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Complex and lean *or* lean and complex? The role of supply chain complexity in lean production

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Abstract
Research on Lean indicates that its association with performance improvement, although compelling, is not uniformly positive. Prior researchers have posited that plants implementing Lean may become too lean or may only implement selected aspects without fully embracing Lean's synergistic prescriptions. We explore another potential reason for lower-than-expected performance sometimes associated with Lean: supply chain complexity. Using survey data from 209 manufacturing plants in seven countries across three industry groups, we test two alternative mechanisms by which supply chain complexity may influence performance improvements expected from Lean: moderation and mediation. We find that, while supply chain complexity has very little moderating impact on this relationship, it mediates the relationship between Lean and performance. While the majority of the significant mediating effects are negative, serving as a tax on Lean's effect on performance, our analysis reveals some positive mediating effects, highlighting the difference between dysfunctional and strategic supply chain complexity. Our results indicate that managers should reduce internal and upstream complexity to improve Lean's effect on performance. In particular, reducing the number of inputs a plant must manage has the widest and largest effect on realizing Lean's positive influence on performance. Further, we highlight the importance of reducing dysfunctional supply chain complexity, while developing strategies to accommodate strategic supply chain complexity.

Keywords Lean · Supply chain complexity · Supply chain management · Complexity

1 Introduction

The practice of Lean has come a long way since its early roots in JIT and the Toyota Production System, spreading to a majority of manufacturing firms in developed and developing economies. Although overwhelming evidence supports the proposition that Lean improves performance, this is not consistently true (Jacobs et al. 2015), and there is evidence that some contextual and environment effects are not well understood (Mackelprang and Nair 2010). Thus, there may be other variables affecting the relationship between Lean and performance that have not been thoroughly investigated.

One potential explanatory factor is supply chain complexity, described as "one of the most pressing issues for contemporary supply chains (Akin Ateş et al. 2022, p. 3)." Global supply chains, by their very nature, are complex, dynamic systems (Prater et al. 2001), with complicated upstream and downstream linkages that are often global and tied by physical and information flows and relationships (Akin Ateş et al. 2022; Shah and Ward 2007). As such, they face the challenge of dealing with "many actors in many tiers, from multiple industries, potentially located everywhere on the globe (Bier et al. 2020, p. 1835)." Although the negative outcomes of supply chain complexity are well understood, managers may have difficulty identifying the mechanisms by which supply chain complexity impacts performance of

In Memoriam: Prof. Cecil Bozarth led the early efforts on this research, which extends from the work that appeared in the highly influential 2009 article that he co-authored with others on this paper. With Cecil's passing in 2018, our remaining co-author team continued to refine and develop the research that was guided by Cecil's early influence and direction, ultimately resulting in this paper. We are grateful for the contributions Cecil made to this work, and we are honored to have our names appear with his as a posthumous tribute to his contributions to the field of Operations Management.

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initiatives like Lean (Manuj and Sahin 2011), and little is known about how robust Lean's outcomes are in the context of supply chain complexity. Thus, understanding the sensitivity of Lean to supply chain complexity is paramount.

However, the above perspective presents an overly simplistic view, ignoring the fact that not all supply chain complexity is exogenous. A manufacturer's competitive strategies (including Lean) may actually increase the very complexities Lean is expected to mitigate. For example, as Lean encourages firms to develop deep, cooperative relationships with suppliers or develop backup suppliers to mitigate risk, the unintended outcome can be increased supply chain complexity. Further, the above perspective ignores the fact that some types of supply chain complexity may be strategic (Suri 2016); for example, expanding the customer base is associated with increased revenues despite driving increases in downstream complexity. While traditional thinking about supply chain complexity has focused primarily on dysfunctional complexity associated with outcomes such as supply chain disruptions, quality problems, and lack of robustness in supply chain design, strategic supply chain complexity (although challenging to manage) can be associated with desirable outcomes such as technological innovation, product variety, improved customer service, and greater profitability.

Thus, a key question is what the mechanisms are by which supply chain complexity impacts the relationship between Lean and performance (Chand et al. 2022)—specifically, to better explain the "how" and "why" of the observed relationships. Understanding how the relationship between Lean and performance is impacted by supply chain complexity can lead to identifying complexity levers with the greatest impact, to target them for simplification and subsequent performance enhancement (Hoole 2005). We examine whether and how supply chain complexity affects the performance expected to be associated with Lean, looking at two potential mechanisms: moderation and mediation. The moderation mechanism argument focuses on the "complex and lean" perspective, where Lean practices are implemented in an increasingly complex supply chain environment that may impact Lean's ability to improve performance. On the other hand, the mediation mechanism argument examines the "lean and complex" perspective, where Lean practices have the unintended consequence of increasing supply chain complexity, which may be either positively or negatively related to performance, depending on whether the complexity is strategic or dysfunctional.

To explore whether and how supply chain complexity influences Lean's potential benefits, we develop measures of Lean based on Shah and Ward's (2007) prescriptions, using survey data from 209 manufacturing plants, spanning seven countries and three industries. Although these practices can be grouped into distinct bundles, we show that they are by and large implemented holistically, both within our sample and in typical manufacturing plants. We test two competing models. The first proposes that supply chain complexity inherent in the business environment moderates the positive relationship between Lean and performance, i.e., in the presence of higher levels of supply chain complexity, the expected performance gains from Lean are diminished. The second is that supply chain complexity mediates the relationship between Lean and performance; Lean increases some aspects of supply chain complexity, which can have either a positive or negative impact on performance, depending on the reason for the complexity. The results are obtained using the analytic tool of seemingly unrelated regression (SUR). What we find is both interesting and somewhat counterintuitive. Supply chain complexity primarily mediates the relationship between Lean and performance, with only a very minor moderating effect. The specific mediating mechanisms, however, depend on the type of complexity experienced and the way in which performance is operationalized. Further, at least one type of supply chain complexity (number of customers) may actually improve performance, indicating that potential benefits derived from the increased complexity in a supply chain as a result of Lean (e.g., an expanded customer base or serving more lucrative customers whose demands are more difficult to predict) may outweigh their costs.

We contribute to the literature by connecting the extensive body of research on Lean with the emerging literature on supply chain complexity, focusing in particular on synthesizing measures from Shah and Ward (2007) and Bozarth et al. (2009), widely cited studies of Lean and supply chain complexity. We show that increases in supply chain complexity are not necessarily undesirable, supported by the literature on strategic vs. dysfunctional complexity. We also show the perhaps counterintuitive importance of the mediation perspective and how it can support a firm's competitive performance.

We begin by briefly reviewing the literature on supply chain complexity and Lean, synthesizing them to develop alternative theoretical models of the role of supply chain complexity in the relationship between Lean and performance. We then describe our method, data source, variable operationalization, and analytical methods. We present the findings of our tests of the two perspectives, followed by discussing the insights and counterintuitive findings they reveal, delving into the "how" and "why" of the role of supply chain complexity in the relationship between Lean and performance. This is followed by presenting the managerial implications of our findings, limitations, and opportunities for future research on this interesting and important topic.

2 Literature review

2.1 Supply chain complexity

Driven by evolving business needs, supply chain complexity is often the "cumulative outcome of many seemingly unrelated functional decisions, …leaving in their wake supply chain artifacts that service needs that may no longer exist (Hoole 2005, p. 3)." The literature highlights disruptions, schedule instability, and sub-optimal decisions as drivers of diminished performance in the face of supply chain complexity (Chand et al. 2022).

The literature on supply chain complexity draws from broad literature streams in complexity science and supply chain management, and supply chain complexity research has correspondingly evolved into two tracks. The graph theory-based approach defines supply chain complexity using the number of nodes and arcs in a firm's ego-network (firms directly or indirectly connected to a buying firm), applying mathematical and social network analysis approaches to understand it (e.g., Sharma et al. 2020), which is effective in visualizing the structure of very large supply networks. However, though more recent research has refined definitions and operationalizations of graph-based measures of supply chain complexity, it provides few insights on managing the complexities of large supply networks.

The supply chain management literature on supply chain complexity (e.g., Aitken et al. 2016; Bozarth et al. 2009; Chand et al. 2022; Gerschberger et al. 2017) provides a more detailed view. Bozarth et al. (2009) drew upon the complexity dichotomy described by Simon (1991), Casti (1979), and Senge (1991) to define supply chain complexity as "the level of detail complexity and dynamic complexity exhibited by the products, processes and relationships that make up a supply chain." *Detail complexity* is driven by the number of entities (e.g., component parts, suppliers, customers) that must be managed, and *dynamic complexity* is driven by uncertainty in the way supply chain entities react to volatility and variability due to complex relationships experienced by a plant over time, where a "linear change in one part of a system may cause nonlinear and unexpected changes in other parts of the system (Manuj and Sahin 2011, p. 513)." This research has motivated multiple studies examining the effects of upstream (supplier induced), downstream (customer induced), and internal (within plant) supply chain complexity.

Upstream supply chain complexity is based on complex supply markets, where a plant may face unreliable suppliers and a large number of suppliers (Blome et al. 2014). It is driven by the number of suppliers in a firm's supply base, the number of tiers in its supply chains, the geographic distribution of its supply base (Chand et al. 2022), and complex relationships with upstream supply chain members. Similarly, Bode and Wagner (2015) define vertical complexity as the number of tiers in the supply chain and spatial complexity as the geographic spread of the supply chain, both of which were associated with increased supply chain disruptions. In their meta-analysis of 123 supply chain complexity studies, Akin Ateş et al. (2022) found that upstream detail supply chain complexity is associated with greater transaction costs and information processing needs, reduced supply base control, challenges in obtaining consistent inputs from multiple suppliers, and increased probability of disruptive events. Upstream dynamic supply chain complexity incorporates the challenges of dealing with suppliers with different cultures, languages and institutional environments, high search and evaluation costs in heterogeneous supply bases, difficulties in establishing collaborative relationships and building social capital, and reduced likelihood of receiving preferential supplier treatment (Akin Ateş et al. 2022), as well as logistical challenges related to the number of international borders crossed, number of transportation modes, and technical infrastructure of countries where suppliers are located (Prater et al. 2001).

In terms of internal supply chain complexity, key drivers include the variety and numerousness of parts and products, process complexity, and complexities associated with managing the product life cycle (Chand et al. 2022). An important dimension of internal supply chain complexity deals with the customizability, number of varieties, and intricacy of the products produced by a plant (Blome et al. 2014). Internal detail supply chain complexity results in increased inventory, reduced scheduling efficiency, higher probability of quality problems, and a higher chance of late deliveries. Internal dynamic supply chain complexity is caused by complexities in internal relationships, types of processes, and communication challenges (Akın Ateş et al. 2022; Flynn and Flynn 1999).

Drivers of downstream supply chain complexity include the number of customer orders, number of customer-specific product requirements, and customer demand variability (Chand et al. 2022). Downstream detail supply chain complexity associated with larger numbers of customers is related to lower volumes per run and more downtime for changeovers. Downstream dynamic supply chain complexity associated with diverse customers reduces the efficiency with which the customer base is managed, while increased customer dispersion increases the amount of inventory held, increasing costs and cash-to-cash cycle times. For example, B2B firms experience lower downstream supply chain complexity because they deal more intimately with a smaller number of clearly delineated individual business customers. In contrast, B2C firms experience higher downstream supply chain complexity as they deal with thousands or millions of diverse individual consumers (Jacobs et al. 2015).

Potential drivers of decreased performance associated with supply chain complexity include both structural and cognitive elements. Structurally, supply chain complexity increases the likelihood that an upstream process will not be able to meet the requirements of a downstream process (Gerschberger et al. 2017). From a cognitive perspective, supply chain complexity makes obtaining actionable information more difficult, decreasing the predictive validity of management systems.

Supply chain complexity has been found to negatively impact supply networks, buying firms, and plants (Bode and Wagner 2015; Bozarth et al. 2009; Shou et al. 2017). The meta-analysis by Akin Ateş et al. (2022) shows that supply chain complexity negatively impacts plant performance in cost, quality, delivery, and flexibility through increased transactions costs for production, inventory, logistics and communication, reduced efficiency, long and unreliable lead times, difficulties in schedule attainment, and inconsistent product quality. The strongest effects on performance they found were for upstream detail complexity associated with using a large number of suppliers, including transaction costs associated with managing a large supply base, increased information processing needs, managing heterogeneous suppliers, reduced supply base control, and an increased probability of disruptive events. Akin Ateş et al. (2022) found relatively less prior research on downstream supply chain complexity but concluded that it still suggested a negative relationship between downstream supply chain complexity and performance. Somewhat surprisingly, Akin Ateş et al. (2022) found a positive relationship between internal complexity and financial performance. They conclude that additional research is needed to understand when and where supply chain complexity is more detrimental to performance, in other words, the mechanism(s) by which supply chain complexity impacts performance.

2.2 Lean

Lean is a multifaceted approach to improving process flows while minimizing waste, based on JIT and synergistic practices focused on reducing throughput time (Hopp and Spearman 2021). Waste reduction can take many forms, but practitioners and scholars agree that it is accomplished by creating an organization that sharply focuses on reducing inventory, reducing throughput times, and eliminating or reducing non-value-added activities. A key area of emphasis of Lean is improved inter- and intra-organization information flows, often driven by higher levels of autonomy by employees and suppliers. Examples at the intersection of information flows and employee autonomy include Kanban production control and statistical process control, which complement small-lot flows and allow greater decision-making autonomy for frontline employees and more extensive partnering with first-tier suppliers. A precursor to reducing inventory and the implementation of Kanban is process improvement that results in reducing lead times and lead time variability.

Shah and Ward (2007) identify ten sets of practices that comprise the domain of Lean: pull (Kanban-based production control), continuous flow, JITdelivery by suppliers, setup time reduction, total productive/preventive maintenance, statistical process control, employee involvement, supplier feedback, supplier development, and customer involvement. Although these sets of Lean practices constitute independent constructs, most implementations involve a holistic approach to Lean. Thus, although Shah and Ward (2007) further grouped their practice sets into "bundles" of related practices, they are typically not implemented as bundles, but as an integrated, holistic set of practices that yields synergies. For example, Cua et al. (2001) and Flynn et al. (1995) found that JIT-specific practices work synergistically with more generic best manufacturing practices like TQM, total productive maintenance, and employee involvement to achieve positive manufacturing performance. However, much of the prior research on Lean neglects the supply chain context or only focuses on a single industry, thus, it does not give a holistic perspective of Lean and how its outcomes are influenced by supply chain complexity (Tortorella et al. 2017).

As manufacturing plants outside of Japan began implementing Lean in the late twentieth century, many struggled to achieve the marked improvements in operational and financial performance noted in Japan. Information processing theory (Galbraith 1974, 1977) provides a theoretical basis for understanding how Lean's performance improvements may diminish as supply chain complexity increases. Galbraith (1974) broadly defines organizations to include what we now commonly call supply chains; thus, supply chain complexity limits the ability of manufacturers to preplan activities and increases the amount of information that must be processed during task execution (Bode et al. 2011; Srinivasan and Swink 2015; Wang et al. 2021). It stands to reason, then, that manufacturing practices that involve preplanning or making decisions about activities significantly in advance of their execution will not work well in environments marked by high levels of supply chain complexity (Bode and Wagner 2015). Thus, managers' decision-making ability is hampered by supply chain complexity. Galbraith (1974, 1977) describes various types of dynamic complexity that make it difficult for managers to ascertain whether a decision will have the intended outcome, which may require managers to delay important decisions as they await accurate or more timely information, or it can cause them to hedge their decisions by dedicating additional resources or reducing their commitments.

Lean has been widely discussed in terms of its performance benefits (Peralta et al. 2020; Jacobs et al. 2015), and Mackelprang and Nair (2010) present an extensive review and meta-analysis of the empirical research investigating the link between Lean and performance. In synthesizing this research, they point out that Lean is an abstract construct, with different perspectives on the specific elements that comprise it. Lean is costly and disruptive to adopt because it requires substantial modification of ongoing tasks and responsibilities (Jacobs et al. 2015). Thus, it is important to understand the nuances of the mechanisms by which Lean is associated with performance improvements (Birkie and Trucco 2016; Tortorella et al. 2017).

3 Conceptual model and hypotheses

Without clear guidance from theory or previous research, we offer two competing mechanisms for explaining the role of supply chain complexity in the relationship between Lean and plant performance (Sparrowe and Mayer 2011). Competing theoretical models are appropriate when research is nascent in a particular domain, intersects established domains, or spans the boundaries of existing theories (Barratt et al. 2011; Gephart Jr 2004; Rungtusanatham et al. 2005). The moderation perspective specifies that performance associated with Lean is negatively moderated by exogenous supply chain complexity (see Fig. 1), implying that performance is contingent upon both the level of Lean and the level of supply chain complexity and that managers should coordinate Lean with actions to reduce supply chain complexity. In contrast, the mediation perspective posits that Lean may be associated with higher levels of supply chain complexity which block some of the positive impact of Lean on performance (see Fig. 2). Thus, the cost of Lean, coupled with its diminished impact on performance due to supply chain complexity, can make its implementation questionable.

3.1 The case for moderation

A strong argument can be made for supply chain complexity moderating the relationship between Lean and performance

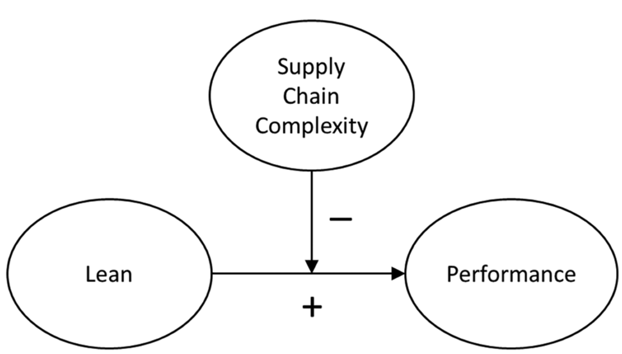

Fig. 1 SC Complexity negatively moderates the relationship between Lean and Performance

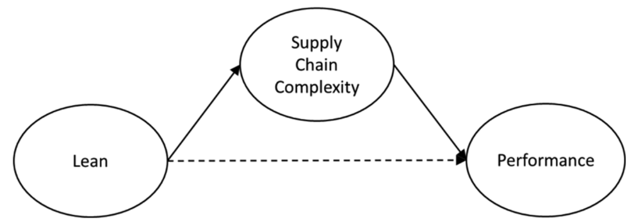

Fig. 2 SC Complexity mediates the relationship between Lean and Performance

(Eckstein et al. 2015). In other words, Lean is more effective in low supply chain complexity contexts (Tortorella et al. 2017). For example, high velocity organizations compete in complex environments characterized by high uncertainty and rapid change (Jacobs et al. 2015). Such environments are less supportive of Lean, diminishing its expected positive impact on performance. When supply chain complexity is low, Lean's positive effects outweigh the negative effects of supply chain complexity, leading to benefits to firm performance. However, beyond the point where the negative impact of supply chain complexity outweighs the positive impact of Lean, there is diminished performance as a plant must invest in additional equipment, distribution points, production lines, etc. to improve its performance (Menezes et al. 2021). This contingency approach suggests that contextual variables like supply chain complexity determine an organization's performance in response to Lean (Tortorella et al. 2017). Because supply chain complexity is considered exogenous by the moderation perspective, managers are not able to influence or manipulate it in the short run (Tortorella et al. 2017).

For example, pull systems seek to coordinate material flows and inventory levels between supply chain links based on a pre-established demand rate and replenishment lead time. Although these systems attempt to limit replenishment to only that driven by actual demand, they can pull unanticipated work into the process when demand is not highly stable. Pull systems thus only function well in highly repetitive environments and are less effective when implemented under conditions of high demand volatility (greater downstream complexity). Suri (2016) provides an excellent analysis of how downstream complexity transforms Kanban into a push system that generates substantial excess inventory. Similarly, to the extent that continuous flow production systems attempt to establish the flow of production units through a system prior to actual demand, they can flounder in high supply chain complexity environments unless the complexity is accommodated by suitable planning and control systems. In another example, because B2B firms have more predictable demand from less diverse customers than B2C firms do, they are better able to develop an understanding of how to apply specific Lean practices to better meet their business needs (Jacobs et al. 2015). They have fewer, better documented relationships with their customers, who are more likely to appreciate the firm's adoption of Lean as an indirect signal of the quality of its products.

The moderation perspective is supported by research on related initiatives. For example, Blome et al. (2014) position supply chain complexity as moderating the relationship between knowledge transfer and performance, viewing complexity as a "given" in the environment, with the potential to influence the effectiveness of various initiatives. Gimenez et al. (2012) found that more complex products typically require more complex supply chains, that in turn require additional information flows between supply chain members. Complex supply chains require higher levels of integration to achieve performance comparable to simpler supply chains (Gimenez et al. 2012). Information regarding problems is more difficult to track in a complex supply chain, causing problems to cascade through the chain without being detected (Bode and Wagner 2015). Further, although a firm may attempt to reduce its supply chain complexity and improve information flows by decreasing its number of first tier suppliers, complexity in supply chain tiers further upstream is often reflected in lower financial performance (Lu and Shang 2017).

In this way, contingent variables like supply chain complexity may also explain why performance gains from Lean are often lower than expected (Mackelprang and Nair 2010). For example, Qi et al. (2009), using a sample of 604 Chinese manufacturing plants, show that Lean strategies (focused on waste reduction and streamlined flow) and Agile strategies (focused on responsiveness to demand) perform differently depending on the product type (internal supply chain complexity). Lean tends to be associated with better performance in plants focused on functional products (lower downstream complexity), while an Agile strategy is more appropriate than Lean for innovative products (higher downstream complexity). This contingency (mis)match of Lean to upstream, internal, and downstream complexity has been demonstrated using large secondary datasets. Azadegan et al. (2013) demonstrate that environmental dynamism (a form of complexity) negatively moderates the effect of Lean on performance. As the environment becomes more dynamic (complex), it is more difficult to synchronize production and establish causal attribution to changes in manufacturing systems. Examining inventory records for publicly traded firms, Eroglu and Hofer (2011) established that the relationship between Lean and performance varies in functional form by industry. Over half the industries they studied had an inverted U-shaped relationship between Lean and performance. The authors surmise that this is because some plants, given their inherent operating conditions (supply chain complexity), can become too lean. For a given level of complexity within an industry, reducing inventory too much increases costs and offsets potential savings from Lean's lower inventory levels. Lu and Shang (2017) noted that detail complexity had an inverted U-shaped relationship with financial performance, which they attributed to bounded rationality; managers have limited cognitive capability for dealing with complexity and their decision-making ability may be compromised when they are overwhelmed. Thus, detail complexity can lead to improved financial performance up to a certain level of supply chain complexity, after which financial performance declines. On the other hand, they noted a U-shaped relationship between dynamic complexity and performance, as supply chain complexity can be a result of capitalizing on opportunities that result in financial gains.

In summary, the supply chain complexity inherent in the business environment diminishes managers' ability to identify and act upon critical information required to manage Lean, according to the moderation perspective. As supply chain complexity increases, synchronizing a plant's Lean system with supply chain complexity becomes more difficult, diminishing the performance improvements normally realized from Lean.

> **H_1:** Higher levels of supply chain complexity will negatively moderate the impact of Lean on plant-level performance.

3.2 The case for mediation

The case for mediation positions supply chain complexity as an unintended effect of Lean, which subsequently influences performance (Chand et al. 2022). Lean is a complex intervention that requires modification of many practices and operating principles, increasing internal complexity (Soliman and Saurin 2022). Lean's many interacting components and synergies require changes to behaviors that cut across different organizational levels, impact a variety of outcomes, require customization to the local context, and can lead to unintended consequences (Soliman and Saurin 2022), resulting in increased levels of dynamic complexity. In other words, the steps taken to implement Lean result in increases to supply chain complexity, which can diminish Lean's potential (Prater et al. 2001). Thus, the case for mediation is based on the notion that Lean can cause increased supply chain complexity, rather than simply being a passive victim of it, as the moderation perspective suggests.

Further, many of the characteristics that support the strategic goals of Lean also drive supply chain complexity. Thus, organizations that are able to accommodate supply chain complexity may have an advantage over those that focus only on reducing it. As firms chase higher profitability, they have "proliferated nearly everything: products, customers, markets, suppliers, facilities, locations, etc. (Mariotti 2007; Menezes et al. 2021)." Although such proliferation often results in increased revenues, it is rarely reflected in increased profitability (Menezes et al. 2021). Thus, an argument can be made for a mediating effect of supply chain complexity on the relationship between Lean and performance. Menezes et al. (2021) describe the "complexity crisis" where product variety, multi-market, and multi-channel strategies are valued because of their positive impact on sales and market performance, yet the supply chain complexity they introduce can negate potential performance gains.

For example, Saunders et al. (2021) found that delayed deliveries of a part used in multiple products (due to Lean's reduction of design redundancies) caused frequent production stoppages and subsequent interruptions of customer deliveries. Although Lean's prescribed demand pooling for this single, low-cost part used across 36 SKUs was expected to lead to performance improvements, long and variable lead times coupled with correlated demand for the end products led to frequent stock-outs. To prevent Lean from being frequently forced to stop production to deal with stock-outs, Soliman and Saurin (2022) and Saunders et al. (2021) recommended that plants should add flexibility in the form of additional inventory, which increases internal complexity. In another example, a recent case study found that Lean requires increased resources and time to cope with resulting supply chain complexity (Soliman and Saurin 2022). Dynamic complexity in the form of demand variability, unreliable or long supplier lead times, and unstable master production schedules, can degrade the performance of Kanban, JIT deliveries, and continuous flow systems (Birkie and Trucco 2016). This internal complexity makes it difficult for managers to preplan or make decisions about manufacturing activities in advance of their execution (Schmenner and Swink 1998; Soliman and Saurin 2017). Closs et al.'s (2008) simulation results show that fill-rate performance is negatively affected by downstream complexity, including product line breadth, demand uncertainty, and its skew pattern across the periods in any given planning horizon. The negative effects of lower fill-rates can impact multiple operations relying on the same parts, and the complexity of products leads to more frequent process disruptions (Inman and Blumenfeld 2014).

Thus, there are multiple ways in which Lean can directly increase supply chain complexity. Frequent production interruptions, production schedule changes, and expediting of incoming parts negatively impact customer deliveries, costs, and plant competitiveness. Thus, Lean may be associated with greater supply chain complexity, which in turn is associated with diminished performance.

However, the above analysis is predicated on the assumption that Lean increases *dysfunctional* supply chain complexity which necessarily has a negative impact on performance. Dysfunctional supply chain complexity is "deleterious" complexity that is not required for achievement of a business unit's strategy (Turner et al. 2018). Because it prevents a plant from achieving improved performance, dysfunctional supply chain complexity should be reduced to the extent possible. On the other hand, *strategic* supply chain complexity is beneficial to a plant. When Lean increases strategic supply chain complexity, the resulting performance improvements exceed the cost of the complexity increase. Further, strategic complexity is required to execute a business unit's competitive strategy (Turner et al. 2018). Examples of strategic supply chain complexity include higher levels of customization to target new markets, globally diverse supply chains, and expanded sets of targeted customers (Turner et al. 2018). This suggests that increasing supply chain complexity resulting from Lean, properly managed, may positively impact performance. Thus, the mediating effect of supply chain complexity on the relationship between Lean and performance can be either positive or negative (Blome et al. 2014), depending on whether specific practices contribute to strategic complexity or dysfunctional complexity (Soliman and Saurin 2022).

We therefore hypothesize that the level of supply chain complexity mediates the relationship between Lean and plant-level performance, as follows:

> **H_2:** Supply chain complexity will mediate the effect of Lean on plant-level performance.

4 Methodology

4.1 Sample

This study uses data from the third round of the High Performance Manufacturing (HPM) project data set, which is the same data set used by Bozarth et al.'s (2009) study of supply chain complexity. It is comprised of responses from plants in three industries (machinery, electronics, and transportation components) in seven countries (Austria, Finland, Germany, Japan, South Korea, Sweden, and the U.S.) The sample plants were randomly selected from the sampling frame in each country. All plants had at least 100 employees and had different parent corporations. Participating plants received a profile comparing their performance on a variety of measures to responses from other plants in their industry, as an incentive for participation.

4.2 Instrument

Upon agreeing to participate, each plant was sent a battery of 23 separate questionnaires, each targeted at the respondent who was best informed about the content of the questionnaire. For instance, HR managers were questioned about employee involvement efforts in the plants, while production and inventory managers were asked questions regarding supplier delivery performance. A mix of item types, multiple respondents per measure, and some reversed scales were used to minimize the potential for common methods variance (Crampton and Wagner III 1994).

4.3 Operationalization of measures

4.3.1 Independent variables

Lean Our operationalization of Lean is based on a holistic view reflecting the perspective of manufacturing plants that implement Lean as a system of practices, rather than in a piecemeal fashion. Their goal is to replicate the Toyota Production System, or at least its performance. Thus, we created a Lean index. We started with the instrument that Shah and Ward (2007) developed and tested to measure their Lean dimensions described above. We attempted to replicate their measurement by building measures from items in the HPM dataset. We first identified conceptually similar measures of their dimensions. As many of Shah and Ward's items were based on previous research using the HPM data set, we had access to similar constructs and nearly identical items, thus we developed measures with high face validity with the Shah and Ward (2007) measures. After mapping relevant HPM items to Shah and Ward's (2007) factors (see Appendix A), we tested content validity using a Q-sort procedure (see Appendix B), then further refined the measures using factor analysis (see Appendix C). To operationalize the Lean index, we began by conducting inter-rater reliability analysis for each dimension of Lean, since the HPM data project used multiple respondents for each measure, in order to prevent common method bias. As reported in Appendix D, this analysis yielded satisfactory results, so we then calculated mean scores across the responses within each dimension and summed the dimension means for each plant to develop the Lean index.

Supply chain complexity In operationalizing supply chain complexity, we began with Bozarth et al.'s (2009) set of twelve measures of supply chain complexity upstream (number of suppliers, lead time variability, supplier delivery reliability, percent of international purchases), internal to the firm (number of parts, number of products, schedule instability, process type), and downstream (number of customers, customer heterogeneity, demand variability, product life cycle variability). All measures were scaled so that higher values represented greater supply chain complexity. The measures for number of customers, number of products, product life cycle variability, number of parts, number of suppliers, and percent of international purchases were log transformed, to adjust for normality. The measure for process type was transformed to an ordinal value where −1 = continuous flow process, 0 = line or large batch process, and + 1 = job shop or small batch process. Because of the potential for overlap between these measures, we ran a principal components factor analysis with orthogonal rotation. As a result, we developed three new measures that each incorporated several of Bozarth et al.'s (2009) original measures. *Flow variability* includes demand variability, process type, and schedule instability, which builds on overlap between downstream and internal complexity. Similarly, *number of inputs* combines two measures of detail complexity: an upstream complexity factor (number of suppliers) and an internal complexity factor (number of parts). Finally, *supplier variability* combines two measures of upstream dynamic complexity: *lead time variability* and *supplier delivery reliability*. The three new measures and the five final measures of supply chain complexity used by Bozarth et al. (2009) are found in Table 1.

Control variables Covariates were used to control for potential industry and country effects. Two dummy variables described plant membership in the three industries, and six dummy variables described plant location across the seven countries.

Table 1 Summary of Variables

Control Variables	Lean Composite Index	Supply Chain Complexity	Performance
Industry	• Supplier Development	**Detail**	• Unit Cost
• Electronics	• Supplier Feedback	• # Inputs	• Schedule Attainment
• Machinery	• Supplier Selection	• # Products	• Margin
• Transportation Components	• Kanban	• # Customers	• Customer Satisfaction
Country	• SPC	**Dynamic**	• Plant Competitiveness
• Austria	• Employee Input	• Flow Variability	
• Finland	• Employee Teams	• Supply Variability	
• Japan	• Lean Systems	• % International Purchases	
• Germany	• External Pull	• Life Cycle Variability	
• South Korea	• Customer Development	• Customer Heterogeneity	
• Sweden			
• United States			

4.3.2 Dependent variables

Five dependent variables measured aspects of plant performance. Unit cost, schedule attainment, and customer satisfaction were measured using multi-item measures that rated how well a plant performed on a particular measure, relative to its competitors. Operating margin was calculated for each plant as:

$$\text{Operating margin} = \left[\frac{Revenue - \left(\begin{matrix} Operating \\ expense \end{matrix} + \begin{matrix} Investment\ in\ plant \\ and\ equipment \end{matrix} \right)}{Revenue} \right]$$

Plant competitiveness was operationalized as a weighted index, as follows. Plant managers were asked to assign a level of criticality to ten strategic and operational goals: unit cost of manufacturing, conformance to product specifications, on-time delivery performance, fast delivery, flexibility to change product mix, flexibility to change volume, inventory turnover, cycle time, development lead time, and product capability and performance. Relative importance (*Imp*) is rated from 1 = Least Important to 5 = Absolutely Critical. The managers were then asked how well the plant had achieved these goals (*Ach*), rated from 1 = Poor to 5 = Superior. The goals and achievement scores were standardized across each response (by row in the dataset), then multiplied. Thus, the competitiveness of a plant is operationalized as:

$$Plant\ Competitiveness_n = \sum_{i=1}^{10} \left[\frac{Imp_i - Avg(Imp_{(1-10)})}{StDev(Imp_{(1-10)})} \times \frac{Ach_i - Avg(Ach_{(1-10)})}{StDev(Ach_{(1-10)})} \right]$$

Table 2 lists the variables analyzed in the regression equations and shows the principal components factor loadings.

5 Analysis and results

5.1 Descriptive statistics and correlations

Table 3 shows the descriptive statistics and correlation matrix for the measures. It reveals that there is no multicollinearity between the dimensions of supply chain complexity, although several of them are correlated with Lean.

Table 2 Supply Chain Complexity Factor Loadings

	Final Supply Chain Complexity Measures								
Original Measures	**Flow Variability**	**# Inputs**	**Supply Variability**	**# Customers**	**% International Purchases**	**Life Cycle Variability**	**Customer Heterogeneity**	**# Products**	**Communality Estimate**
Demand variability	**0.817**	0.021	0.063	-0.019	-0.108	0.104	0.175	0.131	0.742
Process type	**0.705**	0.210	-0.106	0.290	0.291	-0.029	-0.270	-0.039	0.796
Schedule instability	**0.675**	0.217	0.081	-0.239	0.018	-0.128	0.225	-0.027	0.634
# Suppliers	0.087	**0.847**	-0.078	0.076	0.000	-0.128	0.118	0.076	0.773
# Parts	0.264	**0.696**	-0.052	0.320	-0.277	0.213	0.084	0.068	0.985
Leadtime variability	-0.042	-0.217	**0.886**	0.119	-0.085	0.061	-0.140	0.097	0.888
Supplier delivery reliability	0.312	0.461	**0.624**	-0.295	0.208	-0.049	0.027	-0.040	0.835
# Customers	-0.047	0.181	0.032	**0.911**	-0.054	-0.049	0.057	0.007	0.875
% International purchases	0.024	-0.091	-0.008	-0.062	**0.943**	0.091	0.095	0.019	0.920
Life cycle variability	-0.007	-0.022	0.037	-0.039	0.089	**0.967**	-0.051	0.110	0.961
Customer heterogeneity	0.171	0.161	-0.127	0.065	0.102	-0.053	**0.900**	-0.041	0.901
# Products	0.069	0.097	0.069	0.010	0.017	0.111	-0.037	**0.976**	0.767
Prob > ChiSq	< 0.0001	< 0.0001	< 0.0001	< 0.0001	0.000	0.002	0.013	0.023	
Variance	1.83	1.63	1.23	1.19	1.11	1.06	1.02	1.01	
% variance explained	15%	14%	10%	10%	9%	9%	9%	8%	

For the dependent variables, Unit Cost was significantly correlated with Schedule Attainment and Plant Competitiveness, and Schedule Attainment was correlated with Customer Satisfaction.

5.2 Criterion-related validity

To confirm the criterion validity of the supply chain complexity measures and the Lean index, we ran a direct effects regression model. The model regressed the eight supply chain complexity measures and Lean against the five performance measures, using seemingly unrelated regression (SAS 2018), which allows simultaneous estimation of multiple regression equations and mitigates against biased estimators related to correlated dependent variables. In the first step, the OLS estimates are calculated. The residuals are then used to determine the correlation between the six equations. In the second step, these correlations are used to determine unbiased parameter estimates.

Table 4 indicates that various measures of supply chain complexity were related to all five measures of performance. With one exception, all the relationships were negative, confirming the finding of the prior research that higher levels of supply chain complexity are related to lower levels of performance (Akin Ateş et al. 2022). Similarly, Lean is positively related to dimensions of performance, replicating prior findings that higher levels of Lean are related to higher levels of performance (Mackelprang and Nair 2010). Thus, the findings in Table 4 support the criterion-related validity of our measures.

The significant positive relationship between *number of customers* and both Plant Competitiveness and Schedule Attainment warrants further discussion. It indicates that plant competitiveness and schedule attainment are enhanced by the number of customers, a measure of detail complexity. Combined, the findings in Table 4 suggest that most of our supply chain complexity measures represent dysfunctional complexity, but that the number of customers may be a measure of strategic complexity. For example, while having more

Table 3 Descriptive Statistics and Correlations

(a) Independent Variables

	Lean	Flow Variability	# Inputs	Supply Variability	# Customers	% International Purchases	Life Cycle Variability	Customer Heterogeneity	# Products
Lean	1	-0.280***	-0.218**	-0.629***	-0.003	-0.016	0.076	0.011	-0.053
Flow variability		1	0.030	0.005	-0.035	-0.011	0.017	0.030	0.007
# Inputs			1	-0.001	0.008	0.011	-0.050	0.002	0.009
Supply variability				1	-0.017	0.015	-0.004	-0.009	0.020
# Customers					1	-0.025	0.022	0.017	0.010
% International purchases						1	-0.006	0.021	-0.032
Life cycle variability							1	-0.006	0.045
Customer heterogeneity								1	0.000
# Products									1
n	210	210	210	210	210	210	210	210	210
Mean	0	-0.005	-0.040	0.008	-0.009	-0.003	0.007	0.013	-0.008
Std. Dev	1	0.982	0.927	0.927	0.927	0.938	0.873	0.976	0.889

(b) Dependent Variables

	Unit Cost	Schedule Attainment	Customer Satisfaction	Operating Margin	Plant Competitiveness
Unit cost	1	0.233**	0.128	0.114	0.228***
Schedule attainment		1	0.378***	-0.025	0.142*
Customer satisfaction			1	0.057	-0.015
Operating margin				1	0.136
Plant competitiveness					1
n	210	210	210	210	210
Mean	0	0	0	0	0
Std. Dev	1	1	1	1	1

*$p < .05$; **$p < .01$; ***$p < .001$

customers increases the complexity of managing relationships with them, there are undeniable benefits to competitive performance of having a greater number of customers. Thus, our analysis of criterion-related validity suggests that *flow variability*, *number of inputs*, and *supply variability* are valid measures of dysfunctional complexity, while *number of customers* is a valid measure of strategic complexity. Thus, we expect that *number of customers* may function differently as a mediator or moderator than the other measures of supply chain complexity. Our findings did not support criterion-related validity for *percent of international purchases*, *life cycle variability*, *customer heterogeneity*, and *number of products* as measures of supply chain complexity.

5.3 Analysis of moderation effects

After confirming criterion-related validity of our factors, we ran the moderated regression model. Table 5 contains the results from the SAS Proc Syslin procedure, in which the control variables, direct effects, and interaction effects were all mean-centered. A robustness check was performed using the SAS Proc Process (Hayes 2017) and the SAS Mediation Macro (Valeri and VanderWeele 2013) yielding similar results.

The results for the main effects of Lean and supply chain complexity were similar to the results described in Table 4. Measures of supply chain complexity were associated with four of the five dimensions of performance (the coefficient for *flow variability* decreased slightly in the presence of the interaction terms and was no longer significant). Dimensions of supply chain complexity were negatively associated with Unit Cost, Schedule Attainment, and Operating Margin, illustrating the effect of dysfunctional complexity. Interestingly, both significant measures of detail complexity (*number of inputs* and *number of customers*) were positively associated with Plant Competitiveness, functioning as measures of strategic complexity. *Number of customers* continued to be positively associated with Schedule Attainment.

Our results revealed a single moderating effect. *Customer heterogeneity*, although nonsignificant as a main effect, moderated the relationship between Lean and Schedule Attainment, such that it was stronger in the presence of more heterogeneous customers. Overall, our results suggest that support for supply chain complexity moderating the relationship between Lean and performance is weak, failing to support H_1.

5.4 Analysis of mediation effects

Mediation was tested using the SAS Proc Syslin two-stage least squares regression procedure. Each equation was run separately, due to d.f. limitations in the first stage equation.

Table 4 Regression Results for Criterion-Related Validity

	Unit Cost	Schedule Attainment	Customer Satisfaction	Operating Margin	Plant Competitiveness
Intercept	-0.19	0.31	0.38	0.16	-0.21
Industry1	0.42**	-0.27	0.3	0.11	0.3
Industry2	0.25	-0.08	0.3	-0.19	0.2
Country1	-0.06	-0.34	-0.58**	-0.38	-0.03
Country2	-0.15	-0.18	0.02	0.37	0.55
Country3	0.04	-0.06	-1.32***	-0.21	0.01
Country4	0.19	-0.11	-0.23	0.18	0
Country5	-0.36	-0.25	-0.51	-0.85*	-0.53
Country6	0.03	-0.51	-1.05***	-0.27	0.29
Lean	0.07	0.32***	0.39***	-0.1	0.11
# Inputs	-0.04	-0.18**	0.05	-0.18*	-0.19*
# Products	-0.13	0.09	-0.02	-0.02	-0.13
# Customers	-0.01	0.17**	-0.02	0.02	0.18*
Flow variability	-0.33***	-0.20**	-0.17*	-0.02	-0.13
Supply variability	-0.17	-0.41***	-0.1	-0.08	-0.02
% International purchases	-0.07	0.05	0	0.1	-0.12
Life cycle variability	0.09	-0.09	-0.1	-0.07	0.03
Customer heterogeneity	0.09	-0.03	-0.01	0.02	0.14
d.f	187	187	187	187	187
F	2.56	12.22	8.3	2.23	3.1
Adj. R^2	0.12	0.5	0.4	0.1	0.16

$*p<.05$; $**p<.01$; $***p<.001$

Table 5 Moderated Regression Results

	Unit Cost	Schedule Attainment	Customer Satisfaction	Operating Margin	Plant Competitiveness
Lean	0.10	0.33***	0.41***	-0.09	0.09
# Inputs	-0.02	-0.16**	0.05	-0.20*	0.20*
# Products	-0.15	0.06	-0.02	-0.04	-0.14
# Customers	0.00	0.19***	-0.02	0.02	0.20*
Flow variability	-0.32*	-0.20**	-0.16	-0.01	-0.16
Supply variability	-0.16	-0.40***	-0.07	-0.09	-0.06
% International purchases	-0.06	0.05	0.01	0.10	-0.13
Life cycle variability	0.09	-0.09	-0.10	-0.05	0.02
Customer heterogeneity	0.10	-0.03	-0.02	0.02	0.14
Lean x # Inputs	0.00	0.07	0.04	0.04	0.12
Lean x # Products	-0.04	-0.03	0.04	0.03	-0.04
Lean x # Customers	-0.03	-0.09	-0.01	-0.05	-0.09
Lean x Flow variability	0.05	0.02	-0.01	0.02	-0.05
Lean x Supply variability	-0.01	-0.06	0.10	-0.09	-0.09
Lean x % Int'l. purchases	-0.04	-0.10	-0.07	0.06	-0.03
Lean x Life cycle variability	0.02	0.00	0.03	0.09	-0.09
Lean x Cust. heterogeneity	-0.02	0.12*	0.09	0.01	-0.06
d.f	187	187	187	187	187
F	1.75	9.19	5.87	1.63	2.53
Adj. R^2	0.09	0.52	0.39	0.08	0.17

Control variables were entered in the first step of this analysis, but their effects are not shown here, in the interest of space

$^*p<.05$; $^{**}p<.01$; $^{***}p<.001$

For each equation, the supply chain complexity variable was set as endogenous, with the control variables and Lean as predictors. The first stage of mediation analysis regresses the predictors on the endogenous variable to form the predicted value of the supply chain complexity variable in question. In the second stage, the control variables and Lean are regressed on the performance variable and added to the first stage's predicted variable. SAS Proc Syslin is similar to Baron and Kenny's (1986) well-known approach, with several important distinctions. Proc Syslin simultaneously estimates the second stage equations and allows for correlation of the error terms among the predicted endogenous, exogenous, and dependent variables. This relaxation of the standard ordinary least squares (OLS) independence assumption reflects more recent thinking on mediation, based on the possibility of missing effects (Valeri and VanderWeele 2013). This approach can be viewed as hybrid of structural equation modeling (SEM) and OLS. Like regression, control variables can easily be entered into the equation and standard fit statistics for regression are used to assess significance. Like SEM, this approach also allows the analysis to address the possibility of non-independent errors.

We find that multiple supply chain complexity variables mediate the relationship between Lean and performance. These mediated effects are substantial and, in many cases, negate the positive effects driven by Lean implementation. For example, the first stage analysis predicts that plants that are one standard deviation higher in Lean should expect to be 0.29 standard deviations more competitive in Unit Cost (in the upper 60th percentile). However, if a plant is one standard deviation higher in *supply variability*, it will perform slightly below average (0.29–0.38 = –0.09) in Unit Cost. Similar results are seen throughout Table 6., which reveals that the relationship between Lean and Unit Cost is negatively mediated by *flow variability*, *supply variability*, and *number of products*. The relationship between Lean and Schedule Attainment is mediated by all measures of supply chain complexity except *flow variability*. *Number of inputs*, *supply variability*, *number of customers* and *number of products* negatively mediate this relationship while *international sourcing*, *life cycle variability*, and *customer heterogeneity* positively mediate this relationship. Lean's effect on Operating Margin is fully mediated by *number of customers* (positive) and *number of products* (negative). Lastly, supply chain complexity mediates Lean's effect on Plant Competitiveness; *international sourcing*, *customer heterogeneity*, and *number of products* negatively mediate this relationship, whereas *number of customers* and *product life cycle variability* positively mediate it. Thus, H_2 was strongly supported.

6 Discussion

6.1 Summary of results

This research focuses on the role played by supply chain complexity in the relationship between Lean and plant performance. This is important because Lean, although widely implemented, sometimes yields performance that is not as strong as expected. We examine the role of supply chain complexity in this relationship through two lenses. First, we position supply chain complexity as moderating the relationship between Lean and plant performance, taking a "complex and Lean" perspective. This perspective positions supply chain complexity as inevitable in today's dynamic global business environment, examining whether Lean will be as effective as expected in such an environment. Thus, it views supply chain complexity as an exogenous factor upon which plant-level managers have limited influence. Alternatively, we position supply chain complexity as mediating the relationship between Lean and plant performance, taking a "Lean and complex" perspective. It views increasing supply chain complexity as a consequence of Lean that potentially has a direct effect on plant performance. In other words, practices meant to reduce waste may have the unintended consequence of also increasing a plant's supply chain complexity. If the negative effect of increased complexity exceeds the benefits of Lean, it will be reflected in diminished plant performance. Thus, the mediation approach views supply chain complexity as endogenous to a plant, capable of being influenced by managerial decisions. Combined, these two perspectives allow us to dig into the nuances of supply chain complexity, to explore mechanisms behind the relationship between Lean and performance.

There were several important findings. First, our criterion-related validity analysis found that Lean, considered in isolation, was positively related to several measures of performance. This is consistent with the extensive prior literature supporting the expected benefits of Lean (Mackelprang and Nair 2010). Also, as expected, we found that supply chain complexity was related to plant performance. Similar to results found by Akin Ateş et al. (2022), aspects of supply chain complexity were significantly associated with every measure of plant performance, and different aspects of supply chain complexity were related to each measure of plant performance, illustrating the importance of measuring this

Table 6 Mediated Regression Results

	Unit Cost		Schedule Attainment		Customer Satisfaction		Operating Margin		Plant Competitiveness	
	Est *(SE)*	**R^2**	**Est** *(SE)*	**R^2**	**Est** *(SE)*	**R^2**	**Est** *(SE)*	**R^2**	**Est** *(SE)*	**R^2**
FIRST STAGE:										
Lean	0.29**	0.12	0.61***	0.40	0.47***	0.43	-0.09	0.15	0.17***	0.15
	(0.08)		*(0.06)*		*(0.06)*		*(0.08)*		*(0.07)*	
SECOND STAGE:										
# Inputs	-0.13	0.00	-0.90***	0.08	-0.50**	0.03	0.09	0.00	-0.08	0.00
	(0.21)		*(0.21)*		*(0.20)*		*(0.19)*		*(0.19)*	
# Products	-0.33*	0.02	-0.27	0.01	-0.32*	0.02	-0.53**	0.05	-0.33*	0.02
	(0.15)		*(0.15)*		*(0.15)*		*(0.18)*		*(0.15)*	
# Customers	0.29	0.02	0.02	0.00	-0.65***	0.06	0.37*	0.03	0.58***	0.06
	(0.17)		*(0.16)*		*(0.18)*		*(0.18)*		*(0.16)*	
Flow variability	0.21*	0.02	-0.41***	0.08	0.03	0	0.12	0.01	-0.04	0
	(0.10)		*(0.10)*		*(0.10)*		*(0.11)*		*(0.10)*	
Supply variability	-0.38***	0.06	-0.81***	0.28	-0.68***	0.18	0.09	0.00	-0.16	0.01
	(0.11)		*(0.09)*		*(0.10)*		*(0.12)*		*(0.11)*	
% International purchases	-0.18	0.01	-0.11	0.00	0.48**	0.05	-0.19	0.01	-0.43**	0.04
	(0.16)		*(0.14)*		*(0.15)*		*(0.15)*		*(0.15)*	
Life cycle variability	-0.19	0.00	0.56	0.02	0.65*	0.02	-0.48	0.00	0.51	0.01
	(0.30)		*(0.31)*		*(0.32)*		*(0.56)*		*(0.31)*	
Customer heterogeneity	0.07	0.00	0.15	0.00	0.37*	0.03	-0.19	0.01	-0.43*	0.03
	(0.16)		*(0.15)*		*(0.16)*		*(0.18)*		*(0.18)*	

*$p < .05$; **$p < .01$; ***$p < .001$

multi-dimensional construct by its individual elements, rather than as a formative measure. Most of the significant relationships were negative, supporting the literature on the expected detrimental effect of supply chain complexity on performance. However, *number of customers* (a measure of detail complexity) was positively associated with both Schedule Attainment and Plant Competitiveness. This suggests that the number of customers may represent strategic supply chain complexity, while the other significant aspects represent dysfunctional complexity.

Second, although our moderation analysis revealed direct effects similar to those described above, there was very little evidence supporting moderation effects of supply chain complexity in the relationship between Lean and plant performance. This result differs from several studies that have found that Lean's performance improvements are moderated by aspects of supply chain complexity (e.g. Azadegan et al. 2013; Birkie and Trucco 2016). Only a single aspect of supply chain complexity (*customer heterogeneity*) had a significant moderating effect. At first glance, this is a surprising result. The level of supply chain complexity in the business environment has certainly increased and continues to increase; however, this is not related to the relationship between Lean and plant performance. We believe that this indicates that managers have grown accustomed to increasing levels of supply chain complexity in the business environment and have been able to successfully accommodate it. Thus, although supply chain complexity continues to increase, managers are able to implement Lean effectively within this changing environment. This is supported by prior empirical findings on the benefits of Lean (Browning and de Treville 2021).

Third, our mediation analysis strongly supported a mediating role for supply chain complexity. The first stage of the analysis revealed a positive relationship between Lean and almost every measure of plant performance. However, the second stage analysis indicated that higher levels of Lean were associated with many aspects of supply chain complexity, reflected in their significant increases to R^2. This was true for multiple aspects of supply complexity for every dimension of performance. Thus, we conclude that supply chain complexity mediates the relationship between Lean and plant performance. Further, this may explain the statistical results from the two meta-analyses in the Lean and supply chain complexity domains. Both Mackelprang and Nair (2010) and Akin Ateş et al. (2022) tested for the likelihood of additional contextual variables using heterogeneity analysis. These studies found evidence that moderating or missing variables are required to explain relative performance across the studies in their samples. Our results indicate that supply chain complexity may be the missing variable in the Lean–performance relationship and alternatively, the chosen production system is the missing variable in the complexity–performance relationship.

Fourth, examination of the significant mediating relationships yields additional insights. Although most of the mediation effects were negative, implying that Leaner plants tend to have higher levels of dysfunctional supply chain complexity, which in turn has a detrimental association with plant performance, some of the significant mediating relationships were positive, indicating the presence of strategic supply chain complexity. Specific examples of strategic supply chain complexity and associated positive performance include *% international purchases, life cycle variability and customer heterogeneity* for Customer Satisfaction; *number of customers* for Unit Cost; *number of customers* for Operating Margin*; and number of customers* for Plant Competitiveness. Though these results appear counterintuitive, they may indicate that Lean plants focus on placing emphasis on maximizing customer value. To accomplish this, Lean plants decrease costs through international purchases, manage product life cycles, and sell to a large and diverse customer base. Though they face penalties from dysfunctional supply chain complexity, Lean plants are rewarded with customer satisfaction and margins. However, these trade-offs must be carefully managed (Browning and Heath 2009; Sharma et al. 2020). The negative effect of dysfunctional supply chain complexity on performance can easily negate the benefits from strategic complexity. Many of the coefficients for dysfunctional supply chain complexity were highly significant, including *supply variability* and *number of products* for Unit Cost, *number of inputs* and *supply variability* for Schedule Attainment, *number of inputs*, *supply variability* and *number of customers* for Customer Satisfaction, and *percent international purchases*, *customer heterogeneity* and *number of products* for Plant Competitiveness. Critically, the combined effects for ten of the mediating relationships were negative. The trade-off between strategic and dysfunctional supply chain complexity may be difficult to manage, as demonstrated by examining the combined effects of Lean and supply chain complexity on Operating Margin. The direct effect shows that a Lean plant improves Operating Margins by increasing the number of customers its serves (+ 0.37). However, if managers of a Lean plant increase the number of customers by increasing the number of products (–0.53), the net effect is to lower operating margins by –0.16 (0.37–0.53). Thus, increasing the number of customers by increasing the number of products can result in lower performance.

Fifth, the robust design of the HPM project and its data supports the reliability and validity of these findings. Specifically, because the data was collected from manufacturing plants in seven countries, the generalizability of the findings is enhanced. In addition, the use of multiple well-informed respondents within each plant and our detailed inter-rater reliability analysis supports the reliability of our findings.

Finally, our results show the importance of broadly defining supply chain complexity to include both detail (*number of inputs*, *number of customers*, *number of plants*) and dynamic (*flow variability*, *supply variability*) complexity. This allows a more nuanced examination of the role of supply chain complexity in the relationship between Lean and plant performance We found examples of both dysfunctional and strategic complexity among the significant mediating effects for all four performance measures with significant first stage effects. In addition, some aspects of supply chain complexity functioned as strategic supply chain complexity for some measures of plant performance and as dysfunctional supply chain complexity for others. For example, *number of customers* (detail supply chain complexity) was a strategic source of complexity for Plant Competitiveness, but a dysfunctional source of supply chain complexity for Customer Satisfaction. Similarly, *customer heterogeneity* (dynamic complexity) was a source of strategic supply chain complexity for Customer Satisfaction, while it was a source of dysfunctional supply chain complexity for Plant Competitiveness.

6.2 Contributions to research

Our findings make important contributions to the literature on both Lean and supply chain complexity. While our findings generally support the beneficial relationship between Lean and plant performance, we find that Lean may contribute to increased supply chain complexity in some cases, with a detrimental effect on performance. This complements previous research on the negative effect of uncertainty and variability on Lean but expands the explanation to include detail complexity. Thus, our research provides an important and more complete explanation for why Lean is not always associated with expected performance improvements. We contribute to the supply chain complexity literature through our comparison of the potential moderating vs. mediating effects of supply chain complexity with a specific production system. While supply chain complexity is typically positioned as a moderator, our findings provide very little support for this and strongly support supply chain complexity as a mediator in this context. Looking at supply chain complexity as an outcome of various initiatives with the potential to influence performance may provide important insights to research on other initiatives.

Our work also contributes to the literature by synthesizing two seminal studies. The Shah and Ward (2007) paper is the gold standard for empirical research on Lean, with over 3000 citations in other research studies, while the Bozarth et al. (2009) article is widely cited as a foundation for empirical research on supply chain complexity, with almost 1000 citations. We replicate Shah and Ward's (2007) measures of Lean, then use them to develop a Lean index that reflects the holistic approach used in implementing Lean. We also replicate, as well as improve upon, the in-depth quantitative and qualitative measures of supply chain complexity developed by Bozarth et al. (2009). Synthesizing measurement and theoretical backgrounds from these two important studies provides important insights about the role of supply chain complexity in the relationship between Lean and performance.

Additionally, measuring Lean practices using the diversity of respondents in the HPM dataset allows us to measure practices from the perspective of both shop floor employees and managerial employees. We found that several Lean scales demonstrate diminished validity when measured at the shop floor employee and supervisor level. We suspect that, when viewed from the front line, variance in the level of Lean is less detectable. However, there is also a possibility that shop floor workers focus primarily on their own tasks, without developing a good understanding of the big picture regarding Lean, compared with managers. Future research is necessary to clarify this result.

Our measurement analysis expands upon Bozarth et al.'s (2009) operationalization of supply chain complexity. We show that seven of the twelve components of supply chain complexity initially proposed in their study are highly correlated. This means that firms tend to face these factors simultaneously and that reducing just one aspect would be difficult. From a measurement perspective, we found that normality for six measures of supply chain complexity was improved by transcendental transformations. As a result, our results indicate that additional supply chain complexity factors impact a manufacturing plant’s performance.

Along these lines, our research generates interesting insights regarding the effects of Lean practices on plant performance in the presence of varying levels of supply chain complexity. Since several variables were log-transformed in our analysis, it implies that those measures may exhibit non-linear relationships with plant performance. For example, if we focus on the relationship between detail complexity and plant performance, we can use the results of Table 5 to build a simplified expression to show how Lean practices and a focused measure of detail complexity, such as the *number of components* managed by the plant, affect a focused measure of plant performance, such as Schedule Attainment. From Table 5, we see that a one-unit increase in the log-transformed, mean-centered value of “number of inputs” leads to a –0.9 unit decrease in the schedule attainment index. Working to mitigate this, a one-unit increase in the Lean practices index leads to a 0.6 unit increase in schedule attainment. Mathematically, this can be stated as:

$$SchedAttain_{STD} = 0.6 \times LeanIndex_{STD} - 0.9 \times \left[\frac{Ln(\#Parts) - \mu_{Ln(\#Parts)}}{\sigma_{Ln(\#Parts)}} \right]$$

While we recognize that this expression does not capture the other effects from the regression results, it does demonstrate the Lean interplay with supply chain complexity. Figure 3 displays a response plot of this relationship using the mean-centered Lean index score, *number of parts* (as the measure of detail complexity), and the mean centered index score for Schedule Attainment (as our measure of plant performance), where $\mu_{Ln(\#parts)} = 8.2$ and $\sigma_{Ln(\#parts)} = 2.0$.

As the figure shows, the drop in performance is steep up to approximately 4,000 parts and then the slope levels off, though still negative, through the median number of parts in our sample (6,000) and up to 10,000 parts (the 90th percentile). Though very lean plants can still see improved Schedule Attainment over their less lean competitors, plants in the lower quartile of number of parts realize a significant competitive advantage over their competitors with more inputs to manage. These non-linear results are supported by the quadratic (inverted-U) relationships found in studies such as Eroglu and Hofer (2011) and Lu and Shang (2017), which indicate that there may be tipping points in supply chain complexity. Once these tipping points are passed, supply chain disruptions may overwhelm production systems, causing systemic degradation in performance (Bode and Wagner 2015). Thus, our research complements previous works that hypothesize and test theoretical models that provide researchers and practitioners with more detailed information on the expected results from supply chain and operations strategy.

We also contribute to the literature by showing Lean is sensitive to multiple forms of supply chain complexity. Our results indicate that Lean's effect on plant performance is both positively and negatively mediated by supply chain complexity. The negative mediation is important not just theoretically, but also methodologically. When negative mediators are missing from regression analyses, positive direct effects can become insignificant. Our results may explain why prior research has not found stronger relationships between Lean and certain types of performance – the missing variable effect.

Finally, our research provides an overview of the recent thoughts on testing for moderation and mediation. The use

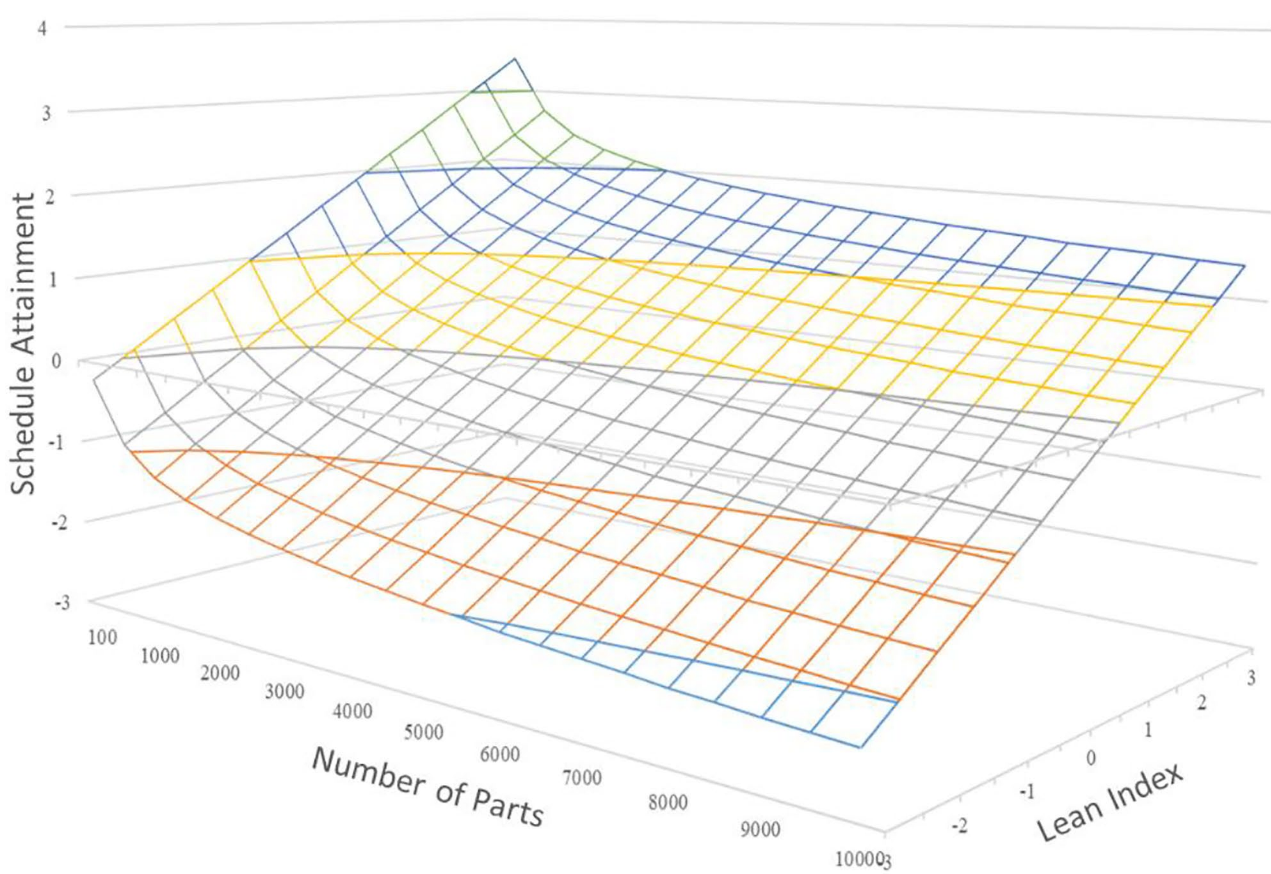

Fig. 3 Standardized Schedule Attainment vs. Number of Parts and Standardized Lean Index

of simultaneous estimation for testing effects on multiple dependent variables and seemingly unrelated regression for endogenous mediating variables increased the validity and interpretability of our analysis. Our robustness checks demonstrated that these statistical techniques possess similar or increased ability to detect moderators and mediators.

6.3 Managerial implications

By understanding why and how supply chain complexity impacts the performance outcomes of Lean, we can begin to understand the extent to which performance can be improved by taking managerial actions (Chand et al. 2022; Hoole 2005). Further, by understanding that supply chain complexity has a mediating effect, managers can be alert for ways in which Lean has the unintended consequence of increasing supply chain complexity. Although some of the resulting increases in supply chain complexity can likely be reduced through approaches related to this understanding, it implies the importance of developing approaches for accommodating supply chain complexity. In other words, while dysfunctional supply chain complexity resulting from Lean should be reduced to the extent possible, strategic supply chain complexity will need to be accommodated to avoid compromising performance.

Our findings indicate that there is probably more strategic complexity on the downstream side, at least for detail complexity. As a general guideline, managers should look for strategic complexity in downstream supply chains and focus on accommodating it. Upstream and internal supply chain complexity is probably better reduced, for the most part, since it is more likely to be dysfunctional.

Typically, after a plant begins to implement Lean, there are many visible signs of progress on the shop floor. Although things may look different, several key operational performance indicators may not change, or perhaps get worse. Manufacturing plants that have implemented Lean but not addressed higher levels of dynamic supply chain complexity (*flow variability*, *supply variability*) are unlikely to see improvements in Unit Cost and Schedule Attainment. Further, *supply variability* negates Lean's potential to significantly improve Customer Satisfaction. Types of detail supply chain complexity (*number of inputs*, *number of products*) have a similar detrimental effect. Both can negate Lean's positive benefits on Schedule Attainment and Customer Satisfaction, and *number of products* also reduces Lean's impact on Unit Cost.

Operating Margin and Plant Competitiveness, which are more strategic measures of performance, appear less sensitive to dynamic forms of supply chain complexity. Detail supply chain complexity has a more interesting and mixed effect on these strategic measures of performance. While the *number of customers* positively mediates the relationship between Lean and Plant Competitiveness, *customer heterogeneity* almost negates this improvement and *number of products* negatively mediates the relationship for both Operating Margin and Plant Competitiveness. These downstream drivers of supply chain complexity provide two valuable insights for managers of Lean plants:

1. Add Customers, not Products

   Lean provides quantifiable improvements to tangible measures of performance with higher levels of customers. Larger numbers of similar customers provide volume and economies of statistics – a pooling-based reduction in the variance of demand. These two factors promote "swift even flow" which is the hallmark of efficient production systems (Schmenner and Swink 1998). Adding too much product-based complexity, however, can lead to significant challenges in achieveing higher levels of manufacturing performance, as evidenced by our development and discussion of Fig. 3, above.
2. Replace, rather than Support

   Contrary to expectations, Lean works synergistically with shorter life cycles. A manufacturing plant that continues to produce older products faces a dilemma. With each new product offered, the catalogue of products that must be supported increases. Supporting a larger number of products makes it more difficult for a plant to dedicate operations to technologically similar products that are then sold to homogenous customers. As new products are introduced, older products should be discontinued, or their production outsourced.

These two findings are particularly salient as reshoring increases in prevalence. Tariffs, coupled with lead-time variability of extended supply chains and supply risks stemming from black swan events like a global pandemic, have motivated many companies to purchase or produce closer to sources of demand. Manufacturing plants in advanced economies are seeing new demand from existing customers and new orders from new customers (Branicki et al. 2021). Lean manufacturing plants should accept such new orders with caution. The addition of customers with special requirements may negatively impact a Lean plant's performance. Adding customers that increase detail and dynamic supply chain complexity may ultimately decrease the plant's ability to meet delivery dates and hit its cost targets. Ultimately, these types of customers can drive down a Lean plant's competitiveness and margins.

6.4 Limitations and opportunities for future research

As with all research, there are a number of limitations to this project, many of which provide opportunities for future research. The first is the limitations of survey-based research. This research attempted to overcome some of these limitations by employing multiple respondents and using a combination of perceptual reports and objective measures in operationalizing Lean, supply chain complexity, and plant performance. Additionally, the sample was drawn from three industries and multiple countries, which supports generalizability, at least within this sampling frame, compared with survey studies employing more of a shotgun approach.

A second limitation is the sample size relative to the number of statistical tests that were performed. Therefore, several of our analyses may have suffered from diminished statistical power, potentially leading to an increased chance of Type II errors. However, it is important to note that although we analyzed data from a sample of 209 plants, each measure aggregated responses from at least three well-informed respondents and that we carefully analyzed inter-rater reliability before aggregating them. Thus, the responses were more reliable than individual responses normally are.

This sample is from the third round HPM survey conducted between 2005 and 2007. Though the data is over a decade old, the Lean practices studied and drivers of supply chain complexity are still present in today's manufacturing plants. The concurrence of our criterion validity test results with Akin Ateş et al.'s (2022) meta-analysis and the fact that this recent meta-analysis confirmed the findings from Bozarth et al. (2009), which uses the same dataset as we did, demonstrates that this dataset is still relevant and that the underlying co-variance between the variables can provide new and additional insights to researchers and managers. It could be argued that several drivers of supply chain complexity, such as international sourcing, product life cycle, and supply lead time, have become more pronounced since the data was collected, and we expect that the relationships between Lean, plant performance, and supply chain complexity persist and have likely intensified since the time the data was collected. Updating these findings is an important opportunity for future research. We note, however, that the Lean scales used in the HPM survey are still considered one of the most complete and valid measures of Lean (Schroeder and Flynn 2002).

In addition, internal, upstream, and downstream supply chain complexity can interact, with a negative impact on firm performance (Chedid et al. 2021; Prater et al. 2001), as a firm simultaneously faces complexity in its internal and external networks. Potential interactions are an important topic, since plants do not face individual sources of supply chain complexity; rather supply chain complexity sources exist as a *Gestalt*. The potential for interactions is especially relevant to dynamic complexity, since interactions may produce unexpected results in other parts of a system (Bode and Wagner 2015). This complicated topic is beyond the scope of this research but is an interesting opportunity for future research.

The impact of Covid-19 on supply chains illustrates dramatic, sudden increases in supply chain complexity, rather than gradual increases (Shen and Sun 2021). Other types of supply chain disruptions can also cause dramatic, sudden increases in supply chain complexity. Case analysis will be useful in studying the effects of sudden changes to supply chain complexity on the relationship between Lean and plant performance. For example, there may be more evidence of a moderating effect when exogenous supply chain complexity changes suddenly.

Akin Ateş et al.'s (2022) meta-analysis describes understanding the effects of upstream dynamic complexity, downstream detail complexity, and internal dynamic complexity on performance as "untouched territory (p.18)." They also discuss the importance of investigating the potential for trade-offs in the presence of aspects of supply chain complexity that have both positive and negative mediating effects, depending on the dimension of performance. These are both very relevant extensions to our research on the role of supply chain complexity in the relationship between Lean and plant performance.

One final interesting extension is the topic of reshoring. As companies carry out more reshoring, what is the impact on upstream and internal supply chain complexity? Does internal supply chain complexity immediately increase, then return to stasis, or is there an enduring increase? Does the resulting increase in internal supply chain complexity have less impact on the relationship between Lean and performance than the increase in upstream supply chain complexity?

7 Conclusions

Overall, our results indicate that many forms of supply chain complexity dampen or negate the positive effects of Lean production practices. Supply chain complexity acts as a tax on Lean, reducing its effectiveness at both the operational and strategic levels of a plant. The good news is that, as most of the effects that we found were mediating effects, managers have the opportunity to influence the sources of complexity. We support the recommendations of Turner et al. (2018) that emphasize accommodating strategic supply chain complexity, while reducing sources of dysfunctional supply chain complexity. In this way, the negative implications of strategic supply chain complexity can be reduced without affecting its beneficial effects on performance.

Appendix A. Items and respondents

Construct[a]	HPM Items	HPM Respondents[b]
Setup time reduction	Our crews practice setup to reduce the time required	PC, IM, SP
	We are aggressively working to lower setup times in our plant	PC, IM, SP
	We have low setup times of equipment in our plant	PC, IM, SP
Total productive/ preventive maintenance	We upgrade inferior equipment, in order to prevent equipment problems	PE, SP, PS
	In order to improve equipment performance, we sometimes redesign equipment	PE, SP, PS
	We estimate the lifespan of our equipment, so that repair or replacement can be planned	PE, SP, PS
	We use equipment diagnostic techniques to predict equipment lifespan	PE, SP, PS
	We do not conduct technical analysis of major breakdowns (reverse-scored)	PE, SP, PS
Statistical process control	A large percent of the processes on the shop floor are currently under statistical quality control	DL, PE,QM
	We make extensive use of statistical techniques to reduce process variance	DL, PE,QM
	We use charts to determine whether our manufacturing processes are in control	DL, PE,QM
Employee involvement	During problem solving sessions, we make an effort to get all team members' opinions and ideas before making a decision	DL, QM, SP
	Our plant forms teams to solve problems	DL, QM, SP
	In the past three years, many problems have been solved through small group sessions	DL, QM, SP
	Problem solving teams have helped improve manufacturing processes at this plant	DL, QM, SP
	Employee teams are encouraged to try to solve their own problems, as much as possible	DL, QM, SP
	We don't use problem solving teams much, in this plant (reverse-scored)	DL, QM, SP
	Management takes all product and process improvement suggestions seriously	DL, SP, PS
	We are encouraged to make suggestions for improving performance at this plant	DL, SP, PS
	Management tells us why our suggestions are implemented or not used	DL, SP, PS
	Many useful suggestions are implemented at this plant	DL, SP, PS
	My suggestions are never taken seriously around here (reverse-scored)	DL, SP, PS
	Employees are cross-trained at this plant, so that they can fill in for others, if necessary	HR, SP, PS
Pull	Our customers are linked with us via JIT systems	PC, IM, SP
	Our customers have a pull-type link with us	PC, IM, SP
	We use Kanban squares, containers, or signals for production control	PC, IM, SP
	We use a Kanban pull system for production control	PC, IM, SP
Continuous flow	We have laid out the shop floor so that processes and machines are in close proximity to each other	PC, IM, SP
	Our machines are grouped according to the product family to which they are dedicated	PC, IM, SP
	We have organized our plant floor into manufacturing cells	PC, IM, SP
	The layout of our shop floor facilitates low inventories and fast throughput	PC, IM, SP
	Our processes are located close together, so that material handling and part storage are minimized	PC, IM, SP
	We have located our machines to support JIT production flow	PC, IM, SP
JIT delivery by suppliers	Our suppliers deliver to us on a just-in-time basis	PC, IM, SP
	We receive daily shipments from most suppliers	PC, IM, SP
	We can depend upon on-time delivery from our suppliers	PC, IM, SP
	Our suppliers are linked with us by a pull system	PC, IM, SP
	Suppliers frequently deliver materials to us	PC, IM, SP

Construct[a]	HPM Items	HPM Respondents[b]
Supplier feedback	We are comfortable sharing problems with our suppliers	IM, SP, PS
	In dealing with our suppliers, we are wiling to change assumptions, n order to find more effective solutions	IM, SP, PS
	We believe that cooperating with our suppliers is beneficial	IM, SP, PS
	We emphasize openness of communications in collaborating with our suppliers	IM, SP, PS
	We work as a partner with our suppliers, rather than having an adversarial relationship	IM, SP, PS
	We strive to establish long-term relationships with suppliers	IM, SP, PS
Supplier development	We maintain cooperative relationships with our suppliers	DL, IM, QM
	We provide a fair return to our suppliers	DL, IM, QM
	We help our suppliers to improve their quality	DL, IM, QM
	Our key suppliers provide input into our product development projects	DL, IM, QM
	We strive to establish long-term relationships with our suppliers	DL, IM, QM
	Our suppliers are actively involved in our new product development process	DL, IM, QM
	Quality is our number one criterion in selecting suppliers	DL, IM, QM
	We use mostly suppliers that we have certified	DL, IM, QM
	We maintain close communication with suppliers about quality considerations and design changes	DL, IM, QM
	How many suppliers does this plant have?	QM
	We actively engage suppliers in our quality improvement efforts	DL, IM, QM
	We would select a quality supplier over one with a lower price	DL, IM, QM
Customer involvement	We frequently are in close contact with our customers	DL, QM, SP
	Our customers seldom visit our plant (reverse-scored)	DL, QM, SP
	Our customers give us feedback on our quality and delivery performance	DL, QM, SP
	Our customers are actively involved in our product design process	DL, QM, SP
	We consider our customers' forecasts in our supply chain planning	IM, SP, PS

[a]Based on Shah and Ward (2007)

[b]*PC* production control manager, *DL* direct labor, *IM* inventory manager, *SP* supervisor, *PE* process engineer, *PS* plant superintendent, *QM* quality manager, *HR* human resource manager

Appendix B. Q-Sort analysis

		Expert Rank				Item Cumulative Rank																
	Item	A	B	C	D	1	2	3	4	5	6	7	8	9	10	11	12	∑High[a]	∑Low	Odds Ratio[b]	Ln(OR)	Probability
SuppFeed_01	We are comfortable sharing problems with our suppliers	5	5	4	3	0	0	1	1	2	0	-	-	-	-	-	-	1	3	0.1	-2.2	1%
SuppFeed_02	In dealing with our suppliers, we are willing to change assumptions, in order to find more effective solutions	6	6	6	6	0	0	0	0	0	4	-	-	-	-	-	-	0	4	0.0	0.0	0%
SuppFeed_03	We believe that coopreating with our suppliers is beneficial	6	4	9	6	0	0	0	1	0	2	-	-	-	-	-	-	0	3	0.0	0.0	0%
SuppFeed_04	We emphasize openness of communications in collaborating with our suppliers	6	2	3	2	0	2	1	0	0	1	-	-	-	-	-	-	3	1	9.0	2.2	99%
SuppFeed_05	We work as a partner with our suppliers, rather than having an adversarial relationship	6	6	6	6	0	0	0	0	0	4	-	-	-	-	-	-	0	4	0.0	0.0	0%
SuppFeed_06	We frequently are in close contact with our suppliers	1	6	8	4	1	0	0	1	0	1	-	-	-	-	-	-	1	2	0.3	-1.1	14%
SuppJIT_01	Our key suppliers deliver to plant on JIT basis	3	1	1	6	2	0	1	0	0	1	0	-	-	-	-	-	3	1	9.0	2.2	99%
SuppJIT_02	We receive daily shipments from most suppliers	1	3	5	6	1	0	1	0	1	1	0	-	-	-	-	-	2	2	1.0	0.0	50%
SuppJIT_03	We can depend upon on-time delivery from our suppliers	4	5	4	3	0	0	1	2	1	0	0	-	-	-	-	-	3	3	1.0	0.0	50%
SuppJIT_04	Our suppliers are linked with us by a pull system	5	2	3	1	1	1	1	0	1	0	0	-	-	-	-	-	3	1	9.0	2.2	99%
SuppJIT_05	Suppliers frequently deliver materials to us	2	4	2	2	0	3	0	1	0	0	0	-	-	-	-	-	4	1	100.0	4.6	100%
SuppJIT_06	We have a formal supplier certification program	6	2	5	6	0	1	0	0	1	2	0	-	-	-	-	-	1	3	0.1	-2.2	1%
SuppDev_01	We maintain cooperative relationships with our suppliers	12	12	12	5	0	0	0	0	1	0	0	0	0	0	0	3	1	3	0.1	-2.2	1%

	Item	Expert Rank				Item Cumulative Rank												∑High[a]	∑Low	Odds Ratio[b]	Ln(OR)	Probability
		A	B	C	D	1	2	3	4	5	6	7	8	9	10	11	12					
SuppDev_02	We provide a fair return to our suppliers	6	10	12	2	0	1	0	0	0	1	0	0	0	1	0	1	2	2	1.0	0.0	50%
SuppDev_03	We help our suppliers to improve their quality	12	12	12	12	0	0	0	0	0	0	0	0	0	0	0	4	0	4	0.0	0.0	0%
SuppDev_04	Our key suppliers provide input into our product development projects	8	9	10	9	0	0	0	0	0	0	0	1	2	1	0	0	0	4	0.0	0.0	0%
SuppDev_05	We strive to establish long-term relationships with suppliers	5	5	5	6	0	0	0	0	3	1	0	0	0	0	0	0	4	0	100.0	4.6	100%
SuppDev_06	Our suppliers are actively involved in our new product development process	9	8	6	10	0	0	0	0	0	1	0	1	1	1	0	0	1	3	0.1	-2.2	1%
SuppDev_07	Quality is our number one criterion in selecting suppliers	6	6	2	12	0	1	0	0	0	2	0	0	0	0	0	1	3	1	9.0	2.2	99%
SuppDev_08	We use mostly suppliers that we have certified	4	3	12	12	0	0	1	1	0	0	0	0	0	0	0	2	2	2	1.0	0.0	50%
SuppDev_09	We maintain close communications with suppliers about quality considerations and design changes	12	12	7	12	0	0	0	0	0	0	1	0	0	0	0	3	0	4	0.0	0.0	0%
SuppDev_10	We take active steps to reduce the number of suppliers in each category	3	5	12	4	0	0	1	1	1	0	0	0	0	0	0	1	3	1	9.0	2.2	99%
SuppDev_11	We actively engage suppliers in our quality improvement efforts	1	4	1	1	3	0	0	1	0	0	0	0	0	0	0	0	4	0	100.0	1.6	100%
SuppDev_12	We would select a quality supplier over one with a lower price	7	7	12	7	0	0	0	0	0	0	3	0	0	0	0	1	0	4	0.0	0.0	0%
CustDev_01	We frequently are in close contact with our customers	1	4	5	5	1	0	0	1	2	-	-	-	-	-	-	-	1	3	0.1	-2.2	1%
CustDev_02	Our customers seldom visit our plants (reverse coded)	3	5	3	5	0	0	2	0	2	-	-	-	-	-	-	-	2	4	0.3	-1.4	8%
CustDev_03	Our customers give us feedback on quality and delivery performance	5	1	2	2	1	2	0	0	1	-	-	-	-	-	-	-	3	1	9.0	2.2	99%

		Expert Rank				Item Cumulative Rank																
	Item	A	B	C	D	1	2	3	4	5	6	7	8	9	10	11	12	∑High[a]	∑Low	Odds Ratio[b]	Ln(OR)	Probability
CustDev_04	Our customers are activly involved in current and future product offerings	2	2	1	3	1	2	1	0	0	-	-	-	-	-	-	-	4	1	12.0	2.5	99%
CustDev_05	Our customers frequently share current and future demand information with marketing department	4	3	4	4	0	0	1	3	0	-	-	-	-	-	-	-	1	4	0.1	-2.5	1%
PullSys_1	Our customers have a pull type link with us	2	2	4	4	0	2	0	2	-	-	-	-	-	-	-	-	2	2	1.0	0.0	50%
PullSys_2	Production is "pulled" by the shipment of finished goods	2	3	3	2	0	2	2	0	-	-	-	-	-	-	-	-	2	2	1.0	0.0	50%
PullSys_3	We use Kanban, squares, or containers of signals for production control	3	1	1	3	2	0	2	0	-	-	-	-	-	-	-	-	2	2	1.0	0.0	50%
PullSys_4	We use a kanban pull sytem for production system	1	3	2	1	2	1	1	0	-	-	-	-	-	-	-	-	3	1	9.0	2.2	99%
LeanFlow_01	We have laid out the shop floor so that processes and machines are in close proximity to each other	6	5	3	2	0	1	1	0	1	1	-	-	-	-	-	-	2	2	1.0	0.0	50%
LeanFlow_02	Our machines are grouped according to the product family to which they are dedicated	2	6	5	4	0	1	0	1	1	1	-	-	-	-	-	-	1	3	0.1	-2.2	1%
LeanFlow_03	We have organized our plant floor into manufacturing cells	4	3	4	3	0	0	2	2	0	0	-	-	-	-	-	-	2	2	1.0	0.0	50%
LeanFlow_04	The layout of our shop floor facilitates low inventories and fast throughput	5	2	6	6	0	1	0	0	1	2	-	-	-	-	-	-	1	3	0.1	-2.2	1%
LeanFlow_05	Our processes are located close together, so that material handling and part storage are minimized	3	4	2	1	1	1	1	1	0	0	-	-	-	-	-	-	3	1	9.0	2.2	99%
LeanFlow_06	We have located our machines to support JIT production flow	1	1	1	6	3	0	0	0	0	1	-	-	-	-	-	-	3	1	9.0	2.2	99%
SetupRed_1	Our emplyees practice setups to reduce the time required	3	3	3	3	0	0	4	-	-	-	-	-	-	-	-	-	0	4	0.0	0.0	0%

		Expert Rank				Item Cumulative Rank																
	Item	A	B	C	D	1	2	3	4	5	6	7	8	9	10	11	12	∑High[a]	∑Low	Odds Ratio[b]	Ln(OR)	Probability
SetupRed_2	We are working agressively to lower setup times in our plant	2	2	2	2	0	4	0	-	-	-	-	-	-	-	-	-	2	2	1.0	0.0	50%
SetupRed_3	We have low set up times of equipment in our plant	1	1	1	1	4	0	0	-	-	-	-	-	-	-	-	-	4	0	100.0	4.6	100%
SPC_01	A large percentage of equipment/processes on shop floor are currently under SPC	3	1	2	3	1	1	2	-	-	-	-	-	-	-	-	-	2	2	1.0	0.0	50%
SPC_02	We make use of extensive use of statistical techniques to reduce process variance	2	3	1	1	2	1	1	-	-	-	-	-	-	-	-	-	3	2	3.0	1.1	86%
SPC_03	We use charts showing defect rates are used as tools on the shop-floor	1	2	3	2	1	2	1	-	-	-	-	-	-	-	-	-	3	1	9.0	2.2	99%
EmpInv_01	During problem solving sessions, we make an effort to get all team members' opinions and ideas before making a decision	9	6	4	3	0	0	1	1	0	1	0	0	1	0	0	0	3	1	9.0	2.2	99%
EmpInv_02	Our plant forms teams to solve problems	5	2	2	1	1	2	0	0	1	0	0	0	0	0	0	0	4	0	100.0	4.6	100%
EmpInv_03	In the past three years, many problems have been solved through small group sessions	4	5	8	5	0	0	0	1	2	0	0	1	0	0	0	0	3	1	9.0	2.2	99%
EmpInv_04	Problem solving teams have helped improve manufacturing processes at this plant	1	4	12	12	1	0	0	1	0	0	0	0	0	0	0	2	2	2	1.0	0.0	50%
EmpInv_05	Employee teams are encouraged to try to solve their own problems, as much as possible	3	3	9	2	0	1	2	0	0	0	0	0	1	0	0	0	3	1	9.0	2.2	99%
EmpInv_06	We don't use problem solving teams much, in this plant	2	11	7	6	0	1	0	0	0	1	1	0	0	0	1	0	2	2	1.0	0.0	50%
EmpInv_07	Management takes all product and process improvement suggestions seriously	6	6	6	10	0	0	0	0	0	3	0	0	0	1	0	0	3	1	9.0	2.2	99%

	Item	Expert Rank				Item Cumulative Rank												∑High[a]	∑Low	Odds Ratio[b]	Ln(OR)	Probability
		A	B	C	D	1	2	3	4	5	6	7	8	9	10	11	12					
EmpInv_08	We are encouraged to make suggestions for improving performance at this plant	10	1	1	4	2	0	0	1	0	0	0	0	0	1	0	0	3	1	9.0	2.2	99%
EmpInv_09	Management tells us why our suggestions are implemented or not used	11	7	5	8	0	0	0	0	1	0	1	1	0	0	1	0	1	3	0.1	-2.2	1%
EmpInv_10	Many useful suggestions are implemented at this plant	8	8	9	7	0	0	0	0	0	0	1	2	1	0	0	0	0	4	0.0	0.0	0%
EmpInv_11	My suggestions are never taken seriously around here	7	10	10	9	0	0	0	0	0	0	1	0	1	2	0	0	0	4	0.0	0.0	0%
EmpInv_12	Shop-floor employees undergo cross functional training	12	9	3	11	0	0	1	0	0	0	0	0	1	0	1	1	1	3	0.1	-2.2	1%
TPM_01	We upgrade inferior equipment, in order to prevent equipment problems	3	4	2	3	0	1	2	1	0	-	-	-	-	-	-	-	3	1	9.0	2.2	99%
TPM_02	In order to improve equipment performance, we sometimes redesign equipment	5	3	3	4	0	0	2	1	1	-	-	-	-	-	-	-	1	3	0.0	-2.2	1%
TPM_03	We estimate the lifespan of our equipment, so that repair or replacement can be planned	4	2	5	1	1	1	0	1	1	-	-	-	-	-	-	-	2	2	1.0	0.0	50%
TPM_04	We use equipment diagnostic techniques to predict equipment lifespan	2	1	1	2	2	2	0	0	0	-	-	-	-	-	-	-	4	0	100.0	4.6	100%
TPM_05	We do not conduct technical analysis of major breakdowns	1	5	4	5	1	0	0	1	2	-	-	-	-	-	-	-	1	3	0.1	-2.2	1%

[a]Rounding of n/2 increased the ∑High count and lowered the ∑Low consistently benefiting the item

[b]In some instances, the odds ratio was adjusted to avoid extreme values / error messages

Appendix C. Varimax PCA lean factors comprising the lean index

Item Name	Item	Factor Score	Reliability
Suppfeed_01	We are comfortable sharing problems with our suppliers	0.76	0.795
Suppfeed_02	We believe that cooperating with our suppliers is beneficial	0.76	
Suppfeed_03	We emphasize openness of communications in collaborating with our suppliers	0.69	
Suppfeed_04	In dealing with our suppliers, we are willing to change assumptions, in order to find more effective solutions	0.55	
ExtPull_01	Our customers are linked with us via JIT systems	0.79	0.807
ExtPull_02	Our suppliers deliver to us on a just-in-time basis	0.71	
ExtPull_03	We receive daily shipments from most suppliers	0.72	
ExtPull_04	We can depend upon on-time delivery from our suppliers	0.52	
ExtPull_05	Our suppliers are linked with us by a pull system	0.52	
SuppDev_01	We maintain cooperative relationships with our suppliers	0.74	0.883
SuppDev_02	We provide a fair return to our suppliers	0.54	
SuppDev_03	We help our suppliers to improve their quality	0.73	
SuppDev_04	We take active steps to reduce the number of suppliers in each category	0.78	
SuppDev_05	Our key suppliers provide input into our product development projects	0.53	
SuppDev_06	We strive to establish long-term relationships with suppliers	0.58	
SuppDev_07	Our suppliers are actively involved in our new product development process	0.58	
SuppDev_08	We maintain close communications with suppliers about quality considerations and design changes	0.64	
SuppDev_09	We maintain close communication with suppliers about quality considerations and design changes	0.78	
SuppDev_10	We actively engage suppliers in our quality improvement efforts	0.70	
SuppSel_01	Quality is our number one criterion in selecting suppliers	0.62	0.764
SuppSel_02	We would select a quality supplier over one with a lower price	0.77	
CustDev_01	We frequently are in close contact with our customers	0.62	0.644
CustDev_02	Our customers are actively involved in our product design process	0.78	
CustDev_03	We consider our customers' forecasts in our supply chain planning	0.47	
Kanban_01	We use a kanban pull system for production control	0.86	0.859
Kanban_02	We use kanban squares, containers or signals for production control	0.81	
LeanSys_01	We have laid out the shop floor so that processes and machines are in close proximity to each other	0.80	0.844
LeanSys_02	The layout of our shop floor facilitates low inventories and fast throughput	0.77	
LeanSys_03	Our processes are located close together, so that material handling and part storage are minimized	0.71	
LeanSys_04	We have located our machines to support JIT production flow	0.53	
LeanSys_05	We are aggressively working to lower setup times in our plant	0.52	
LeanSys_06	We have low setup times of equipment in our plant	0.53	
SPC_01	A large percent of the processes on the shop floor are currently under statistical quality control	0.81	0.844
SPC_02	We make extensive use of statistical techniques to reduce variance in processes	0.74	
SPC_03	We use charts to determine whether our manufacturing processes are in control	0.61	

Item Name	Item	Factor Score	Reliability
EmpInp_01	During problem solving sessions, we make an effort to get all team members' opinions and ideas before making a decision	0.53	0.875
EmpInp_02	Management takes all product and process improvement suggestions seriously	0.74	
EmpInp_03	We are encouraged to make suggestions for improving performance at this plant	0.72	
EmpInp_04	Management tells us why our suggestions are implemented or not used	0.79	
EmpInp_05	Many useful suggestions are implemented at this plant	0.70	
EmpInp_06	My suggestions are never taken seriously around here	0.51	
EmpTBPS_01	Our plant forms teams to solve problems	0.74	0.89
EmpTBPS_02	In the past three years, many problems have been solved through small group sessions	0.71	
EmpTBPS_03	Problem solving teams have helped improve manufacturing processes at this plant	0.72	
EmpTBPS_04	Employee teams are encouraged to try to solve their own problems, as much as possible	0.56	
EmpTBPS_05	We don't use problem solving teams much, in this plant	0.77	

Appendix D. Inter-rater correlation

Respondents to the various measures in the HPM project were selected based on the following objectives: 1) Most knowledgeable respondents for the content included in the measure, and 2) At least three respondents per measure, in order to minimize the potential for common method bias. Thus, respondents in different respondent groups (direct labor, supervisor, production control manager, plant superintendent, inventory manager, process engineer, quality manager, and human resource manager) provided responses to each measure. This necessitates assessing inter-rater reliability to ensure that all respondents provided valid responses. For some measures, we put together the set of items that was closest to the items used by Shah and Ward (2007), rather than using the measures originally developed for the HPM project.

To assess the validity of the measures, we first performed principal components analysis with varimax rotation within each respondent group. Exploratory factor analysis was used since the proposed items were not initially designed as complete measures, the wording of some items did not correspond exactly with those used by Shah and Ward (2007), and respondents from different respondent classes could potentially have different perspectives. Factor scores, loadings (both in the table below), and Q-sort results (Appendix B) for each item were compared within respondent groups. The number of factors was chosen based on content analysis, eigenvalues, and scree-plots. Factor loadings were then used to assess the convergent and discriminant validity of the factors.

The results were satisfactory with three exceptions. Direct labor and supervisor respondents tended to view the Employee Involvement measure as being composed of two factors, while quality manager respondents did not. This is not surprising, since Employee Involvement is a twelve-item measure constructed from two HPM measures: Team Problem Solving and Employee Suggestions. Because of the content concordance with Shah and Ward's (2007) Employee Involvement measure, we kept this measure intact. There were also two examples of cross-loadings. There was some cross-loading of responses by direct labor and quality manager respondents between the Customer Development and Supplier Development measures; similarly, the inventory manager responses for Supplier Development and Supplier Feedback showed some cross-loading. However, previous research has shown that companies tend to integrate their supply chains upstream, downstream, or both upstream and downstream simultaneously (Schoenherr and Swink 2012). Therefore, finding a degree of cross loading within and between supply facing and customer facing activities is not surprising.

Factor scores were then calculated for each respondent group, followed by examining the intra-rater correlation matrix below for the ten factors. It revealed that seven of the ten factors demonstrated a high degree of inter-rater correlation. Plant superintendent responses for Total Productive Maintenance (TPM) and Supplier Feedback correlated with Supplier JIT, Lean Flow, and Setup Reduction, with an average cross-factor correlation of 0.316. However, TPM correlated at 0.591 between the plant superintendent and supervisor responses, showing that these respondents had a high level of agreement on the level of TPM occurring in their plants. Thus, we were confident we had adequately measured the operational definition of Lean as composed of the ten practices identified by Shah and Ward (2007).

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	SuppJIT_IM	**1.00**																
2	SuppJIT_PC	**0.54**	**1.00**															
3	SuppJIT_SP	**0.41**	**0.87**	**1.00**														
4	SuppDev_DL	0.18	0.23	0.22	**1.00**													
5	SuppDev_IM	**0.70**	0.16	0.16	0.09	**1.00**												
6	SuppDev_QM	0.13	**0.31**	**0.26**	**0.65**	0.01	**1.00**											
7	SuppDev2_IM	-0.08	-0.09	-0.09	0.04	-0.13	-0.20	**1.00**										
8	SuppDev2_QM	0.21	0.05	0.05	**0.46**	0.18	-0.01	**0.28**	**1.00**									
9	SuppFeed_IM	-0.58	-0.04	-0.05	-0.15	-0.71	0.05	0.03	-0.30	**1.00**								
10	SuppFeed_PS	-0.14	0.11	0.13	0.02	-0.14	0.15	-0.07	-0.05	**0.32**	**1.00**							
11	SuppFeed_SI	-0.14	0.10	0.15	-0.03	-0.16	0.07	-0.03	0.01	**0.32**	**0.81**	**1.00**						
12	LeanFlow_IM	0.08	0.05	0.06	0.06	0.08	0.11	-0.04	0.12	0.01	0.16	-0.05	**1.00**					
13	LeanFlow_PC	-0.05	0.10	0.09	-0.02	-0.04	0.11	-0.06	0.03	**0.27**	**0.36**	0.15	**0.76**	**1.00**				
14	LeanFlow_SP	0.06	0.10	0.05	0.06	0.00	0.11	-0.02	0.11	0.07	0.09	-0.04	**0.49**	**0.79**	**1.00**			
15	Setup_IM	-0.42	-0.04	-0.13	0.07	-0.50	0.03	-0.02	0.01	**0.45**	-0.04	0.01	-0.04	0.05	0.04	**1.00**		
16	Setup_PC	0.12	-0.03	-0.09	0.14	0.10	-0.02	0.02	0.21	-0.03	-0.13	-0.03	0.01	-0.01	0.08	**0.51**	**1.00**	
17	Setup_SP	0.18	0.04	-0.14	0.15	0.14	0.00	0.03	**0.25**	-0.14	-0.28	-0.12	-0.11	-0.18	-0.02	**0.35**	**0.81**	**1.00**
18	EmpInv_DL	0.17	-0.02	-0.02	0.14	0.19	-0.08	0.18	**0.69**	-0.26	0.11	0.11	0.15	0.15	0.12	-0.01	0.16	0.15
19	EmpInv_PS	-0.02	0.01	0.01	-0.08	0.06	-0.02	-0.04	0.10	0.00	-0.02	0.05	-0.03	0.18	0.15	0.14	**0.32**	0.13
20	EmpInv_QM	0.00	0.05	0.00	-0.01	-0.03	-0.03	0.15	0.02	0.12	0.23	0.11	0.12	**0.30**	0.19	0.10	0.09	0.00
21	EmpInv_SP	-0.05	-0.14	-0.17	-0.06	0.02	-0.04	0.03	0.15	-0.07	-0.06	-0.05	-0.03	0.06	0.07	0.09	**0.28**	0.10
22	EmpInv2_DL	-0.05	0.07	0.07	-0.04	-0.03	0.05	0.07	-0.12	0.15	0.22	0.13	0.04	**0.26**	0.18	0.12	0.05	-0.05
23	EmpInv2_SP	-0.05	0.06	0.01	-0.15	-0.03	-0.07	-0.11	-0.21	0.14	0.12	-0.01	0.12	**0.30**	0.05	0.12	-0.02	-0.03
24	PullSys_IM	-0.43	0.14	0.14	0.00	-0.59	0.09	-0.07	-0.11	**0.53**	0.16	0.17	0.01	0.17	0.11	**0.36**	-0.09	-0.14
25	PullSys_PC	0.07	0.06	0.10	0.01	0.05	0.05	-0.11	-0.02	0.01	0.10	0.10	0.04	0.09	0.10	-0.12	-0.05	-0.10
26	PullSys_SP	-0.03	-0.02	-0.01	-0.01	-0.01	0.12	-0.05	-0.09	0.07	0.09	0.08	0.04	0.06	0.06	-0.12	-0.04	-0.10
27	TPM_PE	0.12	0.15	0.07	0.17	0.03	0.11	0.04	**0.27**	-0.02	0.05	0.08	0.00	0.05	0.09	0.23	0.22	0.23
28	TPM_PS	**0.31**	**0.31**	0.17	0.11	0.20	0.09	0.03	0.22	-0.07	0.04	-0.12	**0.25**	**0.29**	**0.27**	0.14	**0.39**	**0.48**
29	TPM_SP	0.04	0.00	-0.09	-0.02	0.04	-0.06	0.14	0.07	0.05	**0.30**	-0.01	0.22	0.18	0.02	-0.06	-0.04	-0.10
30	SPC_DL	0.04	0.05	0.02	0.08	-0.02	0.07	-0.01	-0.05	0.12	0.14	0.07	0.10	0.15	0.05	0.03	0.13	0.14
31	SPC_PE	0.14	0.05	0.02	0.02	0.17	-0.07	0.08	0.02	0.01	0.09	0.08	0.05	0.03	-0.03	-0.05	0.20	0.19
32	SPC_QM	0.05	0.05	0.00	0.06	0.05	-0.05	-0.01	0.03	0.07	0.08	0.02	0.09	0.16	0.11	0.06	0.22	**0.25**
33	CustDev_DL	0.06	0.06	0.13	-0.08	0.02	0.23	-0.35	-0.35	0.11	**0.32**	0.16	0.11	0.14	0.00	-0.20	-0.17	-0.30
34	CustDev_QM	0.09	0.03	0.13	-0.06	0.05	0.10	-0.28	-0.16	0.04	**0.34**	0.16	0.07	0.10	-0.01	-0.23	-0.18	-0.33
35	CustDev_SI	-0.08	0.00	0.01	0.01	0.04	0.07	-0.22	-0.24	0.06	**0.30**	0.10	0.11	0.09	-0.12	-0.09	-0.15	-0.12

		18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
18	EmpInv_DL	**1.00**																	
19	EmpInv_PS	**0.28**	**1.00**																
20	EmpInv_QM	0.25	0.22	**1.00**															
21	EmpInv_SP	**0.29**	**0.85**	0.12	**1.00**														
22	EmpInv2_DL	0.07	0.17	**0.89**	0.03	**1.00**													
23	EmpInv2_SP	-0.06	0.15	**0.34**	-0.08	**0.34**	**1.00**												
24	PullSys_IM	-0.15	0.10	-0.02	-0.01	-0.01	0.08	**1.00**											
25	PullSys_PC	-0.06	0.23	-0.01	0.11	-0.01	0.04	**0.55**	**1.00**										
26	PullSys_SP	-0.11	0.19	0.02	0.14	0.01	-0.04	**0.39**	**0.86**	**1.00**									
27	TPM_PE	0.21	0.23	0.21	0.16	0.13	0.13	0.14	0.10	-0.01	**1.00**								
28	TPM_PS	**0.26**	0.10	0.16	0.09	0.13	0.21	-0.07	-0.02	-0.14	**0.29**	**1.00**							
29	TPM_SP	0.17	-0.05	0.15	0.09	0.12	0.06	-0.08	-0.11	-0.14	0.05	**0.59**	**1.00**						
30	SPC_DL	-0.10	0.07	0.14	0.03	0.13	0.21	0.01	0.09	0.11	0.15	0.21	0.11	**1.00**					
31	SPC_PE	-0.06	-0.03	0.07	-0.05	0.06	0.00	-0.13	0.04	0.00	0.01	0.20	0.13	**0.33**	**1.00**				
32	SPC_QM	-0.08	0.06	0.12	0.01	0.13	**0.26**	0.03	0.15	0.13	0.20	**0.27**	0.08	**0.88**	**0.43**	**1.00**			
33	CustDev_DL	-0.18	-0.04	-0.09	-0.12	-0.06	0.09	0.11	0.11	0.03	-0.04	-0.04	0.11	0.09	-0.02	0.04	**1.00**		
34	CustDev_QM	0.00	0.00	0.00	-0.07	-0.03	0.05	0.04	0.06	-0.03	0.03	-0.06	0.14	0.06	0.00	-0.01	**0.89**	**1.00**	
35	CustDev_SI	-0.16	-0.04	0.01	-0.13	0.01	0.06	0.08	0.04	-0.06	-0.14	0.01	0.06	0.05	-0.02	0.03	**0.34**	**0.29**	**1.00**

Data availability The data that support the findings of this study are not openly available due to a non-disclosure agreement with the participating firms. Descriptive statistics, correlations, and sample characteristics are available from the corresponding author upon reasonable request.

References

Aitken J, Bozarth C, Garn W (2016) To eliminate or absorb supply chain complexity: a conceptual model and case study. Supply Chain Manag 21(6):759–774

Akin Ateş M, Suurmond R, Luzzini D, Krause D (2022) Order from chaos: a meta-analysis of supply chain complexity and firm performance. J Supply Chain Manag 58(1):3–30

Azadegan A, Patel PC, Zangoueinezhad A, Linderman K (2013) The effect of environmental complexity and environmental dynamism on lean practices. J Oper Manag 31(4):193–212. https://doi.org/10.1016/j.jom.2013.03.002

Baron RM, Kenny DA (1986) The moderator–mediator variable distinction in social psychological research: Conceptual, strategic, and statistical considerations. J Pers Soc Psychol 51(6):1173

Barratt M, Choi TY, Li M (2011) Qualitative case studies in operations management: Trends, research outcomes, and future research implications. J Oper Manag 29(4):329–342

Bier T, Lange A, Glock CH (2020) Methods for mitigating disruptions in complex supply chain structures: a systematic literature review. Int J Prod Res 58(6):1835–1856

Birkie SE, Trucco P (2016) Understanding dynamism and complexity factors in engineer-to-order and their influence on lean implementation strategy. Prod Plan Control 27(5):345–359

Blome C, Schoenherr T, Eckstein D (2014) The impact of knowledge transfer and complexity on supply chain flexibility: a knowledge-based view. Int J Prod Econ 147:307–316

Bode C, Wagner SM (2015) Structural drivers of upstream supply chain complexity and the frequency of supply chain disruptions. J Oper Manag 36:215–228. https://doi.org/10.1016/j.jom.2014.12.004

Bode C, Wagner SM, Petersen KJ, Ellram LM (2011) Understanding responses to supply chain disruptions: Insights from information processing and resource dependence perspectives. Acad Manag J 54(4):833–856

Bozarth CC, Warsing DP, Flynn BB, Flynn EJ (2009) The impact of supply chain complexity on manufacturing plant performance. J Oper Manag 27(1):78–93

Branicki L, Sullivan-Taylor B, Brammer S (2021) Towards crisis protection (ism)? COVID-19 and selective de-globalization. Crit Perspect Int Bus

Browning TR, de Treville S (2021) A lean view of lean. J Oper Manag 67(5):640–652

Browning TR, Heath RD (2009) Reconceptualizing the effects of lean on production costs with evidence from the F-22 program. J Oper Manag 27(1):23–44

Casti JL (1979) Connectivity, complexity and catastrophe in large-scale systems (Vol. 7). John Wiley & Sons

Chand P, Kumar A, Thakkar J, Ghosh KK (2022) Direct and mediation effect of supply chain complexity drivers on supply chain performance: an empirical evidence of organizational complexity theory. Int J Oper Prod Manag

Chedid F, Kocabasoglu-Hillmer C, Ries JM (2021) The interaction between supply networks and internal networks: Performance implications. Int J Oper Prod Manag

Closs DJ, Jacobs MA, Swink M, Webb GS (2008) Toward a theory of competencies for the management of product complexity: Six case studies. J Oper Manag 26(5):590–610

Crampton SM, Wagner JA III (1994) Percept-percept inflation in microorganizational research: an investigation of prevalence and effect. J Appl Psychol 79(1):67

Cua KO, McKone KE, Schroeder RG (2001) Relationships between implementation of TQM, JIT, and TPM and manufacturing performance. J Oper Manag 19(6):675–694

Eckstein D, Goellner M, Blome C, Henke M (2015) The performance impact of supply chain agility and supply chain adaptability: the moderating effect of product complexity. Int J Prod Res 53(10):3028–3046. https://doi.org/10.1080/00207543.2014.970707

Eroglu C, Hofer C (2011) Lean, leaner, too lean? The inventory-performance link revisited. J Oper Manag 29(4):356–369

Flynn BB, Flynn EJ (1999) Information-processing alternatives for coping with manufacturing environment complexity. Decis Sci 30(4):1021–1052

Flynn BB, Sakakibara S, Schroeder RG (1995) Relationship between JIT and TQM: Practices and performance. Acad Manag J 38(5):1325–1360

Galbraith JR (1974) Organization design: an information processing view. Interfaces 4(3):28–36

Galbraith JR (1977) Organization design. Addison Wesley Publishing Company

Gephart Jr RP (2004) Qualitative research and the Academy of Management Journal. In (Vol. 47, pp. 454–462). Academy of Management Briarcliff Manor, NY 10510

Gerschberger M, Manuj I, Freinberger P (2017) Investigating supplier-induced complexity in supply chains. Int J Phys Distrib Logist Manag 47(8):688–711. https://doi.org/10.1108/IJPDLM-07-2016-0185

Gimenez C, van der Vaart T, van Donk DP (2012) Supply chain integration and performance: The moderating effect of supply complexity. Int J Oper Prod Manag 32(5):583–610. https://doi.org/10.1108/01443571211226506

Hayes AF (2017) Introduction to mediation, moderation, and conditional process analysis: a regression-based approach. Guilford Publications

Hoole R (2005) Five ways to simplify your supply chain. Supply Chain Manag: Int J

Hopp WJ, Spearman MS (2021) The lenses of lean: Visioning the science and practice of efficiency. J Oper Manag 67(5):610–626

Inman RR, Blumenfeld DE (2014) Product complexity and supply chain design. Int J Prod Res 52(7):1956–1969. https://doi.org/10.1080/00207543.2013.787495

Jacobs BW, Swink M, Linderman K (2015) Performance effects of early and late Six Sigma adoptions. J Oper Manag 36:244–257

Lu G, Shang G (2017) Impact of supply base structural complexity on financial performance: Roles of visible and not-so-visible characteristics. J Oper Manag 53–56:23–44. https://doi.org/10.1016/j.jom.2017.10.001

Mackelprang AW, Nair A (2010) Relationship between just-in-time manufacturing practices and performance: a meta-analytic investigation. J Oper Manag 28(4):283–302

Manuj I, Sahin F (2011) A model of supply chain and supply chain decision-making complexity. Int J Phys Distrib Logist Manag

Mariotti JL (2007) The complexity crisis: Why too many products, markets, and customers are crippling your company - and what to do about it. Simon and Schuster

Menezes MB, Ruiz-Hernández D, Chen Y-T (2021) On the validity and practical relevance of a measure for structural complexity. Int J Prod Econ 240:108243

Peralta CBDL, Echeveste ME, Lermen FH, Marcon A, Tortorella G (2020) A framework proposition to identify customer value through lean practices. J Manuf Technol Manag

Prater E, Biehl M, Smith MA (2001) International supply chain agility - Tradeoffs between flexibility and uncertainty. Int J Oper Prod Manag

Qi Y, Boyer KK, Zhao X (2009) Supply chain strategy, product characteristics, and performance impact: Evidence from Chinese manufacturers. Decis Sci 40(4):667–695. https://doi.org/10.1111/j.1540-5915.2009.00246.x
Rungtusanatham M, Forza C, Koka B, Salvador F, Nie W (2005) TQM across multiple countries: Convergence hypothesis versus national specificity arguments. J Oper Manag 23(1):43–63
SAS (2018) SAS (Version 9.4). Cary, NC USA: SAS Institute Inc
Saunders LW, Merrick JR, Holcomb MC (2021) Microdosing flexibility in an efficient supply chain. J Oper Manag 67(3):407–416
Schmenner RW, Swink ML (1998) On theory in operations management. J Oper Manag 17(1):97–113
Schoenherr T, Swink M (2012) Revisiting the arcs of integration: Cross-validations and extensions. J Oper Manag 30(1–2):99–115
Schroeder RG, Flynn BB (2002) High performance manufacturing: Global perspectives. John Wiley & Sons
Senge PM (1991) The fifth discipline, the art and practice of the learning organization. Performance+ Instruction 30(5):37–37
Shah R, Ward PT (2007) Defining and developing measures of lean production. J Oper Manag 25(4):785–805
Sharma A, Pathak S, Borah SB, Adhikary A (2020) Is it too complex? The curious case of supply network complexity and focal firm innovation. J Oper Manag 66(7–8):839–865
Shen ZM, Sun Y (2021) Strengthening supply chain resilience during COVID-19: a case study of JD. com. J Oper Manag
Shou Y, Li Y, Park YW, Kang M (2017) The impact of product complexity and variety on supply chain integration. Int J Phys Distrib Logist Manag 47(4):297–317. https://doi.org/10.1108/IJPDLM-03-2016-0080
Simon HA (1991) The architecture of complexity. In Facets of systems science (pp. 457–476). Springer
Soliman M, Saurin TA (2017) Lean production in complex socio-technical systems: a systematic literature review. J Manuf Syst 45:135–148
Soliman M, Saurin TA (2022) Lean-as-imagined differs from lean-as-done: The influence of complexity. Prod Plan Control 33(11):1097–1114
Sparrowe RT, Mayer KJ (2011) Publishing in AMJ—part 4: Grounding hypotheses. In (Vol. 54, pp. 1098–1102): Academy of Management Briarcliff Manor, NY
Srinivasan R, Swink M (2015) Leveraging supply chain integration through planning comprehensiveness: an organizational information processing theory perspective. Decis Sci 46(5):823–861
Suri R (2016) It's about time: The competitive advantage of quick response manufacturing. Productivity Press, New York
Tortorella GL, Miorando R, Marodin G (2017) Lean supply chain management: Empirical research on practices, contexts and performance. Int J Prod Econ 193:98–112
Turner N, Aitken J, Bozarth C (2018) A framework for understanding managerial responses to supply chain complexity. Int J Oper Prod Manag
Valeri L, VanderWeele TJ (2013) Mediation analysis allowing for exposure–mediator interactions and causal interpretation: theoretical assumptions and implementation with SAS and SPSS macros. Psychol Methods 18(2):137
Wang Y, Yan F, Jia F, Chen L (2021) Building supply chain resilience through ambidexterity: an information processing perspective. Int J Logist Res Appl 1–18