Production Management and Supply Chain Integration

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Abstract

Digitalization not only improves the individual's performance but also helps orchestrate supply chain partners to serve a bigger goal. To fully benefit from supply chain digitalization, a high level of integration between different functioning blocks is required. This chapter investigates the major interactions between production management decisions and the supply chain strategy, structure, and performance to explore Supply Chain Integration (SCI). For this purpose, the design and development issues of production management are first investigated. On this basis, decisions with a strategic nature, including product design (what), material and technology selection (which), process design (how), and facility layout (where) optimization are analyzed. Next, the planning and control issues, including production scheduling (when), quality management, resource management and supervision (who), and planning for disruptions are explored, which have a rather tactical nature with short- to mid-range goals in response to the aggregate plan (why) of the supply chain. Every section is concluded by suggesting rooms for pursuing SCI.

Keywords

Supply chain strategy, product and process design, production planning and control, interactions, performance improvement, operations management.

Contents

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1. Introduction

The fourth industrial revolution, widely known as Industry 4.0, has transformed research and practice in many fields; supply chain management is no exception to this trend. Industry 4.0 is formed around digitalizing processes, making them interconnected, and interoperable, while ensuring that they occur in a smart environment enabled by real-time data-driven decision-making (Gunnarsson et al. 2006). Industry 4.0 and its enabling technologies have the potential to improve individuals' performance in every corner of the supply chain by improving productivity and flexibility, resource and energy efficiency, as well as waste reduction. However, the effective integration of processes and activities is essential to fully exploit the advantages of supply chain digitalization at a systemwide level (Ghobakhloo et al. 2021). Achieving greater degrees of integration requires considering the impact of individuals' decisions on the performance of other players. Besides, individual decisions can be well-informed and aligned with the bigger goal with visibility over supply chain collaborators. In addition to reduced costs and response time, enhanced integration has implications for improving supply chain quality, flexibility, and resilience (Danese et al. 2020; Tiwari 2020).

Supply Chain Integration (SCI) refers to the extent to which a company and its supply chain collaborators work together to more effectively manage intra- and inter-organizational processes and improve the flow of products/material, information, and funds (Zhang et al. 2015). In this definition, the activities, and processes from the acquisition of raw material and sourcing to those involved in producing and distributing the final goods interact. Some of the interactions are more notable than others, making it necessary to simultaneously plan/optimize their associated operations.

As a major process in the manufacturing supply chain, production interacts with all the logistical functions (i.e., inventory, facility, transportation, and sourcing). Questions regarding what to deliver, who, when, where, and how to complete the operations should be answered considering both supply chain and production management aspects of operations. Whether the company targets cost-effectiveness, responsiveness, or it wants to differentiate its products and services from those of rivals, production management decisions can help adjust the operational capabilities to establish strategic fit. Besides, the production management decisions should be aligned with the supply chain strategy to better complement it. For example, a cost-effective supply chain is mostly concerned with enabling low-cost operations. In this situation, the way the production operations are handled influences the performance of downstream players and the supply chain cost as a whole. On the other hand, the production operations are significantly impacted by the performance of the upstream collaborators, which may have a different competitive strategy. This interaction manifests itself in both macro and micro managerial decisions. Therefore, it is important to understand the underpinnings of production management decisions and the way they influence supply chain operations.

This chapter elaborates on the interactions between the major production management topics and the supply chain structure, strategy, and performance. For this purpose, the managerial decisions pertinent to the development and design issues, as well as planning and control issues are considered to investigate the possible interdependencies. Section 2 discusses the design decisions and the way they interact with supply chains strategy, structure, and decisions; that is, why to enter a market and what to produce (product development), how to produce the products (process design), which technologies and materials to use (technology selection), and where to do the operations (facility layout planning). Section 3 elaborates on the question of when to conduct the operations (production scheduling), quality control issues, who should conduct the operations (resource management and supervision), as well as planning for possible disruptions. The chapter is concluded in Section 4 with major remarks and managerial insights.

2. Development and design issues, and supply chain management

Product development

The performance of a supply chain depends on many factors one of which is the characteristics of the products it accommodates (what). A continuous evaluation of the efficiency and effectiveness of the product portfolio and adjusting them is necessary to maintain the supply chain's competitiveness. Well-informed product design/redesign decisions are one of the managerial tools to help improve supply chain performance, e.g., reduce inventory times (e.g., the use of standard modules), transportation volume (e.g., the postponement of assembly operations), and, overall, the operational cost (Handfield et al. 2020). Product development and supply chain management capabilities counterbalance each other (Morita et al. 2018). In addition to product design elements for mass customization, i.e., modularity and multi-skill employees, high supplier involvement and the supply chain's moderating role are required to ensure the best outcomes (Ye et al. 2018). For example, companies can reduce the time-to-market if they include supply chain partners in the product development process. On the other hand, the bargaining power of suppliers and customers (Porter 2008), as well as the strategic partnerships, should be considered in the product development process. It is also suggested that new product development (Reitsma et al. 2021), and other product management decisions, like product revitalization and discontinuation, should be made considering the supply chain-related factors (Pourhejazy et al. 2019, 2020, 2021b). These interdependencies emphasize the impact of product management decisions on supply chain strategy and performance.

The supply chain operations are impacted by product design decisions both at the network and node levels (Reitsma et al. 2021). From a network-level perspective, the product design decisions interact with the supply strategy: whether to outsource certain parts/services to a third party or keep them in-house. They also define the extent to which the supply chain partners, particularly suppliers, should be involved in the design process. If the parts and/or products are planned to be outsourced, one should certify and/or train the third-party actor. Otherwise, if the operations are decided to be completed internally, which of the manufacturing facilities should produce the product, and what should be the operational capabilities of other facilities. Besides, one should select the most appropriate transportation mode considering the product features, compartments, and needs. Overall, these aspects both directly and indirectly influence supply chains' fixed and variable costs. Supply chain reconfiguration for managing risks in time of new product development is another strategic topic at the intersection of product development and SCI (Sabzevari et al. 2019).

From the node-level perspective, packaging operations are impacted the most by product design. For example, a fragile product requires more rigorous packaging; in this situation, alternative material and design approaches that increase the robustness of the product reduce packaging costs. Taking IKEA's approach to product design as an example, postponing the final assembly until the point of consumption is a paradigm shift in the supply chain of furniture and home appliances. In addition to reducing the transportation cost and inventory times enabled by increased modularity, the downstream supply chain nodes do not require assembly-related capabilities, like space, machine, and/or workforce, hence, fixed costs can also be reduced. In addition to the node- and network-level activities, product design decisions have an impact on supply chain planning, in particular, demand forecasting, capacity planning, and inventory management (Reitsma et al. 2021). For example, the use of common parts in the design of products reduces the variety of required inventory, which alleviates the warehousing complexities and reduces sensitivity to the forecasting outcomes (Jha et al. 2017).

In addition to improving the financial performance of the companies, integrating product development and supply chain management helps improve less-tangible aspects of supply chain performance, like open innovation, supply chain trust (Rahmanzadeh et al. 2020), visibility, responsiveness, and risk (Khan et al. 2016). It also has implications for a circular economy (Burke et al. 2021), and the adaptation of Industry 4.0 (Benzidia et al. 2021), among other examples. Alleviating profit-loss due to remanufacturing and improving environmental performance were recognized as the major advantages of integrating product design into green supply chain management (Liu et al. 2019).

Concerning the barriers to integrating the product development and supply chain, loss of intellectual property may be worrisome for companies who seek vertical integration, especially high-tech and sensitive products, like chip manufacturing. Besides, it may be a challenge for international companies with offshore production activities in distant locations to take full advantage of product design and SCI. New technologies, like Virtual Reality and 3D printing, can come to play to bridge the gap.

Product design has an impact on technology and material selection and the design of production processes (Marsillac and Roh 2014), like handling and storage of the incoming and outgoing materials and the flow of materials on the shop floor, which are the determinants of internal logistics performance. We will delve deeper into these subjects in the next subsections.

Technology and material selection

Given the characteristics of a company’s products, production managers are responsible for selecting the right technology and material before designing the production processes. As a strategic production management decision with long-term implications, technology selection should be done considering the capabilities and requirements of the supply chain partners (Farooq and O’Brien 2012). These requirements are pertinent to the cost of the material/parts, their quality, delivery speed, the flexibility of the technology to adjust to the changing market needs, and the commitment of the corporations to innovativeness. On the other hand, the selected technology should be compatible with those of the partners, their technical constraints, and the available supply chain infrastructure.

A production (or logistics) technology alternative that best serves the supply chain strategy and goals should receive a higher priority than the technology that maximizes individuals' performance. A cost-effective supply chain benefits from well-established and mature technologies with bringing down the fixed and variable costs being the goal. An original part manufacturer that selects expensive technologies, which produces high-end parts but cannot offer a competitive price, may not fit in a cost-effective agenda. On the other hand, responsiveness and differentiation-oriented supply chains require new technologies with higher degrees of innovativeness to stay ahead of the competition.

Depending on the corporate strategy and the type of product/market, the managers may prioritize their technology investment plans for a particular function block of the supply chain; this may limit the budget for the rest of the company-owned facilities. From the perspective of the competitive forces (Porter 2008), the supply chain players should be concerned about what technologies are used by the existing and potential rivals, otherwise, it may be hard to stay competitive. Besides, depending on the market, the customers may be willing to pay for the products and services that are produced using the latest technologies. The type of technology used in production and logistics processes also plays a major role in the sustainability of the supply chains; a supply chain with old technologies that is running in its optimum norms may have a higher overall carbon footprint than that of an underperforming supply chain that is equipped with state-of-the-art machinery. Selecting greener technologies is especially important for corporations seeking to promote a green image. Overall, technology is an enabling factor for the supply chain's competitiveness regardless of the competitive strategy.

Adaptation to new technology may require a change in the supply chain structure, especially when it emphasizes a disruptive innovation. In this situation, delivery time, cycle times, labor cost, manufacturing cost, inventory levels, and required production capacity will be all impacted (Coronado Mondragon et al. 2017). Taking additive manufacturing (3D printing) as an example, the production sites can be more distributed and located in closer proximity to the point of consumption or remote areas. Besides, such technologies can change the sort of partnership a supply chain seeks. For example, 3D printing service providers may come to play, and shorter supply tiers may be involved in the production of semi-finished materials, components, and structures. Blockchain technology for regulating the information and funds flow is another prime example of disruptive technologies with implications for SCI. In particular, the adaption of smart contracts can streamline the procurement formalities, and time, and address legal issues and partnerships. These examples further highlight the role of technology selection in SCI.

Technology selection literature has been well supplied by decision-making frameworks including supply chain-related considerations (Farooq and O'Brien 2012; Xia et al. 2017). Relatively limited attention has been directed toward incorporating technology selection variables in supply chain optimization. Supply chain network design considering location and technology selection (Elhedhli and Gzara 2008; Marvin et al. 2013) may be the most relevant integration scheme considering that both decisions have a long-term and strategic nature. Supply chain tactical decisions, like planning and coordinating demand and supply, as well as managing inventories in a supply chain are also interrelated with manufacturing technology selection decisions but have not been investigated by practitioners and academics. For example, the optimal level of product availability may vary considering different production technologies considering that the speed at which a unit of product is produced and the required skilled staff and/or labor force for running the process are different.

Material selection has received relatively more attention in the supply chain context, especially because it is closely relevant to supplier selection. Supply chains are loaded with materials and the characteristics of the selected material determine the operational requirements. For example, the distribution and warehousing facilities should be equipped with refrigeration gear for handling perishables; selecting materials with milder requirements reduces the supply chain’s fixed costs and operational complexities. Besides, packaging and storage costs may be minimized by selecting the material with the right physical state (Tzetzis and Symeonidou 2015). In the upstream supply chain, selecting materials that are subject to less supply process complexity, like tariffs, local and international regulations, and those with alternative supply sources are preferred. The power of suppliers is another relevant aspect that emphasizes the role of material selection decision variables in supply chain optimization; selecting material from monopolized markets increases supply risk and reduces the control of the focal company over price and quality aspects.

Like technology selection, material selection should be well aligned with the supply chain strategy; cost, quality, and delivery speed of the final product are directly impacted by the material type, while it also can hinder or facilitate operational flexibility and innovativeness. From a supply chain sustainability perspective, selecting materials with a lower carbon footprint and avoiding materials with negative environmental and health impacts have become a necessity. Besides, material selection has implications for supply chain structure and reverse logistics activities. As a prime example, selecting recyclable materials facilitates closing the supply chain loop, making it easier to take them back into the production cycle (Ndiaye 2012). In contrast, the use of non-sustainable materials may exacerbate the complexities involved in the corporate social/environmental responsibility in the supply chain. The characteristics of the selected technology, material, and requirements determined by the product development/design process are used as inputs to the process design subject, which is discussed in the next subsection.

Process design

The activities performed to add value and the associated preparations are referred to as the production process; the overall goal is transforming inputs (i.e., raw material and energy) into outputs (i.e., products and services). Conversion, fabrication, setup and preparation, machining, assembly, and quality control are some of the usual operations involved in the production processes. Production process design considers the following inputs to decide the sort of required operations, and sub-processes: flexibility of the available equipment, labor, the selected technology, inputs from the product development and management disciplines concerning the required variety of the products/services, and the expected sale volume from the forecasting department.

Selecting what processes need to be executed in each of the facilities is a strategic production management decision with implications for supply chains. This decision is often influenced by physical limitations in the upstream supply chain. For example, access to raw materials and suppliers, skills and knowledge, technology, and low wages can make a location more desirable for certain production processes (Pourhejazy and Ashby 2021). Furthermore, technical requirements may necessitate certain processes to be performed together, and/or within a certain time gap, or in a certain climate condition due to the product characteristics. Intellectual property-related factors are other examples that influence the selection of processes and their location.

Process structure (production setting) is another strategic-level decision in the design of production processes; it is made based on the operational characteristics, in particular product variety and volume. Selecting the process structure determines the pattern of material movements in the manufacturing plants. Job shops, flow shops, and open shops are seminal examples of different process structures. The flow shop category requires all the items to go through an identical sequence and number of machines/processes; it is suitable for high-volume production of similar/standard items. When the variety of products is high and the required production volume is low, a job shop may be the best alternative. Under the job shop setting, the items should be processed on every machine but in different orders. Finally, in the open shop, the items can be processed in an arbitrary order (there are no precedence constraints), and a different number of machines/processes. Other production settings, like hybrid and flexible flow shops, combine the above major categories to better match the case-specific industrial needs; they will be discussed in more detail in Section 3.1.

The logistical requirements for the above production settings may vary. For transportation on the shop floor, the production process in open shops is subject to irregular movements, which is in contrast with flow shops where less intensive and more regulated material movements are prevalent. That is, internal logistics in flow shops can be handled using more automated means of transportation while this level of automation may be infeasible and/or economically less viable in the job shop and open shop settings. We could not find any evidence that proves that there is a significant difference in the inventory level on the shop floor for different production settings.

In terms of external logistics, given that flow shops deal with a high volume of standardized products, the economy of scale plays a significant role in their supply chains when compared to the job shop and open shop productions. In this situation, the continuous flow of inbound and outbound logistics highlights the need for advanced decision synchronization, information sharing, and collaborative performance systems (Simatupang and Sridharan 2008) and more effective supply chain collaboration and coordination. Besides, each of the production process structures has different facility investment requirements. In a job shop, general-purpose machinery is required to ensure the flexibility of the operations and the labor should be multi-task and highly skilled. Flow shops do not require these but may need a higher process continuity and automation level. Overall, flow shops require relatively higher investment (Mohammadi and Forghani 2017); therefore, they are economically viable when a highly stable market in terms of demand and variety is targeted.

If the production process is designed in isolation, small fluctuations in the supply and demand sides of the supply chain can be amplified as they progress along the chain (Blackhurst et al. 2005). Given the significance of this amplification effect, integrating the production and supply chain process design elements should be mainly investigated from the material flow perspective. In the upstream supply chain, extreme demand fluctuations may put pressure on the manufacturing and procurement cycles. In the downstream supply chain, delays in the production process can interrupt the replenishment and customer order cycles. Disruption propagation across the supply chain (i.e., the ripple effect), emphasizes the interdependencies among supply chain operations and entities, suggesting that the supply chain-related decisions, like the number of deliveries (inbound and outbound), and the time interval between them (Chung and Wee 2012) should be considered when designing the production process structure. Such integration helps reduce inefficiencies (Geismar et al. 2008), improves organizational performance, and environmental factors (Khanuja and Jain 2019), and facilitates supply chain digitalization (Tiwari 2020).

In addition to the above considerations, the process design should account for less-tangible tactical and operational factors like maintenance and inspection mechanisms, which should be made considering the logistical elements of the supply chain, i.e., inventory management and distribution operations. For example, production downtimes can be planned considering the state of the logistics elements and in coordination with the supply chain partners. The integration of production process design and supply chain can also be investigated from a quality perspective. Traditionally, logistics operations are designed assuming that the products are perfect while imperfect quality items are hard to avoid. Reworking the imperfect quality products helps reduce the total costs (Ouyang and Chang 2013); however, the returned items may be burdensome to the supply chain if the reworking processes and logistics are not well coordinated. On the other hand, the quality of raw materials may be deteriorating, which makes it necessary to manage them in an integrated manner. Another relevant aspect is the integration of reverse logistics and the design of the production process. In particular, an integrated design of the collection and disassembly processes helps alleviate the impact of the uneven and uncertain flow of returned materials in production continuity and cost.

Facility layout design and optimization

Acknowledging the importance of material movement in the productivity of manufacturing and logistics operations, the design [and optimization] of facilities' layout impacts the supply chain performance. This impact is mostly related to the connectedness of the individuals in the supply network, where improving the efficiency of the nodes results in reduced supply chain time, cost, and enhanced agility in the long run. Industry 4.0 and the need for higher degrees of automation further highlight the importance of connecting the internal and external material flows in smart facilities. Despite the benefits of including facility layout variables in the supply chain context, it has been largely overlooked by academics and practitioners.

The facilities should be designed considering the production process, selected technology/machinery, expected production capacity, and the supply chain strategy. The first three determine the material flow while the last specifies the broader objective and the broader needs a facility should serve. Recalling from the process design subsection, the flow shop setting is best suited if high-volume standardized products are produced, otherwise, other production settings may be preferred. Within this general framework, the details of positioning things may differ depending on the company's desire to run a cost-effective system or seek high levels of responsiveness and/or flexibility. Having designed the facility layout, the managers can determine the optimum level of product availability and the aggregate plan based on the actual production capacity, the available inventory-carrying space, as well as the market situation.

In manufacturing facilities, the buffer zones for keeping raw materials, parts, and work-in-progress are limited; sound layout design decisions help maximize space utilization and make room for keeping inventories. Besides, an optimum layout helps a smoother material flow on the shop floor, which, in turn, reduces operational costs and improves agility. This helps avoid bottlenecks in the supply chain network where an interruption in material inflows to one node due to lack of space or inefficient movements inside the facility may spread across the downstream supply chain. Integrating the facility layout variables into supply chain risk and optimization models helps address disruption among other operational uncertainties caused by poor synchronization.

As another supply chain network element, warehouses are often necessary to provide the right quantity of materials, parts, and products available at the right time/space. Otherwise, managing supply and demand mismatches in a volatile market becomes a prohibitive task. Simultaneous determination of warehouse layout and the inventory control policies, such as storage policies and inventory routing, have implications for supply chain performance improvement (Roodbergen and Vis 2006; Roodbergen et al. 2015). Taking internal material handling (i.e., movements and storage) as an example, automatic guided vehicles, optical guidance systems, and robots are being increasingly deployed to load/unload incoming and outgoing trucks. In this situation, the major facility elements, like the unloading gates, recharging stations, sorting, and buffer areas, as well as waypoints and optical paths for the navigation of automatic guided vehicles, should be optimized considering the inbound and outbound flow variables to reduce avoidable delays (Ribino et al. 2018).

More advanced supply chain practices like cross-docking have been used in certain industries to streamline the response time to customers' orders. Given the dynamics in cross-docking facilities, real-time data collection, synchronization, and analysis should be used for dynamic reconfiguration of the storage area to better integrate the inbound and outbound flows (Vis and Roodbergen 2011). From a supply chain information flow perspective, considering historic data on suppliers’ performance and customer demand patterns facilitate well-informed layout optimization in the upstream and downstream supply chain facilities, respectively. For example, the layout design of retail stores, as the interface component between customers and goods in a supply chain, can be dynamically adjusted by investigating less-tangible operational needs extracted from historic demand data (Ozgormus and Smith 2020), for example, strategic positioning of products in the store. The other example relates to the seasonal supply chains or those expected to experience occasional but dramatic changes. Massive demand variations for a company with many products necessitate operational strategic adjustment of the production processes for which updating the facility layout may be necessary. Layout redesign considering supply chain parameters and product demand variations for disaster relief operations is a good example of this type (Tayal and Singh 2019).

Finally, the decision of resizing, repurposing, or moving strategic functioning blocks across the existing supply chain facilities is another relevant responsibility of the production managers. The location-allocation and network optimization problems are well addressed in the supply chain context (see (Eskandarpour et al. 2015)) but assigning departments to different supply chain facilities and moving them received limited attention. The Research & Development and Engineering Design departments, as prime examples of delicate units of a corporation, are often located in closer proximity to the production sites and/or in the focal company. Intellectual property, access to state-of-the-art technologies, knowledge, and resources, as well as geopolitical considerations, maybe in favor of relocating and/or decentralizing sensitive departments. Such decisions result in long-term and sustainable outcomes if made considering wider optimization goals. Overall, layout design and determining the location of the departments within and across facilities requires both financial and non-financial supply chain considerations in addition to optimizing cost and productivity.

Section 2 discussed the major design and development topics and their interactions with supply chain management. Planning and control issues are elaborated on in the next section.

3. Planning and control issues, and supply chain management

Considering the long-term strategy for the supply chain, aggregate planning is required to direct the business activities over an intermediate time horizon. Aggregate planning is a supply chain tool that sets a tactical framework for demand fulfillment decisions; it uses the inputs from the forecasting department to determine the production, inventory, and outsourcing levels, as well as possible backlogs to maximize profitability (Chopra and Meindl 2015). The aggregate plan becomes a basis for the production managers to decide the production schedules, organize the available resources, and deal with the quality control issues to serve the tactical goals at the factory level. This section elaborates on these production management topics and the way they interact with supply chain structure, strategy, and decisions.

Production scheduling

Once the aggregate plan is determined by the supply chain managers, production managers are responsible for scheduling the operation at the level of individual production units. Production scheduling consists of determining the order of jobs to be dispatched to machines/units such that the available time and resources are used efficiently. In a broad sense, production scheduling can be categorized into single-machine, parallel-machine, flow shop, job shop, and open shop settings; several other variants combine two or more of these production settings, which are named hybrid settings. There are many extensions to each of the main production configurations, which are proposed to address case-specific industry situations, and practical needs, and facilitate the real-world applications of the scheduling theory.

Given a set of jobs to be completed on a set of different machines (production stages), all jobs in a flow shop require an identical sequence of operations. In a job-shop environment, however, jobs go through a pre-specified but different sequence of operations (precedence constraints). In an open shop, the sequence of operations for every job is different but arbitrary with no precedence constraints. In the job- and flow-shop constructs, each operation should be completed on a specific machine while in the flexible variant of these production settings, the operations can be assigned to any machine from a given set. Finally, in the parallel machine setting, machines are either identical or uniform and jobs should go through one of the available parallel machines for a certain number of stages, which can be different from one job to another.

In addition to the operational characteristics that determine the type of production setting, supply chain considerations may have an impact. For example, the supply chain may require the assembly operations to take place at the same facility where the parts are manufactured, which can be modeled as distributed two-stage assembly scheduling (Pourhejazy et al. 2021a). Otherwise, assembling at a separate facility should be modeled using the distributed assembly permutation flow shop scheduling (Ying et al. 2020). As another example, a responsive supply chain may require a set of machines in each production stage (redundant capacity; instead of a single machine) to better respond to demand surges; this may make flexible flow shop and job-shop more viable settings than their basic production variant. The desired flexibility in the production process (i.e., single- Vs. multi-purpose machines) is another relevant supply chain factor with implications for scheduling.

Recent studies recognized the need for a supply chain-oriented view toward production scheduling. These models can be categorized into distributed scheduling problems and production routing problems. In the former group, production operations across distributed manufacturing facilities are scheduled simultaneously. Extending production scheduling from an isolated optimization approach to an integrated one, this category emphasizes coordination between different production units for fulfilling global demands while optimizing the collective performance of the system. Distributed blocking flow-shop, distributed no-wait flow shop, distributed no-idle flow shop, distributed parallel-machine, distributed job shop, and distributed flexible job shop scheduling problem are some of the recent variants of supply chain-oriented scheduling problems. Such models can incorporate order assignment variables for better integration of customer orders and manufacturing cycles. In so doing, the possibility of rejecting an order and backlogging them may be of interest to certain use cases. On the other hand, procurement-related decision variables can be incorporated into distributed production scheduling with release dates to take into consideration the possibility of delays in receiving raw materials and parts.

The latter category is rather focused on the concurrent planning of sequential [and heterogeneous] operations along the value chain, i.e., the production and distribution activities. In the traditional approach, production scheduling solutions are used as inputs for optimizing the distribution operations, which may result in the following planning issues. First, the distribution operations may be planned based on infeasible input data, for instance, the delivery may be scheduled for an order that is experiencing a production delay. Second, a lack of coordination between the two processes may result in sub-optimal solutions. For example, a customer order with less urgency may be prioritized in the production stage earlier than more urgent ones, which results in poor responsiveness, operational burden, and unnecessary cost. Third, integrated planning of the production and distribution processes is important for maintaining product quality in the supply chain of time-sensitive and perishable products (Ullrich 2013), while a stand-alone approach may not effectively account for this requirement.

The scheduling variants are predominantly developed in response to case-specific and technical production requirements. For example, the no-wait setting indicates that a work-in-progress job should proceed to the next operation immediately after finishing the current one. In the no-idle setting, the focus is on the idle time of resources, where machines must start processing new jobs immediately after completing a current task without delays. In addition to these technical features, operational requirements, like setup time and due dates, are considered in the form of mathematical constraints to better reflect the real situation. As another optimization aspect, the optimization criterion of distributed scheduling models is directly influenced by supply chain objectives. The maximum completion time of all jobs (makespan) determines the response time to new demands; the number of tardy jobs and maximum lateness are service-oriented measures, and total weighted tardiness prioritizes more urgent demands;

these measures support a strategic fit in responsive supply chains. On the other hand, total completion time emphasizes better utilization of the resources, and total flow time concerns minimizing the work-in-process inventory; these objective functions are suitable for supply chains with cost-effectiveness agenda.

There are other opportunities for extending production scheduling to improve SCI. From a market perspective, the product mix and the demand size in various regions are dynamic. An optimal location-allocation solution for a certain period may not remain optimum in the next periods. In this situation, facility transfer is a possible option for adjusting the supply chain. Facility transfer adjusts the factories' cell formation and production capacity, which have an impact on production schedules in different planning periods. Given the mutual relationship between facility location (a supply chain network optimization decision) and production planning considerations, they should be optimized simultaneously (Liu et al. 2018). From an operational viewpoint, make-to-stock supply chains require real-time coordination between production and inventory management (Dong and Maravelias 2021). That is, producing additional units of products should be subject to inventory variables and limitations. On the other hand, rescheduling might be necessary to boost production and reload the product inventory. Finally, production scheduling can be extended to consider product defects and account for possible reworks, in particular, considering its interactions with the transportation variables (Gheisariha et al. 2021).

Given the tactical plans like production scheduling, the production managers should control the operations to check whether they are being performed as planned. As the next control topic that interacts with supply chain decisions, quality management issues are discussed next.

Quality management

Quality is one of the main determinants of supply chain strategy. A cost-effective supply chain may not emphasize high-quality materials, parts, and services. Besides, the cost-effective strategy is in favor of minimizing the investment of resources and selecting cheaper logistics operations (i.e., slower modes of transportation and less frequent replenishments), which may have negative consequences for quality, particularly for consumables. On the other hand, product quality and safety may be compromised if the supply chain overemphasizes responsiveness, for example by relaxing the quality control processes and measures. All downstream and upstream supply chain partners should adopt a coordinated quality control system that serves the competitive strategy (Jraisat and Sawalha 2013).

From a supply chain structure perspective, more distributed facilities may be better for the quality of perishable goods, where a shorter distance to the supply and demand nodes reduces the odds of spoilage and degradation. In other cases, centralized facilities may benefit from economies of scale and more delicate quality control tools and approaches. The absence of integrated quality control/visibility over the supply chain partners may put supply continuousness at risk (Tsai and Faa-Ching Wang 2004); quality assurance may be in favor of supply chain vertical integration and in-house production of parts/components (for example, using additive manufacturing) where the manufacturer has better control over the quality of raw material and parts.

The quality of the products a supply chain offers depends on various aspects among which, the input materials/parts, workforce skill, the state of machinery, tools, and production processes contribute the most; continuous evaluation and improvement of these elements facilitate better design, optimization, and management of supply chains (Grenzfurtner and Gronalt 2021). The interactions between quality management and supply chain should, therefore, be explained considering the role of material, man, machine, and methods in production management.

Material. When it comes to the procurement of raw materials and parts, the main interaction happens between the quality control aspect of production management and the pricing element, which is regulated by the supply chain strategy. As an intersection between production and supply chain management, material quality has been well investigated in the academic literature (Xie et al. 2011; Chen et al. 2014). Integrating the quality control variables into inventory optimization models allows for addressing uncertainties from an operational perspective. New inventory management strategies (e.g., consignment stock and vendor-managed) have been introduced as a result of this integration; such strategies extend the supplier's responsibility for the quality of the product until the consumption point (Alfares and Attia 2017). The cost (time) of quality control operations is another production management aspect that is investigated from a supply chain optimization perspective (Cogollo-Flórez and Correa-Espinal 2019).

Expectedly, less attention has been directed toward the intersection of quality control with the transportation and facility elements of the supply chain. This is particularly relevant for the logistics of consumer goods and perishables, where time and keeping conditions impact product quality. Considering the information technology element of the supply chain, access to real-time data on the status of materials, parts, and products helps improve quality control. The role of blockchain in confirming the source of the material (i.e., suppliers of suppliers) is a prime example of disruptive technologies with implications for quality control and counterfeit issues.

Machine. In addition to the quality of incoming material/parts, using calibrated and well-maintained machines for processing them has a positive impact on the quality of the final product. There is a bidirectional interaction between the reliability of different supply chain stages and product quality, which should be considered in the maintenance of machinery in multi-stage systems (Zhou and Lu 2018). Channel coordination in the maintenance practices by individuals in a supply chain enhances the machine availabilities, and product quality, and reduces production costs (Chong et al. 2012). These, together, increase supply chain profitability under certain coordination strategies (Maletič et al. 2012; Jiang et al. 2020). More rigorous preventive maintenance operations may be required in supply chains with a responsiveness strategy. On the contrary, emphasizing reactive maintenance may decrease the individuals' short-term costs (when compared to preventive maintenance) but can hurt supply chain performance even if the supply chain pursues a cost-effective strategy. From a supply chain structure perspective, centralized production reduces the cost of maintenance services; this may improve the effectiveness of quality control activities and enhance product quality.

Integrating maintenance decisions in supply chain tactical planning improves optimization outcomes (Fatehi-Kivi et al. 2019). Besides, supply chain optimization can benefit from integrated quality control and maintenance (Jiang et al. 2020). From an information viewpoint, the recent advances in big data analysis and machine learning help predict possible failures by early detection of anomalies in the real-time data collected using sensors (Cheng et al. 2021); this facilitates quality control along the value chain. Maintenance information and quality history of material/parts from across the supply chain can also be used for optimizing product quality and lifecycles (Madenas et al. 2015).

Methods. Production processes along the value chain are another determinant of the quality of materials, parts, and products. Process control and improvement are necessary for maintaining quality at the desired norms. The production manager in each manufacturing unit is responsible for reacting to anomalies detected through process information analysis (Schiefer 2002). The complexities of the process control system depend on the supply chain structure. In a highly distributed manufacturing setting, coordinated process control is necessary to enable supply chain managers to trace anomalies to prevent the propagation of quality loss and delays in a timely fashion. As a means of improving process and product quality, Lean and Six Sigma concepts have been widely adopted for process improvement in supply chains (Chugani et al. 2017). The classical supply chain optimization models have been extended to account for process control-related variables. For example, inventory models are improved by including the variables pertinent to production process adjustments (e.g., stopping production and performing setups) in case of quality issues (El Saadany and Jaber 2008). From an information flow perspective, radio frequency identification technologies can assist lean production to further improve the transportation, storage, and retrieval processes in a supply chain (Chen et al. 2013). In addition to improving product and service quality, process improvements reduce scrap, and reworks, among other types of waste, which help the company to stay competitive by lowering the final prices they offer in the market.

Manpower. There is consensus on the positive impact of supplier development programs on the quality of materials/parts (Karaer et al. 2020). Production management practices, training, development, and performance management of the employees within the company-owned facilities have seen little progress in the supply chain context despite its significant impact on supply chain quality and innovativeness (Haq et al. 2021). With a strategic view towards quality, integrative, exportive, or adaptive human resource practices help create synergy and improve the individuals' performance should it follow a supply chain-oriented approach (Lengnick-Hall et al. 2013). Regardless of the sort of supply chain strategy, successful SCI requires training, development, and performance management of the employees (Menon 2012); however, the objective of these human resource practices may vary depending on the supply chain strategy. Overall, integrating human resources and supply chain management helps boost competitive strategy and organizational performance (Jena and Ghadge 2021). The next subsection elaborates on the organization and management of resources.

Resource management

The rapid changes in consumer preferences and shortened products' lifecycles have added to demand volatilities and supply process complexities. In this situation, the available resources should be managed effectively to meet the demand at the lowest operational cost. While material resource management is closely related to handling the physical flow in the supply chain, other resources, like manpower, machines, as well as land, energy, and water, are managed at the factory level. The way the decisions on managing these resources interact with supply chain strategy, structure, and performance is now discussed.

Supply chain management is mostly concerned with managing supplier and customer relationships while manpower capital plays a pivotal role in integrating the operational elements (Song et al. 2019). At the factory level, production managers are responsible for the supervision and organization of workforces in close collaboration with the human resource department. Manpower supply practices (i.e., recruitment, planning, and training) are essential to maintain the operations at the desired norm. The shortage of skilled workers in individual production sites propagates along the supply chain and results in an array of operational issues, from quality degradation to delays. An integrated view towards manpower resource and supply chain management, therefore, improves corporates' performance while it has been largely overlooked (Jena and Ghadge 2021).

Supply chain strategy directs the recruitment, planning, and training programs. A cost-effective supply chain emphasizes highly repetitive routines while a responsive supply chain strategy requires multiskilling and workforce empowerment. Besides, supply chains that compete on differentiating their products and services often tend to spend more on training programs. On the other hand, the supply chain structure is impacted by manpower resource considerations, like access to skilled workers, cheap labor, work culture, and social sustainability issues. From an operational perspective, the organizational interdependencies between the workforce across supply chain entities and departments make it necessary to consider manpower resource shortage along with the physical resources to mitigate the disruption effects (Aviso et al. 2018). Given the less tangible nature of decisions on the organization and supervision of workforces, limited integrations of such variables can be found in the supply chain optimization context. Integrating the decision variable on the type of workers for executing certain production tasks (considering their competencies) into the supply chain network optimization models (Paquet et al. 2008) and reverse logistics operations (e.g., electronics waste collection (Pourhejazy et al. 2021c)) are some of the major examples.

For managing machinery and equipment, resource redundancy is a safe way of coping with demand fluctuations. Supply chains with a responsiveness agenda typically use such resource management strategies while cost-effective supply chains are mostly cognizant of maximizing the utilization of the available resources. Line balancing is a possible way of balancing the machine time and adjusting the production rate for demand fulfillment, especially when the production system has tight utilization rates of machinery resources. In this approach, the number of machines (and operators) assigned to each task is rebalanced to adjust the production rate. This kind of optimization tool provides decision support to production managers, but it can result in better outcomes when coordinated with supply chain variables. Including the assembly and disassembly line balancing variables into the supply chain network optimization and closed-loop models is a good example of this type of integration (Yolmeh and Saif 2021). New technologies, like additive manufacturing, make it easier to manage resources and adjust to demand changes. Besides, the use of big data analysis and machine learning approaches helps improve resource management by reducing non-value-adding activities and addressing less-tangible aspects of operations.

Finally, land, energy, and water are the basic resources required for any supply chain activity with the production sites being the most resource-intensive facilities. The amount of required resources of this type is a matter of technical requirements (e.g., semiconductor production sites require huge water reservoirs). Access to such resources is considered one of the essential criteria for selecting the location of production facilities as strategic supply chain decisions. Production managers are responsible for managing the available land, energy, and water resources at the operational level. Managing such resources at the factory level has little interaction with supply chain strategy but it impacts the supply chain structure. For example, limited land, energy, and water may encourage extending the supply tiers to find alternative sources for the products that cannot be produced in-house due to land, energy, and water limitations. Besides, distributed and geographically dispersed facilities or relocation decisions may be triggered by resource limitations. A holistic view of the long-term requirements, as well as the profile of available resources across the supply chain, are prerequisites for informed resource management decisions (Taherzadeh 2021). At the factory level, the availability of land resources may influence inventory management decisions as well as the production level. Adaptive resource planning may be required to adjust to the changing operational conditions. In particular, dynamic adjustment of the available spaces is a relevant decision that can be considered to best manage such resources in volatile times.

The planning and control issues discussed up to this point in Section 3 are meant for routine operations (i.e. when everything goes as planned). Disruptions, especially those impacting factory level operations, change the situation, hence, require decisive actions and alternative solutions to mitigate the adverse supply chain effects as much as possible. This is discussed in the next subsection.

Planning for disruptions

Impacting the availability of resources (i.e., power, machines, material, and manpower), unexpected events can interrupt the production processes at the factory level, which may result in major supply chain disruptions. Planning for disruptions consists of preparing for unexpected situations, finding alternative solutions for maintaining the production facilities as operational as possible, and having strategies for a quick recovery after a major disruptive event. Digitalization and SCI improve connectivity, transparency, and effective information flow between different departments within and outside of the factory, which enables a timely and well-informed course of managerial actions in times of disruption (Treber and Lanza 2018). Training programs, which are discussed earlier in the chapter, and drills are some of the initiatives for disruptions preparedness at the factory level.

From an operational perspective, the production processes can be impacted by a disruption in (1) supply (material, parts, and components); (2) manpower, machines, energy, and water; as well as (3) demand. Supply and demand disruptions relate to the management at the supply chain level. Supply chain decisions, like the location and volume of redundant inventory in the network, help alleviate the negative impact of material disruptions, for example, by buying time for finding alternative resources and/or addressing the shortage problem. At the factory level, the production manager considers the severity of the disruption and its root cause(s), which requires up-to-date knowledge of the state of the system at the time of disruption, and decides to delay the operations, outsource them, or renegotiate the accepted orders for possible backlog or cancellation. Production rescheduling is a possible production management solution in response to production disruptions (Katragjini et al. 2013). Production management decisions, like rescheduling, have implications for supply chain performance (Rao and Ranga Janardhana 2014). In addition, rescheduling production operations is the most common way of minimizing losses after disruptions (Paul et al. 2015). In either case, the company may have to employ additional machines and manpower or adjust the working hours of the existing ones (additional shifts and/or overtime work) to fulfill the backlogged demands. Such decisions should also be made in coordination with the supply chain partners to ensure a smooth flow of raw materials and finished products.

Production managers may take advantage of alternative solutions (e.g., disruptive new technologies) for producing delayed (or interrupted) parts/components in-house. For example, additive manufacturing can be used as an alternative production method in times of supply disruptions. Possible changes in the production methods on the shop floor impact the supply chain structure. Taking the alternative manufacturing methods for producing parts/components as an example, the company may have to seek material suppliers and/or third-party 3D printing service providers, which can shorten or extend the partnerships, and supply tiers, and alter the network configuration. This also has implications for supply chain performance in terms of cost, quality, speed, and flexibility. Dual-channel supply chain optimization models should be developed to account for the possible shift between the regular and alternate production approaches considering various disruption scenarios.

In times of disruption in the market demand for certain products, the shop floor may not be required to operate at normal capacity due to the physical limitations in the factory and supply chain. Slowing down the operations and/or reallocating the available resources in response to demand disruptions are some of the possible production management solutions in such circumstances. These factory-level decisions should be made in coordination with downstream entities, in particular warehouses, distribution centers, and retail stores, to pursue optimum outcomes. As another example, a disruption in outbound distribution operations due to accidents, vehicle breakdowns, and weather conditions may impact production operations. In this situation, integrated planning of production and distribution activities provides better outcomes than an isolated optimization approach (Li and Li 2020). Overall, the production management decisions, like production scheduling and line balancing on the shop floor, may interact with those of the supply chain, like a change of transportation modes, inventory, sourcing, and pricing policies; integrated optimization models may be helpful for well-informed decisions. Integrated optimization of the production and inventory variables considering the possible disruption risks in the production process (Malik and Sarkar 2020) is a recent example.

Using redundant resources is a common strategy for dealing with disruptions caused by manpower no-shows and machine breakdowns. From a planning perspective, employing additional manpower and machines reduces dependency on individual resources. The main tradeoff is between the fixed/variable costs of redundant resources and the ability of the system to remain operational in times of disruption. Crucial resources and bottleneck operations should receive a higher priority for building redundancy. Besides, the break-even point of using redundant resources varies depending on the supply chain strategy; a cost-effective supply chain may not use many redundant resources when compared to a responsive one. Cost-benefit analysis for deciding the use of redundant resources should consider a systemwide perspective. That is, the decisions should not be focused on the optimality of an individual production facility, or, more generally, a supply chain entity. From a technical perspective, informed maintenance of machinery and equipment is necessary to prevent unplanned breakdowns. In the case of reactive maintenance, 3D printers can be used to facilitate repair and maintenance activities by producing machinery components and tooling equipment that may require weeks or months to be supplied in a regular situation. Concerning disruptions in the energy sources, alternative solutions like the use of solar panels are becoming more viable options. The geographical characteristic of the production facility is an enabling factor for the selection of alternative energy sources.

Overall, different combinations of production management and logistics measures result in different outcomes when reacting to disruptions (Peukert et al. 2020). In this situation, a standalone planning approach may result in either infeasible or suboptimal solutions. On the other hand, the possible disruptions in the system are usually reflected through parameter changes in the optimization models. In addition to stochastic optimization approaches and dynamic programming that can account for such features, applications of simulation-based optimization models help address the underlining uncertainties effectively, especially when planning for possible disruptions.

4. Concluding remarks

As a prerequisite to supply chain digitalization, SCI requires that the possible interactions between individual units and/or operations are taken into consideration for design and planning purposes. This will help pursue a global optimum when improving operations. The integration between supply chain elements has seen developments in both academic literature and practice. Production management topics, which are rather concerned with shop floor decisions, and their interactions with the supply chain have directed relatively less attention. To investigate the major links between the two managerial topics, we first considered the design and development issues, including product design (what), material and technology selection (which), process design (how), and facility layout (where). Planning and control issues, including production scheduling (when), quality management, resource management and supervision (who), and planning for possible disruptions are then considered. Every subsection discussed the interdependencies between the subject matter and the supply chain strategy, and structure, and elaborated on the impact of the respective decisions on the supply chain performance. The subsections were concluded by providing insights into some of the latest technological and/or academic developments and suggestions for future works on the subject.

Overall, we think that there are many opportunities for improving the supply chain performance beyond its optimality norms by considering product management-related decisions. This includes joint optimization of production and supply chain variables as well as decision-making considering the factors within the premises of the shop floor. Given the tradeoff between the complexity of an optimization model and its practicability, the sort of integration should be determined considering the targeted competency and the core interactions. For example, integrating the production scheduling and inventory management variables should be targeted when achieving a short product shelf-life is the optimization priority. On the other hand, disassembly and reverse logistics variables should be optimized simultaneously when the supply chain emphasizes the use of recycled material and closed-loop operations. Besides, operational mandates may impact the sort of integration, for instance, just-in-time production requires an advanced level of connectivity between the production and distribution operations. From a methodological perspective, simulation-based optimization frameworks should receive more attention in SCI. This is particularly relevant for integrating the micro and macro processes at the intersection of production management and SCI. Reducing modeling assumptions, generating more accurate model parameters, more realistic performance evaluation, and the effective inclusion of various uncertainty sources are some of the major advantages of simulation-based optimization methods.

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