviewed individually and collectively to achieve consistency and inclusivity. This approach suits this review because it aids in identifying themes and core ideas within data for gathering insights and learning lessons from the corpus or records. Accordingly, the reporting entailed initially reading through the articles which yielded a set of OSCM-related transition and integration questions for production systems in the Industry 5.0 era. The process for clustering, in line Guest, MacQueen, and Namey (2012) and Nowell et al. (2017), proceeded with steps for: (i) segmenting the text by creating a review matrix containing the purpose, key findings, Industry 5.0-related questions, theories, and main concepts of each article, (ii) iteratively examining and assigning the questions within the matrix as transition-related or integration-related questions in a deductive approach, (iii) conducting similar examinations and assignments of the purpose, key findings, theories, and main concepts within the matrix to identify OSCM-related priorities, (v) sorting and collating each priority from the previous step to find commonalities and merging related priorities to create subthemes and themes, in an inductive approach. In essence, these steps involved triangulation and tabulation to identify unique codes and concepts within each question. Using this process, current OSCM practices within the articles are clustered and presented as strategy, while uncertainties are presented as variabilities and vulnerabilities because these factors represent classic situations of insufficient information and inadequacies in discriminating between related and unrelated data (Durugbo et al. 2020; Flynn, Koufteros, and Lu 2016; Sreedevi and Saranga 2017). Two independent researchers reviewed the themes to improve the review's reliability and internal validity while setting the inclusion criteria to peer-reviewed OSCM-themed scientific journal articles on the ABS and ABDC journal quality lists seeks to enhance external validity by reducing potential risks to the review from unreliable sources.

4. Findings

Analysing the research studies reveals fragments of supply chain transition and integration approaches such as mitigation strategies to overcome implementation barriers (Mukherjee, Raj, and Aggarwal 2023), interactive collaboration strategies for human-robot collaboration (Lu et al. 2022), and innovative manufacturing strategies that build on Industry 4.0 principles (Sharma and Arya 2022) such as wisdom (Ma, Yao, and Wang 2024; Yao et al. 2024), human-centric (Pistolesi, Baldassini, and Lazzerini 2024), sustainable (Dacre et al. 2024), responsible (Ghobakhloo et al. 2024), zero defect (Leng et al. 2022; Modad et al. 2024), individualised (Leng et al. 2022), and intelligent (Dwivedi et al. 2023) manufacturing concepts. However, thematic analysis shows the body of work contains elements for a holistic and inclusive OSCM strategy, which supports supply chain transition and integration, based on Industry 5.0 architectures and assessments, as summarised by Figure 3.

For this holistic OSCM strategy, supply chain transition and integration are determined by *productivity-related conditions* for production schedules, allocations, and interactions (Battini et al. 2022; Destouet et al. 2023; Leng et al. 2022; Agrawal et al. 2024; Sun and Song 2025) during routine, disruptive and crisis times. Here, Industry 5.0 demands strategic designs, valuations, benchmarks, and technologies for productivity that guarantee the autonomy, safety, trustworthiness, and human-centricity of production (Ahmed et al. 2023; Goujon et al. 2024; Rožanec et al. 2022; Sahoo, Saraf, and Uchil 2024; Wang et al. 2023; Xu et al. 2021). Thus, arrangements for Industry 5.0 production systems must conform to conventional regulatory frameworks for quality (Corallo et al. 2024) as well as contemporary and renewed focus on human behaviour which impacts production system performance (Bouaziz et al. 2024). Primarily a production quality concern, these frameworks and foci for productivity enable manufacturers achieve high production rates when answers are provided on what constitutes optimal operating conditions for machines and workload for workers in human-centred smart environments (Coronado et al. 2022; Chang, Jia, and Ren 2024; Thangavel, Maheswari, and Priyanka 2024).

Additionally, OSCM strategy based on Industry 5.0 architectures and assessments are shaped by *creativity-based considerations* for the types, contexts, and mixes of innovation capabilities (van Oudenhoven et al. 2023; Horvat, Jäger, and Lerch 2024; Mahroof et al. 2024; Modad et al. 2024; Narula et al. 2024), designs (Wen et al. 2024), and ecosystems (Li, Sun, and Yu 2024) that continuously monitor, fix anomalies, improve and reengineer Industry 5.0 systems. Accordingly, research observes unique opportunities to harness collaborative, self-learning, and crowd intelligence in the Industry 5.0 era (Leng et al. 2024). Here, OSCM strategies are required for systems that respect privacy, complement human capability, and maximise well-being (Huang et al. 2022; Pistolesi, Baldassini, and Lazzerini 2024). Due to the costs and complexities of implementation, there tends to be hesitance to embrace these systems (Ghobakhloo et al. 2024).

Overall, what emerges from an initial analysis of the literature is the key role of reference architectures, global standards, and assessment frameworks in formulating OSCM strategy for Industry 5.0 production systems. Interestingly, continuing the digitisation journey (Hein-Pensel et al. 2023; Corallo et al. 2024) remains central to this strategy due to shifts in foci to synergistic and digitally transformed economies. Based on a scrutiny of current literature, the rest of this section reports the review findings on transition and integration uncertainties due to Industry 5.0, as compared by Table 4. These uncertainties are the different operational unknowns arising due to a renewed focus on implementing human-centric, sustainable, resilient, and connected production systems that advance knowledge-oriented and circular economies.

4.1. Transition uncertainty

Transition uncertainty is a category of variabilities associated with the way supply chains migrate, switch, convert, and changeover to Industry 5.0 systems for production. Here, the questions for OSCM relate to 'acceptance', 'adaptation', 'adoption', 'change', 'commitment', 'diffusion', 'evolution', 'maturity', 'migration', 'modernisation', 'preparedness', 'shifts', 'transformation' and 'upgrades' for operations, particularly in the context of implementing

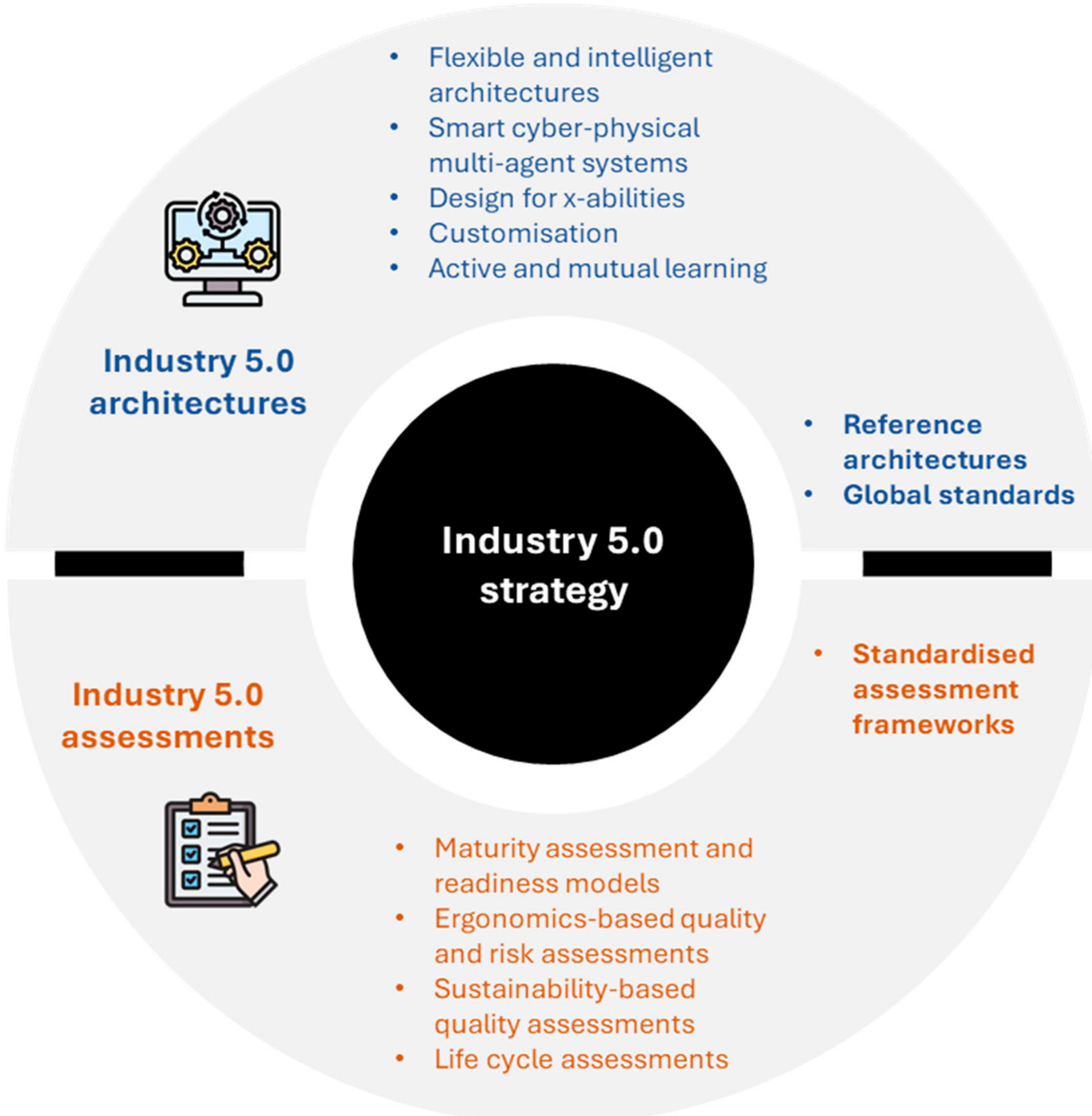

Figure 3. Overview of OSCM strategy for Industry 5.0.

digital technologies and management practices. Along these lines, uncertainty beleaguers digitalisation (Peruzzini, Prati, and Pelicciari 2023; Kaswan et al. 2025; Sarkar, Sharma, and Shardeo 2025) and transition uncertainty exists due complex decision problems related to how organisations migrate to automated operations and segmented human-machine tasks where machines tackle routine, demanding and high-risk activities (Enang, Bashiri, and Jarvis 2023; Narkhede et al. 2025; Yao et al. 2024). In contrast to Industry 4.0, as summarised by Table 5, supply chain uncertainty for Industry 5.0 is also posed by transition decisions pertaining to how organisations switch to human-centric operations where well-being and engagement is emphasised (Fani et al. 2024) or convert their flexible modularised production systems into autonomous learning production systems (Leng et al. 2022; Leng et al. 2023).

For manufacturers, there are additional conundrums on the compositions of production plans (Azani et al. 2025), action plans (Mukherjee, Raj, and Aggarwal 2023) and viable models (Caggiano, Semeraro, and Dassisti 2023; Ivanov 2023) that aid in migrations towards networks of interconnected manufacturing ecosystems. Recent research observes and argues that transitions for modern firms is essentially a duality for digital and green-based upgrades to production systems, which promote digital transformation, energy efficiency, and eco-friendly solutions. Accordingly, a common rallying point for production managers regarding transition uncertainty is the preparedness, maturity level and readiness requirements (Caggiano, Semeraro, and Dassisti 2023; Hein-Pensel et al. 2023; Kaswan et al. 2025) for progressing through stages of advancement towards digitalisation and greenisation.

Table 4. Variabilities of supply chain transition and integration for Industry 5.0.

Variability type	Overview	Metrics	Key references
Transition uncertainty	Uncertainties in how operators migrate or changeover to Industry 5.0 systems for production	• Consistency of change to automated systems • Consistency in segmented human-machine tasks • Consistency of conversion to autonomous learning systems • Level of readiness for transition • Frequency of upgrades to systems • Transition steps and policies	(Leng et al. 2022; Caggiano, Semeraro, and Dassisti 2023; Leng et al. 2023; Mukherjee, Raj, and Aggarwal 2023; Peruzzini, Prati, and Pelicciari 2023; Enang, Bashiri, and Jarvis 2023; Grosse et al. 2023; Hein-Pensel et al. 2023; Ivanov 2023; Dacre et al. 2024; Narkhede et al. 2025; Sarkar, Sharma, and Shardeo 2025; Yao et al. 2024; Fani et al. 2024; Guo et al. 2024; Kaswan et al. 2025)
Integration uncertainty	Uncertainties in how operators incorporate and consolidate Industry 5.0 capabilities	• Uniformity of sociotechnical requirements • Uniformity in architectures for system designs • Uniformity of interactions for human-machine and human-robot collaboration • Best practice for technology integration • Integration routines and policies	(Thakur and Sehgal 2021; Battini et al. 2022; Orso et al. 2022; Sharma and Arya 2022; Lu et al. 2022; Valette, Bril El-Haouzi, and Demesure 2023; Dwivedi et al. 2023; Gladysz et al. 2023; Karmaker et al. 2023; Ordieres-Meré, Gutierrez, and Villalba-Díez 2023; Ali and Johl 2024; Panagou, Neumann, and Fruggiero 2024; Passalacqua et al. 2024; Ruso et al. 2024; Sharma et al. 2024; Tomelleri et al. 2024; Wang et al. 2024; Fernández-Miguel et al. 2024; Leng et al. 2024; Ma, Yao, and Wang 2024)

Table 5. Comparing sources of supply chain transition uncertainty and nature of transition assessments for Industry 4.0 and Industry 5.0.

	Industry 4.0	Industry 5.0
Core sources of transition uncertainty	• Network-based disruption • Digital transitions and transformation	• Crisis-based disruption • Twin transition • Human-centric transitions
Nature of transition assessments	• Technology-driven • Quality and risks assessments of smart factories, products and staff • Digital human modelling with focus on assessments of environmental, psychosocial, cognitive, and behavioural factors	• Value-driven • Adaptations of Industry 4.0 assessments towards more human-, resilient – and substantiality-centric measures
Ergonomics-based assessment frameworks to inform supply chain transition efforts	Focus on task analysis for risk factors using guidelines such as the: • European Assembly Worksheet (EAWS) • Health Hazard Evaluation (HHE) programme by the National Institute for Occupational Safety and Health (NIOSH), • Loading on the Upper Body Assessment (LUBA), • National Aeronautics and Space Administration Task Load Index (NASA-TLX), • Ovako Working posture Assessment System (OWAS), • Rapid Entire Body Assessment (REBA), • Rapid Upper Limb Assessment (RULA), • Strain Index (SI), • Subjective Workload Assessment Technique (SWAT), • Workload Profile (WP).	Industry 4.0 assessments with proactive orientations towards embedding well-being and society-centric policies such as the: • UN's Sustainable Development Goals and Ecosystem Accounting • Paris Agreement • OECD's Better Life Index • Well-being of Future Generations Act • Gross National Happiness Index

Transition requires assessments of Industry 5.0 implementations, and the analysis of trends in literature shows emphasis on maturity assessments and models to objectively evaluate the transition (Caggiano, Semeraro, and Dassisti 2023) and transformation (Hein-Pensel et al. 2023) readiness of production systems for Industry 5.0. Assessments involve impact analysis while the maturity models appraise the range of assets, infrastructure, and competences that facilitate transitions and expose potential areas for improvements to ensure the smooth and continued development of Industry 5.0 production systems. Underpinning transition assessments for Industry 5.0 are standardised ergonomics-based frameworks alongside well-being and society-centric policies, as shown by Table 5. Hence, it is worth noting that assessments of quality for Industry 5.0 production systems require a sociotechnical approach that incorporates agile practices to foster sustainability (Ali and Johl 2024). Along these lines, there are life cycle assessments (Corallo et al. 2024; Guo et al. 2024; Ivanov 2023; Narula et al. 2024; Sharma and Arya 2022) that evaluate the environmental impact and energy footprint during product life

Table 6. Comparing sources of supply chain integration uncertainty, reference architectures for integration, and integration management standards for Industry 4.0 and Industry 5.0.

	Industry 4.0	Industry 5.0
Core sources integration uncertainty	• Foundational variabilities due to sociotechnical requirements, architectures, and best practices • Implemental variabilities due to digital technology application for automating, networking, and monitoring processes	Industry 4.0 foundational variabilities along with uncertainties concerning • Policies for welfare and well-being • Human-centric motivational and reward systems Industry 4.0 implemental variabilities as well as uncertainties surrounding • Digital integration with minimal human intervention and priority for sustainable development • Digital mechanisms for enhanced human-machine and human-robot collaboration
Reference architectures for integration	Service-oriented and focused on Cyber Physical Systems (CPS) using frameworks such as: • Reference Architecture Model Industrie 4.0 (RAMI4.0) • Big Data Value Reference Model • Industrial Internet Reference Architecture • Industrial Internet Security Framework (IISF)	Human-centric and focused on cobots and digital twins using adapted Industry 4.0 frameworks and new models such as the Extended Reality 5.0 (XR5.0) architecture
Standards for management systems to inform supply chain integration efforts	Mainly production and technology standards, such as: • ISO 9001 (quality management systems) • ISO 14001 (environmental management systems) • ISO 45001 (occupational health and safety management systems) • ISO/IEC 27001 (information security management) • ISO 50001 (energy management systems) • ISO 9241 (ergonomics of human-system interaction) • ISO 10218–2 (safety requirements for industrial robots) • ISO 11226 (ergonomics – evaluation of static working posture) • ISO 13482 (personal care robots) ISO 13855 (safety of machinery) • ISO 26000 (social responsibility) • ISO/IEC 25002, ISO/IEC 25010, and ISO/IEC 25019 (systems and software engineering) • ISO/TC 184 (Automation systems and integration)	Dynamic standards that reflect a synergy of human-centricity, connectivity, sustainability and resiliency, such as: • 2024 editions of ISO 9001, 14001, 27001, 45001 and 50001 with climate action amendments • ISO 9241-210:2019 (ergonomics of human-system interaction Part 210: Human-centred design for interactive systems) • ISO 20400:2017 (sustainable procurement) • ISO 25550:2022 (ageing societies) • ISO 37120:2018 (sustainable cities and communities) • ISO/TS 15066:2016 (collaborative robots) – reviewed and consolidated in 2022 • ISO 22301:2019 (Security and resilience – business continuity management systems – requirements) • ISO 28000:2022 (Security and resilience – security management systems – requirements) • ISO 23247–1 (Automation systems and integration – Digital twin framework for manufacturing)

cycles – offering recommendations for novel, enhanced and more sustainable forms of materials, resources and products.

4.2. Integration uncertainty

Integration uncertainty is the next category of variabilities surrounding how supply chains can incorporate, unite and consolidate capabilities within Industry 5.0 systems for production. This uncertainty for manufacturers stems from contemporary OSCM imperatives for 'alignment', 'balance', 'bridging', 'compatibility', 'fit', 'fusion', 'harmony', 'interoperability', 'linkage', 'symbioses, and 'synergy' within operations, which impact operational decisiveness when selecting and reviewing competences. Thus, there are uncertainties on effective system integration (Ma, Yao, and Wang 2024), harmonised sociotechnical links within production systems (Ali and Johl 2024), integration of worker attributes (Battini et al. 2022), and adoption of systems designs (Leng et al. 2024) that strike a balance between effective system monitoring, reduced equipment downtime and operators' growth and well-being.

At the *foundational* level, manufacturers must answer questions on principles (Ivanov 2023), data (Passalacqua et al. 2024; Gaffinet et al. 2025), requirements (Lu et al. 2022; Gladysz et al. 2023), designs (Ordieres-Meré, Gutierrez, and Villalba-Díez 2023; Keshvarparast et al. 2024; Wang, Tong, and Zhuang 2024; Leng et al. 2025), carbon footprints (Rejeb et al. 2024), knowledge (Su et al. 2024), and best practices (Dwivedi et al. 2023) for production systems, as well as policies for creating rewarding and motivating work environment that align with human workers' needs (Orso et al. 2022). At the *implemental* level, there are quandaries on how organisations determine and apply networked technologies, smart monitoring technologies, and highly automated and intelligent digital ecosystems (Dwivedi et al. 2023; Karmaker et al. 2023; Sharma and Arya 2022; Sharma and Arya 2022), with minimal human intervention and for sustainable development. Overall, Industry 5.0 demands answers to integration-related questions on the nature of interactions required for human-machine and human-robot collaboration (Ordieres-Meré, Gutierrez, and Villalba-Díez 2023; Panagou, Neumann, and Fruggiero 2024; Passalacqua et al. 2024; Wang et al. 2024) as well as evaluations on how technology solutions and data align within the Industry 5.0 paradigm (Thakur and Sehgal 2021; Valette, Bril El-Haouzi, and Demesure 2023; Fernández-Miguel et al. 2024; Gaffinet et al. 2025).

Integration depends on architectures for Industry 5.0, and perspectives on the characteristics of these architectures tend to revolve around a flexible (Ordieres-Meré, Gutierrez, and Villalba-Díez 2023; Keshvarparast et al. 2024) and intelligent (Rožanec et al. 2022) architecture composed of heterogeneous smart cyber-physical (Thakur and Sehgal 2021) and multi-agent (Leng et al. 2022; Bouaziz et al. 2024) industrial systems. Also of interest in the literature are suggestions that operators build Industry 5.0 architectures from reference architectures and global standards for management systems, as shown by Table 6. The table compares Industry 4.0 and Industry 5.0 in terms of the core sources of integration uncertainty, reference architectures for integration, and potential integration management standards and frameworks.

4.3. Supply chain transition and integration vulnerabilities for Industry 5.0

Further analysis of the literature produces the next set of findings which focus on the core vulnerabilities of supply chain transition and integration for Industry 5.0. These vulnerabilities render transitioned and integrated supply chains exposed, and involve 'disruption', 'tension', and 'competition' forms of uncertainties, which if unchecked tend to result in crisis events. Figure 4 gives an overview of these vulnerabilities for Industry 5.0 and some key questions for operators.

4.3.1. Disruptions-as-uncertainties

Disruptions-as-uncertainties are susceptibilities triggered by disturbances which change the regular flow of goods or services and unsettle the status quo for operations and supply chains. Recent events such the COVID-19 pandemic reveal how modern operations and supply chains are vulnerable (Ahmed et al. 2023; Mahroof et al. 2024), and the literature uses insights from recent trends to argue that no organisation is exempt from or immune to disruptions in the Industry 5.0 era (Karmaker et al. 2023; Leng et al. 2022). 'Damages', 'delays', 'discontinuation', 'interruptions', 'interferences', 'shortages', 'survival', and 'suspension', are some of the terms used with reference to disruptions and there are OSCM challenges to restore normalcy and learn lessons from disturbances. In line with *complex network theory*, the primary challenge posed by disruptions for OSCM is to design and deploy optimal configurations for capabilities that collaboratively minimise disruptions and the effects of disruptive events (Ma, Yao, and Wang 2024).

Under disruptions, some of the emerging OSCM questions relate to the role of enabling technologies (Fernández-Miguel et al. 2024) and production/task schedules (Leng et al. 2022; Lu et al. 2025) for responding, offering relief and recovering from disruptive events. For operators, answers are also required on forms of intelligence and resilience (Ahmed et al. 2023; Caggiano, Semeraro, and Dassisti 2023) that aid in predicting potential disruptions, reconfiguring production systems, and providing secure, rapid, agile, effective and efficient responses to disruptions (Huang et al. 2022; Ivanov 2023; Ma, Yao, and Wang 2024). Additionally, the need for preparedness to respond to disruptions requires improvements in restorative, absorptive and adaptive capacities within supply chains (Agrawal et al. 2024).

4.3.2. Competitions-as-uncertainties

Competitions-as-uncertainties are instabilities stemming from the competitiveness of competitors and the emergence of new competitors, resulting in changes to the competitive dynamics of operations and supply chains. In accordance with *absorptive capacity theory*, adopting digital capabilities provides knowledge-based and value-based outcomes that afford firms with a technology-driven competitive edge (Fernández-Miguel et al. 2024; Horvat, Jäger, and Lerch 2024) but firms are also required to assess the impact of these capabilities on their competitiveness (Caggiano, Semeraro, and Dassisti 2023). 'Rivalry', 'survival', 'viability', 'position', 'superiority', 'advantage', 'edge', 'pressure', 'struggle' and 'co-existence' are some terminologies used vis-à-vis competition and there are OSCM imperatives to seek out practices that develop and strengthen competitiveness. The quest for competitiveness in the Industry 5.0 era forces firms to shift business practices to more sustainable models (Dwivedi et al. 2023) and countries increasingly strive for global competitiveness by crafting policies and providing investments to boost industrialisation (Xu et al. 2021; Battini et al. 2022; Leng et al. 2022).

Due to contestability and intensity of competitions across industries, OSCM questions continue to arise on both the ability of operators to be competitive and the underlying factors that shape competition within industries and marketplaces. For a start, widespread adoption of process optimisation (Ghobakhloo et al. 2024) and continuous improvement practices such as lean (Hadi et al. 2023; Cuevas, Mira-Solves, and Verdu-Jover 2024; Fani et al. 2024) and agile (Ali and Johl 2024) systems tends to heighten competitiveness within

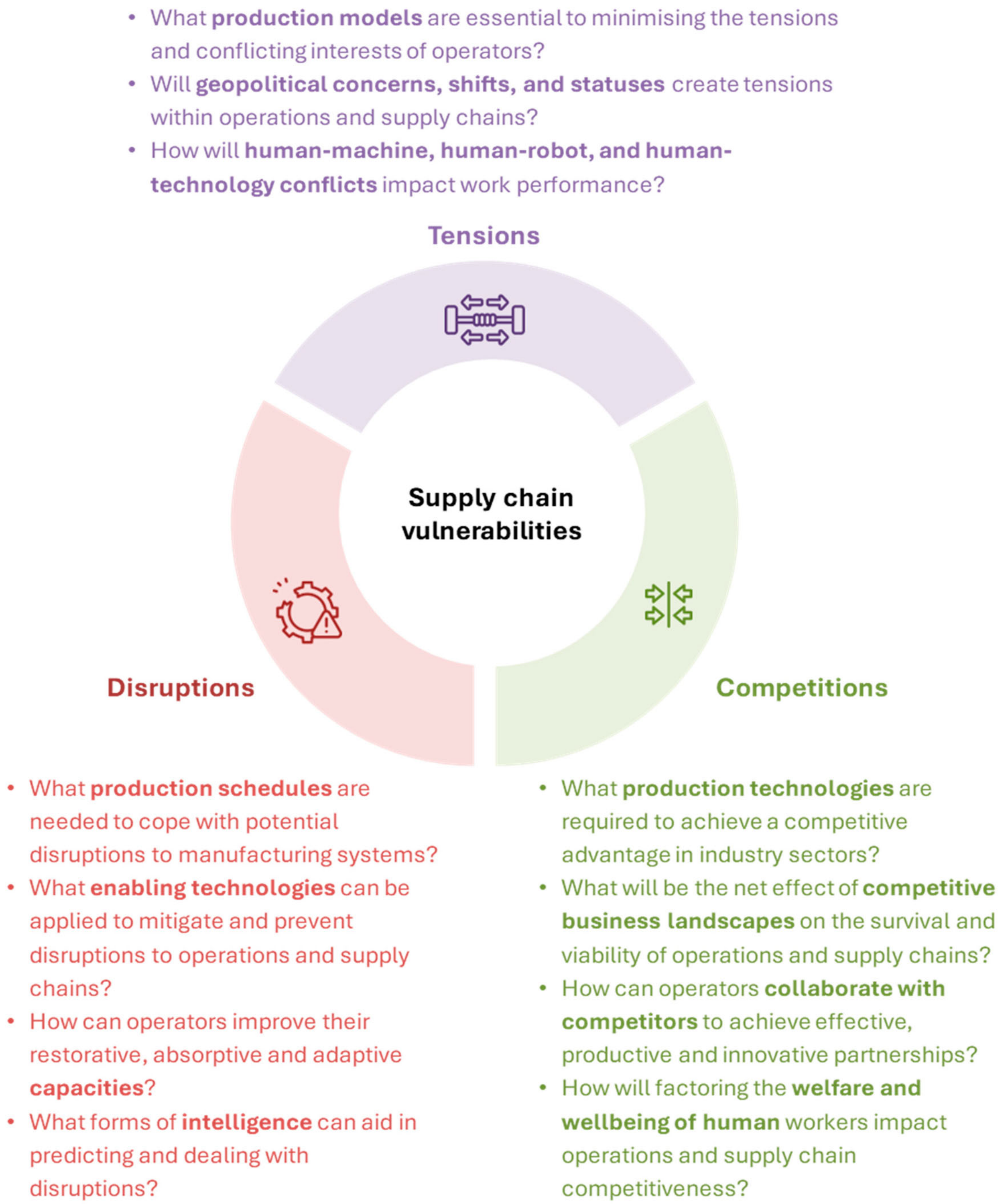

Figure 4. Supply chain vulnerabilities of Industry 5.0.

industry – leading to competitive pressures on existing firms and competitive hostilities to potential new entrants. At the firm level, there are core issues regarding the selection and mix of advanced technologies for improving firm competitiveness, with research stressing the importance of mass personalisation and smart automation for real-time decision-making (Peruzzini, Prati, and Pelicciari 2023; Narkhede et al. 2025). As a result of production efficiency and investment implications, there are also firm-level questions on how considering worker's health and wellbeing will impact the competitiveness of operations and supply chains in the long-term (Rožanec et al. 2022) and how operators partner effectively with competitors to acquire disruptive technologies (Narkhede et al. 2025).

4.3.3. Tensions-as uncertainties

Tensions-as-uncertainties are insecurities due to uneasiness or mistrust in work climates and working environments, leading to tense or damaged relationships within operations and supply chains. In the literature, geopolitical (Xu et al. 2021; Fernández-Miguel et al. 2024) and organisational (Ghobakhloo et al. 2024) tensions are examples used to illustrate operational vulnerabilities and to argue for transformation initiatives that resolve tense relationships within supply chains. 'Contradiction', 'opposing', 'antagonistic', 'inconsistent', 'hostility', 'anxiety', 'contrasting', 'incompatible', 'friction', 'strain', and 'stress' are common concepts applied in connection with tensions and there are OSCM requirements to avoid escalations, rebuild trust, and manage potential conflict.

Consistent with *paradox theory*, operators face tensions and conflicting interests in regard to task management by separate departments (van Oudenhoven et al. 2023) and the pursuit of OSCM goals of transformation, sustainability, innovation, resilience, and so on (Ghobakhloo et al. 2024; Narula et al. 2024). In these situations, the differences in capabilities and operating procedures pose operational challenges for firms to balance priorities and there are catch-22s on the precedence of competing yet complementary goals, e.g. greenisation vs digitalisation or implementation vs experimentation. Tensions due to geopolitical concerns, shifts and mishaps by home governments (Xu et al. 2021; Leng et al. 2022; Narkhede et al. 2025) along with the geopolitical statuses of capabilities such as nuclear fusion energy (Mukherjee, Raj, and Aggarwal 2023) represent added dimensions of insecurities for operators, particularly when substantial portions of operations and supply chains involve cross-border partnerships, sourcing and trade. Multi-objective problems and decision-making to cope with various forms of tensions are longstanding technical concerns for OSCM (Chang, Jia, and Ren 2024) but these concerns in the Industry 5.0 era assume added safety-performance and intent-state considerations to factor potential human-machine, human-robot, human-technology, and people-systems conflicts (Battini et al. 2022; Coronado et al. 2022; Lu et al. 2022; Ali and Johl 2024), in keeping with *socio-technical theory*.

5. Discussion

This section of the review serves three main purposes. First, the section discusses the main theoretical and managerial implications of the review findings. Second, there are reflections on the limitations of the review scope and methodology. Third, the section presents an agenda for potential future research studies.

5.1. Theoretical contributions

Theoretically, this review contributes to OSCM research via a theoretical model of uncertainty management for Industry 5.0, shown by Figure 5, which summarises the main review findings into an inclusive framing of strategy, variability and vulnerability management. In keeping with strategic choice theory, the key aspect of the model is the proposition of an **embedded-extended logic** of OSCM based on embedded strategies that address variability concerns and extended management that prevents, prepares for, and tackles effects of vulnerabilities. In this framing, the key questions and uncertainties that *ab initio* embedded OSCM strategy can tackle are the variabilities of supply chain transition and integration. In contrast, but complementary to the efforts of an embedded strategy, extended OSCM initiatives tackle potential uncertainties for disruptions, tensions, competitions that render operations and supply chains vulnerable – implying an embedded management strategy is a *sine qua non* of crafting and implementing any extended management initiatives. Along these lines, this review has OSCM theoretical implications because supply chain uncertainty remains a strategic OSCM issue (Sanchez-Rodrigues et al. 2008) and influences the strategic choices of operators (Zhao, Liu, and Zhang 2024). Studies of the pre-Industry 5.0 era suggest that uncertainty management strategies seek to reduce and cope with uncertainty in proactive and reactive approaches that focus on disruptive and crisis-related events (Simangunsong, Hendry, and Stevenson 2012, 2016; Angkiriwang, Pujawan, and Santosa 2014; Roscoe et al. 2020). As opposed to offering a one-size-fits-all or round-the-clock approach for OSCM, the embedded strategy implements architecture and assessments that deliver proactive and reactive (along with coactive) responses to routine operations. Complementarily, the extended disruption-tension-competition uncertainty management initiatives strive for readiness, responses, relief, restoration and recovery of production systems during non-routine and potentially crisis situations for operations and supply chains.

With a long history in OSCM research (Davis 1993; de Lima, Seuring, and Sauer 2022; Durugbo and Erkoyuncu 2016; Roscoe et al. 2020), inquiries into the nature of supply chain uncertainty for emerging industry paradigms afford operators with opportunities to rethink OSCM practices. Similarly, this review uses insights from previous studies to capture '**toss-up' effects** due to variabilities associated with industrialisation, digitalisation of industrial activity, and emerging industrial paradigms triggered by technological advances. Merriam-Webster (2024) describes a toss-up as 'something that offers no clear basis for choice', while Encyclopædia Britannica (2024) defines it as 'a situation in which there is no clear right choice or in which what will happen is not known'. For operations and supply chains, toss-up effects are determined by the threshold effects of processes (Horvat, Jäger, and Lerch 2024) and the constraints of multi-objective problems to trade-off and balance

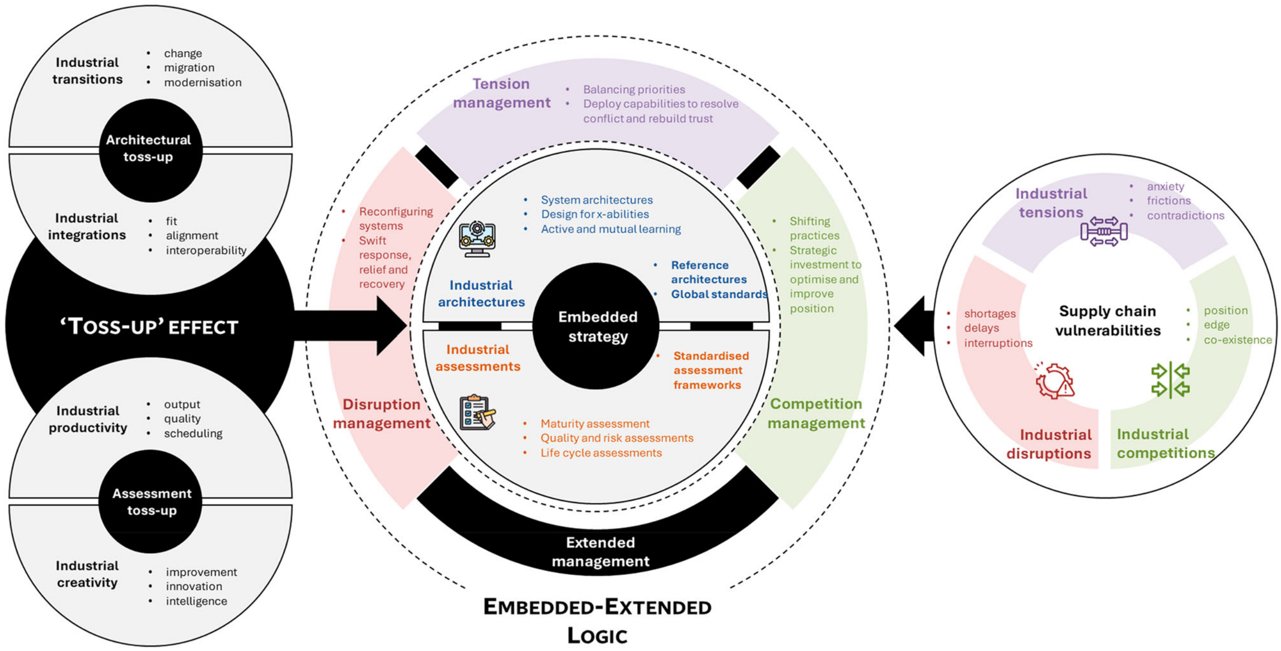

Figure 5. Summary of review findings and an embedded-extended logic of uncertainty management for operations and supply chains in the Industry 5.0 era.

contrasting attributes (Battini et al. 2022; Chang, Jia, and Ren 2024). Table 4 and Figure 4 present some core variabilities and vulnerabilities for Industry 5.0 which when taken together reflect complexities and contradictions of OSCM to maintain decisiveness and avoid paralysis within supply chains. In addition to toss-up effects triggered by factoring these predominantly technology-based attributes, Figure 5 also poses two potential 'toss-up dualities' between the levels of integration and transition for production systems and between the conditions for productivity and creativity within human-centric operations. In keeping with paradox theory, the toss-up effect from technology-based strategies and variations poses dilemmas to consider straightforward options and trade-offs in objectives akin to trade-off demands by the 'bull-whip' effect stemming from demand-based fluctuations (Lee, Padmanabhan, and Whang 1997) and the 'ripple effect' owing to supply-based disruptions (Ivanov, Sokolov, and Dolgui 2014; Dolgui, Ivanov, and Sokolov 2018).

5.2. Managerial implications

Managerially, this review has implications for OSCM in the Industry 5.0 era. As a start, the review sets forth an uncertainty-based perspective on the Industry 5.0 vision for human-centric, sustainable, resilient, and connected systems for production. Table 3 and Figure 4 highlight core supply chain transition and integration variabilities and vulnerabilities due to Industry 5.0, while Figure 5 posits on the potential integration-transition and productivity-creativity toss-ups for operators in the Industry 5.0 era. Based on insights from pre-Industry 5.0 practices, previous studies (e.g. Flynn, Koufteros, and Lu (2016) and Roscoe et al. (2020)) make the case for OSCM focus on achieving supply chain integration. However, based on expositions and justifications in current studies (e.g. Leng et al. (2022), Orso et al. (2022), Caggiano, Semeraro, and Dassisti (2023), Enang, Bashiri, and Jarvis (2023), Gladysz et al. (2023), Grosse et al. (2023), and Narula et al. (2024)), this review argues that transitions by supply chains has become just as, if not more, important than integration. In other words, journeying and navigating through emerging trends is increasingly crucial for operators who must also deploy and combine resources ethically and with efficacy. Researchers (Horvat, Jäger, and Lerch 2024; Ma, Yao, and Wang 2024; Narkhede et al. 2025) make similar arguments on the limits of focus on productivity and the need to harness human creativity. Accordingly, the first suggestion for supply chain managers, based on review insights, is for implementations of OSCM systems and practices that compartmentalise integration-transition initiatives to cope with supply chain uncertainties and complexities. In other words, the review findings lead to suggestions for OSCM repertoires that demarcate but interlink transition and integration strategies for roles, processes, and technologies within supply chains.

Continuing with the review findings, there are managerial implications concerning OSCM guidelines for

Industry 5.0 systems of production. The segmentation of overall strategy into embedded and extended options, as depicted by Figure 5, could provide OSCM orientations to business practices, such as staffing, financing, and innovation, which support routine and crisis-oriented operations and supply chains. For example, OSCM analysts may adopt the embedded-extended logic to contemplate potential mixes of strategic priorities and procedures for creating smart human-centric production designs. Equipped with these innovative designs, the Operator 5.0 gains from distinctive architectures that create innovative human-machine collaborations with enhanced workforce well-being and welfare. Thus, the second suggestion from this review for supply chain managers is for OSCM orientations and mindsets that formulate action plans according to the needs of embedded integration-transition management strategies and extended disruption-tension-competition management measures.

5.3. Review limitations

Methodological and topical reflections on this article's focus and findings suggest two main limitations of this review. First, the focus of the review is limited to 'supply chain transition and integration uncertainties for Industry 5.0' and a literature review that identifies studies which acknowledge and explicitly use 'Industry 5.0' or 'fifth industrial revolution' as terms in their expositions. Industry 5.0 is being championed in industry and practice at a time when organisations are still coming to grips with Industry 4.0 – and the dual presence of both paradigms could create ambiguity and confusion for OSCM practitioners. Accordingly, further insights could be garnered from examining the Industry 5.0 concepts and technologies (e.g. value-driven initiatives and bio-inspired technologies) which research (Xu et al. 2021) argues differentiates Industry 5.0 from Industry 4.0.

Second, the review involves a systematic approach that analyses themes of uncertainty and provides added insights on OSCM-based priorities for Industry 5.0 in English-language journal articles. Thus, the review is limited in coverage of perspectives from conference papers, book chapters, and grey literature. Such limitations underscore the prospects for other methodology-driven reviews such as meta-analyses and meta-syntheses to provide more theoretically-focused, empirically-focused and grounded contributions to OSCM knowledge. Further analysis on co-citations could provide insights into the nature of Industry 5.0 research citation dynamics and potential links between articles, offering fresh perspectives on the depth and breadth of studies on the Industry 5.0 paradigm.

5.4. Future research directions

Futuristically, this review offers some topics for further OSCM research studies. To begin with, the current topical focus of Industry 5.0 on supply chain architectures could benefit from systemic explorations of ergonomic and resilient design options while assessments could expand their focus to systematic evaluations of innovation and intelligence associated with creativity. Examinations on the nature of the technology-based toss-up effects within supply chains and operations could add to the discourse on managing digital supply chains while explorations on the embedded-extended logic of OSCM could unravel and operationalise novel Industry 5.0 phenomena which lie within and at the intersection of both supply chain strategies. The remainder of this section advances OSCM scholarship by setting a research agenda for further studies based on a methodical reflection of the review findings.

5.4.1. Industry 5.0 co-creation and intelligence for supply chain transition

Industry 5.0 is a value-driven (Enang, Bashiri, and Jarvis 2023; Ivanov 2023; Dacre et al. 2024; Goujon et al. 2024; Leng et al. 2024) paradigm for solving emerging societal problems and delivering sociotechnical solutions. In this paradigm, value co-creation is essential (Enang, Bashiri, and Jarvis 2023; Yao et al. 2024) and centres on involving beneficiaries in open innovation processes within supply chains to enable operators gain deeper insights into societal challenges. Similar to recent calls for studies on resilient and sustainable co-creation for Industry 5.0 systems (Leng et al. 2022; Ivanov 2023), this review urges for expanded focus of future research to include co-creation during supply chain transitions. Emphasis on transition uncertainty raises questions on how beneficiaries are co-opted for active roles in inventing, customising changes, and upgrading digital systems. Here, future research studies could include exploring the digital profiles and communities of transition co-creators and identifying configurations and strategies for facilitating transition co-creation.

Likewise, artificial intelligence research studies dominate the current focus on Industry 5.0 intelligence (Rožanec et al. 2022; Ahmed et al. 2023; Ghobakhloo et al. 2024; Pistolesi, Baldassini, and Lazzerini 2024), but the scope and potentials for intelligence that delivers creativity within supply chains is broader. For instance, Lu et al. (2022) ideate human-machine collaborative intelligence that synergises human and artificial intelligence systems to creatively sense a human operator's well-being. Thus, supply chain transition studies could consider computational, organoid, and synthetic forms of intelligence and other emerging paradigms for digitally-enabled intelligence which offer potentials for enhanced autonomous learning and smart production systems. In furtherance of innovation for OSCM practice, this review challenges researchers to widen the attention on Industry 5.0 intelligence for supply chains to consider computational, organoid, and synthetic forms of intelligence. With the spotlight on transition as a category of supply chain uncertainty, there is room for future Industry 5.0 research studies on the behavioural variabilities and characteristics of intelligent operators and the determinants of intelligent behaviours within supply chains. In-depth empirical insights on potential deliberate, flow, and spontaneous varieties of intelligence required of Operator 5.0 could also provide knowledge for clarifying creativity in supply chains and transition uncertainty.

5.4.2. Industry 5.0 risks and affordances for supply chain integration

Conventionally, OSCM research recommends focus on supply chain integration to mitigate uncertainties (e.g. (Flynn, Koufteros, and Lu 2016) and (Roscoe et al. 2020)) but an analysis of the Industry 5.0 literature indicates embedded and extended forms of OSCM strategies which challenge previous premise on the peak strategic role of supply chain integration. For instance, supply chain transitions are increasingly pivotal for supply chains because changeovers and upgrades enable supply chains to fix potential shortcomings and risks of existing systems. Broadly, an analysis of current research shows substantial work on risks assessments and maturity models (Hein-Pensel et al. 2023; Tomelleri et al. 2024) even more so for ergonomics, sustainability and safety, in comparison to resiliency of Industry 5.0 systems. Although, resiliency is an ability that enables operators recover from disruptions (Ahmed et al. 2023), it is crucial to how operators cope with tense and competitive situations. Thus, insights on the nature of risks to system resiliency from tense and competitive situations could offer risks indicators to inform and improve vulnerability management for supply chains. Further reflections on integration uncertainty presents opportunities for research studies on potential integration risks associated with toss-up effects, human-robot collaboration, intelligent digital ecosystems, and sustainable production systems.

Similarly, existing research argues for ergonomics-based risk and quality assessments (Battini et al. 2022; Coronado et al. 2022; Calzavara, Faccio, and Granata 2023; Destouet et al. 2023; Pistolesi, Baldassini, and Lazzerini 2024) with considerations for human well-being and welfare during supply chain integration. In support of the human-centric vision of Industry 5.0, these assessments lead to enhancements in work environments and systems for realising the Operator 5.0 concept (Destouet et al. 2023; Gladysz et al. 2023). In ergonomic designs, affordances (Gibson 1979), such as the appearance of robots (Panagou, Neumann, and Fruggiero 2024), are characteristics of systems that suggest opportunities for action. With evidence showing that affordances offer viable options for enhanced designs of production systems (Durugbo 2012), this review recommends further research studies on affordances for supply chain integration in line with Industry 5.0 principles. Concentrating on integration, as a category of supply chain uncertainty, offers avenues for studying Industry 5.0 architectural variabilities and the contingencies that determine affordances for human-centric operations and supply chains. Further research could also focus on identifying and modelling real and perceived affordances to aid in creating more robust and resilient systems designs for manufacturing, service and logistics operations.

6. Conclusions

Industrialisation is a transformative process that is innately complex, socio-technical, and knowledge-driven. Striving for gains beyond production efficiency, Industry 5.0 manifests an industrialisation era with ambitious visions of symbiotic human-machine collaborations for human-centric, sustainable, resilient, and connected production systems and solutions. Inevitably, this disruptive paradigm creates supply chain uncertainties and there are OSCM obligations to craft strategies that mitigate the emerging supply chain variabilities and vulnerabilities arising from Industry 5.0. In efforts to advance OSCM scholarship on Industry 5.0, this review set out to address questions on:

- **R1.** What is the current state of OSCM literature on supply chain strategy for Industry 5.0?
- **R2.** What are the uncertainties (i.e. variabilities and vulnerabilities) of supply chain transition and integration for Industry 5.0?
- **R3.** How can OSCM practitioners improve uncertainty management for supply chain transition and integration in the Industry 5.0 era?

Using insights from a systematic literature review of **73** journal articles from publications on the ABS and ABDC journal lists, this article applies thematic analysis to identify a holistic and inclusive OSCM strategy for Industry 5.0 based on: (i) flexible and intelligent architectures for social or human cyber-physical multi-agent systems, in line with reference architectures and global standards, and (ii) ergonomics-based and sustainability-based quality and risk maturity assessments and readiness models, informed by industry-wide standardised assessment frameworks (addressing **R1**). Further analysis of literature identifies a cluster of variabilities concerning human-centric and twin transition uncertainties alongside foundational and implemental integration uncertainties for Industry 5.0 architectures and assessments, and a triad of supply chain vulnerabilities concerning disruptions, tensions, and competitions (addressing **R2**). Collectively, these uncertainties demand an embedded-extended logic from OSCM practitioners based on embedded strategies that deal with variabilities and extended measures enacted to cope with events due to vulnerabilities (addressing **R3**). Additionally, the review theorises on how technology-based variabilities induce a 'toss-up effect' or indecisiveness due to the wide range of options available to supply chains. Managerially, the review has implications for how operators compartmentalise integration-transition within supply chains and segment the overall OSCM strategy into embedded and extended options. Based on a methodical reflection of the key findings, the review proposes topical areas for future OSCM research in terms of Industry 5.0 intelligence and co-creation for supply chain transition, and Industry 5.0 affordances and risks for supply chain integration.

In summary, Industry 5.0 strives to consolidate advances from Industry 4.0 by prioritising employee well-being, respect for the environment, robust systems, and digitalised interactions. Thus, the race in on for supply chains to fulfil and harness the opportunities of this vision, but as experience has taught OSCM researchers and practitioners alike, an awareness and factoring of supply chain uncertainties is crucial to navigating the potentials of industrialisation eras and paradigms.

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Data availability statement

No new data were created or analysed during this study. Data sharing is not applicable to this article.

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