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RESEARCH ARTICLE

The Product Quality Impact of Aligning Buyer-Supplier Network Structure and Product Architecture: an Empirical Investigation in the Automobile Industry

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Abstract There has been a trend, in the last decade, of buyers outsourcing new product development (NPD) activities to suppliers. This study examines the impact of (mis) alignment between buyer-supplier network structure and product architecture on two product development outcomes: product quality and product recalls. The hypotheses are tested on a uniquely assembled database of supplier networks of automakers for 12 vehicle systems. The results suggest that while dense supplier network are associated with higher future product quality and lower future recall magnitude, structural holes are associated with lower future product quality and higher future recall magnitude. Further, the results suggest that product quality partially mediates the relationship between supplier network characteristics and recall magnitude. Interestingly, these effects are significantly moderated by the product architecture. While network density is positively related to product quality of weak design interfaces (i.e., modular systems), structural holes in the supplier network are positively related to product quality of strong design interfaces (integral systems). The results offer valuable insights to managers about the appropriate supplier network structure for superior quality.

Keywords Buyer-supplier networks · Outsourcing · Product quality · Product architecture · Organizational networks

Successful buyer-supplier relationships are critical to the performance of firms because most firms require outside capabilities and resources to compete effectively in the marketplace. Leading companies such as Sony, Dell, Nike, and Toyota rely to a great extent on leveraging supplier networks to achieve industry leadership [20]. Researchers in marketing have shifted their focus from buyer-supplier dyads to buyer-supplier networks [3, 34, 45, 77]. In the last decade or so, there has been a trend of buyers farming out critical processes in the value chain such as product design and manufacturing to suppliers [7, 11, 42, 49]. The business press refers to this phenomenon as "hollowing of the corporation" or "open innovation" and notes that firms might be able to increase outsourcing to the point that they primarily become assemblers of purchased components and services or even pure contractual brokers [52].

While the trend towards vertical disintegration is dictated by the need to be responsive to varying demands, the impact of these changes on quality is far from clear. Understanding this is important and timely because recently there has been a palpable increase in the number of consumer products deemed hazardous that were subsequently recalled (see http://www.cpsc.gov/cpscpub/prere//prerel.html). It is plausible that the increase in the number of recalls in recent years is a consequence of increased outsourcing and traceable to problems in the buyer's supplier network. For example, in

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2005, the German auto manufacturer, Audi, recalled several thousand vehicles following concerns of faulty diesel injection pumps. This incident resulted in shareholder value destruction in the three digit million Euro mark. While Bosch GMBH was the supplier of the fuel injection system, it turned out that the defect was because of the Teflon coating on a 1.5-cm small socket. It is noteworthy that the socket was not made by Bosch but was manufactured by Federal Mogul, a US-based supplier that in turn sourced the Teflon from Dupont [76]. While the business press is replete with examples of dysfunctional supply chains, empirical evidence on the influence of buyer-supplier network structure on product recalls is missing in the literature.

The objective of this study is to develop and test a conceptual model of the relationship between buyer-supplier network structure, future product quality, and future product recall outcomes. Our study makes two contributions to the emerging literature on product recalls. *First*, we test the impact of density and structural holes in a buyer's supplier network on product quality and recall magnitude. While previous research in marketing, economics, and strategic management has examined the impact of product recalls on (a) shareholder wealth [17, 72], (b) effectiveness of marketing mix instruments [75], and (c) learning outcomes [37, 41], there is no empirical research on the supplier network antecedents of product recalls. Similarly, marketing researchers have examined the impact of network characteristics on project success in a software development context [34, 47]. Product development in the automobile industry is a complex endeavor involving relationships between manufacturers, tier 1 suppliers, tier 2 suppliers, and others. Direct evidence on the appropriate supplier network configuration is helpful in understanding the risks and vulnerabilities products are exposed to when firms outsource new product development.

Second, we examine the contingent role of product architecture on the relationship between buyer-supplier network structure and product quality. Previous research on product development and organization theory recognizes that a match between organization structure and task characteristics is needed to realize superior product development outcomes [8]. Building on this stream of research, we propose that the extent of alignment between buyer-supplier network structure and product architecture should bear a significant relationship with product quality. The rationale for this argument stems from the fact that task requirements in product development for modular and integral systems are different [61, 74]. Therefore, the benefits offered or constraints posed by buyer-supplier network structure for product development would vary based on the architecture of the product.

To test the moderating influence of product architecture, we examine the strength of design interfaces (SDI) of systems. SDI refers to the extent to which physical components share *design* dependencies across systems in a complex product [5, 40, 69, 74]. We classify systems that share few design dependencies with other systems as "Weak (Modular) Design Interfaces" and systems that share many dependencies with other systems as "Strong (Integral) Design Interfaces."

Third, we test the research hypotheses on a unique dataset painstakingly assembled by combining primary and archival data in the US automobile industry. The data is comprised of supplier networks of 13 automobile firms (i.e., BMW, Chrysler, Ford, General Motors, Honda, Hyundai, Kia, Mazda, Mercedes-Benz, Mitsubishi, Nissan, Subaru, and Toyota) having manufacturing plants in the USA and 12 vehicle systems (i.e., transmission, major engine system, engine cooling, suspension, drive systems, exhaust, electrical, power equipment, body hardware, braking system, climate system, and fuel system). The supplier networks of the 13 automobile firms are comprised of 964 suppliers and a total of 12,667 relationships. Data on SDI is collected through in-depth interviews with design engineers of automobile and supplier firms.

The results suggest that while dense supplier networks are associated with higher future product quality and lower future recall magnitude, structural holes in the supplier network are associated with higher future recall magnitude. Our findings support the view that dense and cohesive supplier networks improve information exchange and benefit product development ([21, 34] but incongruent with the view networks with structural holes are associated with superior product development outcomes [36]. The results further suggest that the impact of network structure characteristics on future recall magnitude is partially mediated by future product quality.

Importantly, the findings suggest that the relationship between structural characteristics of buyer-supplier network and product quality is significantly moderated by the SDI or product architecture. Specifically, the positive relationship between network density and subsequent product quality is stronger for weak design interfaces (modular systems) than for strong design interfaces (integral systems). In contrast, the negative relationship between structural holes and subsequent product quality is weaker for strong design interfaces than for weak design interfaces. The managerial implication is that aligning dense buyer-supplier networks with modular systems and buyer-supplier networks with structural holes with integral systems is beneficial for improving quality.

1 Conceptual Framework and Hypotheses

We build on insights from the product development literature which suggest that frequent and appropriately structured task communication results in better performing development processes [8, 34]. It has also been recognized for long that an organization's structure should be designed to reflect the nature of the tasks they perform [67]. Researchers have further explored this idea and examined whether the degree of correspondence between organizational structure and product architecture improves product development outcomes. For instance, Sosa et al. [69] examined the nature of team interactions in a development project and its relationship to interdependencies that existed between different parts of a product's design. Likewise, Cataldo et al. [12] offer empirical evidence to suggest that tasks were completed faster when the patterns of communication between team members were aligned with the patterns of interdependency between components. Finally, Gokpinar et al. [32] investigate the implications of misalignment between organizational communications and interdependencies of the technical interface. We build on this stream of research and examine the consequences of aligning buyer-supplier network structure with the product architecture on product quality and frequency of product recalls. We present our conceptual framework in Fig. 1.

2 Product Performance Effects of Buyer Network Density

Network density offers distinct advantages for product development. Because of dense connections between buyers and suppliers, the actors in the network have access to the same information and there is less information variation. In other words, the actors within a dense network would be structurally equivalent because no particular entity has access to unique information [31]. The frequent sharing of information facilitates the development of shared routines for product development [15, 21]. For example, buyers and suppliers could facilitate the diffusion of best practices for product development. For example, it is known that Toyota's supplier network has over time become highly interconnected with dense ties between Toyota and its different suppliers. The quality conference organized by Toyota is designed to improve the quality capabilities of its suppliers. Toyota frequently proposes a theme (in conjunction with suppliers) for the conference such as lowering "supplier designed defects" and meets with its suppliers frequently (e.g., up to six times a year) to exchange knowledge. This information-sharing network of Toyota and its suppliers is recognized to be a source of advantage [21]. More generally, buyer network density provides the means to foster trust and establish norms of cooperation [15, 54].

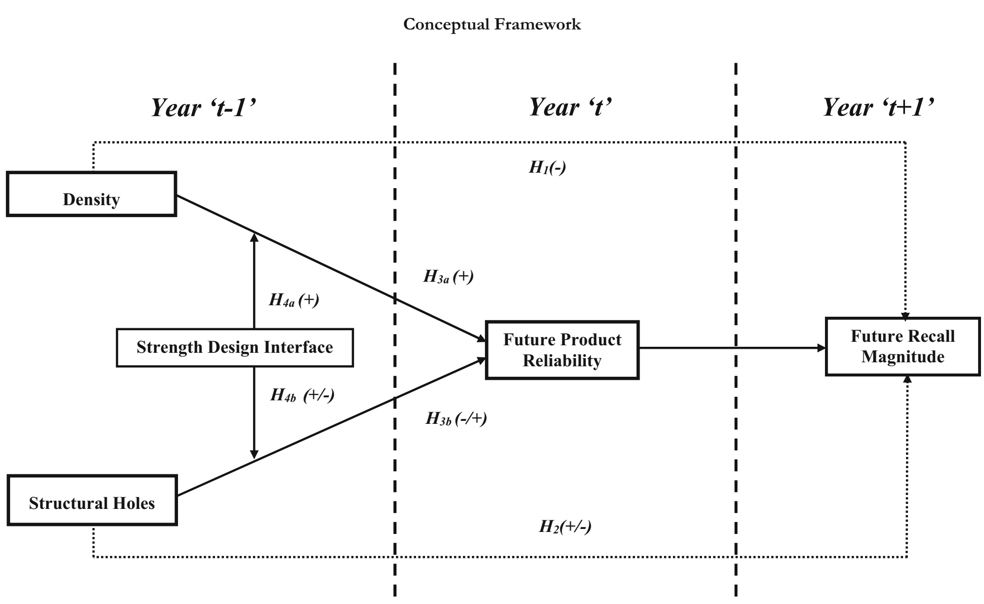
The other benefit of information sharing in a dense B-S network is that because "everybody knows one another," buyers can collectively monitor and prevent opportunistic behavior. The possibility of opportunism arises when suppliers are not exclusive and they work with multiple buyers in the same industry. If suppliers act in self-interest, such behavior is likely to be noticed by other members of the network and the deviant behavior would be sanctioned. Network density in some aspects acts as an informal governance mechanism and lowers uncertainty in complex product development. All else equal, network density offers buyers the benefits of information sharing and sanctions and enables coordination and improvement in product quality. Hence we hypothesize that:

> H1: *Buyer network density is positively associated with product performance (lower recall magnitude and higher product quality).*

3 Product Performance Effects of Buyer Network Centrality

Network theorists contend that organizations could also benefit from its social network by positioning themselves in gaps

Fig. 1 Conceptual framework



between nodes in the network [10]. Here, the role of the supplier network is to provide a recombination potential or the generation of novel combinations. The premise is that information and values are more similar within groups than between groups. That is, the recombination potential arises from the buyer connecting to suppliers that are not connected to a firm's existing group of suppliers.

The benefit of network centrality is that it offers the buyer access to novel information and unique resources and opportunities. A tie with a supplier will provide access to new information to the extent that it offers access to non-redundant sources of information [30]. The possibility to create non-redundant ties or have distinct cliques of suppliers is not equally spread across buyers. A central position in the network is critical to have these benefits [10]. Access to unique information enables the buyer to benefit from a positive resource asymmetry. In addition, the central position provides earlier access to relevant new information and strengthens the competitive capability of the buyer [31]. Buyers that are centrally positioned in supplier networks thus have the *flexibility* of accessing valuable information from supplier cliques in a timely manner ([1, 36]. At times, solutions to improve the product performance require creative inputs [2]. Access to unique and non-redundant ties brings forth novel information relevant for quality improvements in complex product development [1, 54]. The ability to access novel information from supplier cliques (i.e., distinctiveness) and act in a timely fashion (i.e., responsiveness) akin to loosely coupled networks should aid product performance. All else equal, buyer network centrality is likely to be beneficial for product quality.

> H2: *Buyer network centrality is positively associated with product performance (lower recall magnitude and higher product quality).*

4 Product Architecture and Complex Product Development

Complexity in product development arises when there are a large number of interdependent decisions. Because there are multiple interactions, it is often difficult to infer the properties of the whole system [67]. *Product architecture* refers to the arrangement of functional elements of a product into several physical building blocks with the goal of understanding how these elements interact with each other. For example, the design of personal computers can be broken down into distinct building blocks such as microprocessors, memory chips, monitors, keyboards, and disk drives. Modular product architectures allow firms to manage complexity in product development and offer product variety [56, 61]. Extant research conceptualizes modularity in three stages of product development; modularity in design, modularity in production, and modularity in use [5]. We conceptualize product architecture in terms of modularity in design.

Modularity in design refers to breaking up a complex product into separable units that communicate with each other through standardized interfaces (i.e., invariant over some period of time) or rules and specifications [43, 62]. While the genesis of modular designs is traceable to the personal computers industry (hardware and software), the concept has been extended to several industries such as automobiles, bicycles, and personal music systems. Following previous research [5], we imply modularity to reflect the true underlying structure of the product. In our context, modularity implies that the design interactions between different systems of the product are well-understood and well-recognized. Because interfaces are standardized or loosely coupled, modularity facilitates the introduction of variations in components or systems without design changes of other components or systems. In contrast, in integral or tightly coupled product designs, design changes in a component or system cannot be achieved without design changes in other systems.

5 The Moderating Role of Product Architecture

The main effect hypotheses argue for the benefits/constraints of buyer-supplier network structure without considering the nature and content of activities in product development. This is unrealistic as task requirements for product development vary depending on the architecture of the product. Our argument is that the extent to which a system is modular or integral should moderate the impact of buyer-supplier network structure on product quality. In other words, the alignment between buyer-supplier network structure and product architecture should improve product quality. The notion of alignment has been referred to as "fit" in the organizations [19, 76].

Previous research in marketing, strategic, and operations management has examined the impact of product architecture on different performance outcomes. For instance, modular designs are recognized to be more beneficial than integral designs in reducing the time-to-market [78], lowering costs [26], and increasing the number of product variants offered to the market [18, 39]. Integral systems, in contrast, offer superior product performance [73, 74].

The objective of a modular design, as noted before, is to standardize interfaces so that they could be mixed-and-matched to create product variants. The plug-and-play property of modular designs allows marketers to pursue a postponement or made-to-order strategy. Based on the design strength of the interface, systems can be classified as either modular or integral [68]. Interfaces with higher (lower) design strength are akin to integral (modular) systems.

Networks with dense ties facilitate interaction among members and help coordinate activities. For weak design interfaces or modular systems, an overarching objective in product development is to maintain acceptable levels of quality and lower costs at the same time [23, 26]. There are two reasons why dense networks are likely to be more beneficial for modular systems than for integral systems. First, since buyers outsource design and manufacturing of modular systems to a greater extent, there is increased responsibility on supplier networks to ensure that the performance of the modular system is not compromised [26]. Second, modular systems contribute to product differentiation to a greater extent than integral system because of the ability to mix and match systems across products. Development of modular systems requires coordination in the supplier network to respond to varying downstream demand. Buyers often delay the assembly of certain product-specific modules so that the point of differentiation is delayed. Dense supplier networks enable rapid exchange of information about downstream demand and provide the agility needed to implement postponement strategies. Therefore, greater interaction and exchange of information in the supplier network offers the resources and flexibility to coordinate design and manufacturing of modular systems and reduce errors.

For example, Volvo sources modular systems such as seats from JCI and Lear. Volvo has fashioned a highly complicated and interdependent relationship between the two suppliers. Over the years, the sourcing strategy has evolved to a point where the working relationship between JCI and Lear is now so closely intertwined they must be considered together when Volvo discusses seat sourcing. For instance, JCI makes the front seats and both JCI and Lear make rear seats. In addition, the two suppliers have reciprocal relationships in which Lear assembles front seats for JCI and JCI assembles rear seats for Lear [14].

In contrast, for integral systems, there is relatively less outsourcing of design because of its complexity and criticality for product performance [11, 50]. Similarly, downstream demand is also less uncertain because integral systems are shared across product variants. Thus, there is relatively less coordination needed between suppliers *within* a given integral system [50]. Thus, the coordination benefits of a dense supplier network would be stronger for modular systems than for integral systems. Based on these arguments, we hypothesize:

> *H3a: The positive relationship between density of the buyer's supplier network and future product quality is weakened by the strength of the design interface. The positive relationship is weaker for strong design interfaces (integral systems) than for weak design interfaces (modular systems).*

As noted before, structural holes in the network offer control benefits as the buyer is the conduit for information between suppliers. Systems with strong design interfaces or integral systems are complex because they share dependencies with other systems [22]. Since integral systems are critical to the overall performance of the product, there is need for stronger control over product development. It is known that centralized structures are better-suited to achieve higher performance for complex tasks (Jensen and Meckling 1992). A central position in the supplier network might be better suited for product development of integral systems. For example, automobile manufacturers rely on vehicle integrity teams and in-house plants to develop integral systems such as engine and transmission systems. Supplier networks with structural holes allow buyers to occupy a central position and mediate information flows between suppliers. Therefore, buyers can exercise superior control over product development activities of integral systems. In addition, structural holes present opportunities to tap into different supplier cliques and gather information about product development efforts of related systems. This information is critical as the performance of integral systems depends on the performance of other systems. Thus, structural holes should help improve the quality for integral systems to a greater extent than for modular systems.

> *H3b: The negative (positive) relationship between structural holes in the buyer's supplier network and future product quality is weakened (strengthened) by the strength of design interface. The negative (positive) relationship is weaker (stronger) for strong design interfaces (integral systems) than for weak design interfaces (modular systems).*

6 Buyer-Supplier Network Structure, Product Quality, and Product Recalls

Our preceding arguments assume that product recalls reflect lack of quality in the firm's operations. Although this assumption generally holds, firms may at times recall products as a measure of precaution and to avoid future liabilities (e.g., fines or penalties). Hence, there is a need to test the impact of buyer-supplier network structure on more proximate product development outcomes. Recognizing this, we distinguish between internal and external quality [28]. While internal quality reflects product performance with respect to design adequacy and conformance to standards, external quality captures product performance in terms of quality-in-use. Typically, product recalls occur after an investigation is initiated because of customer complaints about product safety. That is, product recalls are triggered when customers experience less than expected quality-in-use. Examining the relationship between internal quality and external quality, Fynes and Voss [28] find that design quality has a positive effect on conformance quality. Furthermore, conformance and design quality are positively related to quality-in-use. Similarly, there is evidence to suggest that product quality predicts future recalls [6, 13]. Based on the preceding arguments, we expect that network density and structural holes in the supplier network would influence future recall magnitude through product quality.

H4a: Product quality would mediate the relationship between network density and future recall magnitude.
H4b: Product quality would mediate the relationship between structural holes and future recall magnitude.

7 Research Methodology

The automobile industry presents an ideal setting to test the hypotheses. There are several features of the automobile industry that are attractive. There have been important changes in vertical integration decisions (i.e., make or buy) and supplier network configuration of automobile manufacturers. The US automobile manufacturers have traditionally relied on a large numbers of suppliers that were typically managed through short-term contracts. In the 1980s, large US automobile manufacturers had supplier networks comprising of more than 3000 first-tier suppliers. One of the main objectives of traditional sourcing strategies in the West has been to minimize vulnerability to supplier opportunism [63, 70]. For instance, suppliers to the US automobile industry have little expectation of being treated fairly by customers. Further, a large majority believe that if a competitor appeared with comparable quality and a lower price, their customers would switch as soon as technically feasible [38]. However, the early 1990s witnessed the emergence of Japanese automotive manufacturers introducing a different mindset that emphasized building closer relationships with a smaller number of key suppliers [21, 46]. The different mindsets of automakers operating in the USA towards their suppliers have resulted in networks with varied structural characteristics.

8 Data

We assembled the data on buyer-supplier relationships using *ELM Analytics*, a vendor that tracks the supply chain performance for automakers and suppliers in North America. This database has been used in previous research and is the most comprehensive listing of component manufacturers available [46]. We focus on *firm-system* as the unit of analysis. This choice was guided by the observation that there is considerable variation in the composition of supplier networks for different systems for a given firm. Accordingly, we collected data on buyer-supplier links for the 12 vehicle systems between 2005 and 2010. We identify suppliers of 13 automobile manufacturers with significant operations in North America (BMW, Chrysler, Ford, General Motors, Honda, Hyundai, Kia, Mazda, Mercedes-Benz, Mitsubishi, Nissan, Subaru, and Toyota). The 13 auto manufacturers accounted for approximately 85% of the vehicles sold in North America. The systems we examine are as follows: transmission, major engine system, engine cooling, suspension, drive systems, exhaust, electrical, power equipment, body hardware, braking system, climate system, and fuel system. We focus on these 12 vehicle systems instead of more disaggregate sub-systems or vehicle components to keep the functional interactions or dependencies tractable [32, 50]. Additionally, data on product quality and product recalls are available at the vehicle system level rather than at the sub-system level. We construct binary socio-matrices to capture buyer-supplier ties for each vehicle system. Figure 2 depicts the buyer-supplier network for the electrical system. As seen in Fig. 2, the network for the electrical system is comprised of 494 suppliers of 13 automobile manufacturers yielding a total of 3656 ties. We construct similar networks for the remaining vehicle systems. The extensive data collection efforts yielded a total of 964 unique suppliers for 13 automobile firms and 12,667 unique buyer-supplier relationships.

The data was assembled using a combination of archival and primary sources. We collected data on product recalls from the *National Highway Traffic Safety Administration* (*NHTSA*), a federally governed organization established under the Highway Safety Act of 1970 to enhance and monitor highway and motor vehicle safety. *NHTSA* is enforced by the US Department of Transportation with the goal of establishing and governing safety standards for motor vehicles in the country. Based on complaints received from consumers and law enforcement authorities, *NHTSA* conducts detailed investigations and directs automakers to issue recalls if needed. *NHTSA* maintains a database of every vehicle safety recall issued from 1966. A typical recall notice provides information on the vehicle make and models likely to be affected, the number of vehicles recalled, and the system that is potentially defective. We obtained annual data on recalls experienced by firms that sold automobiles for 2012. Since our supplier network pertains to models manufactured in the USA, we only included recalls featuring models manufactured in the USA. The data on quality of auto manufacturer's vehicle systems for 2011 was assembled from *Consumer Reports*.

There are two important issues in matching buyer-supplier relationships with quality outcomes. First, data on buyer-supplier relationships was available at the "automaker-vehicle system" level whereas data on product quality is at the "model-vehicle system" level. For example, consider the case of Subaru of America, the automaker. While we constructed the supplier network structure for each of the 12 vehicle systems of Subaru, the quality data is available for the 12 vehicle systems across different models (e.g., Outback, Legacy) of Subaru. We aggregate the model-level quality by weighting

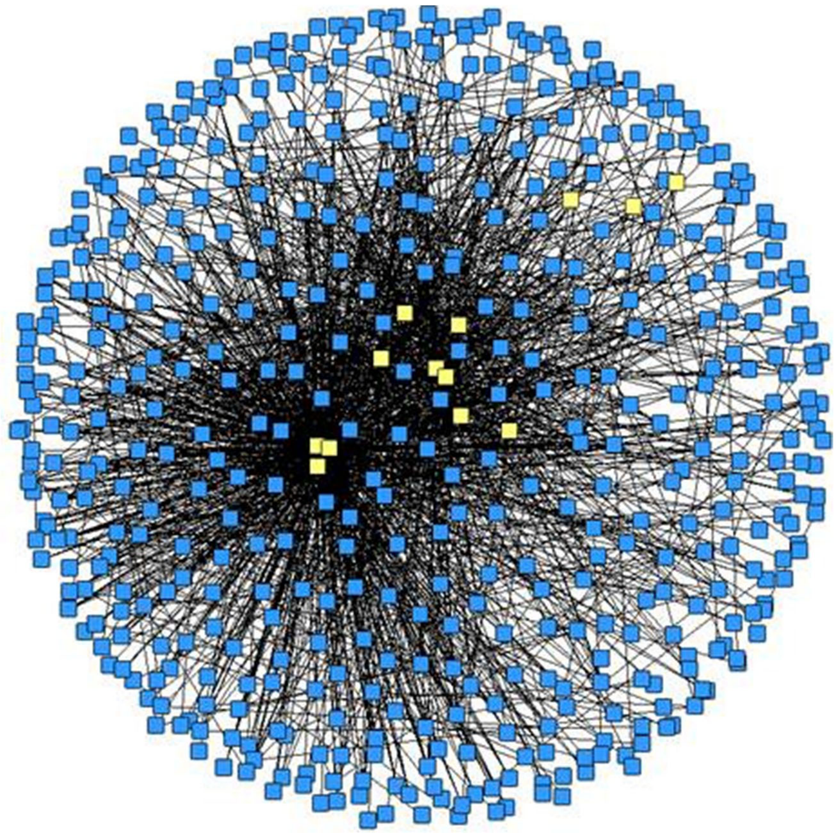


Fig. 2 Buyer-supplier network for the electrical system

on model sales to construct the automaker's quality for a vehicle system. Second, we only include suppliers of models that were manufactured in North America. For example, Subaru of America manufactured three (i.e., Outback, Legacy, and Tribeca) of its five models in its North American assembly plant between 2005 and 2010. We only identify suppliers of these three models of Subaru. Consistent with this approach, we do not collect product quality and product recall data for the two models that are not manufactured in North America.

We relied on primary data sources to operationalize the SDI variable. We conducted 18 in-depth interviews with product and design engineers in automobile and supplier firms to gauge the dependencies of various systems in a vehicle. The in-depth interviews lasted approximately 90 min in duration. The experts participating in the survey were employed at General Motors, Ford, Honda, Toyota, BMW, Hyundai, Bosch, Cummins, Denso, Mando, SAIC Motors, and Ashok Leyland and had on average approximately 10 years of experience in automotive design. To assess SDI, we asked the product and design engineers to evaluate the degree of information, spatial, structural, material, and energy dependencies between vehicle systems (see "Section 9" and the Web Appendix for details on the questionnaire items).

We also collected data on several supplier and buyer characteristics. We collected data from *ELM Analytics* on the size of the supplier's plants (in square feet), distance in miles between the supplier and auto manufacturer, the union status of suppliers, and whether the supplier had received quality awards from the manufacturer. As regards buyer characteristics, we collected data on manufacturer's sales from the *Ward's Automotive Yearbook* and manufacturer's R&D expenditures from COMPUSTAT and annual company reports.

A test of our hypotheses requires a close alignment between the theory, measures, and the empirical model. We achieve this by modeling the impact of buyer-supplier network structural characteristics in time period "$t - 1$" on quality in time period t and recall magnitude in time period "$t + 1$." The temporal separation facilitates a more confident interpretation of the quality consequences of buyer-supplier network structure. Our final dataset for empirical analyses is comprised of 156 firm-system observations (13 makes × 12 systems). The supplier network structural characteristics and control variables are for the 2005–2010 period, product quality data is for 2011, and product recall magnitude data is for 2012.

9 Measures

Product Recall Magnitude We operationalized recall magnitude as the number of vehicles recalled for defects in a system. Recall magnitude or the number of vehicles recalled is influenced in part by the number of vehicles the make has on the road. To account for scale effects, we normalize the number of vehicles recalled in a year by the make's sales in the previous year.

Product Quality We operationalized product quality in terms of the number of problems experienced by vehicles for a particular system relative to the number in all vehicles of the same age. This measure has been adjusted to account for the number of miles driven by consumers in a given year. The quality scores for vehicle systems are between 1 and 5, with 5 indicating highest quality and 1 indicating lowest quality.

Network Density We use non-directional relationship matrices to assess the buyer's network density. Following past research [59, 60], we operationalized network density of an automaker for a particular system as the ratio of the number of ties observed between the buyer's suppliers to the total number of possible ties. It is worth noting that, to compute density, we dissected the network into smaller ego networks and examined local densities [48, 64]. Local density examines the interconnectedness of the buyer's direct suppliers. The ego network density measure is consistent with Coleman's closure argument pertaining to the buyer's suppliers being densely connected to each other [60, 64].

Structural Holes As before, we constructed matrices of non-directional relationships between buyers and sellers [65, 79]. We operationalized structural holes in terms of betweenness centrality. This operationalization is consistent with past research [10, 16, 27]. For example, Burt [10] provides ample evidence that betweenness centrality is an appropriate measure for structural holes. The betweenness centrality for an automaker a_i is defined as proportion of all possible geodesic paths between alters that pass through ego a_i. If $g_{kl}(a_i)$ are the number of geodesic paths between alters k and l that pass through a_i and g_{kl} is the total number of possible geodesic paths then betweenness centrality for automaker a_i is given by: $C_b(a_i) = \frac{g_{kl}(a_i)}{g_{kl}}$. To facilitate comparisons across automakers within a system and across the 12 systems, we adjusted the betweenness centrality measure for network size. The normalized score is given by: $C'_b(a_i) = \frac{C_b(a_i)}{((g-1)(g-2))/2}$, where g is the number of nodes in the network.

As noted before, network density and structural holes are theoretically and empirically distinct concepts. For example, consider an automaker with 10 suppliers for a system. Figure 3 visually depicts the buyer-supplier network for combinations of high and low values of network density and structural holes. For the low network density and low structural hole condition in Fig. 3, the automaker has direct connections with five suppliers (S2, S5, S6, S9, and S10). Of these, only supplier pairs (S5, S2) and (S5, S10) are connected to each other out of a total of 10 possible pairs of direct connections. The normalized network density for this configuration is 20.00%. To construct betweenness centrality, we examine the proportion of geodesic paths between pairs of *all* 10 suppliers (S1–S10) that pass through the automaker. The normalized betweenness centrality measure for this configuration is 7.78%. The visual plots of different combinations of network density and structural holes illustrate that these are distinct constructs. Thus, an automaker could have structural holes in its *extended supplier network* and dense ties in its *local supplier network* at the same time.

Strength of Design Interface Previous research in systems and product development has operationalized product architecture in terms of the relationships between the constituent systems using the Design Structure Matrix (DSM) [71]. The DSM is used to understand complex product development processes by decomposing the product into systems and examining the relationships between systems. Such decomposition has been recognized to be important to managing system complexity [9]. Pimmler and Eppinger [53] examined the functional requirements of products in terms of exchanges of energy, material, and signals between elements. Consistent with past research [53, 69], we sought to identify five types of dependencies for vehicle systems; information, structure, spatial, energy, and material. Spatial dependency refers to the level of physical adjacency required for alignment, orientation, serviceability, assembly, or weight. Structural dependency refers to the existence of a functional requirement for transferring design loads, forces, or containment. Energy dependency considers a functional requirement related to transferring heat energy, vibration energy, electrical energy, or noise. Material dependency captures functional requirement related to transferring air, oil, fuel, or water. Information dependency addresses the functional requirement related to transferring signals or controls.

We interviewed 18 industry experts (product and design engineers at automobile and supplier firms) to assess the criticality of each type of dependency using a five-point scale anchored between −2 and +2 (see the Web Appendix for details on the scale and questionnaire items). The scale captures not only the required and desired dependencies (positive scores) but also detrimental and undesired dependencies (negative scores). SDI is computed as the average score of five types of dependencies across respondents. Higher (lower) scores on functional dependencies refer to strong (weak) design interfaces. Note that this approach is generalizable to different empirical contexts and is identical to approaches used to operationalize functional dependencies between systems in building construction, semiconductors, automobiles and aerospace [9].

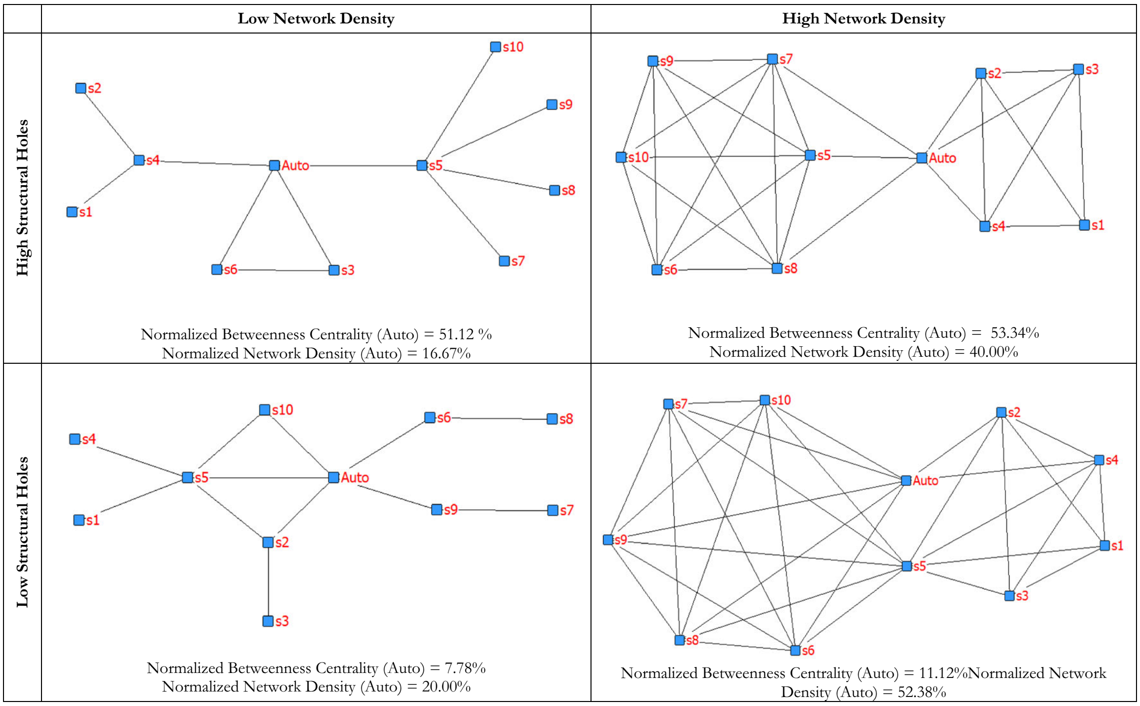


Fig. 3 Example of buyer-supplier network structure for network density and structural holes. Note: *Auto* automaker, *S* supplier

Controls We included *Market Performance* and *R&D Intensity* as controls since they could influence recall magnitude. While market performance was operationalized as the annual number of vehicles sold by the manufacturer, R&D intensity was operationalized as the manufacturer's annual R&D expenses scaled by annual revenues. There is also evidence to suggest that automakers offering considerable product variety are more likely to experience lower quality [25, 57]. We included *Product Line Breadth*, operationalized as the number of models offered by a manufacturer in a given year, as a proxy for product variety. The variables in the study and their operational measures are summarized in Table 1.

10 Model Specification

Buyer-Supplier Network Structure Characteristics ("*t*−1") ➔ Future Quality (*t*) First, we test the impact of buyer-supplier network structure characteristics on subsequent product quality using the following specification:

Model 1:

$$\begin{aligned} QUAL_{ij}^{2011} &= \alpha_0 + \alpha_1 DEN_{ij}^{2005-2010} + \alpha_2 HOLES_{ij}^{2005-2010} \\ &+ \alpha_3 SDI_{ij} + \alpha_4 DEN_{ij}^{2005-2010} \times SDI_{ij} \\ &+ \alpha_5 HOLES_{ij}^{2005-2010} \times SDI_{ij} \\ &+ \alpha_6 MPERF_i + \alpha_7 PBREADTH_i \\ &+ \alpha_8 RDINTEN_i + \lambda_i + \varepsilon_{ij} \end{aligned}$$

where i = firm, j = system, α are the response coefficients, λ is firm specific normally distributed random error component to control for firm heterogeneity, and ε is the random error component. *QUAL* refers to the quality of the firm's system, *DEN*, *HOLES*, and *SDI* refer to density, structural holes, and strength of design interface, respectively, and *MPERF*, *PBREADTH*, and *RDINTEN* are market performance, product line breadth, and R&D intensity, respectively.

11 Buyer-Supplier Network Structure Characteristics ("*t*−1") ➔ Future Recall Magnitude ("*t*+1")

Next, we test the impact of buyer-supplier network characteristics on future recall magnitude using the following specification:

Model 2:

$$\begin{aligned} RECMAG_{ij}^{2012} &= \beta_0 + \beta_1 DEN_{ij}^{2005-2010} + \beta_2 HOLES_{ij}^{2005-2010} \\ &+ \beta_3 SDI_{ij} + \beta_4 DEN_{ij}^{2005-2010} \times SDI_{ij} \\ &+ \beta_5 HOLES_{ij}^{2005-2010} \times SDI_{ij} \\ &+ \beta_6 RELIABL_{ij}^{2011} + \beta_7 PBREADTH_i \\ &+ \beta_8 RDINTEN_i + \mu_i + \upsilon_{ij} \end{aligned}$$

where β are the response coefficients, μ is firm specific normally distributed random error component to control for firm heterogeneity, and ν is the random error component. Other terms were as defined before.

There are a few econometric issues pertaining to the error structure in models 1 and 2 that need to be accounted for. *First*, in our model, network characteristics vary across automakers and systems, whereas strength of design interface varies only across systems. This data structure can lead to clustering of observations within a group. We account for

Table 1 Variable operationalization and data sources

Measure	Variable name	Data period	Operationalization	Data sources
Product quality	$RELIABL^{2011}$	2011	Product defects of a system in 2011 for an automaker on a scale of 1 to 5, where higher number corresponds to higher quality	Consumer reports
Product recall magnitude	$RECMAG^{2012}$	2012	Number of units recalled in 2012 by a manufacturer for defects related to a system adjusted for the sales of the automaker	*NHTSA*
Network density	$DEN^{2005–2010}$	2005–2010	Ratio of the number of ties between the buyer's suppliers to the maximum possible ties	Expert interviews
Structural holes	$HOLES^{2005–2010}$	2005–2010	Betweenness centrality of the buyer in the supplier network. Number of suppliers for a buyer—redundancy	ELM Analytics
Strength of design interface	*SDI*	2005–2010	Average score on a 5-point scale across 5 types of functional dependencies between systems	
Market performance	*MPERF*	2010	Number of units sold by the firm in a year	Ward's Automotive Yearbook
Product line breadth	*PBREADTH*	2010	Number of make models offered by the firm in the year	Ward's Automotive Yearbook
R&D intensity	*RDINNTEN*	2010	Annual research and development expenditures as a percentage of annual revenues	COMPUSTAT

spatial correlation between ε (ν) for different systems across automakers.

Second, there is likely to be heteroskedasticity in the panel errors of Models 1 and 2. We tested for the presence of heteroskedasticity in the panel errors and find that the modified Wald's chi-square statistic for group wise heteroskedasticity [33] for quality and recall magnitude is 202.59 ($d.f. = 13$, $p < .01$) and 14,387.87 ($d.f. = 13$, $p < .01$), respectively. These suggest the presence of panel-level heteroskedasticity in the errors of models 1 and 2.

Following procedures advocated in past research [35, 44], we use the iterative generalized least squares (IGLS) estimator and specify a spatially correlated and heteroskedastic error structure.

12 Results

Table 2 reports the descriptive statistics and correlations between the variables. The mean annual market performance (i.e., sales in units) for automakers is 481,126. We also find considerable variation in product line breadth across automakers. The mean product line breadth for automakers in a given year is 27 models and the standard deviation is 25. However, R&D expenditures vary less across automakers in our data. The mean R&D expenditure is 3.88% of annual revenues and the standard deviation is 1.27.

In Table 3, we report the summary statistics for the 12 vehicle systems. The summary statistics from the interview reveal that while engine and electrical systems have the strongest design interfaces (integral), climate and body hardware systems have the weakest design interfaces (modular). Importantly, the expert interviews reveal that the strength of the design interface *does not* vary either across models or over time. The experts had, on average, work experience of 10 years in automotive design. As noted before, we interviewed experts from both automobile manufacturers and original equipment suppliers. Table 3 also indicates significant variation in network density and structural holes scores across automaker systems. Importantly, network density and betweenness

Table 2 Correlation matrix and summary statistics

Variable	Mean	S.D.	1	2	3	4	5	6	7
1. Product quality	4.36	.74							
2. Product recall magnitude	1.72	6.44	−.13						
3. Strength of design interface (SDI)	17.00	11.76	.33	−.01					
4. Network density (%)	6.87	9.85	−.06	.02	.00				
5. Structural holes (%)	2.65	6.63	.03	−.05	−.13	−.17			
6. Market performance (in millions of units)	.48	.28	.03	.13	.00	.29	−.13		
7. Product line breadth	26.92	25.37	−.03	.03	.00	.53	−.13	.39	
8. R&D intensity (% of sales)	3.74	1.27	.01	.07	.00	.31	−.03	.26	.32

Table 3 Summary statistics of buyer-supplier network structure characteristics in vehicle systems

	Number of nodes	Number of ties	SDI	Network density Mean	Network density S.D.	Structural holes Mean	Structural holes S.D.
Body hardware	154	968	9.2	3.72	2.60	6.82	8.76
Brakes	192	1113	10.6	1.75	1.97	7.07	10.21
Climate system	71	208	10.2	6.33	9.55	5.82	8.42
Drive system	99	407	21.6	.77	1.31	6.85	10.56
Electrical	507	3656	23.0	2.70	2.88	7.05	10.37
Engine cooling	102	471	14.0	2.75	2.22	6.35	8.65
Engine major	218	1306	50.8	.82	.80	6.90	10.10
Exhaust	122	602	5.0	6.76	17.50	7.03	9.36
Fuel system	92	341	8.4	.45	1.27	7.09	11.12
Power equipment	170	1145	10.4	1.31	1.09	7.10	9.22
Suspension	222	1509	22.4	3.54	7.23	6.82	8.99
Transmission major	187	941	18.4	.86	1.28	7.54	12.05

centrality scores also vary significantly across automakers within a given system. Therefore, the supplier network structure characteristics of a given vehicle system for automakers are quite different.

12.1 Model Fit

We test the impact of buyer-supplier network structure characteristics on quality and recall magnitude in a stepwise manner. Tables 4 and 5 present the results. The model fit statistics of the quality model (Table 4) suggest that the full model is the best fitting model as the chi-square difference between the full model (column 4-3) and next best fitting model (column 4-2) is statistically significant ($\chi^2_{\mathrm{Diff}} = 6.84$ (2), $p < .05$). Additionally, the model comparisons ($\chi^2_{\mathrm{Diff}} = 15.13$ (3), $p < .01$) reveal that adding supplier network structure characteristics (column 4-2) to control variables (column 4-1) improves the model fit significantly. Similarly, the model fit statistics of the recall magnitude model (Table 5) suggest that full model ("direct + indirect effect," column 5-4) has a significantly better fit ($\chi^2_{\mathrm{Diff}} = 62.88$ (1), $p < .01$) than the next best fitting model ("direct effect only," column 5-3). Also, the full model ("direct + indirect effect," column 5-4) has a significantly better fit ($\chi^2_{\mathrm{Diff}} = 124.24$ (5), $p < .01$) than the indirect effect only model (column 5-2). Additionally, both "direct effect only" (column 5-3) and "indirect effect only" (column 5-2) are better fitting ($\chi^2_{\mathrm{Diff}} = 95.74$ (1), $p < .01$, $\chi^2_{\mathrm{Diff}} = 114.53$ (5), $p < .01$) than "controls only" model (column 5-1).

12.2 Hypotheses Testing

We interpret the results of the full model to test the hypotheses. H1 states that greater the density is in the buyer's supplier network, lower is the future recall magnitude. As evidenced in Table 5, the relationship between network density and future recall magnitude is negative (−.0240, $p < .05$). H1 is supported. Consistent with this result, Table 4 suggests that the relationship between network density and future quality is positive (.0328, $p < .05$). Recall that we proposed a non-directional hypothesis for the relationship between structural holes in the buyer's supplier network and future recall magnitude. The relationship between structural holes and future recall magnitude is positive and significant (.0404; $p > .01$). However, structural holes are negatively related to future product quality (−.0232, $p < .05$). Thus, network density and structural holes have differential relationship with future product quality and future recall outcomes. Taken together, our findings imply that dense supplier networks benefit buyers to a greater extent compared to supplier networks with structural holes.

As regards the moderator results, we find that the coefficient for the direct impact of SDI on quality is positive (.0102, $p < .01$). That is, integral systems have higher quality compared to modular systems. This is consistent with research which points out that integral systems are critical for overall product performance [74].

H3a states that SDI will weaken the positive relationship between network density and future product quality. Consistent with H3a, the coefficient for the interaction of network density and SDI on quality is negative (−.0018, $p < .10$). This suggests that dense supplier networks are associated with enhanced product development outcomes of modular systems to a greater extent compared to integral systems.

Consistent with H3b, the coefficient for the interaction of structural holes and SDI on quality is positive (.0027, $p < .05$). The implication is that buyers whose supplier networks are characterized by the presence of structural holes experience

Table 4 Results: the impact of buyer-supplier network structure on product quality

	Dependent variable—product quality in 2011 ($RELIABLE^{2011}_{ij}$)	Controls only 4–1 Coeff. (S.E.)	Controls + main effects 4–2 Coeff. (S.E.)	Full model 4–3 Coeff. (S.E.)
Hypothesized variables (2005–2010)	Network density ($\boldsymbol{H_{3a}}$)		.0054*	.0328**
			(.0031)	(.0155)
	Structural holes ($\boldsymbol{H_{3b}}$)		−.0187*	−.0232**
			(.0109)	(.0108)
	Strength of design interface (SDI)		.0099***	.0102***
			(.0030)	(.0030)
	Density × SDI ($\boldsymbol{H_{4a}}$)			−.0018*
				(.0010)
	Structural holes × SDI ($\boldsymbol{H_{4b}}$)			.0027**
				(.0013)
Controls (2010)	Market performance	.2921***	.2124**	.2084**
		(.1069)	(.1092)	(.1058)
	Product line breadth	−.0028	.0037	.0044
		(.0018)	(.0043)	(.0042)
	R&D intensity	.0777**	.0904**	.0924***
		(.0369)	(.0359)	(.0348)
	Automaker random effects	Included	Included	Included
	Intercept	4.2342***	3.9859***	4.0172***
		(.1622)	(.1701)	(.1744)
	Chi-square (parameters)	13.80 (3)	28.93 (6)	35.77 (8)

Note: S.E. in parentheses

*p < .10; **p < .05; ***p < .01

higher quality for integral systems than for modular systems. Collectively, the evidence supports the argument that the relationship between buyer-supplier network structure and product quality is contingent on the strength of the design interface.

We follow the guidelines proposed by Preacher et al. [55] to test H4a and H4b, the mediation hypotheses. The relationship between supplier network characteristics and recall magnitude is mediated by quality and the strength of this mediation is dependent on SDI. The estimate of the conditional indirect effect of network density and structural holes on recall magnitude is given by $\beta_6(\alpha_1 + \alpha_4 \times SDI)$ and $\beta_6(\alpha_2 + \alpha_5 \times SDI)$, respectively. Because the conditional indirect effects are sensitive to the parametric assumptions, we generate 1000 bootstrap standard errors and 1.96 standard deviation asymptotic interval of the coefficients. Figure 4 depicts the results graphically. The range of SDI scores in which the conditional indirect effect is significant indicates mediation by quality. We find that the relationship between network density and recall magnitude is negative for SDI scores of less than 8.5 (i.e., exhaust and fuel system) and positive for SDI scores above 22 (i.e., suspension, electrical, and engine major). In contrast, the relationship between structural holes and recall magnitude is positive for SDI scores less than 8.5 (i.e., exhaust and fuel system) and negative for SDI scores above 21.5 (i.e., drive system, suspension, electrical, and engine major). For intermediate SDI scores in the range of 8.5–22 (8.5–21.5), the impact of network density (structural holes) on recall magnitude is not significant. Collectively, the analyses suggest that future quality mediates the relationship between network density, structural holes, and future recall magnitude. H4a and H4b are thus supported.

12.3 Control Variables

As regards the results for control variables, we find that market performance is positively associated with product quality (.2084, p < .05). We also find that product line breadth is positively associated with recall magnitude (.0216, p < .01). As expected, we find that R&D Intensity is positively related to product quality (−.0924, p < .01) and negatively related to recall magnitude (−.3113, p < .10).

13 Discussion

Our study was motivated by two key questions: How do supplier network structure characteristics of buyers influence

Table 5 Results: the impact of buyer-supplier network structure on product recall outcome

	Dependent variable—product recall magnitude in 2012 (*RECMAG*$^{2012}_{ij}$)	Controls 5–1 Coeff. (S.E.)	Controls + quality 5–2 Coeff. (S.E.)	Direct effects 5–3 Coeff. (S.E.)	Full model 5–4 Coeff. (S.E.)
Hypothesized variables (2005–2010)	Network density (***H*₁**)			**−.0221****	**−.0240****
				(.0106)	(.0145)
	Structural holes (***H*₂**)			**.0408*****	**.0404*****
				(.0144)	(.0171)
	Strength of design interface (SDI)			−.0108	−.0235
				(.0176)	(.0149)
	Density × SDI			**.0073***	**.0086****
				(.0038)	(.0035)
	Structural holes × SDI			**−.0038*****	**−.0035*****
				(.0014)	(.0013)
	Quality in 2011 (***H*₃ₐ,*H*₃ᵦ**)		**−.7210****		**−.5195*****
			(.2722)		(.2063)
Controls (2010)	Product line breadth	**.0001*****	.0064	**.0229*****	**.0216*****
		(.0000)	(.0055)	(.0058)	(.0041)
	R&D intensity	**−.2577***	**−.3041****	**−.2016***	**−.3113***
		(.1497)	(.1640)	(.1431)	(.1439)
	Automaker random effects	Included	Included	Included	Included
	Intercept	**.2996****	**2.4573*****	.4555	**3.1049*****
		(.1578)	(.4251)	(.4027)	(.5362)
	Chi-square (parameters)	40.02 (2)	135.76 (3)	154.55 (7)	217.43 (8)

Note: S.E. in parentheses

**p* < .10; ***p* < .05; ****p* < .01

future product quality and future recall magnitude? Does the normative buyer-supplier network structure vary depending on product characteristics? To address these questions, we develop and test a contingency model delineating how product architecture poses boundary conditions, systematically affecting the impact of density and structural holes in the buyer-supplier network on product performance. We examine internal (product quality) as well as external (recall magnitude) product performance outcomes.

13.1 Theoretical Contributions

Our study makes important theoretical contributions by investigating the supplier network-related antecedents of product recalls. Following extant literature that presents two contrasting views on how network structure creates economic benefits, we test the impact of network density and structural holes in the buyer-supplier network on product quality and recalls. Our findings suggest that buyers with dense supplier networks are more likely to improve future quality and lower the magnitude of future recalls. This finding is consistent with previous research which suggests that dense networks facilitate the easy dissemination and exchange of information [21, 47] and greater supplier compliance because of collective monitoring and greater trust [15, 48]. Thus, ceteris paribus, buyers with dense supplier networks are likely to experience superior product development outcomes.

In contrast, we find that structural holes in buyer-supplier networks are likely to decrease product quality and aggravate the magnitude of recalls. This finding is consistent with research that finds that structural holes have an adverse impact on innovation output [1], dampen market performance [66], and are not significantly related to innovation involvement [51] but incongruent with research that finds structural holes to be positively related to innovation performance [29, 36]. The implication is that the information control advantages that structural holes bestow on buyers are detrimental for product development in an outsourced environment. This is perhaps because control of information by buyers may stifle the autonomy and creativity of suppliers especially when they are entrusted with the task of delivering a complete "turnkey" system [4, 11].

Importantly, our study finds that product architecture exerts significant contingencies on the relationship between buyer-supplier network characteristics and quality. Specifically, we find that weak design interfaces enhance the benefits of dense buyer-supplier networks. Previous research examining the interplay between product development team interactions and

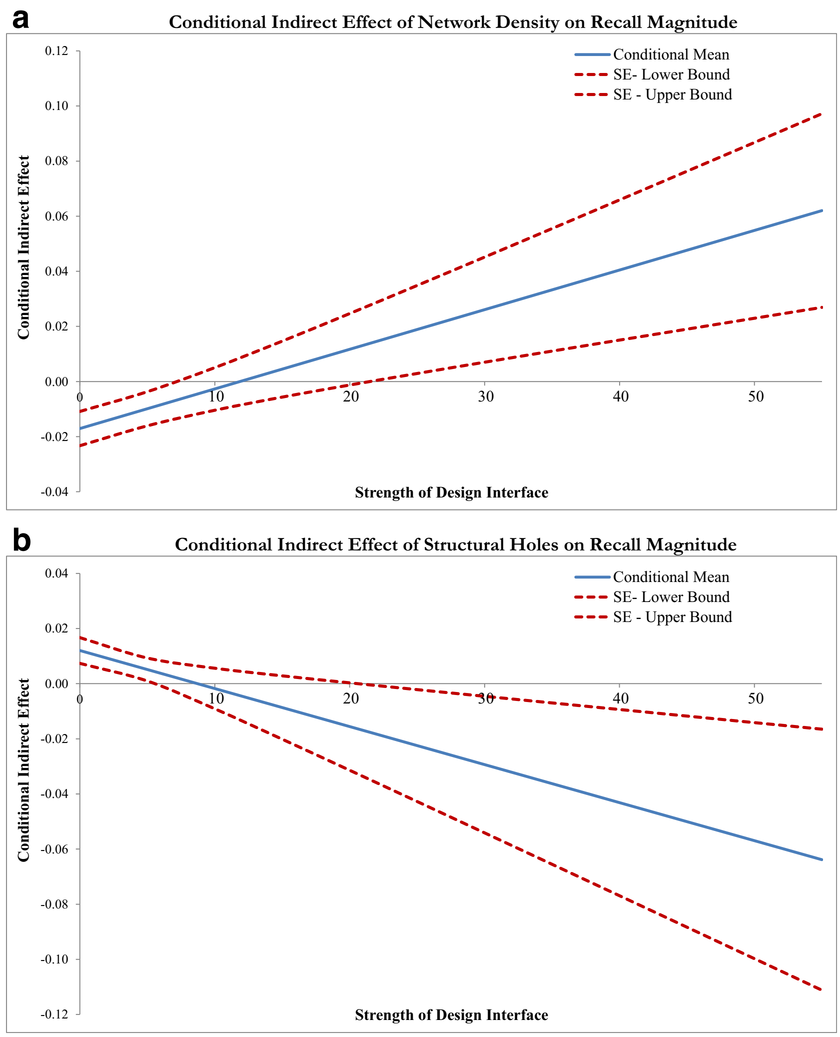


Fig. 4 Conditional indirect effects of buyer-supplier network characteristics. **a** Conditional indirect effect of network density on recall magnitude. **b** Conditional indirect effect of structural holes on recall magnitude. Note: *X axis*, SDI scores; *Y-axis*, conditional indirect effect on recall magnitude; *SE*, standard errors

design interfaces finds that teams that matched communication patterns with communication requirements between interfaces experienced better outcomes [58, 69]. Likewise, we find that strong design interfaces amplify the information control benefits of structural holes in buyer-supplier networks. That is, the development of strong design interfaces requires centralized control. Our findings cast doubt on the notion that advances in communication technologies allow complex activities to be coordinated through decentralized structures. It might be conjectured that a distributed design environment might aggravate errors and degrade the performance of strong design interfaces or integral systems. More generally, our study shows that the extent to which buyer-supplier network structures are matched with product architecture is a significant indicator of subsequent quality and subsequent recall magnitude experienced by buyers. Our findings should encourage future researchers to further examine the interplay between supplier network characteristics and product architecture. It might be particularly worthwhile to examine the effects of single sourcing versus multisourcing strategies on quality and whether these effects vary based on the product architecture.

13.2 Managerial Implications

The findings of this study offer numerous valuable insights for managerial practice. In recent years, there has been increased emphasis on improving supply chain performance. The emphasis has been using concepts such as modularization, flexible manufacturing, and lean versus agile manufacturing to boost performance. Despite such advances, the poor performance of supply chains, as evidenced in growing number of product recalls in the marketplace, continues to frustrate and disenchant managers. An article in the *Harvard Business Review* poses a managerially relevant question as to why have new ideas and technologies not led to improved performance [24]? Our study offers valuable insights in this regard and shows that mismatch between structure of buyer-supplier networks and product architecture aggravates crises such as product recalls.

We find that network density and structural holes have different effects on recall outcomes. Dense supplier networks are associated with superior outcomes such as better quality and lower magnitude of recalls whereas supplier networks with structural holes are associated with greater recall magnitude. The implication for buyers is that they ought to encourage its suppliers to forge ties with each other and facilitate exchange and sharing of information. For example, a supplier facing a quality problem with the root cause not known can benefit from the exchange of solutions from the supplier network. Although maintaining a dense supplier network is costly, the information exchange benefits are significant especially when buyers farm out important processes such as product design and manufacturing to suppliers. In contrast, structural holes in a supplier network increase the magnitude of recalls experienced by buyers.

Importantly, our findings caution managers to refrain from viewing dense supplier networks as beneficial and supplier networks with structural holes as detrimental for quality. Our findings, instead, point to the need to evaluate the normative supplier network structure in conjunction with the architecture of the product. The findings suggest that dense networks are beneficial for weak design interfaces (modular systems) than for strong design interfaces (integral systems). As noted before, when buyers outsource design and manufacturing of modular systems, they cede control to supplier networks. Thick ties between suppliers facilitate coordination and information exchange and ensure that buyers are able to meet varying downstream demand without compromising the quality of weak design interfaces. In contrast, structural holes in supplier networks are more beneficial for strong design interfaces than for weak design interfaces. Buyers need to be located centrally in supplier networks and mediate information flows between suppliers to ensure that the quality of integral systems does not degrade.

We performed a univariate transfer function analysis to better understand the economic value of matching buyer-supplier network structure and product architecture [35]. We computed the direct impact of a one standard deviation (S.D.) increase in network density and structural holes in the supplier network on quality and recall magnitude. We evaluate this relationship for strong and weak design interfaces. The high and low levels of SDI are set at the +1 S.D. and −1 S.D. from mean values of the variable, respectively. To compute the dollar impact of decrease in recall frequency because of matching, we turn to previous research that has assessed the shareholder value destroyed by product recalls. Barber and Darrough [6] note that on average a product recall in the automobile industry eroded shareholder wealth by $72.99 million. This amounts to $125.62 million in 2011 dollar terms.

Our post hoc analyses reveal that a 1 S.D. increase in network density increases economic value by $29.85 million at low levels of SDI and decreases economic value by $106.41 million at high values of SDI. The total economic value was destroyed because of a mismatch between supplier network density and product architecture is $136.26 million. While dense networks are costly to maintain because of higher number of ties and greater information flow, our findings show that the economic value of dense ties in supplier networks is quite substantial. Similarly, a 1 S.D. increase in structural holes increases economic value by $219.31 million at high levels of SDI and diminishes economic value by $14.27 million at low levels of SDI. The total economic value was destroyed because of a mismatch between structural holes and product architecture is $233.59 million. Cumulatively, mismatches between supplier network structure characteristics and product architecture destroy the buyer's shareholder wealth to the tune of $369.85 million on an annual basis. Table 6 summarizes the economic implications of our findings.

13.3 Limitations

We would like to acknowledge some limitations that recommend caution in interpreting our results. First, given that the empirical findings are based on a single industry (i.e.,

Table 6 Post hoc analyses: annual impact of matching buyer-supplier network structure and product architecture

	Impact on	Weak design interface (modular system)	Strong design interface (integral system)	Net impact of matching
1 S.D. increase in "Network density"		Match	Mismatch	
	Quality (points)	.21	−.02	.23
	Recall (frequency)	−.23	.82	−1.05
	Economic value ($m)[a]	$29.85	−$106.41	$136.26
1 S.D. increase in "Structural holes"		Mismatch	Match	
	Quality (points)	−.04	.82	.86
	Recall (frequency)	.11	−1.69	−1.80
	Economic value ($m)	−$14.27	$219.31	$233.59

[a] The figure in the cells represents the shareholder value created or destroyed because of the impact of an increase in network structural characteristics on number of product recalls. Positive values indicate shareholder value added and negative values indicate shareholder value destroyed

automobile), caution is warranted in generalizing the findings to various empirical settings. Nonetheless, we believe that the findings of this study should generalize to other complex product development settings such as software development, computers, and aircraft manufacturing. Similarly, the findings of this study need to be interpreted within the context of the US automobile industry. It is not clear whether the espoused benefits of density and structural holes transcend different cultures. A recent effort appears to suggest that the control advantages of structural holes may not manifest in collectivistic cultures and in organizations with high levels of commitment [80]. Comparing the consequences of buyer-supplier network structure in Western and Eastern economies represents a promising area of future inquiry.

In sum, our study shows that quality outcomes such as quality and product recalls could be managed by limiting the extent of misalignment between buyer-supplier network structure and product architecture. Our study cautions managers to carefully assess the sourcing strategies for product systems as it shapes the supplier network structure and impacts product development outcomes.

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