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# Complementarities Between Product Design Modularity and IT Infrastructure Flexibility in IT-Enabled Supply Chains

Ashley A. Bush, Amrit Tiwana, and Arun Rai

**Abstract**—As contemporary firms become reliant on networks of supply chain partners, their performance increasingly depends on their supply chains' ability to be responsive to changing markets. This research addresses the theoretically neglected question of how and why the interplay between product design modularity and information technology (IT) infrastructure flexibility influences supply chain performance. We develop two key ideas. First, product design modularity enhances performance because it increases supply chain responsiveness, a critical mediating explanatory concept. Second, product design modularity and IT infrastructure flexibility are complementary design choices: Increasing one increases the benefits of increasing the other. We propose a mediated-moderation relationship; IT infrastructure flexibility enhances performance by strengthening the influence of product design modularity on supply chain responsiveness. Tests using primary and archival data from 102 firms provide strong support for both ideas. Implications for theory and practice are also discussed.

**Index Terms**—Complementarities, information technology (IT) infrastructure flexibility, mediated-moderation, modular systems theory, product modularity, supply chain responsiveness.

## I. INTRODUCTION

AS CONTEMPORARY firms become increasingly reliant on their network of partners, their performance hinges critically on their supply chains. Recent research recognizes that a firm's ability to respond to evolving market preferences and emerging opportunities increasingly resides in its supply chain rather than within the firm [13], [31]. However, it is often difficult to accurately predict demand in many markets [20], and as firms are increasingly characterized by high levels of production outsourcing and capital intensity, it is often risky to build large inventory or invest in redundant capacity. How can firms enhance their operational performance in changing markets, and how do product design choices and information technology (IT) infrastructure design facilitate such performance? An important set of antecedents of high performing supply chains, we believe, lies in modularizing product designs and complementing them with a highly flexible IT-enabled supply chain infrastructure.

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One product design decision characteristic that has noticeably been touted by industry thought leaders as well as scholars is the notion of modularity in product designs [21], [50], [51]. However, prior research has neither developed nor tested a theoretical explanation for how and why product design modularity influences operational performance of the firm. For example, prior studies have observed the association of modular product designs with organizational performance [3], [28], that product modularity influences evolution of markets [25], that it influences imitation by competitors [43], and that product design modularity can influence what supply chain configurations are suitable for producing them [51]. Notwithstanding the emphasis on product design modularity in prior research, a theoretical explanation for "how" (i.e., through which intervening mechanisms) product design modularity leads to improved organizational performance remains neglected in theory development. This represents a theoretical gap in the extant literature.

Furthermore, contemporary supply chain activities are deeply embedded in software systems and, therefore, are enabled and constrained by supply chain IT applications and infrastructure. The importance of the supply chain-enabling IT infrastructure has been emphasized across a variety of industries in the practitioner literature [23, p. 123]. The implicit argument is that a flexible IT infrastructure allows firms to flexibly connect to other firms and rapidly incorporate their complementary capabilities into their supply chains [23, p. 176]. Proponents of this view argue that the ability to tap into complementary capabilities outside the focal firm are just as important as the capabilities that the focal firm internally possesses. The key to developing supply chain coordination mechanisms, as our subsequent Li and Fung example illustrates, is flexibility of the enabling IT infrastructure used by the focal firm.

We believe that the flexibility provided by modular product designs is likely more beneficial if their production is supported by a flexible IT infrastructure that enables exploiting that flexibility. The role of IT infrastructure capability, its complementary interactions with product design, and the intervening mechanisms through which this complementarity enhances focal firm performance has not received direct attention in previous research. We believe that this is partly because IT infrastructure flexibility has been studied in mutual isolation from product design modularity. The complementarities between IT infrastructure flexibility and product design modularity, therefore, remain poorly understood. This represents a second theoretical gap in the extant literature. Understanding these issues is important for both practice and research because of the potentially symbiotic

relationship between the design of products and the design of the IT-enabled supply chains used to support their production.

Consider the example of Apple's iPod product line, which illustrates how these two complementary facets of supply chain design allowed Apple to be more responsive to emerging market opportunities and threats. Beginning with its original iPod in 2001, Apple rapidly introduced 110 model variants during 2001–2009 to capitalize on emerging market opportunities and to exploit advances in individual components (e.g., color LCD displays, wireless networks, and solid-state drives). To exploit new opportunities created by advances in broadband cellular data networks and demand for “smart” phones, it introduced five model variants of a phone-iPod hybrid (iPhone) from 2007 to 2009. As the consumer popularity of digital photography grew, it also introduced model variants to capitalize on this opportunity (iPod Photo and Video in 2005). This ability to rapidly revamp and expand its product line allowed it to grow its market share to 70% by early 2009. Sales generated by this product line that was nonexistent until 2001 accounted for half of its annual \$35 billion revenue by 2009 [47]. Thus Apple was able to rapidly adapt to market changes, using them to grow its market share amidst intensive competition. One key to Apple's ability to be highly responsive to emerging market opportunities arguably was the iPod's modular, malleable product design.

Industry observers have also attributed some of Apple's success to the flexible design of its IT-enabled supply chain, in addition to the design of the iPod product family [1]. This, they suggest, has allowed Apple to realize a better return on assets, grow revenue, and improve inventory turns relative to its competitors (all indicative of stronger operational performance) [1]. The flexibility engendered by its product design by itself would have been of limited value without the highly flexible IT-enabled design of Apple's supply chain to complement it. The complexity of each iPod variant requires a complex supply chain (e.g., spanning 30 companies in three continents for the iPhone), which itself was designed to be highly flexible to accommodate Apple's evolving market needs. The flexibility of its supply chain IT infrastructure allowed Apple to rapidly replace suppliers, integrate new ones, and reassign existing ones to alter production mix without compromising production costs [1].<sup>1</sup> Overall, this example illustrates how the malleability of a firm's product line can allow it to avoid foregoing potential market opportunities and the reconfigurability of its IT-based supply chain infrastructure allows it to be responsive without making dedicated investments in manufacturing capacity. Similarly, contract manufacturer Li and Fung uses a product modularization approach coupled with a flexible Web-services-based IT infrastructure to flexibly coordinate production with over 8000 manufacturers in its supply network [61]. (We subsequently also

<sup>1</sup>For example, when demand for specific models exceeded supply, Apple was able to ramp up production volume by rapidly adding additional contract manufacturers, such as Solectron, Flextronics, and Hon Hai Electronics, to its supply chain. Similarly, when initial sales for its black versus white iPod Nano turned out to be an 8:1 ratio instead of an anticipated 1:8, Apple was quickly able to change its production mix. To exploit component-level innovations, Apple was able to rapidly add Samsung to its supply chain to exploit its solid state drive technology, Synaptics for its touch pads controllers, Broadcom for its touch screens, and Primax for its camera modules.

introduce examples from Ericsson, Nokia, Lands' End, Hewlett-Packard, Sony, and Chrysler to further illustrate these points.)

In this vein, the question of how product design characteristics and IT-enabled supply chain infrastructure characteristics, individually and jointly, lead to greater operational performance remains of considerable interest for supply chain management theory [20], [40]. However, as previously discussed, such complementarities between IT infrastructure flexibility and product design modularity represent a theoretical gap in the literature. We address this research gap in this study, guided by the following two research questions.

- 1) Why does product design modularity influence operational performance?
- 2) How does IT infrastructure flexibility strengthen the benefits derived from greater product design modularity?

Our unit of analysis is a focal firm's supply chain for the family of products from which it derives the majority of its revenues (hereafter “primary product line”). We build on modular systems theory to theoretically develop two ideas. First, we theorize that product design modularity enhances operational performance *because* it increases supply chain responsiveness, our critical mediating concept. Second, product design modularity and IT infrastructure flexibility are complements, i.e., increasing one increases the benefits of increasing the other. In particular, we propose a mediated-moderation relationship; IT infrastructure flexibility enhances performance by strengthening the influence of product design modularity on supply chain responsiveness. Tests using data from supply chain and logistics managers in 102 firms provide considerable support for both ideas.

Our overarching contribution is the development and testing of a theoretical explanation for *how* product design modularity influences the operational performance of the focal firms in their supply chains. Our central explanatory concept for “how” is the mediating notion of supply chain responsiveness. We show that product design modularity enhances operational performance *because* it increases supply chain responsiveness. We also show that IT infrastructure flexibility serves as a powerful complement to product design modularity; it strengthens the positive effect of product design modularity on supply chain responsiveness, which fully mediates its joint influence on operational performance.

The remainder of the paper is structured as follows. The next section theoretically develops the hypotheses, followed by the methodology (Section III), analyses (Section IV), and a discussion of the results (Section V). The paper concludes with a discussion of the implications of the results for theory and practice.

## II. THEORETICAL DEVELOPMENT

### A. Theoretical Foundation: Modular Systems Theory

Complex systems are composed of distinct components or subsystems that interact with each other [56]. Products, organizations, and organizational networks are different types of complex systems. Modularity is a general design principle for any complex system that intentionally creates loose-coupling between subsystems to lower their mutual interdependence [29],

[53], [55]. Such subsystems of a larger system in product designs are the components of a product; in a supply chain, they are represented by the partnering organizations that collectively constitute a supply chain.

Modular systems theory [54], which builds on this notion of modularity, is the theoretical foundation of our study. The basic premise of modular systems theory is that greater modularity increases flexibility [52]. The underlying motivation for modularizing complex systems is that the resulting decrease in interdependence among the components of a system provides greater autonomy in their evolution without compromising the ability of the components to coherently work together. In other words, one component in a modular system can be changed without requiring extensive adjustments or triggering unanticipated disruptive effects in other components of that system. In contrast, tweaking individual components of nonmodular (“integral”) systems is more likely to require changes in other components with which they interact.

Modular systems theory identifies two facets of modularity, modularity in the designs of products themselves and modularity in the structure of the organization that produces these products [29]. In our study’s supply chain context, these are represented by product design modularity and the design of the IT-enabled supply chain. Although modularity of products is relatively simple to recognize from a careful examination of the design of the product itself, the organizational facet is more nuanced and less directly observable. Organizations that produce products are often multifirm supply chains whose activities and processes are linked together through a complex portfolio of IT applications and infrastructure. Therefore, the organizational facet of modularity can be thought of in terms of the organizational design of the supply chain that is used to produce a product, which itself is deeply embedded in the IT infrastructure that is used by the firms in a supply chain to interact with each other [5], [39]. Product modularity and IT infrastructure characteristics, therefore, represent two complementary dimensions of supply chain design. Design of either products or supply chain infrastructure is not a given, but rather represents design choices that firms consciously make.

This leads to two reasons for the importance of simultaneously studying product design modularity along with IT infrastructure characteristics, as we do in this study. First, contemporary supply chains and their underlying interfirm processes are deeply embedded in information technology infrastructure and applications [44]. Supply chain IT infrastructure, therefore, provides the foundational platform for developing processes and mechanisms that networks of collaborating firms in a supply chain use to coordinate their joint activities. Second, the architecture of products influences the ability of firms to rapidly adjust to changing market conditions [62]. More modular products are inherently more malleable, can more readily be used to generate new variants to target emerging market segments, are more amenable to rapidly exploiting technological advances in individual components of the product, and allow firms to more easily disperse production activities across a broader set of supply chain partners [53], [65]. However, even when product designs have higher flexibility due to their modular design,

the embeddedness of supply chains in enabling IT infrastructure means that the full benefits of flexible, modular product designs might be difficult to realize unless the supply chain IT infrastructure itself can be rapidly adapted. In other words, changes in product designs also need changes in the IT infrastructure that is used to coordinate supply chain activities to produce the adapted products. Therefore, increasing IT infrastructure flexibility can increase the benefits derived from modularizing product designs, and modularizing product designs can increase the benefits of increasing the flexibility of IT infrastructures that undergrid supply chains. Although such joint, mutually reinforcing effects of product design modularity and IT infrastructure flexibility are important to understand, they have not previously been studied together. We consider each in turn before we develop an explanation for how and why they individually and jointly influence the focal firm’s operational performance.

### B. Product Design Modularity

*Product design modularity* is defined as the degree to which a firm’s primary products are composed of loosely coupled components connected with standardized interfaces [53], [62]. Products with such designs represent modular product designs [53], [62]. The standardized interfaces between such loosely coupled components of modular product designs provide what Sanchez and Mahoney [53] describe as an “embedded coordination mechanism.” Components in such modular product designs have lower interdependencies relative to integral product designs [57]. When the coupling among a product’s components is modular, one component can be changed relatively independently without compromising its ability to work with others in a product [35]. This “information hiding” property inherent to modular designs shields individual firms in a supply chain from having to know detailed information about components other than the one for which they are responsible [29], [53]. Therefore, firms in a supply chain for a modular product design need to understand details of the components from other suppliers to a lesser degree than for integral product designs [29]. It is important to emphasize that greater product design modularity involves standardization of the interfaces among components, not necessarily standardization of the components themselves. More modular product designs, as we subsequently describe in detail, are important from a supply chain perspective because they provide greater flexibility in the design of the supply chains that are used to produce such products.

Central to understanding why product design modularity enhances a focal firm’s operational performance is the notion of supply chain responsiveness. We define *supply chain responsiveness* as the degree to which a focal firm’s supply chain can meet changing customer demand patterns, expectations, and preferences [31]. This construct, therefore, taps into the focal firm’s ability to understand and effectively address the changing demand patterns and needs of its customers. We theoretically develop the relationship between product design modularity and operational performance in three incremental parts that together represent the interwoven pieces of our first overarching idea: 1) how greater product design modularity increases supply chain

responsiveness, 2) how greater supply chain responsiveness enhances the focal firm's operational performance, and 3) how supply chain responsiveness mediates the effect of product design modularity on operational performance. Supply chain responsiveness is the central theoretical explanatory concept for *why* product design modularity enhances operational performance. In other words, product design modularity increases operational performance because it enhances supply chain responsiveness.

1) *Influence of Product Design Modularity on Supply Chain Responsiveness*: The relationship between product design modularity and supply chain responsiveness represents the first element of the proposed tripartite relationship. The overarching logic for this relationship grounded in modular systems theory is that greater product design modularity eases coordination among members of the focal firm's supply chain producing that product vis-à-vis integral product designs in three ways. Inter-firm coordination here refers to integration of activities across a supply chain in the presence of interdependence and uncertainty, and is a key challenge in organizing effective supply chains [40].

First, as environmental uncertainties (e.g., volume uncertainty, supplier uncertainty) increase, greater product modularity creates alternate sourcing options that allow firms to rapidly respond to such uncertainties. Given the greater use of loosely coupled components with standardized interfaces, the focal firm can add or change suppliers more readily when its product designs are modular relative to one whose designs are integral. This is illustrated by contrasting competing cellular phone manufacturers Nokia and Ericsson, which respectively, use more modular and more integral product designs [12]. In March 2000, a lightning strike-triggered fire in a chip plant owned by Dutch supplier Philips Electronics resulted in plant closure and damaged millions of microchips that it supplied to both Nokia and Ericsson. Nokia immediately switched its chip orders to other Japanese and US suppliers, whereas Ericsson's production was disrupted for several months at a cost of \$400 million in lost sales. The more modular design of Nokia's products allowed its supply chain to be more responsive to this unexpected disruption relative to the more integral Ericsson. Furthermore, greater product design modularity might lead to the focal firm seeking out new suppliers. This creates a more powerful incentive for existing suppliers to be more responsive to the focal firm's changing needs because the implicit threat of switching to different suppliers is more likely to be credible when product designs are more modular than when they are integral.

Second, greater product design modularity allows the focal firm to postpone differentiation. This allows its supply chain activities to be synchronized with changes in demand by changing product and volume mix of what it produces. For example, Lands' End, the clothing manufacturer, uses a modular dress shirt design with substitutable components (fabric, collars, and cuffs) to custom manufacture approximately 8000 variants of its basic men's dress shirt. This product design allows it to delay differentiation until after an order is placed. This increases supply chain responsiveness to customer demand patterns and preferences. This flexibility to postpone differentiation also facilitates the rapid correction of emergent mismatches between supply and demand. Therefore, modular product designs enable

firms to rapidly alter their production mix to better match market demands, resulting in greater supply chain responsiveness.

Third, greater product design modularity eases component substitution [17], allowing innovations and improvements in individual components to be more rapidly incorporated into existing products. This is because individual components in modular designs can more readily be substituted with newer components to create improved product variants, as long as they comply with the product's interface standards. Since components of modular product designs rely more heavily on standardized interfaces, internal changes in one component do not compromise the integrity of the entire product. This allows one component to be more readily replaced with a different one without having to redesign the entire product [27], [31], [52]. The focal firm can, therefore, modify one component without requiring extensive coordination with organizations in the supply chain responsible for other components [6], [48]. This ability to switch components in modular product designs allows more rapid introduction of new product variants that exploit component-level innovations. This is illustrated by the example of the contrasts between Hewlett-Packard and Sony's competing products that, respectively, emphasize more modular and more integral designs. For example, the modular design of Hewlett-Packard's "netbooks" allowed it to rapidly equip them with new ATOM microprocessors and replace magnetic hard disks with solid-state hard disks shortly after they were introduced. Their design also allowed Hewlett-Packard to adjust its supply chain structure to complement Seagate with Samsung as a disk drive supplier, shortly after Samsung introduced a newer generation of SSD technologies. In contrast, Sony's netbooks were more integral in their design and could not be upgraded at a competitive pace. This contrast is illustrated by the stark differences in the number of product variants that the two companies were able to introduce in the first year of their products' introduction; HP released 52 model variants whereas Sony released eight. We, therefore, expect greater product design modularity to enhance supply chain responsiveness.

*Hypothesis 1a*: Product design modularity is positively associated with supply chain responsiveness.

Fig. 1 summarizes the proposed research model expanding on this point, where we develop two overarching ideas. First, product design modularity enhances operational performance *because* it increases the responsiveness of its supply chain (mediation). Second, greater IT infrastructure flexibility enhances operational performance by strengthening the positive influence of product design modularity on supply chain responsiveness (mediated-moderation). Product design modularity and IT infrastructure flexibility, therefore, exhibit complementarities, which we theoretically develop in the subsequent discussion.

2) *Influence of Supply Chain Responsiveness on Operational Performance*: The relationship between supply chain responsiveness and operational performance represents the second element of the proposed tripartite relationship. *Operational performance* is defined as the extent to which the operations of the firm are superior relative to its direct competitors in the context of its primary product line. Our conceptualization of operational

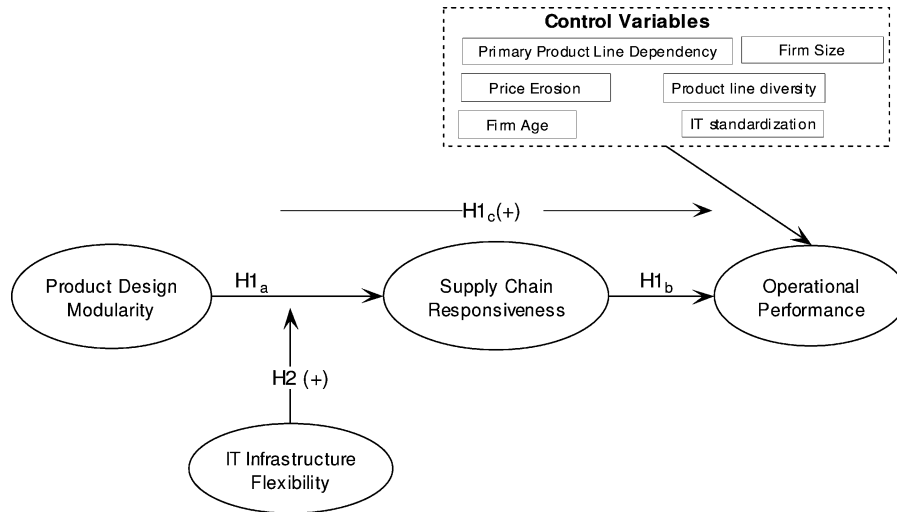


Fig. 1. Research model.

performance is based on Rai *et al.*'s [44] conceptualization of operations excellence, which they define as the degree to which a focal firm is better than its competitors in its responsiveness and generation of productivity improvements. (This approach of measuring performance relative to a firm's competitors rather than in isolation of its context has also been recommended in the supply chain literature [31], [64].) Operational performance taps into three facets of the firm's operations: fixed asset productivity, working capital productivity, and operating costs relative to competitors [44]. Fixed asset productivity is indicative of how much the firm benefits from its investments in fixed assets such as plants, tools, and equipment. Working capital productivity compares the firm's sales with its working capital, and is indicative of how efficient the firm is. If sales increase more rapidly than the financial resources needed to generate them, it shows that a firm and its supply chain are being productively managed. Operating costs are indicative of the daily expenses incurred in the firm's operations; lower operating costs indicate better operational performance. Rather than focus on pure financial performance measures which reflect the firm's performance based on a more diverse array of internal and external factors, we focus on operational performance to tap into performance that is based more on supply chain-related factors directly associated with the focal firm, following Chena and Paulraj [8].

The ability to rapidly adapt their supply chains to changing markets is critical to the operational performance of firms [31]. Firms with greater supply chain responsiveness can be expected to exhibit greater operational performance due to their greater ability to rapidly match supply with market demand (e.g., by rapidly introducing new products and product variants) or changing customer preferences (e.g., by changing production volumes and mix) [30], [31]. This allows the focal firm to avoid foregoing potential sales opportunities or being stuck with unsold inventory due to changes in market preferences. It also allows the focal firm to increase the benefits derived from their fixed assets, increase sales relative to working capital, and lower operating costs relative to competitors, leading

to enhanced operational performance relative to competitors. We, therefore, expect greater supply chain responsiveness to enhance operational performance.

*Hypothesis 1b:* Supply chain responsiveness is positively associated with operational performance.

3) *Mediating Role of Supply Chain Responsiveness on the Relationship between Product Design Modularity and Operational Performance:* The mediating role of supply chain responsiveness in explaining how and why product design modularity results in improved operational performance represents the third element of the proposed tripartite relationship.

An increase in product design modularity allows the focal firm to increase its operating performance relative to its competitors primarily because such modular designs increase supply chain responsiveness. When the focal firm's primary products are composed of loosely coupled components with standardized interfaces, its supply chain is better able to cope with volume uncertainty and supplier uncertainty because of the alternative supplier options that such designs create. Such designs also facilitate postponed differentiation of products, which increases the likelihood that the activities of the supply chain (e.g., production mix) are better synchronized with market demands and lowers the likelihood of being left with unsold inventory. They also allow more rapid exploitation of innovations in individual components because such product designs have higher component substitutability relative to integral product designs. Thus, the adoption of modular product designs lowers the interfirm coordination overhead among members of the supply chain, increasing its responsiveness. It is such increased supply chain responsiveness that increases the focal firm's ability to wring greater productivity out of its fixed assets, improve sales relative to working capital, and decrease operating costs, all of which indicate higher operational performance. We do not expect a direct effect from product design modularity because the adoption of more modular product designs by itself is unlikely to increase the focal firm's productivity of investments in fixed assets, directly increase sales relative to working capital, or improve inventory

turns or operating costs. These benefits result from modular product designs primarily because of the greater supply chain responsiveness that they engender. The operational performance benefits of product design modularity, therefore, arise primarily *because* such modularity enhances supply chain responsiveness. This represents the third of our tripartite argument that complements the two preceding hypothesized positive effects of product design modularity on supply chain responsiveness, and of supply chain responsiveness on operational performance. Therefore, we expect the influence of product design modularity on operational performance to be mediated by supply chain responsiveness. This leads to our next hypothesis.

*Hypothesis 1c:* Supply chain responsiveness mediates the positive effect of product design modularity on operational performance.

### C. IT Infrastructure Flexibility

Supply chain IT infrastructure provides the foundation for implementing the processes that shape interfirm coordination between a focal firm and its supply chain partners. *IT infrastructure flexibility* broadly refers to the degree to which the focal firm's IT resources are malleable [15], [18]. Duncan [15] defines this characteristic of IT infrastructure further in terms of the number and variety of IT platforms the focal firm can connect with ("reach") and its compatibility with IT services and applications of its suppliers and business partners in the supply chain ("range"). Building on this conceptualization and Byrd and Turner's [7] subsequent refinement, in the context of the focal firm's IT-enabled supply chain, we define IT infrastructure flexibility as the extent to which the focal firm can readily change the IT-based communication linkages across the supply chain, switch firms participating in a supply chain, redesign supply chain processes, and change the scale of the supply chain's operations upward or downward [48].

Since contemporary IT-enabled supply chains are heavily embedded in IT applications and IT networks [2], [13], [48], we expect IT infrastructure flexibility to enhance supply chain responsiveness. The flexibility of the supply chain IT applications portfolio used by the focal firm allows the addition or removal of new suppliers and business partners to the supply chain and reconfiguration of the activities of existing ones. This eases integration of new suppliers into the supply chain and reconfiguration of existing linkages among firms across the supply chain; such integration is a critical antecedent to supply chain performance [42]. Furthermore, this flexibility allows firms to ramp up production volume and mix without making dedicated investments in new manufacturing capacity or production facilities [58]. Such ease of reconfiguration allows firms to rapidly pursue new opportunities and to capitalize on emerging market trends by pulling together new combinations of resources and capabilities from a diverse variety of existing and new supply chain partners.

However, the benefits of IT infrastructure flexibility in a supply chain are magnified when the supply chain simultaneously involves modular product designs. The underlying logic for this complementarity grounded in modular systems theory is that

components of modular product designs, by virtue of their relatively well-defined specifications and functionality, can more readily be outsourced by the focal firm to other firms in the supply chain [40], [52]. Thus, modular product designs enable adoption of modular organizational structures for product development, production, and distribution processes [17], [53]. More broadly, Sosa *et al.* [57] have demonstrated using a simulation study that misalignment between product design modularity and the organizational arrangements that are used to produce them can penalize performance.

This is illustrated by contrasting the supply chain design of Chrysler and Mercedes, which focused, respectively, on highly modular and highly integral automotive product designs [19]. Chrysler historically used a highly modular supply chain design involving numerous suppliers to produce components for its modularly designed cars and Mercedes used a nonmodular supply chain with far fewer suppliers to manufacture its integral, high-performance cars. Modular supply chains consist of highly flexible and interchangeable relationships among members of the supply chain, as reflected by our conceptualization of supply chain IT infrastructure flexibility [19]. Although flexible supply chain design encompasses other facets, IT infrastructure flexibility is one important facet of the broader notion of flexible supply chain designs [23]. After their merger in 1998, the combined company Daimler-Chrysler attempted to create synergies across the merged companies by combining components across the two company's product lines. This created a mismatch between the structure of the product designs and the supply chains used to produce them. In other words, the merged company unsuccessfully attempted to use integral supply chain structures to produce modular parts and modular supply chain structures to produce integral parts. This mismatch between product design modularity and the design of the supply chain diminished supply chain responsiveness of the merged company to an extent that the quality of Mercedes vehicles declined to a historical low (resulting in \$960 million in losses in 2001), and Chrysler lost almost \$6 billion in 2001 alone. In other words, mismatched product design and supply chain design can create penalties in cost structures, product quality, and in matching supply chain activities with market needs. This example broadly illustrates the importance of matching product design characteristics with those of the IT-enabled supply chain that is used to produce it.

Based on this logic, we suggest that the adaptive advantages of modular product designs are enhanced by greater IT infrastructure flexibility. Although modular product designs increase the flexibility of the focal firm to adapt its products to emerging market needs, such flexibility cannot readily be exercised unless the design of the IT-enabled supply chain is also malleable enough to produce them. Since supply chains are largely enabled by IT, this perspective is also consistent with the view that the advantages generated by IT resources depend on the extent to which they enhance a firm's core competencies [34], [46]. Therefore, greater IT infrastructure flexibility increases the benefits of modularizing a firm's primary products.

In summary, the responsiveness-enhancing benefits of modular product designs are amplified by greater supply chain IT infrastructure flexibility. We, therefore, expect that IT

TABLE I  
RESPONDING FIRM CHARACTERISTICS

Characteristic	Category	%
Industry (SIC code)	Agriculture, Agriculture, Forestry, and Fishing (1-9)	4.5
	Mining (10-14)	3.4
	Manufacturing (20-39)	64.3
	Transportation, Communications, Electric, Gas, and Sanitary Services (40-49)	3.4
	Wholesale Trade (50-51)	12.6
	Retail Trade (52-59)	9.1
	Services (70-88)	2.2
Firm size (number of employees)	0-100	3.4
	101-500	16.1
	501-1000	10.4
	1001-5000	27.6
	5000 or greater	42.5
Total annual revenue	\$0-10M	1.2
	\$11-50M	2.4
	\$51-100M	6.0
	\$101-500M	23.8
	\$500M or greater	66.6
% of Revenue from primary product line	0-20%	3.0
	21-40%	5.9
	41-60%	8.9
	61-80%	15.8
	81-100%	66.4

infrastructure flexibility will strengthen the effect of product design modularity on supply chain responsiveness, and in turn enhance operational performance. This leads to the final hypothesis, which represents a mediated-moderation relationship.

*Hypothesis 2:* IT infrastructure flexibility enhances operational performance by strengthening the positive influence of product design modularity on supply chain responsiveness.

### III. RESEARCH METHODOLOGY

#### A. Research Context and Data Collection

We tested the proposed model using data collected through a field study of supply chain managers in 102 firms, using the focal firm's supply chain for its primary product line as the unit of analysis. The participants in the study were practitioners who were directly responsible for supply chain management. The majority of these participants had job titles such as managers or directors of logistics, distribution, or supply chain management. Our sampling frame was the membership database of a major national professional logistics organization. The sample was randomly selected from the member database meeting two criteria: 1) the member had a job title indicative of a supply chain function (i.e., managers or directors of logistics, distribution, or supply chain management), and 2) the member had an organizational affiliation in the retail, manufacturing, or distribution sector. Our preliminary interviews suggested that such managers are appropriate informants for the study because they are likely to be sufficiently knowledgeable about both their firms' products as well as supply chain operations. Our unit of analysis for this study is the focal firm's supply chain for a primary product line. All respondents were instructed to respond to all questions with a focus on their firm's supply chain for a primary product line. We defined primary product line as one that commanded a significant portion of a firm's revenues (at least 15%–20% or greater). The largest proportion (66.4%) of firms in our study

indeed derived 81%–100% of their revenues from their primary product line, as shown in Table I.

We contacted 968 prospective respondents and followed up with two reminders. 88 of these declined to participate in the study citing reasons such as company policy, lack of time, or insufficient information to respond. Another 121 could not be reached. We received a total of 124 responses, yielding a response rate of 16.34%. This response rate compares favorably with other field surveys involving managers [14], [33]. 102 of these responses were complete and, therefore, usable in the analyses. *T*-tests comparing the early and late respondents on all key independent variables were nonsignificant, suggesting that nonresponse bias was not a substantial threat.

1) *Descriptive Statistics:* The responding firms represented a variety of industries including manufacturing, wholesale trade, retail, agriculture, mining, transportation, and services. A majority of responding firms were in the manufacturing sector (64.37%). The largest majority of firms in the sample had annual revenues that exceeded \$500 million (66.6%), followed by firms with revenue ranging from \$101 to \$500 million (23.8%). Around 42.5% of the firms had over 5000 employees. A large proportion (66.4%) of firms in the study derived the majority (81%–100%) of their revenues from their primary product line, consistent with our definition of primary product line in our survey instrument. The average age of the firms in the study was about 47 years (S.D. 32). Table I presents a breakdown of the industries and firm characteristics of our sample.

#### B. Construct Operationalization and Scale Development

All key variables in the study were measured using multi-item, seven-point Likert scales, as summarized in the Appendix. Consistent with the theoretical conceptualization in the model, all scales were operationalized at the firm level, in the context of its supply chain. New scales were developed for product design



modularity, IT infrastructure flexibility, and supply chain responsiveness based on an extensive review of the literature. We first generated a measurement item pool based on the literature, which was then iteratively refined based on feedback from 12 logistics and supply chain managers and eight academic experts. The purpose of this iterative refinement process was to ensure content validity, clarity, and face validity of the items. The pool was iteratively refined to ensure that the items were unambiguous and accurately tapped into the content of each construct.

*Product design modularity* was measured using items based on prior descriptions of product design modularity [29], [35], [53], [65]. A new five-item scale was developed. The five items tapped into the extent to which the products in a firm's primary product line shared product parts and subassemblies, had a modular design, new products reused the designs of existing components, product offerings integrated components from multiple suppliers, and consisted of components that could be mixed and matched in a variety of configurations. *IT infrastructure flexibility* was conceptually based on similar IT infrastructure flexibility measures developed by Duncan [15] and by Byrd and Turner [7]. Since contemporary supply chains are enabled by information systems that connect organizations that collaborate across a focal firm's supply chain [26], [30], [59], our measures specifically tapped into the flexibility and malleability of the IT applications used in IT-enabled supply chains. This approach focuses on the enabling technological structures through which firms coordinate with their supply chain partners [13], [48], [58]. The final purified measure used four items that tapped into the extent to which the IT infrastructure was conducive to changing communication and reporting linkages across the supply chain, scaling transaction processing up or down as needed, changing supply chain partners including suppliers, customers, and logistics partners, and redesigning supply chain processes to meet the changing information requirements of the firm's customers and supply chain partners.

*Supply chain responsiveness* was measured using a new three-item scale that tapped into the extent to which the focal firm in the supply chain was able to develop a precise knowledge of changing customer buying patterns, had a strong and continuous bond with customers in its markets, and how effectively it was able to service its customers. This operationalization is consistent with our theoretical definition of the construct, which focused on the degree to which the focal firm in the supply chain, in its supply chain activities, was able to keep pace with changing customer preferences, demands, and expectations. *Operational performance*, the dependent variable, was measured using three items that assessed the organization's performance relative to its competitors in the context of the selected primary product. Our measure is based on Rai *et al.*'s [44] conceptualization of "operations excellence," which they define as the degree to which a focal firm is better than its competitors in its responsiveness and generation of productivity improvements. In their study, this was a subdimension of a broader firm performance construct, which tapped into the degree to which a focal firm has superior performance relative to its competitors. Specifically, the items measured fixed asset productivity, working capital productivity,

and operating costs of the focal firm relative to competition. This approach of measuring performance relative to a firm's competitors rather than in isolation of its context has been emphasized in the supply chain literature [13], [31], [64]. Anchoring performance measures with respect to the firm's competitors allowed us to safeguard against confounds in operational performance caused by industry differences. The anchors for the seven-point scale ranged from being the same as the firm's competitors at the midpoint, and much better/much worse at the end points of the scale. For the subset of firms that we collected secondary, matched pair performance data, we computed these three items from archival public records in Compustat and then used these items as indicators of a latent operational performance measure. This, as discussed later, allowed us to assess the threat of common methods bias. For our control variables, firm age and product line diversity used ratio scales. We used an ordinal set of categories to collect the survey data for price erosion, primary product line dependency, and firm size, as our preliminary interviews revealed that respondents are more likely to be able to specify a range than to be able to specify an exact number for these questions. Interconstruct correlations, means, and standard deviations are summarized in Table II.

#### IV. RESULTS

Partial least squares (PLS)—a second-generation structural equation modeling technique—was used to validate the measurement model and then to test the hypothesized relationships. The analyses were conducted using Smart-PLS 2.03, a variant of the older PLS-Graph [49]. The choice of PLS was motivated by two considerations [11]. First, the ability of PLS to assess the measurement model within the context of its theoretical mediated model makes it superior to multiple regression, especially when using new scales. Second, unlike LISREL, PLS makes no *a priori* assumptions about data normality [9]. We also verified the results using Baron and Kenney's [4] mediated-multiple regression procedure and replicated using PLS-Graph 2.91, neither of which revealed any significant differences.

##### A. Measurement Model Validation

Convergent and discriminant validity for all construct scales were assessed before the structural model was tested. The questionnaire items and scale alphas are summarized in the Appendix. The high scale alphas ( $\geq 0.77$ ) and eigenvalues ( $> 1$ ) of all constructs provide the first indication that the scales have high convergent validity and reliability. Cronbach's  $\alpha$  for all constructs exceeded the 0.7 threshold recommended by Nunnally [41], confirming convergent validity [22]. The loadings of all indicators on their corresponding theoretical constructs exceeded the recommended 0.7 threshold in the PLS measurement model. Discriminant validity was indicated by three assessments in the PLS measurement model: 1) items had low ( $< 0.3$ ) and nonsignificant cross-loadings, 2) the bold diagonal elements representing the square root of average variance extracted exceeded the off-diagonal elements in the construct correlation matrix (see Table II), and 3) the ratio of the variance in the indicators for each construct relative to the total amount

TABLE II  
CONSTRUCT CORRELATIONS AND PSYCHOMETRIC PROPERTIES

Construct	Mean	Std. Dev.	Items	Scale $\alpha$	Construct correlation matrix									
					1	2	3	4	5	6	7	8	9	
1. Product design modularity	4.39	1.42	5	0.83	<b>0.78</b>									
2. IT infrastructure flexibility	4.04	1.18	4	0.78	0.17	<b>0.77</b>								
3. IT infrastructure standardization	4.00	1.32	3	0.77	0.24*	0.48*	<b>0.83</b>							
4. Supply chain responsiveness	5.08	1.08	3	0.84	0.21*	0.25*	0.28*	<b>0.87</b>						
5. Operational performance	4.77	1.03	3	0.79	0.03	0.16	0.25*	0.53**	<b>0.85</b>					
6. Firm age	47.19	32.05	—	—	0.08	-0.05	-0.01	-0.01	-0.1	1				
7. Product line diversity	2404	11584	1	—	0.07	-0.14	-0.05	0.02	-0.16	-0.16	1			
8. Price erosion	11-20% <sup>a</sup>	—	1	—	-0.06	-0.25*	-0.1	-0.05	-0.04	-0.06	0.17	1		
9. Primary product line dependency	0-20% <sup>a</sup>	—	1	—	0.13	0.03	-0.05	0	-0.13	-0.01	-0.11	-0.03	1	
10. Firm revenue	>\$500 mil <sup>a</sup>	—	—	—	-0.14	-0.1	-0.1	0.05	-0.03	-0.22*	0.12	0.06	-0.11	1

\* $p < .05$ ; \*\* $p < .01$ ; **bold** diagonals represent the square root of average variance extracted for multi-item scales. <sup>a</sup> Modal value.

of variance exceeded 0.5 [22]. In summary, these assessments suggest that the constructs exhibit sufficient reliability and discriminant validity to proceed with the analysis of the structural model.

### B. Structural Model Assessment

A PLS structural model, which represents the relationships among various latent constructs, was used to test the hypotheses. Paths in this model are interpreted as standardized regression weights and the loadings on each construct as loadings in principal component analyses. The proposed model represents a *mediated-moderation* model [37]. Mediated-moderation means that the interaction between the predictor and the moderator influences the dependent variable through a mediator [16], [61]. Since our model proposes that the relationship between product design modularity (the predictor) on supply chain responsiveness (the mediator) is moderated by IT infrastructure flexibility (the moderator), and supply chain responsiveness in turn influences operational performance (the dependent variable), it represents mediated-moderation. (An alternative model that also integrates moderation and mediation is the moderated-mediation model where the existence of mediation itself is contingent on the level of the moderator.) We, therefore, followed the guidelines for assessing mediated-moderation outlined by Muller *et al.* [37] and Edwards and Lambert [16]. A bootstrap of 1500 subsamples, which does not require an assumption of normality and is recommended for testing such models [16], was used to estimate the statistical significance of the path estimates. Since the proposed hypotheses are unidirectional, one-tailed  $t$ -tests were used. As a robustness check, we also estimated the model using 1000 and 2000 bootstrap samples and obtained consistent results.<sup>2</sup> A summary of the results is presented in Fig. 2.

<sup>2</sup>To alleviate concerns about the sample size vis-à-vis model complexity in terms of statistical power, we conducted an additional robustness check by re-estimating the model using construct item averages as single indicators for the two independent variables. The multiplicative term for the two single items was used as the sole indicator for the interaction term. The main effects were closely comparable to the PLS results both in terms of their path coefficients and their statistical significance. The values were close in their magnitude and sign: product design modularity's effect on supply chain responsiveness increased

To test the first set of tripartite hypotheses (H1a–H1c), which proposed that the effect of product design modularity on operational performance is mediated by supply chain responsiveness, we followed the mediation tests suggested by Edwards and Lambert [16]. Product design modularity had a positive and significant relationship with supply chain responsiveness ( $\beta = 0.15$ ,  $t$ -value = 1.79,  $p < 0.05$ ), supporting Hypothesis 1a. Supply chain responsiveness had a positive and significant relationship with operational performance ( $\beta = 0.52$ ,  $t$ -value = 4.90,  $p < 0.001$ ), supporting Hypothesis 1b. No significant direct effect was found from product design modularity to operational performance. A mediation test was then used to assess the statistical significance of the mediation. The Sobel mediation test statistic was significant (1.68,  $p < 0.05$ ) and the Goodman mediation test statistic was also significant (1.71,  $p < 0.05$ ), suggesting that the relationship between product design modularity and operational performance was fully mediated by supply chain responsiveness. Hypothesis 1c was, therefore, supported.

Testing *mediated-moderation* proposed in Hypothesis 2 requires demonstrating that supply chain responsiveness mediates the positive interaction effect between product design modularity and IT infrastructure flexibility on operational performance. This requires a relatively new multistep procedure (outlined in [16]) and illustrated in the IS literature in Tiwana and Konsynski [61] to demonstrate the following four things:

- 1) a statistically significant relationship between supply chain responsiveness and operational performance (this was already successfully demonstrated in the support for Hypothesis 1a–Hypothesis 1c);

slightly from 0.15 to 0.18 ( $t$ -stat = 2.21;  $p < 0.05$ ); that of IT infrastructure flexibility increased from 0.21 to 0.28 ( $t$ -stat = 2.67;  $p < 0.01$ ); and supply chain responsiveness did not change from 0.52 ( $t$ -stat = 5.75;  $p < 0.001$ ). The direct effects remained nonsignificant as well. The only notable difference was that the interaction term was nonsignificant in this analysis ( $t$ -stat = 0.79). The change in the  $t$ -statistic for the interaction term should be interpreted with caution because the interaction terms in this analysis relied on a sole indicator term, unlike in the main reported analysis. Therefore, this robustness check largely alleviates the aforementioned concern. Consistency in the results across a multitude of bootstrap sizes provides additional assurance about the robustness of the results. A retest of the model with only the three highest loading of the five indicators of the product design modularity construct also yielded results consistent with the reported analysis.

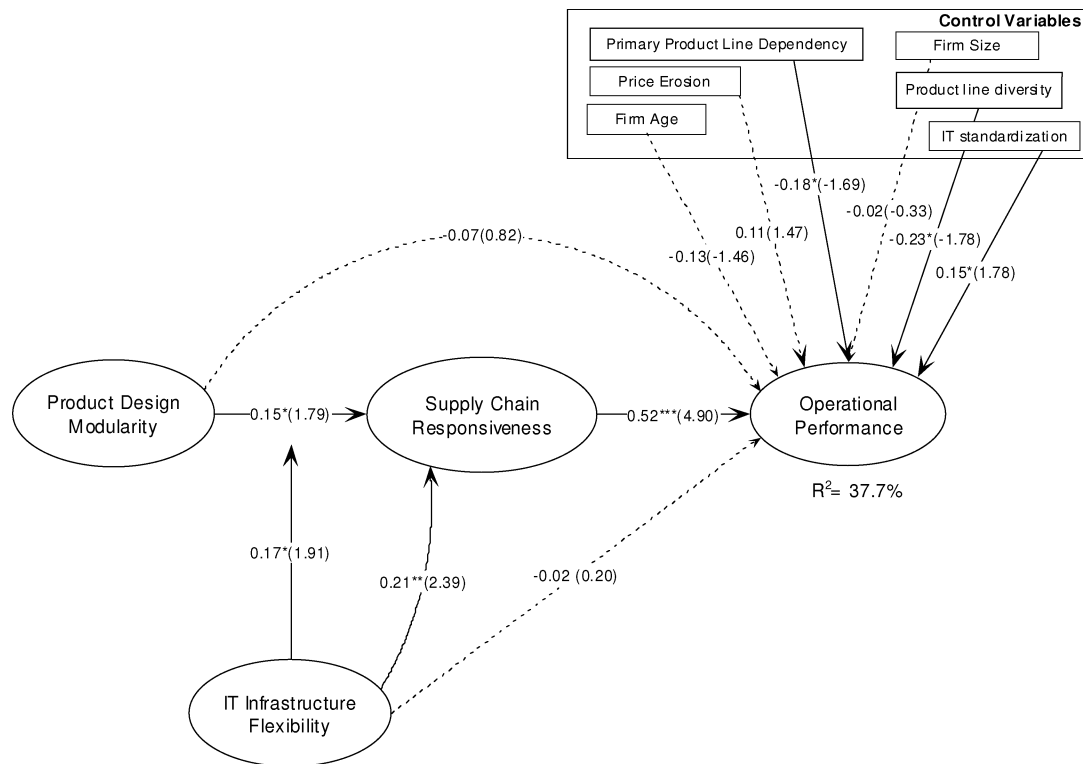


Fig. 2. Results. Solid paths are significant; dotted paths are nonsignificant. The numbers in the path model represent  $\beta$  ( $t$ -value);  $N = 102$ ; \* $p < 0.05$ ; \*\* $p < 0.01$ ; \*\*\* $p < 0.001$ .

- 2) the relationship between product design modularity and supply chain responsiveness is moderated by IT infrastructure flexibility;
- 3) the effect on operational performance of the interaction term used to test moderation in step 2 is mediated by supply chain responsiveness;
- 4) the direct effect of IT infrastructure flexibility on supply chain responsiveness decreases in magnitude in the presence of the interaction term.

We first added to the preceding model the main effect term for IT infrastructure flexibility, which was significant ( $\beta = 0.21$ ,  $t$ -value = 2.39,  $p < 0.01$ ). We then added an interaction term between product design modularity and IT infrastructure flexibility, which we created using Chin *et al.*'s [10] standardized product-indicator approach. This involved creating 20 standardized product terms between the four indicators of IT infrastructure flexibility and five indicators of product design modularity, which were then used as the indicators of the interaction effect term. The interaction term had a positive and significant relationship with supply chain responsiveness ( $\beta = 0.17$ ,  $t$ -value = 1.91,  $p < 0.05$ ). Mediation tests (Sobel test statistic 1.78,  $p < 0.05$ ; Goodman test statistic 1.81,  $p < 0.05$ ) further demonstrated that supply chain responsiveness significantly mediates the effect of the interaction term on operational performance. Adding the interaction term also decreased the magnitude of the direct effect coefficient in the presence of the interaction term of the moderator on the mediator (from  $\beta = 0.26$ ,  $p < 0.01$  down to  $\beta = 0.21$ ,  $p < 0.01$ ). Furthermore, IT infrastructure flexibility

has no direct effect on operational performance and its influence was fully mediated by supply chain responsiveness. Adding the mediator increased the  $R^2$  for the model from 16%–37.7% ( $F$ -change significant at  $p < 0.001$ ), suggesting that it contributes explanatory power to the model. Thus, all four conditions for mediated-moderation were satisfied, supporting Hypothesis 2. (As an added robustness check, retesting the model using a formative measurement model for operational performance yielded consistent results.)

Fig. 3 illustrates the interaction effect supported in Hypothesis 2. The  $y$ -axis represents supply chain responsiveness and the  $x$ -axis represents product design modularity (mean centered values are used). High (the solid line) and low (the dotted line) lines in the interaction plot represent  $\pm 3$  standard deviations from the mean for IT infrastructure flexibility. Interaction plots using  $\pm 1$  and  $\pm 2$  standard deviations showed similar patterns. A direct comparison of the solid line to the dotted line illustrates that an increase in product design modularity is associated with a greater increase in supply chain responsiveness when IT infrastructure flexibility is higher. In contrast, lower levels of IT infrastructure flexibility increase supply chain responsiveness to a lesser degree for the same increase in product design modularity.

### C. Assessment of Rival Explanations

We included six control variables in the model to account for rival explanations of operational performance. Older firms might have greater market experience, which might enhance

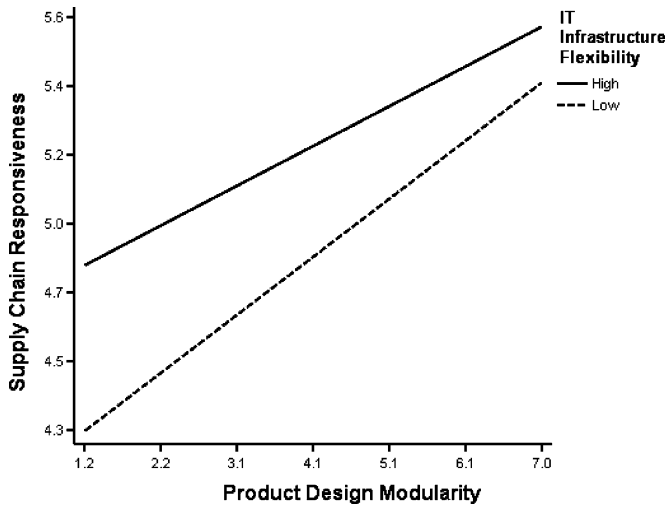


Fig. 3. Interaction plot for high and low ( $\pm 3$  standard deviations) levels of IT infrastructure flexibility.

their performance or may make them more susceptible to a rigid mindset. We, therefore, controlled for *firm age* (measured as the difference between the year of founding and the year 2006). We also controlled for *product line diversity*, measured as the number of products in the firm's product line, with the expectation that firms with a more diverse portfolio of products might have higher levels of operational performance. Greater *price erosion*, measured as the percentage by which the price of the firm's primary product line annually declined, might lower operational performance. The degree to which the revenues of a firm are dependent on its primary product line (*primary product line dependency*, measured as percentage of total revenue derived from the primary product line) might also influence operational performance. We also controlled for *firm size*, which was measured using annual firm revenue as a proxy. Finally, we controlled for *IT infrastructure standardization* as a competing rival explanation for operational performance. IT infrastructure standardization refers to the degree to which information flows in a supply chain are compliant with shared and/or industry standards and the formats of exchanged data (e.g., order status) are standardized across the supply chain [58]. There has been a widespread growth of open and quasi-open standards, which span an industry or a network of partners, for interfirm process integration. Examples of these include Rosetta Net in the electronics industry, and EDIFACT and HL7 in the healthcare industry. These standards ease how firms can enter into and exit from supply chains, lowering what Rai and Sambamurthy [45] describe as "significant structural barriers" to agility. IT infrastructure standardization was measured using three items that tapped into the extent to which the same data (such as order status) stored in different databases across the supply chain was consistent, and the IT infrastructure connecting the focal firm to its supply chain partners was based on common standards and based on industry standards.

Of these control variables, firm age ( $\beta = -0.15$ ;  $t$ -value =  $-1.46$ ;  $p < 0.1$ , marginally significant), product line diversity ( $\beta = -0.20$ ;  $t$ -value =  $-1.78$ ;  $p < 0.05$ ), price erosion ( $\beta =$

$0.11$ ;  $t$ -value =  $1.47$ ;  $p < 0.1$ , marginally significant), primary product line dependency ( $\beta = -0.18$ ;  $t$ -value =  $-1.69$ ;  $p < 0.05$ ), and IT infrastructure standardization ( $\beta = 0.15$ ;  $t$ -value =  $1.78$ ;  $p < 0.05$ ) were statistically significant. The 37.7%  $R^2$  of the overall model suggests that the perspective developed in this paper has substantial explanatory power for operational performance. The control variables explained 16% of the variance in the model. This suggests that our model explains significant additional variance in operational performance beyond the control variables.

#### D. Common Methods Bias Assessment

Since the predictor and dependent variable data were collected from the same respondents, it is necessary to assess the possibility of common methods bias in the results. We conducted three types of analyses to assess the threat of common methods bias: 1) Harman's one-factor test, 2) triangulation using secondary data to estimate statistical agreement with the respondents' perceptual measures of operational performance for the matched pair subset of the data, and 3) Lindell and Whitney's [32] marker variable test. First, Harman's one-factor test is conducted by entering all independent variables, mediating variables, and dependent variables in an exploratory factor analysis. The data would have a common methods bias problem if a single factor emerged that accounted for a large percentage of the variance in the resulting factors. However, a single factor did not emerge in our analyses and the first factor accounted for only 14.1% of the total variance. All items retained in the factor analyses accounted for 68.95% of the total variance.

The second test was triangulation with objective performance data from archival records, following Wernerfelt and Montgomery's [63] precedent of objective performance measures using financial data. The majority of the firms that participated in the study were privately held firms, therefore making it infeasible to estimate the entire model with archival records from annual reports in the Compustat database. We collected objective performance data from Compustat on the 35 identifiable public firms in our sample for the year immediately following our data collection, i.e., 2003. We collected data on total sales, fixed assets, total current assets, total current liabilities, and total inventory. We then used these archival variables to calculate performance measures for each of the following three perceptual items used to measure operational performance:

- 1) fixed asset productivity = {total sales/fixed assets};
- 2) working capital productivity = {total sales/(total current assets-total current liabilities)};
- 3) inventory turns = {total sales/total inventory}.

We then estimated the significance of the correlation between the construct measured using managers' survey measures and the latent construct measured these three objective measures. We repeated the test using 200, 500, 1000, and 5000 bootstraps in PLS. The two constructs have a positive path coefficient of 0.35 and a statistically significant relationship using 500 ( $t$ -value =  $2.94$ ;  $p < 0.01$ ), 1000 ( $t$ -value =  $2.69$ ;  $p < 0.01$ ), and 5000 bootstrap runs ( $t$ -value =  $2.76$ ;  $p < 0.01$ ). This provides some assurance that managers' perceptions of their firm's

operational performance are significantly correlated with objective performance data.

Third, the marker variable technique uses a theoretically unrelated variable (the marker variable) to adjust the correlations among the principal constructs in the model [32]. As a marker variable is unrelated to the study's principal constructs, the correlations should be close to zero. A high correlation of the marker variable with any of the study's principal constructs indicates common methods bias. We separately repeated the marker variable test three times using three marker variables, firm total employee count, respondent experience in years, and paper/electronic survey response format for which we have little theoretical basis to expect a relationship with the study's principal constructs. None of these are included in our model tests. The average correlation between the study's principal constructs for total employee count ( $r = 0.51$ ,  $t$ -value = 0.62), respondent experience ( $r = 0.49$ ,  $t$ -value = 0.65), and paper/electronic survey response format ( $r = 0.03$ ,  $t$ -value = 0.47) was low and nonsignificant, providing no evidence of common methods bias. Collectively, these results provide sufficient assurance that common methods bias is not a serious threat in this study.

#### *E. Limitations and Ideas for Future Research*

Before discussing the results, five limitations of the study should be considered. First, the study used cross-sectional data, which allows us to test the relationships among the constructs in the model but does not allow us to establish causality. The latter requires longitudinal data. Although we took several steps to mitigate this threat, a related caution pertains to the power of our tests given that the interaction term had 20 indicators and our sample size is 102 firms. Second, we used supply chain managers as the key informants in the study. It is possible that the views of supply chain managers will differ from other line function executives (such as marketing managers). However, the significant, positive relationship with managers' survey responses and objective performance data for a subset of the sample provides some assurance that the responding managers could accurately assess operational performance. Further exploring the consistency between supply chain managers' views and those of other managers remains a promising avenue for future research. Third, our model does not directly incorporate industry dynamism (the basis for the distinction between functional versus innovative products [20]), nor considers partner incentives as controls. However, the variety of industries with varying levels of industry dynamism (e.g., manufacturing, retail, agriculture, and services) included in the study increase the generalizability of our results across industries. Additional caution is also warranted because of the use of ratio scales for some of our control variables. Incorporating industry dynamism into the model remains a fertile area for future research. Fourth, future research should also directly incorporate the degree of IT dependence of a supply chain, which was not accounted for in our model. Finally, the firms in our study were large firms with revenues in excess of \$500 million. Caution is warranted in generalizing the findings to smaller firms.

## V. DISCUSSION

The study was motivated by the need for a theoretical explanation for how and why product design modularity influences operational performance of the focal firm in an IT-enabled supply chain, and the complementary role of supply chain IT infrastructure flexibility. Building on modular systems theory, we theoretically developed two ideas. First, greater product design modularity enhances operational performance in the context of a firm's primary products by enhancing supply chain responsiveness. Second, greater IT infrastructure flexibility enhances operational performance by strengthening the positive effect of product design modularity on supply chain responsiveness. Tests using data collected from supply chain managers in 102 firms provide strong support for both of these ideas, which represent two new contributions to the literature.

#### *A. Contributions and Implications for Research*

Our first contribution is a theoretical explanation for why product design modularity enhances operational performance. Although prior studies have observed the association of modular product designs on organizational performance [3], [28], how modularity influences market evolution [25], and influences imitation [43], the intervening mechanisms have largely been neglected in theory development. Our results demonstrate that supply chain responsiveness is an important intervening variable that fully mediates the influence of product design modularity on the focal firm's operational performance (Hypothesis 1a–1c; full mediation).

This implies that greater modularity in the focal firm's product designs increases operational performance because it increases the focal firm's supply chain responsiveness. This has important implications for the modularity and supply chain management literature. First, this contributes an explanation of why modularity translates into superior operational performance, complementing prior work that has recognized product modularity as an important precursor to performance of supply chains but has not theoretically developed an explanation of the intervening mechanisms [48], [58]. Although the modularity literature is built on the widespread but untested assertion of a relationship of product design modularity with performance [36], [52], [62], our results provide direct empirical support for this viewpoint. This finding also provides some of the earliest empirical evidence for the idea that the capacity of supply chains to be adaptive is a precursor to how well the focal firm performs on the market relative to its competitors [24], [38], [60].

Our second contribution is in showing how the positive interaction effect of infrastructure flexibility and product design modularity (Hypothesis 2; mediated-moderation relationship) on operational performance is fully mediated by supply chain responsiveness. IT infrastructure flexibility, therefore, influences operational performance because it enhances supply chain responsiveness, i.e., the effect is fully mediated. Our results suggest that greater modularity of product designs enables firms to better adapt to shifts in market conditions when such modularity is simultaneously reinforced by supply chain IT infrastructure flexibility. Industry thought leaders have

emphasized the ability to tap into complementary capabilities outside the focal firm, and that supply chain-enabling IT infrastructure is a critical enabler for this. Therefore, increasing IT infrastructure flexibility increases the benefits derived from modularizing product designs, and modularizing product designs increases the benefits of increasing the flexibility of IT infrastructure. This finding has theoretical implications for both the IS and supply chain literature.

The demonstrated complementarity of IT infrastructure flexibility with product design modularity offers a theoretical explanation for the symbiotic, mutually reinforcing interactions between product design modularity and IT infrastructure characteristics, complementing a rich stream of work on IT infrastructure flexibility at the intrafirm level (such as Duncan [15] and Byrd and Turner [7]). This finding also extends the supply chain management literature that suggests that feasible supply chain designs are enabled and constrained by product designs [27], [31], [50].<sup>3</sup> More broadly, these results support the idea that IT characteristics and organizational characteristics together generate business value from IT investments [34]. In the case of our model, IT infrastructure flexibility represents the focal IT characteristic at the firm level and product design modularity represents the complementary organizational characteristic.

### B. Implications for Practice

First, managers must recognize that increasing product design modularity increases operational performance of the focal firm by making its supply chain more responsive to shifts in market demands. Thus, more modular product designs are more malleable, and this malleability provides greater flexibility in the supply chain partners that are involved in the production of product variants and allows new firms to be more easily introduced when the product needs warrant. However, they must also consider the costs of modularizing product designs, which are not likely to be trivial. They must also weigh such benefits against the performance tradeoffs that modular products might have to make compared to more integral products [62].

Second, more flexible IT infrastructures also enhance supply chain responsiveness, which can lead to greater operational performance for the focal firm in an IT-enabled supply chain. Greater IT infrastructure flexibility allows new suppliers to be more easily and rapidly added, existing ones to be reassigned to different roles, and work and production processes coordinated through interfirm IT applications to be changed.

Third, our results imply that managers must recognize that product design modularity is not an alternative to IT infrastruc-

ture flexibility but rather a complement. To fully realize the flexibility benefits of modular product designs, focal firms must also simultaneously develop flexible IT infrastructures for information exchange and coordination with a firm's supply chain partners. This finding supports the belief in the practitioner literature that the architecture of the supply chain and the architecture of the product have mutually reinforcing effects [19]. Our results further demonstrate the underlying mechanism; IT infrastructure flexibility underlying IT-enabled supply chains strengthens the influence of product design modularity on supply chain responsiveness.

In conclusion, our overarching contribution is the development of a theoretical explanation for how and why product design modularity influences operational performance in supply chains, and how IT infrastructure flexibility complements it. Nevertheless, this study represents an initial exploratory step in using modularity as a promising conceptual lens for further theory development on designing agile supply chains.

## APPENDIX

### MEASURES FOR THE KEY CONSTRUCTS IN THE MODEL AND THEIR FACTOR STRUCTURE

The respondents were asked to consider their organization's primary product(s) or product line(s) in responding to the survey questions. Primary product(s) or product line(s) were defined as those that commanded a significant proportion of company revenues, usually 15%–20%, or greater. Anchors for all multi-item scales except operational performance were 1 = strongly disagree and 7 = strongly agree. Operational performance used 1 = much less than average; 4 = same; and 7 = much better than average.

Additional control variables

*Firm age* was computed as the difference between 2006 and the year of founding of the firm based on the archival records in the Compustat database.

*Product line diversity* was measured as the total number of products in the firm's product line(s).

*Price erosion* was measured as the rate at which price of primary product(s) or product line(s) decreases per year. The response choices were 0%–10%, 11%–20%, 21%–40%, 41%–60%, and 61%–100%.

*Primary product line dependency* was measured as the percentage of revenue from the firm's primary product(s) or product line(s). The response choices were 0%–20%, 21%–40%, 41%–60%, 61%–80%, and 81%–100%.

*Firm size* was measured using annual revenue range as a proxy. The response choices were \$0–10M, \$11–50M, \$51–100M, \$101–500M, and \$500 Million or greater.

<sup>3</sup>Unlike Schilling's [54] conceptualization of modular systems theory that attempts to predict modularity, our model predicts its consequences (e.g., the influence of modularity on operational performance) and the intervening process mechanisms such as supply chain responsiveness through which they result. This finding also contributes both a theoretical explanation and empirical evidence to the broader modularity literature, which has recently recognized the need for alignment between product design modularity and organizational structure (which can be viewed as an umbrella construct of which IT infrastructure flexibility is one facet) (e.g., [57]).

\*We used an ordinal set of categories to collect the survey data for these measures, as our preliminary interviews revealed that respondents are more likely to be able to specify a range than to be able to specify an exact number for these questions.

	1	2	3	4	5
<b>1. Product design modularity</b>					
Product parts and subassemblies are shared across many products	<b>0.874</b>	0.077	0.121	-0.070	-0.003
Products have a modular design	<b>0.812</b>	0.066	0.099	0.090	0.071
New product offerings reuse the designs of existing components	<b>0.810</b>	0.200	-0.070	0.089	0.075
Our product offerings integrate components from multiple suppliers	<b>0.672</b>	-0.124	-0.070	0.239	-0.113
Our product offerings consist of components that can be mixed and matched in a variety of configurations	<b>0.646</b>	-0.103	0.193	-0.089	-0.050
<b>2. IT infrastructure flexibility</b>					
Our IT infrastructure ...					
...prevents us from changing communication and reporting linkages across the supply chain (reversed)	-0.144	<b>0.820</b>	-0.075	0.042	-0.055
...prevents us from scaling our transaction processing up or down as needed (reversed)	0.113	<b>0.743</b>	0.152	-0.189	-0.113
...prevents us from changing our supply chain partners (e.g., suppliers, customers, logistics partners) (reversed)	0.053	<b>0.737</b>	0.000	0.097	-0.056
...constrains us in redesigning supply chain processes (reversed)	0.038	<b>0.672</b>	0.226	-0.023	0.220
...allows us to meet changing information requirements of our customers ( <i>dropped</i> )	0.114	<b>0.612</b>	0.478	0.101	0.170
...allows us to meet changing information requirements of our supply chain partners ( <i>dropped</i> )	0.106	<b>0.603</b>	0.437	0.274	0.002
<b>3. IT infrastructure standardization</b>					
Same data (e.g., order status) stored in different databases across the supply chain is consistent	0.028	-0.025	<b>0.800</b>	-0.058	0.214
Our IT infrastructure and that of our supply chain partners are based on common standards	0.096	0.359	<b>0.783</b>	0.091	0.067
Our IT infrastructure and that of our supply chain partners are based on industry standards	0.208	0.173	<b>0.702</b>	0.287	-0.016
<b>4. Supply chain responsiveness</b>					
Precise knowledge of customer buying patterns	0.170	0.068	0.043	<b>0.694</b>	0.390
Strong and continuous bond with customers	0.014	0.093	0.085	<b>0.794</b>	0.258
Timeliness of after sales service	0.110	-0.026	0.198	<b>0.791</b>	0.176
<b>5. Operational performance</b>					
Compare your organization's performance in your primary product(s) or product line(s) with that of your competitors by circling the appropriate response using the following scale.					
Fixed asset productivity	0.025	-0.009	-0.034	0.158	<b>0.876</b>
Working capital productivity	0.059	-0.107	0.187	0.245	<b>0.757</b>
Operating costs	-0.095	0.121	0.139	0.150	<b>0.754</b>
Eigenvalue	5.7	3.4	2.9	1.5	1.1
Percentage of variance explained	14.1%	13.7%	11.2%	10.7%	9.1%

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