A Review of Manufacturing Operations Research Integration in Closed-Loop Supply Chains

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Abstract
This paper explores the integration of manufacturing operational potential research towards fulfilling supply chain closed-loop operations. A schematic research approach on the previous literature review is performed to identify the possibility of supply chain management integration starting from outsourcing decision. It also focusses on the simulation approach in addressing core supply chain management challenges such as production layout, product strategy, volume and variety. The paper also highlights the limitations of current simulation practices, including lack of contextualization, limited strategic focus, and insufficient integration with appropriate technologies and substantial government policies. To address these gaps, a manufacturing operation tree diagram is proposed, incorporating manufacturing operation considerations as organizational structure. This diagram aims to guide future research toward more realistic, validated, and industry-relevant simulation models in manufacturing operational research. By aligning simulation techniques with strategic manufacturing norms, the study contributes to the development of agile, resilient, and data-driven supply chains. The findings offer valuable insights for both academics and practitioners seeking to enhance supply chain performance through simulation-driven analysis and planning.
Keywords: Supply Chain Management, Closed-Loop Operations, Simulation Approach, Literature Review, Operational Research, Malaysia

Introduction
In the current global market, manufacturing companies face constant pressure to produce and sell products quickly, safely, and at competitive prices. This is why companies continually

use strategies to improve the performance of their supply chains, ensuring uninterrupted production streams and satisfied customers. There is a supply chain management (SCM) system in every manufacturing firm, and it is regarded as the most complex issue in any firm, as well as the most poorly handled, therefore receiving the most attention. Termed the most complex business issue, it is apparent why the sobriquet is so, as the web of suppliers, manufacturers, and distributors is multifaceted. This is why SCM has had such appeal to the academic community, with numerous research works capturing the essence of certain strategies towards its optimization (Wang et al. 2020, Queiroz et al. 2022).

Though SCM has been the focus of a multitude of studies, there are few multi-dimensional approaches to the topic. Stevenson and Spring (2007) defined SCM as the imbalanced spinal coordination of business functions between an organization and the rest of the world to control supply and demand. There is a strong resemblance to SCM with the 'composition SCM' as defined by Christopher (2022), who viewed it as the SCM with control over the processes and relations of the entire 'value chain' integration to serve the 'end user'. In this case, procurement, transformation, and delivery activities describe pivotal processes of contemporary supply chains centered on the coordination and collaboration of suppliers and distributors concerning the flow of goods and information (Choi et al., 2018). Krajewski et al. (2005) determine that the internal collaboration of functions with suppliers to respond to customer demand has transformed into the concepts of supply chain agility and responsiveness. Dynamic adjustment in response to an increasingly volatile marketplace is emphasized in agile supply chain management (Dubey et al., 2019).

Schroeder Goldstein (2024) considers the inclusion of planning, design, and control activities as foundational., arguing that this is strengthened by the recent advances in digital technologies that provide high supply chain visibility and predictive analytics (Ivanov & Dolgui, 2020). The core SCM goals of inventory reduction, as determined by Nahmias and Olsen (2015), align with the recent initiatives on lean supply chains that emphasize the balance of low costs and high product availability. These working definitions demonstrate SCM as an integrative approach combining strategic planning, operational execution, collaborative partnership, and logistics coordination (Queiroz et al. 2021; Van Nguyen et al., 2023). The seamless networks created by effective SCM reduce waste, improve responsiveness, and enhance customer satisfaction (Salas-Navarro et al., 2024).

Recent developments in simulation software have greatly broadened its usability as a powerful problem-solving resource. Newer simulation packages have become much more intuitive and sophisticated, thus requiring no mathematical or computer programming skills to develop and execute complex, dynamic representations of real-life systems (Law, 2019; Pidd, 2016). Broadly construed, simulation is a collection of techniques and tools used to represent the actions of real or designed systems, frequently using computer systems (Kelton et al., 2020). Simulation in its many forms permeates multiple domains, sectors, and uses, rendering it an essential tool for exploring the behavior of systems in different contexts. Growth in computational and software tools sophistication and capacity has now made simulation more powerful and easier to use in practical applications than ever (Banks et al., 2020).

Fundamentally, simulation is the process of devising and assembling a computer model of a real or imaginary system to perform a series of calculative tests that yield the desired behavior of the system under a particular set of circumstances (Jmaa, 2025). These tests in turn facilitate an understanding of system behavior with the boundaries set. Simulation as a methodology, is, however, neither an optimization system nor a set of mathematical processes. It is more of an explorative and representational approach. Law (2019) claims that it permits "what-if" analyses and exploring the results of various scenarios or alternatives without necessarily attaining one optimal answer. This ease of use is important in supply chains, where closed form answers many times are impossible due to the complexity and uncertainty. From the manufacturing point of view, there is consensus that simulations are one of the best ways to deal with the stochastic variables in supply chains (Napalkova & Merkuryeva, 2012; Nikolopoulou & Ierapetritou, 2012). It offers a dynamic framework that can analyze and capture variabilities in demand, lead times, production, and transportation. Simulation models can deal with the complexity of multi echelon supply chains, help practitioners analyze system performance, identify bottlenecks, and assess different risk and operating policies (Brailsford et al. 2019).

In supply chain literature, simulation models are built using either discrete event simulation (DES) or continuous simulation. Although product and information may have flowing characteristics that are continuous, most literature in supply chains has preferred using discrete event simulation. This is because it is easier to represent individual events like order arrivals, completions of productions, or dispatching shipments (Pawlak et al. 2024). DES models the order of operations and the supply chain in a stochastic way and provides insights into the behavior of the system. In short, this is because simulation can provide a strong and versatile approach to the appraisal of complex, uncertain, and ever-changing systems. It analyzes the supply chain fantasies and strategies that are crucial to operational decision making and planning and does all this without creating a ruckus in the actual operational scenarios of the factory.

Against this backdrop, simulation has become a widely recognized and effective approach for modeling, analyzing, and optimizing complex supply chains. The objective of this study is twofold: first, to identify and synthesize key SCM concepts and definitions as presented in the literature; and second, to review and analyze significant simulation approaches that previous researchers have employed to address SCM problems. Section 2 categorizes the existing literature on simulation within supply chain management (SCM). Section 3 explores the views under two different categories simulation approaches in SCM, and strategic points for manufacturing operation to be considered. Finally, section 4 ends the documents by providing some useful conclusions in a contingency model and thoughts for future research.

Materials and Methods

The purpose of this paper is to address the gaps in supply chain management simulation to enhance manufacturing operations research. To achieve this, a systematic literature review was conducted to gather insights from a representative selection of peer-reviewed articles. The search employed key terms such as "SCM," "simulation," and "manufacturing," alongside related concepts in logistics and production systems. While many studies provided indirect contributions by highlighting the benefits of proposed models, methodologies, or performance analyses, a deeper and more critical review was undertaken by applying guiding

questions. These questions examined whether the selected articles (i) explored the utility and practical applications of SCM, (ii) defined the scope and boundaries of simulation approach within SCM in manufacturing operational research, (iii) proposed methodologies aimed at improving supply chain functions, and (iv) addressed the role of enabling technologies such as simulation software, information technology, and the internet in enhancing SCM. This structured review ensured the extraction of the most relevant and practically aligned contributions, thereby facilitating the identification of gaps within the existing literature.

In addition to the literature review, primary insights were obtained through focus group discussions with Malaysian manufacturing stakeholders, particularly facilitated by agencies central to the nation's industrial development. The Malaysia Automotive, Robotics and IoT Institute (MARii) plays a pivotal role in advancing the automotive sector by supporting digital transformation, supply chain integration, and technology adoption across firms such as PROTON, PERODUA, and their component manufacturers. Similarly, the National Aerospace Industry Corporation Malaysia (NAICO) provides strategic direction for the aerospace sector, fostering global competitiveness through initiatives in supply chain localization, certification, and advanced manufacturing capabilities. Inputs gathered through these agencies highlighted that while conceptual models developed in academia offer useful frameworks, simulation approaches must be carefully calibrated to practical realities such as fluctuating demand, extended global lead times, and stringent quality and compliance requirements set by international supply chains.

Within the scope of simulation techniques, the study identifies DES as the most widely adopted and effective approach for SCM research and practice. DES is particularly relevant to Malaysian automotive firms, where it supports demand variability analysis for production scheduling and supplier coordination, as well as inventory control across tiered supplier networks to minimize holding costs while maintaining service levels. Similarly, in aerospace manufacturing, DES has been applied to lead time optimization in highly regulated environments, where supplier reliability and logistics delays must be carefully managed to meet strict delivery schedules and quality standards. Industrialists agreed that DES offers more intuitive, operationally aligned insights compared to system dynamics (SD) or agent-based modelling (ABM), making it a practical decision-support tool for managing supply chain complexity in these industries. The convergence of insights from literature and practitioner's view strongly emphasizes the necessity of a contingency approach in SCM simulation research. Instead of a one-size-fits-all modelling approach, the evidence suggests that there is a need to align the simulation technique, model complexity, and focus of application to the specific characteristics of the industry, the organization, and the policy framework. For Malaysia, focusing simulation research on the context of its pivotal sectors of automotive and aerospace enhances not only theoretical but also practical relevance. Incorporating such factors will guarantee that decision-making based on simulation will help in directly improving the competitiveness, resilience, and sustainability of the manufacturing ecosystem in Malaysia.

State of the Art

Supply chains are becoming ever more complex and unpredictable, making the need for more nuanced strategic and operational decision-making more urgent than ever. Along with these needs, the challenge in integrating the growing body of logistical information and

theory has made simulations powerful tools for the construction of information-driven evolutionary models for scenario analysis. Indeed, there are very few works that focus on the relevance of simulation techniques within the context of SCM. This is in glaring contrast to the more mathematically tractable techniques, including optimization and forecasting. This section attempts to synthesize the simulation approaches in SCM with their developments on the methods, technologies, and application domains. This is to isolate the gaps to focus on in the next phases of research, including a primary concern about the too distant treatment of strategy-level issues around manufacturing and the gaps that proliferation of digital technologies entail. It is with such an agenda that this review intends to document the practices and developments in the SCM domain, to derive a more robust understanding that can lay the ground for the successive phases of research.

Simulation Approaches In Supply Chain Management

In recent years, simulation has started to be used to address the effects of modern SCM's intricacies and unknowns. The amount of scholarly work addressing directly simulation use in SCM is still comparatively minor in relation to other quantitative and analytical SCM domains, like optimization or forecasting. Most simulation studies in SCM are still centered on the same handful of peripheral components, such as demand uncertainty, lead-time optimization, the bullwhip effect, logistics performance, inventory control, and layout optimization. Broadly, these are the most critical operational issues that determine supply chain responsiveness, cost, and service level.

For instance, demand uncertainty still constitutes an important source of inefficiency and risk, while simulation has been instrumental in modeling stochastic demand patterns to assess their influence on inventory control and capacity planning, thereby gaining useful risk-aware inventory management strategies (Dolgui & Ivanov, 2020). Lead time reduction has also been studied extensively through simulation to find bottlenecks and optimize resource deployment in production and distribution systems (Brailsford et al., 2019; Adeniran et al., 2024). The bullwhip effect, where demand changes increasingly amplified becomes a focus of more attention, with simulation research analyzing the impact of improved information sharing and better coordination on the reduction of such inefficiencies (Dubey et al., 2019; Darmawan et al., 2025). Although these areas are still important, it seems that most attention paid to a limited set of aspects keeps the understanding of the profoundly complex SCM environment far from complete.

Whether manufacturing firms have achieved adequate attention or not, upcoming disruptive challenges like integrating sustainability, improving the resilience of supply chains to disruptions, and the digital transformation of supply chains have not yet received adequate attention in simulation research, despite their increasing strategic and operational relevance (Queiroz et al., 2022; Bruckler et al., 2024). These Simulation studies have not kept pace with the times, which is the reason the most recent such attempts miss the mark been described as imperatives that would assist in predicting decision outcomes in real world supply chains.

The food sector is the focus of most SCM simulation studies (Minard et al., 2024) and some works focus on the chemicals, electronics, automotive, aerospace, and pharmaceutical industries (Nhung, 2024; Sharabati and Jreisat, 2024; Ivanov & Dolgui, 2020). Other industries like retail, textiles, consumer goods, and healthcare are increasingly attracting attention

because of their intricate supply chains and demanding customers (Dubey et al., 2019; Tyagi, 2024). But within the context of the increasing industrial breadth, it is not uncommon for research works to fail to contextually elaborate on most significant real-life problems such as lack of regulations, sustainability challenges, unsustainable collaboration with suppliers, and geopolitical tensions (Rasshyvaloc et al., 2024). Such lack of context reduces the external validity and practical value of the simulations.

The lack of in-depth case studies featuring well-defined methodologies prevents reproducibility and lowers managerial trust in simulation results (Ivanov and Dolgui 2020). Very few studies perform thorough empirical validation or operational data benchmarking, thereby stifling their utility and their value in the decision-making process. Event simulation (DES) continues to dominate in SCM because it captures discrete, stochastic, and dynamic supply chain events (Bottani & Casella, 2024). It also captures sequential processes, queuing, and the interplay of resources in the capture in the capture manufacture-distribution system. On the other hand, it may miss important continuous flow characteristics and temporal relationships in some supply chain situations. Proposed to fill in the gap are hybrid models, which use both discrete and continuous methods (Brailsford et al. 2019). However, these models are still improving, and the use of such models are still low because of the intricacy involved and the steep learning gradient in simulation method modeling.

More recent fuzzy logic and data driven simulation techniques which address some formulated gaps are still lacking robust methodologies for supporting integration reasoning and higher-level decision aids in near real time (Dubey et al. 2019). These methodologies, however, are still underdeveloped in simulation. There is also the integration of big data analytics, artificial intelligence, and the technologies of the Industry 4.0. Such integration holds great promise in improving the responsiveness and accuracy of the model under simulation (Hofmann et al. 2019).

There are still obstacles to face, such as data veracity, model consolidation, and computing requirements, and the understandability of the iteration of more complex frameworks (Melnyk et al., 2024). Addressing these obstacles is fundamental to harnessing the full power of simulation on today's digitally embedded supply chains. ARENA is still the most widely used simulation software in SCM research, owing to its rich features, ease of use, and powerful modeling capabilities (Ravichandran et al., 2024; Lukito et al., 2025). In addition to ARENA, older software like WITNESS, PROMODEL, GPSS, and SIMPROCESS still fulfill modeling requirements, providing specialized alternatives in discrete-event simulation and supply chain process modeling. The engineering of these simulation packages with spreadsheets (like Microsoft Excel), statistical software (SPSS, JMP, Minitab), and programming languages (C++, Matlab, Python) are the example of a practical way of handling complex data sets for intensive analysis in a multi-model simulation-based environment.

The disparate and diverse set of tools still emphasizes the looming gap of standardization and cross-functionality integration in SCM simulation practice. Such fragmentation usually results in custom, opaque models that stifle reproducibility, model reuse, and progress in collective knowledge advancement in the entire field (Dubey et al., 2019). To mitigate these challenges, new systems are increasingly shifting toward cloud-based real-time collaboration simulation platforms that support integrated scaling and user-friendly interfaces. For

instance, AnyLogic has become increasingly popular as a multi-method simulation software that incorporates discrete events, agent-based, and system dynamics modeling, allowing for much more sophisticated and flexible SCM analyses (Ivanov & Dolgui, 2020). Likewise, FlexSim incorporates powerful 3D discrete-event simulation and model visualization, improving user engagement and model interpretability (Sun et al., 2024).

In application to custom architectures, models such as SCSIM (fuzzy logic-based uncertainty modelling), DELFOI PLANNER (investment evaluation) and SCBM (data-driven simulation) outline some of the more promising developments toward a more holistic approach to addressing complex SCM challenges. Still, due to these models' complexity and inaccessibility, they remain rather niche. In addition, it's apparent that most simulation studies still focus on operational or tactical matters, which spars attention on strategic decision making, sustainability, and supply chain resilience are still critical gaps in light of the ever-increasing global volatility and environmental concerns (Dubey et al., 2019). The advances in digital twin technology and Industry 4.0 are starting to change the SCM simulation landscape by providing the ability to model and simulate in real-time and predictively in conjunction with IoT streams and AI frameworks (Hofmann, 2019; Ivanov & Dolgui, 2020).

SCM offers an array of advantages and benefits, but the application of simulation is still lacking in SCM, as it is the most powerful and flexible approach to analyze and enhance SCM. Even though the simulation approach's application to SCM in its entirety is still piecemeal and descriptive, SCM simulation research is still heavily found on DES methodologies. These methodologies are great at simulating the operational parts of the system but tend to dry out on the continuous and broader system level dynamics of the supply chain. Many simulations, in addition, lack domain validation and fail to situate their frameworks in relevant operations or industries. The gap between practical application and academic modelling is what significantly diminishes the tangible SCM simulation research's impact and relevance in decision making circles.

The mergers of simulations with new digital technologies, such as big data analytics, AI, machine learning, digital technologies, and Industry 4.0, are still in the infancy stage (Chauhan & Signh, 2020). Difficulties with data quality, model scalability, computational complexity, and interpretability, as well as technical challenges, still obstruct the use of these new technologies within the SCM simulations. If these issues are not resolved, the simulation models are likely to become obsolete, or at the very least, out of touch with the supply chain technologies of today.

Strategic Approaches for Manufacturing Operation
Figure 1 outlines some of the critical norms influencing manufacturing operations. For this study, seven key industries that contribute substantially to Malaysia's Gross Domestic Product (GDP) were considered. From an organizational standpoint, the differences between manufacturing companies may include not only the operational processes, but also capital expenditure, investment, employee size, market scope, ROI, and production capability. These factors also affect the scope and the competitiveness of firms, determining their resource allocation toward technological investments, global market penetration, and long-term growth. For instance, large multinationals typically possess the ability to lower operational

costs due to the economies of scale and global supply chain networks and enhanced R&D collaterals, while small and medium enterprises (SMEs) specialized at niche markets, leveraging agility, and local market expertise. This elucidates the sheer breadth of organizational approaches possible in the manufacturing industry, and particularly how size and resource availability determine the scope of operational approaches and business outcomes. All these factors, especially digitization, sustainability, and local content development, help boost national competitiveness, especially for Malaysia, as outlined in the Industrial Master Plan 2030. These cross-sectoral plans aid firms in formulating strategies for investing in local workforces, upskilling them, localizing supply chains, and embracing compliance with global standards due to the availability of technology. Access to low interest loans, innovation grants, and partnering opportunities that address collaboration barriers and resource gaps, particularly help SMEs. As a case in point, under these plans, several key government agencies in Malaysia provide the intended support. MIDA is the principal body responsible for the promotion of foreign direct investments, as well as the promotion of local industry upgrading, covering the tax incentives, and pioneer status facilitation in addition to providing high-value manufacturing project facilitation. Sections of the Malaysia External Trade Development Corporation (MATRADE) assist firms, notably the SMEs, to complement SMEs funding and support services through proactive overseas marketing and trade missions, and other capacity-building activities. SME Corp offers and SME comprehensive support including funding schemes, funding and advisory services, as well as technology adoption programs. Likewise, the Malaysian Technology Development Corporation (MTDC) enables the promotion of technology transfer and commercialization through grants and venture capital., especially for Industry 4.0 and green technology firms. Other agencies support the implementation of initiative driven policies. The Human Resource Development Corporation (HRD Corp) fosters the development and learning of the workforce through levy-sponsored training schemes aimed at the development of the workforce in reskilling and continuous learning to bring the systems in place for the shift to match the industry. SIRIM Berhad Standards and Industrial Research Institute of Malaysia helps in the attainment of training and certification for developing the national standards for the enhanced industrial R&D, including product quality control and compliance with international requirements.
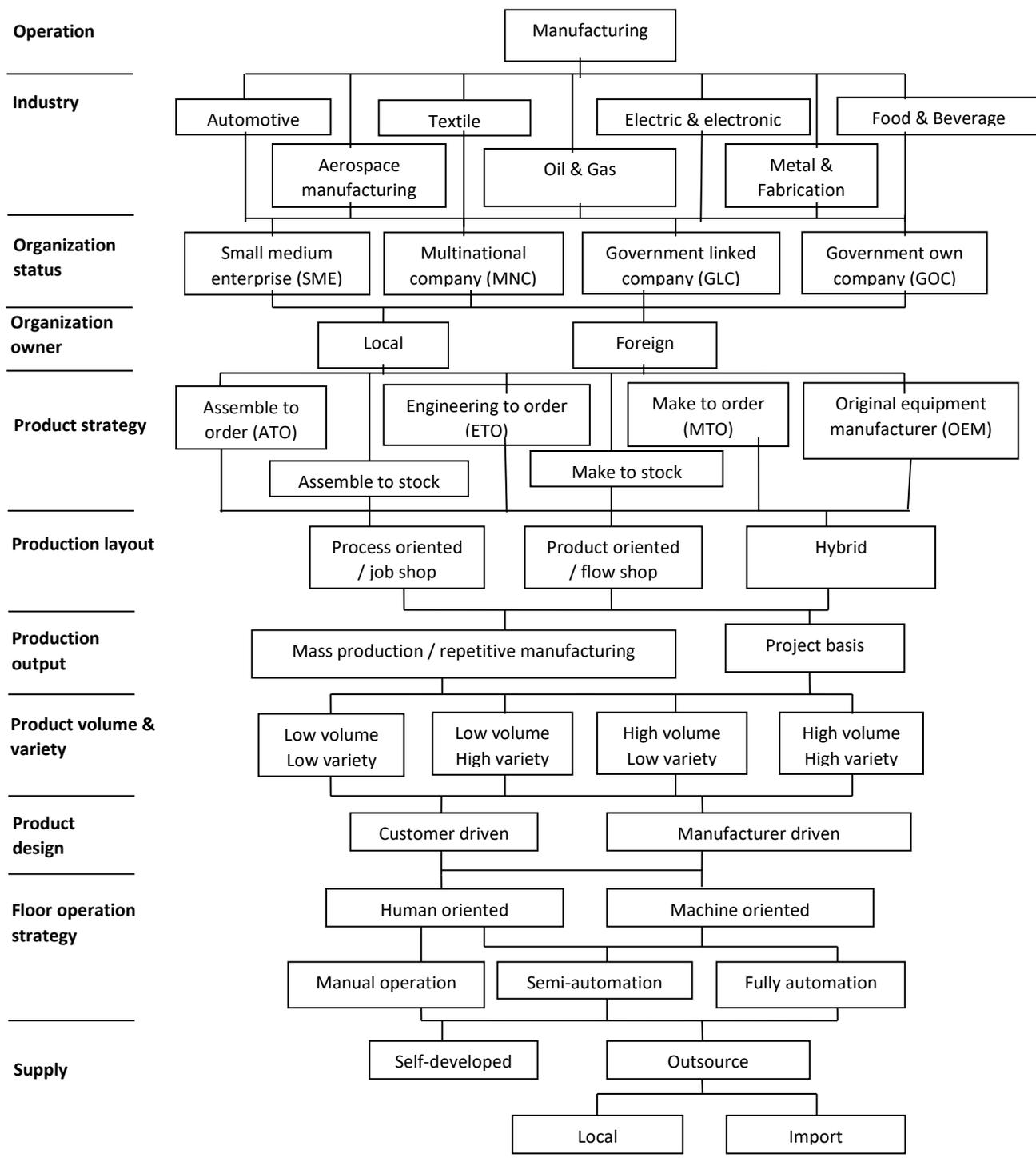
Figure 1 Manufacturing operation tree diagram

Moreover, organizations such as the Halal Development Corporation (HDC) supports manufacturers in accessing these international halal markets, whereas the Malaysian Green Technology and Climate Change Corporation (MGTC) facilitates the adoption of necessary sustainability instruments through carbon financing and reduction programs, as well as eco-labeling schemes. Nevertheless, the impact of these policies and institutions is contingent upon the degree of congruence between overarching industry-level goals and the abilities of the firm at the domestic level. Companies that take advantage of the agency's form

structuring whilst engaging in policy driven internal processes such as digital transformation, lean manufacturing, and sustainable supply chain management, are likely to experience greater international market share as well as sustainable growth.

Another defining factor is the kind of ownership a company has which could be local or foreign (Ghahroudi, 2018). This has a major impact on organizational culture, operational philosophies, and management practices. Local firms often embody national principles and sociocultural customs, placing high value on community, collectivism, and loyalty management of the workforce. Foreign companies, however, are likely to face global best practices, performance management systems, high technology operational models, and huge gaps in local culture. These ownership issues are sociological and psychological in nature, including employee motivation, trust, and engagement, which in turn are major determinants of productivity and innovation. A healthy organizational culture that is anchored on inclusiveness, skills enhancement, and shared leadership will promote commitment. On the other hand, a lack of alignment philosophy and expectation in the workplace will result in resistance, apathy or increased turnover.

Globalization and Industry 4.0 have made these organizational features more interrelated than ever (Chauhan & Singh, 2020). Investments in capital have a direct bearing on the technologies to be adopted and the rest of the supporting skilled workforce to be developed and trained both at the organizational and governmental levels. Such interrelationships are still observed in the ownership structures which impact on the integration of knowledge transfer and cultural integration. Therefore, ongoing industry transformation, with its focus on industrial upgrading and workforce localization, makes understanding the underlying dynamics of manufacturing competitiveness essential (Hofmann et al., 2019). A product strategy is the essence of every manufacturing operation, because it focuses on how organizations gain demand-side agility versus operational efficiency on a trade-off continuum in inventory and production control.

Make-To-Stock (MTS), Assemble-To-Stock (ATS), Make-To-Order (MTO), Assemble-To-Order (ATO), Engineering-To-Order (ETO), and Original Equipment Manufacturer (OEM) are differing levels of customization, lead-time pledge, and inventory exposure (Christopher, 2022; Nahmias and Olsen, 2015). For instance, MTS is based on demand forecasting and aims at high-volume production, thus minimizing unit costs; it also poses risks of obsolete if demand is forecasted inaccurately. On the other hand, MTO and ETO minimize inventory risk; they possess high lead times and Scheduling complexity. ATO and ATS are hybrid approaches that attempt to improve efficiency by postponing product differentiation to the latter stages of production, thus adhering to the mass customization principle that is increasingly gaining traction in highly competitive markets (Hernandez-Ruiz, 2016; Kiran, 2019). On the other hand, OEM strategies position firms at the core of extensive supply networks and thus, also rigidly monitored on quality and cost control, value-adding specialization economies (Jacobides et al., 2016; Wlazlak et al., 2019).

Alignment of strategy and operation makes the production layout choice fundamental., especially when a product strategy has been developed. Between a process-oriented (job shop) layout and a product-oriented (flow shop) layout. Each has its own benefits depending on the characteristics of production (Kiran, 2019). The process-oriented layout is more

flexible in nature, because the resources are grouped by function and capable of performing different types of products (Zhou & Wan, 2017). This has more utility in low volume and high variety cases, for example, in the production of aerospace and medical devices. On the other hand, the more flexible product-oriented processes are organized resources in a line or series of tasks which increase the efficiency in volume and mass production of automotive and electronic devices. This lowers the work in progress by the reduction of cycle times and improves flow, however, it is inflexible and poor in product mix and demand variability (Fernandes, 2012). Most firms, in practice, use a combination of the two layouts and use hybrid or cellular layouts to maximize the efficiency gained from one while minimizing the losses from the other. Most cellular layouts are arranged with functional machines grouped in cells which increase the efficiency of a family of products while reducing the handling of materials and improving the productivity through some flexibility towards variety (Buer et al., 2018). Strategies are changing more rapidly than layouts because of the more advanced Industry 4.0 technologies (Hofmann et al., 2019).

Advanced analytics, IoT automated monitoring, and flexible manufacturing systems allow companies to switch between strategy and layouts quicker, and more cost-effectively, thus catering to shifts in demand more effectively (Wang et al., 2022). The seamless integration of product strategy and layout design is in constant evolution and is no longer a matter of static integration. It is transforming into digitally enabled systems that respond to demand, all while balancing efficiency and flexibility (Fernandes et al., 2012). Firm strategy still mandates that first an attempt is made to define the type of manufacturing system which is termed as best fit (da Silveira & Sousa, 2010). The type of manufacturing which is either mass, repetitive, or project based has a direct impact on the product volume and variety, which in turn is the backbone for determining market responsiveness. Take for instance mass production. It offers standards across the board, thus becoming a low-cost solution, all while requiring limited customization. In the case of repetitive manufacturing, the system is made to produce a batch of items that are standard, with flexibility. Less customization, however, is offered in project-based production, which is scalable to any level. It is this type of production that the market is mostly geared towards. This goes to show the level of balance that is required between responsive adaptation and efficiency. It is this delicate line that determines the entire structure of the market. The design of products, however, has a much greater impact on the processes of production, thus explaining their degree of influence in the matter.

While customer driven designs are responsive to market needs, they still face significant challenges associated with compliance to industry norms and legal compliance. This adds to the operational challenges but also increases the competitive edge for more regulated industries like aerospace, automotive, and medical devices (Hines, 2024). On the other hand, the lack of engineering and production decision control through a manufacturer driven design, leads to greater process efficiency, but an increased cost ratio. This softens the risk of a design misalignment with shifting customer demands. This is to say, design strategies still lie somewhere between the market-product fit and the operational feasibility for manufacture, reiterating the need for the organization to balance the innovation with the capabilities of the business.

On the operational floor, the strategies are more compartmentalized into human and machine approaches. The human-centered production system focuses on manual labor and skilled artistry, thus providing greater flexibility and the capability to adjust easily to custom needs. However, their production is often plagued with high variability, sluggish throughput and lack of scale. On the other hand, machine-centered approaches gain greater efficiency, consistency, and quality control with lower labor dependence through semi or full automated systems.

The advancements witnessed in industry 4.0 have immensely increased the levels of automation within manufacturing, focusing the arms of smart manufacturing systems on the use of robotics, IoT, and real-time data analytics to proactively maintain systems and achieve real time responsiveness (Melnyk et al., 2024). Automation, however, comes at the expense of a substantial capital investment and diminishes the agility of the workforce, further necessitating the incorporation of hybrid models, which can seamlessly merge the machine and human counterparts. Success in maneuvering design orientation within production models relies on the strategy adopted since that is the only way to maintain flexibility, balance efficiency, and responsiveness to the market in the wake of competition.

Supply management regardless of type (raw material or inventory) is necessary in providing operational continuity, resilient operational environment, and resilient uninterrupted operational system in the manufacturing system (Chae et al., 2025). A decision central to the strategy is whether to internally produce supplies (make) or to externally source them (buy) and whether to source internally or import (Chae et al., 2025). These decisions affect direct costs and times to deliver, as well as the ability to control the quality, and monitor the in supply to production system, and exposure to the system as a whole supply chain risk. For instance, local sourcing can increase system agility by reducing the transportation leg of the system, and distribution lead times (Prayitno, 2024; Alam, 2025).

On the other hand, importation usually has lower prices as well as more advanced supplies, but the risk of geopolitical issues, global crises, and logistical delays arising from supply issues are much more exposed. The increased focus on circular economic practices has added pressures on firms to measure suppliers on more than just cost and quality, further complicating and strategically deepening the sourcing decision focus of firms. SCM and manufacturing operations research have usually employed supply issues at the center of these issues in a more peripheral and fragmented manner. Case studies focus more on the adoption of a strategy and its accompanying technologies, quite often ignoring the lower tier, basic, operational mechanisms of supply, such as the access to raw materials, sustainer trustworthiness, and poor inventory controls. This in turn, depressingly narrows the application of the theories, moving from abstract thinking to real-world scenarios, blocking the possibility to broaden the research to the other industries. The gap of under supply, clearly visible during the COVID-19 pandemic, or the semiconductor deficit, coupled with changes in trade policies, have shown the world just how transparently fragile the global supply chains are, as well as just how resilient the sourcing strategies must be (Dienes et al., 2024).

These are, as much as possible, to be integrated in the rest of the SCM research framework and simulation models. Consequently, this allows for tool and strategy

development that manages supply dependence, variability, and risk balancing. It starts with the selection of suppliers as one of the essential trade-offs between local and global sources, safety stocks distribution policies, and sustainable-reshaped procurement. Such factors, if incorporated into research design, will increase SCM research and its practical relevance and interdisciplinary translatability. Resilience and adaptability of supply chain models to the realities of complex manufacturing systems can be introduced with the right framing of the above factors. At the end, if aligned research with SCM operational priorities, it will enhance SCM frameworks' robustness, applicability, and impact, as well as expanding the range of SCM scholarly and practitioner-oriented insights and actions.

Discussion and Conclusion

Simply put, the authors point out that there is still ample opportunity for further research on the combination of simulation techniques and operational practices, especially in SCM. Their extensive literature review, along with the manufacturing dimensions in Figure 1, suggests that there remain several important issues that have either not been studied at all or studied very little. Such issues present an opportunity for further research directed towards better appreciation or use of simulation in intricate supply chains especially for manufacturing operational research.

One key observation is that many existing studies tend to overlook or insufficiently describe the manufacturing operation context, which is essential for readers and practitioners to fully grasp the realities and constraints of real-world production systems. Without a clear depiction of the operational background, simulation models risk being abstract, lacking relevance, and failing to address the practical challenges faced by manufacturing firms. Furthermore, there is limited discussion on how manufacturing-specific factors such as organizational structure, product strategies, production layouts, and supply sourcing decisions directly influence supply chain performance and simulation outcomes.

To bridge these gaps, the authors propose several critical research questions that could serve as a roadmap for future investigations. These questions aim to deepen the understanding of SCM dynamics and clarify the strategic and operational role of simulation technologies in optimizing supply chains:

- What are the preferred simulation packages and software tools currently utilized for managing complex supply chains, and what factors drive their selection?
- Understanding the landscape of simulation software adoption helps identify best practices and technology gaps in SCM modelling.
- What motivates manufacturers to adopt simulation approaches for resource optimization within SCM?

Exploring strategic drivers, such as cost reduction, lead time minimization, or risk mitigation, will clarify the practical value proposition of simulation.
- Which performance metrics and analytical frameworks can be effectively modelled and evaluated through simulation in SCM?
- Identifying key performance indicators (KPIs) such as inventory turnover, service levels, throughput, and resilience metrics will enhance targeted improvements.
- What is the role of simulation as a decision-support tool in SCM, particularly in facilitating real-time, data-driven decision making?

- Examining how simulation integrates with enterprise resource planning (ERP) systems, digital twins, and AI can highlight its evolving influence on supply chain agility.
- How can simulation-driven analysis enhance the overall effectiveness and responsiveness of SCM processes?

    This involves studying the impact of simulation on demand forecasting, production scheduling, supplier coordination, and disruption management.

- What organizational., technological., and operational considerations must manufacturers evaluate before implementing simulation tools?
- Issues such as data availability, model complexity, user expertise, and cost-benefit analysis are crucial for successful simulation adoption.
- To what extent can existing simulation packages be adapted or extended to better address emerging SCM challenges, including sustainability, digital transformation, and supply chain resilience?
- Assessing the flexibility and scalability of current tools is essential for future-proofing simulation applications.

    To sum up, this study advocates for more integrative research approaches that holistically consider manufacturing operations within SCM simulation studies. By addressing these research questions, future investigations can develop more realistic, validated, and strategically relevant simulation models. Such advancements will not only enrich academic knowledge but also offer tangible, actionable insights for practitioners aiming to enhance supply chain performance in an increasingly complex and dynamic global environment. Figure 2 illustrates a proposed contingency research framework designed to guide future investigations that integrate supply chain management systems, manufacturing operations, and simulation techniques, building upon the current state-of-the-art insights presented in this study. This framework provides a structured roadmap for researchers aiming to develop robust and relevant SCM simulation research.
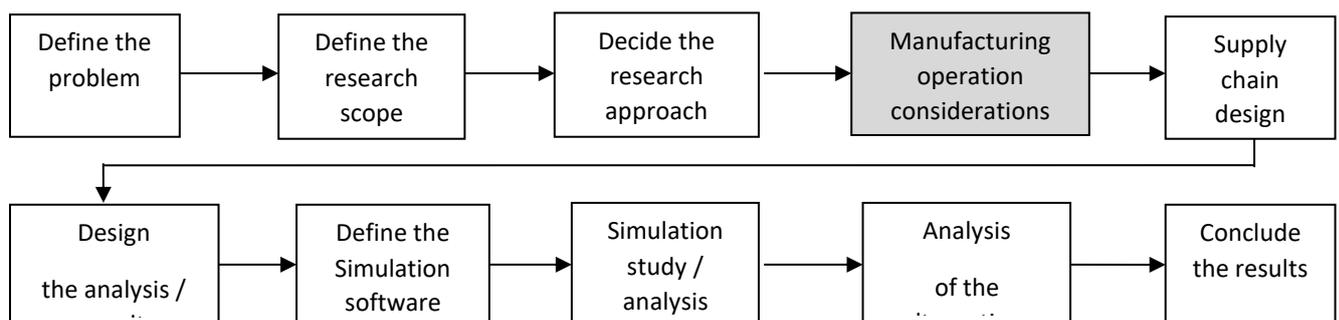

Figure 2 Contingency research framework for manufacturing operational research with SCM simulation Approach

    The research process should begin with a clear and precise definition of the problem, which forms the foundation of the entire study. This initial step is critical as it shapes the direction and focus of the research. Following this, the scope of the research must be carefully delineated, detailing the boundaries and extent of the investigation to ensure it remains manageable and targeted. Defining the research scope provides clarity on which aspects of SCM, manufacturing operations, and simulation will be examined.

Research should thoroughly assess all the relevant criteria before defining the scope. Characteristics of operations such as type of industry, configuration of the production system, marketing and product strategy, organizational structure, and sourcing of supply require background studies at higher levels. This contextual backgrounding fosters grounding to real-world manufacturing and relevance and practicality of the simulation models to be constructed. At the same time, defining the parameters the researcher wishes to work within and developing working hypotheses that will structure his inquiry and tests become the next in line parts to be accomplished. Having parameters and hypotheses fixes the scope of the investigation while providing enough granularity to evaluate the research outcomes systematically. In the case of supply chain studies, more effort should be taken on the case study's supply chain configuration and its description. This consists of defining and outlining the center of gravity, primary branches and bends, and important relationships within the supply chain, as well as specifying the framework for structured analysis and results presentation. The simulation and the corresponding formulated objectives and the problem statement will be, to the best of our ability, everything that we will work on to have these outputs.

Within the scope of these objectives, another important framework boundary is the decision on which simulation software to use. The research aims and the methodical approaches together with required data elements should also dictate the selection of software. Researchers should assess the software's capabilities for modelling, user-friendliness, ease of integration, availability of tiered functionality, and advanced analytics to obtain the best fit. After software selection, meticulous calibration of the input parameters and design of the experiments permits execution of the simulation study with controlled precision. Coherences of input data and the derived output must be synchronized with the earlier set parameters of the analyses and result dispositions to ensure the research's validity and internal consistency. Researchers, and especially those involved with the modelling of the simulation constructs, will benefit from the preservation of alternative scenarios or strategies of the constructs. The research will then be able to carry out comparative analyses of these alternatives and thus determine the best servicing supply chains and improved operational efficiency. The best research takes the form of an insightful analysis, devoid of unsupported assertions and properly encapsulated to demonstrate the research objectives have been attained. The critical elements of the research should also be preserved. This will ensure the applicability of the results, and then properly articulate future research directions, and thereby add value to the research for both theory and practice.

Authors' Note
The authors declare that there is no conflict of interest regarding the publication of this article. The authors declare that they used AI-assisted tools to check and improve the grammar, sentence structure, and overall clarity of the manuscript, to ensure it meets the journal's standards for language quality. Authors confirmed that the data and the paper are free of plagiarism.

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