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WHEN THE MIRROR GETS MISTED UP: MODULARITY AND TECHNOLOGICAL CHANGE

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This study investigates how component technological change affects the relationship between product modularity and organizational modularity (the across-firm mirroring hypothesis). Studying the air conditioning industry, we show that the across-firm mirroring hypothesis does not hold for technologically dynamic components and the associated supply relationships. In this case, the mirror gets "misted up" with buyers and suppliers having recourse to information sharing even in the presence of highly modular components. Our study contributes to the debate on the organizational implications of modularity and its ramifications for the theory of the firm.
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INTRODUCTION

A stream of the modularity literature has dealt with the across-firm mirroring hypothesis; i.e., if and to what extent products and organizations share similar architectural properties and, more specifically, if and to what extent the degree of modularity of sourced components (hereafter component modularity) is inversely related to the "thickness" of buyer–supplier relationships (organizational modularity).

In a recent comprehensive review of the empirical studies concerning the across-firm mirroring hypothesis, Colfer and Baldwin (2010) found that the hypothesis holds in 74% of the analyzed studies. This large body of evidence supports the stream of modularity theory grounded on the ideas pioneered by Baldwin and Clark (1997), Langlois (2002), Fine (1998), Schilling (2000), and Sanchez and Mahoney (1996) that "the [loosely coupled] standardized component interfaces in a modular product architecture provide a form of *embedded coordination* that greatly reduces the need for overt exercise of managerial authority to achieve coordination of development processes, thereby making possible the concurrent and autonomous development of components by *loosely coupled organization structures*" (Sanchez and Mahoney, 1996, p. 64; emphasis in original). Modularity in design works as a functional equivalent of high-powered interfirm integration mechanisms leading to decoupled interorganizational networks (Baldwin and Clark, 2000; Fine, 1998; Sanchez and Mahoney, 1996; Tiwana, 2008). Along the same vein, Fine, Golany, and Naseraldin (2005) maintained that integral products require supply relations that are themselves fairly integral, while modular products "benefit from the speed, flexibility and cost-reduction opportunities offered by modular supply chains" (p. 393).

As Cabigiosu and Camuffo (2012), Galvin and Morkel (2001), and Sturgeon (2002) argued, the "embedded coordination" that modular product

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architectures provide involves at least three aspects of a given component supply relationship: new product development, contract/price negotiation, and logistics. More specifically, Cabigiosu and Camuffo (2012) provided empirical support to the mirroring hypothesis, showing that, under the condition of product architecture stability, component modularity is inversely related to the intensity of buyer–supplier information sharing in the management of the three abovementioned business processes.

This evidence notwithstanding, Colfer (2007) recently suggested that conventional views on mirroring tend to be too simplistic and general. Several empirical studies spanning a range of different industries (Argyres, 1999; Brusoni and Prencipe, 2001, 2011; Hoetker, 2006; MacDuffie, 2006, 2013; Staudenmayer, Tripsas, and Tucci, 2005; Zirpoli and Becker, 2011) have indicated the need for a more nuanced theory of mirroring. Along this vein, Baldwin (2008) shed additional light on the relationship between product modularity and organizational architectures. Disowning any determinism, she maintained that "... the modular structure of the tasks network at a particular point in time results from the interplay of firms' strategies, their knowledge and the physical constraints of specific technologies" (p. 180).

All these contributions call for a more contingent view of the mirroring hypothesis, underlying that the conditions under which it holds are as important, if not more important, than whether it holds. One aspect that most empirical studies do not address is the coevolution of product and industry architectures. More specifically, they have either marginally addressed it while aiming at other research questions, such as technology standards and the evolution of the vertical contracting structure of industries (Campagnolo and Camuffo, 2010; Chesbrough and Prencipe, 2008; Fixson and Park, 2008; Garud and Kumaraswamy, 1993; Gomes and Joglekar, 2008; Jacobs, Vickery, and Droge, 2007; Tiwana, 2008), or offered exploratory contributions (based on qualitative and/or anecdotal evidence), focusing on theory building and the development of testable propositions (Brusoni, 2005; Brusoni and Prencipe, 2001; Brusoni, Prencipe, and Pavitt, 2001; Cabigiosu, Zirpoli, and Camuffo, 2013; Takeishi, 2002).

This study aims at filling this gap. Using a dataset of 100 component and supplier relationships in the air conditioning industry, we investigate if, and to what extent, the mirroring hypothesis is contingent on technological change. More specifically, we directly and explicitly investigate how component technological change affects the strength and significance of the relationships between the degree of the coupling of product components and of organizations (the mirroring hypothesis). Our results show that the across-firm mirroring hypothesis does not hold for technologically dynamic components. The mirror gets "misted up" for components characterized by high technological change with buyers and suppliers engaging in "thick" relationships even in the presence of highly modular components. Component modularity reduces the need for interorganizational coordination only if components are technologically stable.

THEORY AND HYPOTHESES

Research constructs

Before developing the hypotheses of the study, we need to define the three research constructs of component modularity, organizational modularity, and component technological change.

Component modularity is the extent to which a component performs a few functions and is connected to other components by open standard interfaces. Ideally, a perfectly modular product is made of components that perform one or few functions (1:1 component/function mapping) (Ulrich, 1995). When a component fully implements those few functions, it should be easy to isolate its development from the other system components. The higher the number of functions implemented by a component, however, the higher the probability that this component is not fully functionally isolated (i.e., it shares functions and has interdependencies with other components[1]). Furthermore, perfectly modular components interact via codified interfaces (Ulrich, 1995). If these interfaces, i.e., visible communication protocols among components, are widely diffused within a given industry, these components have open standard interfaces. However, if the protocols suit a specific

[1] The number of functions implemented by each component approximates the number of cross-component (visible and hidden) interdependencies and can be considered an inverse proxy of the component's functional isolability (Ulrich, 1995).

firm's requirements, they are closed and nonstandard (Fine *et al.*, 2005). Only open standard interfaces allow the full separation, isolation, and recombination of product components as modules (Fine *et al.*, 2005; Fujimoto, 1999; Salvador, 2007; Ulrich, 1995).[2]

Organizational modularity is related to the complexity, intensity, and frequency of information sharing between two organizations (David and Han, 2004; Parmigiani and Rivera-Santos, 2011). Following previous research (Cabigiosu and Camuffo, 2012; Camuffo, Furlan, and Rettore, 2007; Furlan, Romano, and Camuffo, 2006), this study captures the degree of coupling between organizations (organizational modularity) by analyzing the extent of the buyer–supplier information sharing as regards three key business processes: new product development, contract/price negotiation, and logistics. The degree of buyer–supplier information sharing is therefore used as a proxy for the degree of coupling between organizations (inverse proxy for organizational modularity).

To define component technological change, we refer to Henderson and Clark's (1990) typology and, more specifically, to their definitions of *incremental innovation* and *modular innovation*—the focus of this study. Following Brusoni *et al.*'s (2001) distinction between even and uneven changes of component technologies, we focus on incremental and modular innovations and define component technological change as the rate of change of the product and process technologies underlying a given component within an existing product architecture. This definition of technological change properly fits our research setting (the air conditioning industry), which is characterized by product architecture stability and technological changes confined within components' boundaries.

Hypotheses

Component technological change and organizational modularity (information sharing)

The intent of this study is to nurture a contingent theory of the mirroring hypothesis by studying the combined effect of component modularity and technological change on organizational modularity (buyer–supplier information sharing). Therefore, we must first assess the relationship between component technological change and buyer–supplier information sharing. Indeed, even in the situation of product architecture stability, component technological change should affect the nature and content of supply transactions' increasing uncertainty, information asymmetry, and/or asset specificity (Williamson, 1985), and require more complex interfirm coordination devices (and, hence, more extensive information sharing). For example, Bensaou and Anderson (1999) found that the rate of component technological change is positively related to buyers' idiosyncratic investment in auto supplier relations. They argued that technological change leads the buyer to post idiosyncratic investments as a sign of commitment that, over time, lead to collaborative supplier relations characterized by higher information transparency.

Component technological change increases the performance uncertainty of the sourced component (Bensaou and Anderson, 1999; Parmigiani, 2007). Moreover, it makes it more difficult for the buyer to develop stable measures of the supplier's performance and to monitor the supplier's effort to reduce costs and keep abreast of the technological developments (Camuffo *et al.*, 2007). Buyer–supplier information sharing reduces the information asymmetries between buyer and supplier, thus enhancing their ability to monitor each other. For example, frequent information exchanges allow the buyer to understand the supplier's cost structure and detect if it is shirking

[2] Referring to Baldwin and Clark's (2000) seminal work, MacDuffie (2013) distinguished between two concepts of modularity: modularity-as-property and modularity-as-process. "Modularity is a design property of the architecture of products, (...); modularization is a process that affects those designs while also shaping firm boundaries and industry landscapes; (...) modularity-as-property and modularization-as-process are deeply intertwined; while modularization processes are ubiquitous and perpetual as engineers and managers seek to understand interdependencies across the boundaries of product and organizational architecture, the extent to which modularity-as-property is achieved is subject to contingencies and must be assessed empirically." This distinction is important for this study because it could be argued that high levels of component technological change simply make products less modular, through an increase in the components' hidden interdependencies. Moreover, under general assumptions, intended modularization and actual modularization do not necessarily match with hidden interdependencies lying side by side with visible ones. However, our research setting is characterized by a specific set of conditions (industry maturity, the absence of technological discontinuities, a stable product architecture, and modular or incremental technological changes à la Henderson and Clark (1990) generating innovations that are confined to the component level), under which intended and actual levels of modularity do not differ significantly, and engineers in the industry have been able to make visible most of the cross-component interdependencies.

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efforts to reduce the costs of the sourced component. Furthermore, tapping into the capabilities of the supplier by continuously exchanging information about the product or the process technology allows the buyer to develop component-specific knowledge that facilitates the evaluation of the supplier's offers.

From a contingency theory perspective, changes in component technologies increase coordination costs because they increase the information required to perform a task or, alternatively, decrease the information available to perform a task, making it obsolete (Galbraith, 1973). Consequently, as component technological change increases, buyers and suppliers need to share more information to achieve interorganizational coordination. Further, the necessity to access external sources of innovation and to act as system integrators of complex and technologically dynamic components implies that buyers must keep in-house substantial product and process component-specific knowledge, even about outsourced components. A buyer's knowledge base should be broader than that strictly needed to manage the internal design and production activities (Takeishi, 2001; Zirpoli and Becker, 2011), and one way to nurture this component-specific knowledge is to remain engaged in thick relationships with suppliers. Besides, fast-moving components often generate technological imbalances that call for component-specific knowledge. The unevenness in component technological advances requires that the buyer has some degree of knowledge overlap with its suppliers to "identify potential novelties in fast-moving technological fields, understand their implications for the others, and integrate changes in existing or new product architectures" (Brusoni and Prencipe, 2001, p. 613). High levels of information sharing with suppliers are therefore instrumental to keep in-house this component-specific knowledge base.

Finally, changes in component technologies may also affect the supplier relationships from the logistics and price/contract negotiation perspectives. Frequent changes in product component technologies render inventories obsolete, and changes in process component technologies may disrupt the component's deliveries. Component technological change usually impacts contractual agreements, calling for expensive and, at times, controversial price renegotiations and contract revisions. All in all, more component technological change asks for more interfirm information exchange. Thus, we posit the first hypothesis:

Hypothesis 1. Component technological change is positively related to buyer–supplier information sharing.

Component modularity, component technological change, and organizational modularity

Understanding if and to what extent the degree of buyer–supplier information sharing is contingent on the degrees of component modularity and technological change is key to gaining better insight into how the technological dynamics of the product components within a given product architecture shape interorganizational relations.

As observed by Lau and Yam (2005), studying a global consumer electronics manufacturer, if components are subject to frequent technological changes, intense buyer–supplier information sharing should remain necessary regardless of the degree of component modularity. Similarly, Agrawal (2009) showed that the rate of components' obsolescence moderates the relationship between sourcing and modularity, since obsolescence increases a component's importance for maintaining a technological edge regardless of the product's architecture. In the case of components characterized by high technological change, the firm would therefore either invest in in-house capacity or develop strong supplier relationships to tap into the suppliers' knowledge base.

Brusoni *et al.* (2001) pioneered the knowledge-based analysis of the interplay between component technological change and component modularity. Their case studies revealed that when the architecture of fast-changing components stabilizes, manufacturers outsource both design and production, but keep in-house component-specific knowledge for rapidly changing components whose dynamism generates the possibility for technological imbalances. The unevenness in the technological advances of the different fields requires "some degree of integration at the knowledge level to identify potential novelties in fast-moving technological fields, understand their implications for the others, and integrate changes in existing or new product architectures" (Brusoni *et al.*, 2001, p. 613). Thus, buyers acquire component-specific knowledge, key to maintaining the ability to act as system integrators, by developing collaborative

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relationships with suppliers. This allows buyers to absorb component-specific knowledge (Cohen and Levinthal, 1994) and keep up with technological changes. Zirpoli and Becker (2011) developed Brusoni *et al.*'s (2001) seminal work, arguing that component modularity does not substitute for high-powered interorganizational mechanisms as suggested by the mirroring hypothesis. They showed that modularity does not solve the problem of integrating components' technical performances in motor vehicle design. Defining standardized physical interfaces does not standardize the performance contribution of a component and does not reduce the interdependencies between component and vehicle performances. This is particularly true for complex and technologically dynamic components (such as electronics or car occupant safety systems), but also for more stable and modular components, like air conditioning systems (Cabigiosu *et al.*, 2013). To competently make performance-based trade-offs, assemblers need to keep in-house not only system-level knowledge but also component-specific knowledge. Thus, not only are radical and architectural innovations likely to question product architecture and generate new interdependencies, incremental and modular innovations may also indirectly affect the level of organizational modularity, although not via changes in the product architecture. In any case, technological change calls for a "cognitive overlap" between assemblers and suppliers, no matter how modular the sourced component is. Such cognitive overlap can be achieved by keeping in-house (at least to some extent) the design and production of key components or, alternatively, getting access to component-specific knowledge via collaborative, interactive relationships with suppliers. Similarly, we can argue that by increasing the potential to generate technical imbalances, component technological change shifts the emphasis of buyer–supplier relationships from coexploitation to coexploration (Parmigiani and Rivera-Santos, 2011), entailing more information sharing, regardless of the degree of component modularity.

Hints of a nuanced relationship between component modularity and organizational modularity in the case of intense component technological change also come from the "resource-based view meets organizational economics" perspective (Gibbons and Henderson, 2012; Wolter and Veloso, 2008). When component technological change is high, the uncertainty of transactions rises, as do information asymmetries and moral hazard potential, no matter what the level of component modularity is; consequently, the partners need to share information (and share the necessary level of reciprocal task and relational knowledge[3]) to build clear and credible relational contracts, so that the supplier relations keep working. In other words, component modularization does not neutralize the positive effect of the interaction between transaction costs and supplier's capabilities on information sharing in the presence of high component technological change (Wolter and Veloso, 2008).

Finally, the idea that the relationship between product and organizational modularity might be mediated by other variables also stems from the conceptualization of epistemic interdependence (Puranam, Raveendran, and Knudsen, 2012: p. 420). The underlying analytic separation between tasks' and agents' interdependence suggests that (1) interdependence between agents (buyer and supplier in our case) can be modified even when the interdependence between tasks is shaped by technological choices (i.e., when the task partitioning between buyer and supplier is largely determined by the product modularization efforts/choices of the buyer); (2) the structure of tasks (deriving from the product architectural choices) and the structure of organizations (the thickness of interorganizational relationships) may not resemble each other (i.e., nonmirroring, despite component modularization).[4] While component modularization reduces task interdependencies to the point where, in the case of perfectly modular components, the supplier's tasks are encapsulated within the boundaries of a module and no further information exchange (except for prices) is—in theory—necessary, it does not reduce epistemic interdependence in the presence of technological change. Indeed, rapid component technological change is likely to increase the difficulty for the buyer to predict the supplier's behaviors and therefore to increase the need to have predictive knowledge about

[3] Interestingly, there is a parallel between Gibbons and Henderson's (2012) need to share task and relational knowledge across parties to build relational contracts and Brusoni *et al.*'s (2001) "cognitive overlap" that assemblers and suppliers need to develop and maintain, no matter how modular the sourced component is.

[4] Interestingly, a parallel exists between Puranam *et al.*'s (2012) distinction between task and agent interdependence and Gibbons and Henderson's (2012) distinction between task and relational knowledge (and the need to share them across parties).

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each other's actions. This predictive knowledge is formed by information processing activities, such as periodic communication about each other's progress and mutual observations (Puranam *et al.*, 2012, p. 425).

In general, several streams of research seem to suggest that when technological changes are frequent, component modularity does not necessarily mitigate interorganizational interdependencies, even though it might reduce the thickness of the crossing points bridging suppliers' and buyers' task networks (Baldwin, 2008). Even where the crossing points are thinned by component modularization, buyers and suppliers tend to remain highly interdependent because of the uncertainty brought about by component technological change and therefore must exchange a fair amount of technical and business knowledge and information. Hence, component modularity drives organizational modularity only when technological change is low.

Therefore, the second hypothesis is as follows:

Hypothesis 2. Component modularity is negatively related to buyer–supplier information sharing only when component technological change is low; component modularity does not affect buyer–supplier information sharing when component technological change is high.

A closer look at the interplay of the relative distribution of capabilities between buyers and suppliers and the associated transaction costs in shaping industry architectures may further clarify the above hypothesized misting up (nonmirroring) effect. Wolter and Veloso (2008, p. 599) suggested that in mature industries with an established dominant design, when component technological change is frequent (leading to incremental and/or modular innovations), vertical industry contracting structures characterized by low organizational modularity (high information sharing) will be the system integrator's (or buyer's) rational choice irrespective of the degree of modularity of the sourced components. Even if components are modular, when component technological change is high, buyers remain interested in getting access to incremental or modular innovations, in monitoring suppliers' cost structures to reduce their power, and, hence, in engaging suppliers in thick relationships (the hypothesized and tested misting-up effect).

Instead, when component technological change is low, buyers do not foresee the opportunity to get access to innovative components. Hence, interdependencies between buyers and suppliers remain relevant only if the corresponding sourced components are integral design-wise. In this case, intense information sharing is needed to coordinate the efforts of buyers and suppliers because every change in one component might involve changes in others. Since components' design and development cannot be isolated and conducted separately by suppliers, codevelopment practices are necessary to reap the advantages of relational quasi rents (Asanuma, 1989; Dyer and Singh, 1998). Buyers and suppliers need to engage in thick relationships through which they can continuously improve products and processes, control opportunism, and share risk (Helper, MacDuffie, and Sabel, 2000). Thus, the only situation in which organizational modularity will arise is when components are modular and component technology change is low.

Hypothesis 3 follows:

Hypothesis 3. Components characterized by high modularity and low technological change require comparatively less buyer–supplier information sharing.

Figure 1 shows what happens when the mirroring hypothesis is tested considering the effect of the contingent variable *Technological change*. The mirroring hypothesis *de facto* considers only the two rows in Figure 1, with the degree of component modularity positively correlated with the degree of organizational modularity. Following the mirroring hypothesis, we would expect to observe high levels of organizational modularity (i.e., low levels of information sharing) whenever component modularity is high (i.e., in both the bottom cells of Figure 1). Instead, based on our reading of the literature and on our interpretation of previous empirical work, this study hypothesizes and tests that the mirroring hypothesis gets misted up by component technological change; in other words, organizational modularity remains low, even for highly modular components, if these are characterized by high technological change (the bottom right of Figure 1 corresponding to low levels of organizational modularity).

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		Technological change	
		Low	High
Component modularity	Low	Low organizational modularity (= High Information sharing)	Low organizational modularity (= High Information sharing)
	High	**High organizational modularity (= Low Information sharing)**	Low organizational modularity (= High Information sharing)

Figure 1. A map of the joint effect of technological change and component modularity on organizational modularity (buyer–supplier information sharing)

DATA AND METHODS

The air conditioning industry

The air conditioning (AC) European market is worth approximately €10 billion, and Italy is the main European market, with a share of approximately 29%, as well as the largest European producer, with an output amounting to 70% of total European production. In addition, Italian producers are leaders in several market segments and product typologies, such as chillers and high-precision air conditioners. These products are designed to run continually and provide precise control of temperature and humidity in environments, such as technological and server rooms. Climate conditions are controlled by the use of microprocessor-based control systems that allow users to remotely monitor the systems (Furlan *et al.*, 2006).

We chose to study air conditioners for three reasons. First, the AC industry is mature and technological improvements take place incrementally at the component level[5] (Cabigiosu and Camuffo, 2012). In such a context, it is reasonable to assume that the intended and actual levels of modularity do not differ significantly, and that the interdependencies among components are visible and well known to the engineers in the industry. Combined with our field research methodology (objective and not perceptual measures of modularity), this also ensures the accuracy of our modularity measurement process. Second, high precision air conditioners are complex products made of tens of components whose design principles are located at the crossroads of several technologies, such as coolant chemicals, thermodynamics, heat transfers, metal frames, and electronic and digital controls. The multitechnology, multicomponent nature of these products allows us to study the impact on organizational modularity of both component modularity and component technological change. Third, as illustrated in other studies (Cabigiosu and Camuffo, 2012; Camuffo *et al.*, 2007; Furlan *et al.*, 2006), the air conditioning industry's vertical contracting structure is characterized by original equipment manufacturers (OEMs) that normally act as system integrators. Within a given product architecture (largely similar across competitors within the industry), they design and assemble the final product, putting together parts designed and produced by external suppliers. They are not vertically integrated (purchased parts account for approximately 80% of the full manufacturing cost), focus mainly on design and assembly (and, naturally, on marketing, sales, etc.), and heavily rely on external suppliers for innovation (80% of the components are either designed by the suppliers or co-developed between buyers and suppliers), which takes place mostly at the component level.

Sample and research methods

A product's level of modularity depends on the level of modularity of its components (Sosa, Eppinger, and Rowles, 2004). However, most prior works explored modularity at the product level; i.e., they tried to gauge the level of modularity of the final product and draw managerial implications from it. In contrast, we focus on the microstructure of the products and analyze the components sourced from external, independent suppliers. Therefore, our level of analysis is the sourced component and the corresponding supplier relationship.

[5] The first modern electrical air conditioner was invented in 1902 (Kren, 1997), and current product technology is still grounded in the original refrigeration cycle. In the last two decades, important technological improvements have been introduced (reduction of size, advancements in remote control technology and energy savings, improvement of indoor air quality). However, since the technology, the main components, and their relationships within the refrigeration cycle have remained basically unchanged, the product architecture can be considered stable. Product architecture stability and modular/incremental technological changes à la Henderson and Clark (1990) are complementary: industry maturity and product architecture stability confine technological changes within components (modular/incremental innovations) so that they do not affect the components' boundaries, and original equipment manufacturers can leverage on years of design experience without significant unsolved or new ("hidden") cross-component interdependencies.

This study adopts the same research design and methods, data gathering procedures, and sample features as Cabigiosu and Camuffo (2012). The research was conducted over a two-year period, during which we gathered data on the product architectures and supply relationships of three AC OEMs that are similar in size, product range, scope of activities, and final markets (Cabigiosu and Camuffo, 2012). We selected the top selling air conditioners of each OEM, making sure that they were competing products, homogeneous technology-wise, and targeted at the same market segments. We also doublechecked that the three models were at a similar stage in their product life cycle. The OEMs' chief engineers assisted us in making these choices.

Data collection required extensive fieldwork at the OEMs' locations. We piloted the methodology with one of them and then proceeded with the other two. Based on the three OEMs' bills of materials, we ranked the product components purchased from suppliers according to the proportion of their purchasing cost to the product's total manufacturing cost. For each of the three models, we considered those components whose aggregate value amounted to roughly 80% of the full manufacturing cost of the analyzed products. We took into account only components at the first level of the product architecture hierarchy, and we did not include components with negligible value or simple parts (e.g., screws and bolts).

At the end, we converged a list of 39 components for the first company (OEM_1), 31 for the second company (OEM_2), and 30 for the third company (OEM_3). Our analysis of component modularity was conducted by interviewing extensively the three OEMs' chief engineers and, when necessary or required, the senior engineers or technology specialists.

For all the sampled components, we gathered the information needed to measure product modularity by following a three-step procedure:

1. We prepared a list of component functions for a generic high-precision AC unit (this list was discussed with the chief engineers, who commented on and in some cases adjusted it);
2. We identified the number of functions performed by each component of the three analyzed products;
3. We conducted a design structure matrix (DSM) analysis on the three analyzed products (Ding-Bang, Yao-Tsung, and Chia-Hsiang, 2011; Helmer, Yassine, and Meier, 2010; Pimmler and Eppinger, 1994; Sosa *et al.*, 2004) to count and classify the number of interfaces/interactions for each component (we analyzed four types of interactions: spatial, energetic, material, and informative).

We obtained three DSMs, one for each analyzed product, and with the total number and types of interfaces that each component has with the others. Each DSM was drawn with the direct involvement of the three chief engineers, as well as of some senior engineers, and required approximately 30 hours to complete. After analyzing the product architectures, we moved to the analysis of the buyer–supplier relationships. In this research phase, we obtained the support of the purchasing departments of the three OEMs.

First, for all the sampled components, we identified the corresponding suppliers. After matching components with suppliers, we proceeded with the analysis of the supply relationships. We interviewed the person most knowledgeable on each relationship/component pair and asked him/her to fill out a structured questionnaire derived from previous work on supply relationship management (Bensaou and Venkatraman, 1995; Cabigiosu and Camuffo, 2012; Furlan *et al.*, 2006). Each interviewee filled in one questionnaire for each supplier relation–component pair. For suppliers with multiple components, we collected a questionnaire regarding each component. The questionnaire contained three sections of questions/items regarding the degree of information sharing between the supplier and the buyer (10 items), the rate of component technological change (3 items), and general information about control variables (4 items). We conducted 100 interviews in total—one for each component–relationship pair. On average, each interview, including the completion of the questionnaire, was 90 minutes in length.

Research measures

Component modularity level

We use the measure introduced by Fine *et al.* (2005) as modified by Cabigiosu and Camuffo (2012):

$$CM_i = \frac{\zeta_1}{F_i + \zeta_2 In_i}$$

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where CM_i is the modularity degree of component i; F_i is the number of functions the component performs; In_i is the number of closed interfaces it has with other elements; $\zeta_1 > 0$ and $\zeta_2 > 0$ are two normalization scalars (ζ_1 is selected to bring the modularity values to a range of [0,1]; ζ_2 weighs the interfaces with respect to functions).

A perfect modular component performs only one function and has only open standard interfaces. Accordingly, we set $\zeta_1 = 1$ and $\zeta_2 = 1$ to bring the modularity values to a range of [0,1], where 1 stands for perfect modularity, corresponding to a component that implements only one function and has only open standard interfaces.[6]

Buyer–supplier information sharing

We measure organizational modularity using the level of buyer–supplier information sharing as an inverse proxy. To measure buyer–supplier information sharing, we adopt the scales developed by Cabigiosu and Camuffo (2012) and draw upon several studies on buyer–supplier integration (Camuffo *et al.*, 2007; Das, Narasimhan, and Talluri, 2006; Furlan *et al.*, 2006; Vereecke and Muylle, 2006). This approach appreciates buyer–supplier information sharing with regard to three key interorganizational processes:

1. new product development comprising information sharing about (i) new product development support; (ii) component attributes and performance, and (iii) supplier's R&D efforts;
2. contract and price negotiation comprising information sharing about (i) the component cost structure; (ii) supplier's production capacity, and (iii) supplier's key financials;
3. logistics comprising information sharing about (i) inventory levels; (ii) production planning; (iii) deliveries; and (iv) demand forecasts.

The sample means of these 10 items is used to obtain an overall measure of information sharing. The reliability analysis is supportive (Cronbach's alpha is 0.81).[7]

The rate of component technological change

Our measure of the rate of component technological change refers to Brusoni *et al.* (2001) and Takeishi (2002) and encompasses both product and process technological changes. On the one hand, we measure how frequently the underlying technology of the component changes over time. On the other hand, we measure how frequently the component production process changes over time. Both changes can, in fact, generate interdependencies among buyers and suppliers that need to be managed. We also use an extra item to measure how important suppliers' technological innovativeness is, as a criterion to choose and evaluate the suppliers of the analyzed component. More specifically, our measure comprises three items adapted from previous studies (Bensaou and Anderson, 1999; Cabigiosu and Camuffo, 2012; Takeishi, 2002). The three items show good reliability (Cronbach's alpha is 0.75).[8]

Controls

Since buyer–supplier information sharing might differ across buyers and suppliers within the same industry for reasons related to market structure, suppliers' capabilities, and buyers' sourcing strategy, we follow previous studies (Cabigiosu and Camuffo, 2012; Camuffo *et al.*, 2007) and include several control variables—geographical proximity of the supplier, supplier's size, supplier's capabilities, demand predictability,[9] presence of industry

[6] Different from Fine *et al.* (2005), our measure of modularity not only includes interfaces in the denominator, but also specifically counts only the number of *closed interfaces* as the complementary and opposite category of open standard interfaces. In other words, we measure against the highest level of modularity the number of closed interfaces. Closed interfaces are better suited to capture the overall degree of component modularity because each closed interface is detrimental to the degree of modularity. This approach is in line with the modularity literature emphasizing the key role of open interfaces in modular architectures (Baldwin and Clark, 1997; Fine *et al.*, 2005; Ulrich, 1995). We opted not to assign different weights to the number of functions and interfaces in our modularity measure. However, as a robustness check, we ran all the models with different values for scalar ζ_2 and obtained consistent results. These unreported regressions are available upon request.

[7] Items, scales, and reliability analysis are available in the supporting information Appendix S1.

[8] Items, scales, and reliability analysis are available in supporting information Appendix S1.

[9] Demand predictability is an inverse measure of volume uncertainty defined as the unpredictability of demand that generates an inability to accurately forecast and schedule production (Parmigiani, 2007, p. 289). Volume uncertainty makes it more difficult to contract with suppliers, since it increases their production costs and leads to misunderstandings and inventory coordination problems. We expect, and the results

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standards—and two dummies, one for each OEM (OEM_1 and OEM_2). The control variables are measured using eight items. In the case of supplier's capabilities, a two-item variable, we use the mean value of the interviewees' responses to the two relevant items.[10]

Statistical methods

To test Hypothesis 1, we apply ordinary least squares (OLS) regression with robust standard errors. *Buyer–supplier information sharing* is the dependent variable. In the first model, the independent variable is *Technological change*, besides the five controls, and the two dummies (firm fixed effects). We also test Hypothesis 2 with OLS. In this case, however, we first split the sample into two subsamples on the basis of the median value of the component technological change variable. Then, we run two regressions: one on the subsample with low component technological change and one on the subsample with high component technological change.

To test Hypothesis 3, we follow Combs and Ketchen (1999) and apply an analysis of covariance (ANCOVA). We do not test the interaction effect of component modularity and technological change on buyer–supplier information sharing through moderated regression because the hypothesized interaction is an *a priori* ordinal interaction. In Hypothesis 3, one independent variable (i.e., *Component modularity*) affects the dependent variable (i.e., *Buyer–supplier information sharing*) at only one level of the other independent variable (i.e., *Technological change*). An *a priori* ordinal interaction exists when one cell is significantly different from the other three and the "unique" cell has been specified *a priori* (Combs and Ketchen, 1999, p. 870). In our case, when technological change is low and component modularity is high, firms should share significantly less information than under any other component modularity/component technological change combinations (see Figure 1). Within this setting, a simple moderated regression can mask the interaction, because there is only one combination of the variables' values (i.e., the high modularity–low technological change cell in Figure 1) that has important effects on the dependent variable. The appropriate statistical technique is therefore a comparison of the effects of the different combinations on information sharing, testing the hypothesized differences (i.e., one cell vs. the other three). We proceed by, first, classifying the components into the four cells portrayed in Figure 1 according to their different levels of component modularity and technological change (the median of technological change and component modularity are the threshold levels to distinguish between low/high component modularity and low/high technological change). Second, we identify those components that, being characterized by low technological change and high component modularity, should be designed, produced, and supplied through interorganizational relations characterized by low information sharing (the bottom left cell of Figure 1). Third, we separate these components from all the others. To test the hypothesized differences, we apply an ANCOVA, to remove the variance explained by the control variables.

As a further test of Hypothesis 3, we run an OLS model in which information sharing is the dependent variable and the combinations of component technological change and modularity are the independent variables. Indeed, we wish to test if components characterized by different combinations of technological changes and modularity display significantly different degrees of information sharing. Hence, in this OLS model, the dependent variable is the degree of information sharing and the independent variables are three dummy variables corresponding to three out of the four quadrants represented in Figure 1, keeping low technological change/high component modularity as the omitted category. The first dummy variable, *LowCM_LowTC*, corresponds to the upper left quadrant of Figure 1 (below median levels of both *Component modularity* and *Technological change*); the second dummy variable, *LowCM_HighTC*, corresponds to the upper right quadrant of Figure 1 (below median levels of *Component modularity* and above median levels of *Technological change*). Finally, the third dummy variable, *HighCM_HighTC*, corresponds to the

confirm this expectation, that information sharing reduces the negative effects of volume uncertainty. First, information sharing helps the parties coordinate their logistics, thus minimizing the occurrence of such events as stock-outs or excess of inventory. Second, information sharing increases the ability of the parties to predict future demand by pooling information about demand forecasts and production schedules. Third, information sharing is often associated with buyer's commitment to the relationship (Bensaou and Anderson, 1999).

[10] Items, scales, and reliability analysis are available in supporting information Appendix S1.

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Table 1. Descriptive statistics and correlations

Variables	Mean	Median	S.D.	Correlations 1	2	3	4	5	6	7	8	9	10
Information sharing	3.23	3.47	0.87	1.00									
Component modularity	0.37	0.25	0.30	−0.40*	1.00								
Technological change	3.04	3.00	0.91	0.61*	−0.09	1.00							
Size	3.00	3.00	0.99	0.05	−0.02	0.26*	1.00						
Proximity (distance)	2.61	2.00	1.52	−0.11	0.06	−0.13	0.52*	1.00					
Supplier's capabilities	3.60	4.00	0.81	0.42*	−0.21*	0.58*	−0.06	−0.28*	1.00				
Demand predictability	3.37	4.00	0.94	0.32*	−0.12	0.25*	−0.15	−0.34*	0.16	1.00			
Standards	3.47	4.00	1.10	−0.05	0.06	0.07	−0.07	0.02	0.13	0.30*	1.00		
OEM_1	0.39	0.00	0.49	0.64*	0.015	0.52*	0.08	0.02	0.24*	0.21*	0.05	1.00	
OEM_2	0.31	0.00	0.46	−0.62*	0.21*	0.25*	0.04	0.09	−0.02	−0.68*	0.17*	−0.54*	1.00

$N = 100$
$^*p \leq 0.1$; $^{**}p \leq 0.5$; $^{***}p \leq 0.01$

lower right quadrant of Figure 1 (above median levels of both *Component modularity* and *Technological Change*). Hypothesis 3 is supported if each dummy is significantly positive and an F-test shows that they are collectively significant.

Finally, we analyze the potential endogeneity of the control variable *Supplier's capabilities*. *Supplier's capabilities* might be endogenous in all three hypotheses because buyers might perceive that the suppliers with whom they share information are more capable, or perhaps the buyers seek to share information with higher capability suppliers. In our empirical setting, the buyers from the three OEMs assessed both the degree of information sharing and the degree of supplier's capabilities through the questionnaire (common method bias). Supporting information Appendix S2 summarizes the endogeneity tests that we performed and reports the two-stage least squares models that confirm the robustness of our OLS results even if *Supplier's capabilities* is endogenous in Hypotheses 1, 2, and 3.

FINDINGS

Table 1 reports the descriptive statistics and correlation matrix for all the variables.

Table 2 shows the results of the OLS analyses to test Hypothesis 1. We run a model in which the independent variable is *Technological change* and the dependent variable is *Buyer–supplier information sharing* (*IS* henceforth). We rule out the existence of multicollinearity problems by

Table 2. OLS results for Hypothesis 1 (robust standard errors in parenthesis)

	Information sharing
Intercept	3.36***
	(0.60)
Component modularity	-0.72***
	(0.20)
Technological change	0.32***
	(0.08)
Distance	−0.01
	(0.03)
Standard	−0.07*
	(0.04)
Demand predictability	−0.25**
	(0.12)
Size	−0.05
	(0.06)
Supplier capabilities	0.17*
	(0.08)
OEM_1	0.38***
	(0.13)
OEM_2	−1.00***
	(0.26)
F	39.59
R^2	0.76

$N = 100$
$^*p \leq 0.1$; $^{**}p \leq 0.05$; $^{***}p \leq 0.01$

applying variance inflation factor (VIF) analysis (all values lie within the range of 1 to 2).

The coefficient for *Technological change* (*TC* henceforth) is positive and significant ($\beta = 0.32$; $p = 0.000$), supporting Hypothesis 1. To test Hypothesis 2, we run two OLS models, splitting our sample into two subsamples including,

Table 3. OLS results for Hypothesis 2 (robust standard errors in parenthesis)

	Low technological change	High technological change
Intercept	3.127**	6.307***
	(0.984)	(0.725)
Component modularity	−1.006**	−0.399
	(0.303)	(0.315)
Distance	−0.023	−0.071*
	(0.058)	(0.040)
Standard	0.017	−0.150**
	(0.074)	(0.054)
Demand predictability	−0.121	−0.449**
	(0.178)	(0.142)
Size	−0.005	−0.097*
	(0.018)	(0.050)
Supplier capabilities	0.260*	0.066
	(0.149)	(0.119)
OEM 1	0.650**	0.304
	(0.278)	(0.119)
OEM 2	−0.914**	−1.274***
	(0.427)	(0.353)
R^2	0.64	0.837
F	15.27	38.70

$N = 100$
*$p \leq 0.1$; **$p \leq 0.05$; ***$p \leq 0.01$

Table 4. ANCOVA results for Hypothesis 3

	Df	Mean square	*F*	*P*
Model	8	66.885	32.18	0.000
Group[a]	1	5.674	26.52	0.000
Distance	1	0.150	0.70	0.403
Standard	1	0.561	2.62	0.109
Demand predictability	1	2.594	12.13	0.001
Size	1	0.115	0.54	0.466
Supplier capabilities	1	3.421	15.99	0.000
OEM 1	1	4.296	20.08	0.000
OEM 2	1	7.792	36.42	0.000
Residual	91	0.214		
Total	99	0.753		

$N = 100$
[a] The variable *Group* divides the sample into two subsamples: subsample 1 includes components with above-median component modularity values and below-median technological change values; subsample 2 includes all other components.

respectively, the components with above-median and below-median values of technological change. Table 3 provides the results of the two OLS analyses. We also perform VIF analysis to rule out multicollinearity problems. As hypothesized, in the subsample including the components characterized by below-median technological change, component modularity negatively affects buyer–supplier information sharing (regression coefficient $\beta =$ -1.006; $p = 0.02$). Moreover, in the subsample including the components characterized by above-median technological change, the effect of component modularity on buyer–supplier information sharing disappears (regression coefficient $\beta =$ -0.399; $p = 0.211$).

The results of the ANCOVA, summarized in Table 4, support Hypothesis 3 showing the existence of a significant effect of the *a priori* ordinal interaction between component modularity and component technological change on buyer–supplier information sharing ($F = 26.52$; $p = 0.000$).

Furthermore, the data in Figure 2 provide additional evidence supporting Hypothesis 3 and the mirroring hypothesis as portrayed in Figure 1. More specifically, as predicted in the bottom left cell of Figure 1, Figure 2 shows that we observe high levels of organizational modularity (low levels of information sharing) and component modularity only when component modularity is high and technological change is low (bottom left cell of Figure 2). The average level of information sharing of the bottom left cell is 2.44, with standard deviation $\sigma = 0.849$ (i.e., the mirroring hypothesis as a special case), while the average levels of information sharing displayed in the other cells are 3.10, with standard deviation $\sigma = 0.746$ (top left cell), 3.75, with standard deviation $\sigma = 0.693$ (top right cell), and 3.55, with standard deviation $\sigma = 0.610$ (bottom right cell, i.e., component technological change misting up the mirroring hypothesis). The components in the bottom left cell are those that display a level of buyer–supplier information sharing that is, on average, 40% lower than that of the components included in all other cells. *Post hoc* comparison tests done using the Bonferroni and Scheffé methods (Savin, 1980) confirm that the differences between the bottom left cell and all other cells are significant at $p < 0.05$ and $p < 0.01$. All these results strongly support Hypothesis 3.

Finally, Table 5 shows the results of the OLS analyses to further test Hypothesis 3. We run a model in which the independent variables are the three dummy variables *LowCM_LowTC*,

		Technological change	
		Low	High
Component modularity	Low	3.10 (0.746)	3.75 (0.693)
	High	**2.44 (0.849)**	3.55 (0.610)

F = 14.16; p = 0.000

Figure 2. Average level of information sharing for each component modularity/technological change combination (standard deviations in parentheses). $N = 100$

Table 5. OLS results for Hypothesis 3 (robust standard errors in parenthesis)

	Information sharing
Intercept	2.84^{***}
	(0.76)
LowCM_LowTC	0.70^{***}
	(0.20)
LowCM_HighTC	0.93^{***}
	(0.21)
HighCM_HighTC	0.85^{***}
	(0.29)
Distance	−0.03
	(0.04)
Standard	−0.04
	(0.04)
Demand predictability	-0.27^{**}
	(0.12)
Size	−0.01
	(0.06)
Supplier capabilities	0.25^{***}
	(0.09)
OEM_1	0.48^{***}
	(0.14)
OEM_2	-1.13^{***}
	(0.26)
F	33.36
R^2	0.74

$N = 100$
$^*p \le 0.1$; $^{**}p \le 0.05$; $^{***}p \le 0.01$

LowCM_HighTC, and *HighCM_HighTC*. We omit the direct effects of *Technological change* and *Component modularity* to avoid multicollinearity issues, while we include all the controls. The dependent variable is *IS*.

Each dummy variable regression coefficient is significantly positive, thus providing further support for Hypothesis 3. Furthermore, we perform an F-test that shows that the dummies are collectively significant, $F(3,89) = 6.90$; $p = 0.000$.

DISCUSSION

Within the mainstream modularity theory, modules are interpreted as market-supporting institutions that provide technical design rules that standardize the interfaces between different product components or stages of the production process (Sabel and Zeitlin, 2004). Therefore, firms can specialize in each stage of production and take advantage of economies of scale by producing the same modules in high volumes for a variety of customers, and transact at arm's length with these customers, since most of the communication and information needed to coordinate design and production activities are already embedded in between-module interfaces (Langlois, 2002).

This view, recently framed as the across-firm mirroring hypothesis (Colfer and Baldwin, 2010), is supported by substantial empirical evidence that product modularity is associated with loosely coupled organizations that use market-based coordination mechanisms to coordinate their activities. Other studies, however, have found that product modularity may instead be associated with thick, hand-in-glove interorganizational relationships, where intense information sharing remains necessary to achieve interfirm coordination (Brusoni, 2005; Brusoni *et al.*, 2001; Jacobs *et al.*, 2007; Salvador, Forza, and Rungtusanatham, 2002).

We maintain that an excessive focus on the direct relationship between product and organizational architectures has dimmed the contingent nature of the mirroring hypothesis. In particular, most empirical studies do not explicitly address the role of component technological change when studying the relationship between product and organizational architectures, neglecting the conditions under which interfirm coordination mechanisms may substitute for technical expertise in managing buyer–supplier relationships (Mitchell and Parmigiani, 2010). Our study investigates how component modularity and the rate of component technological change jointly affect the degree of coupling between buyers and suppliers, measured as the extent to which buyers and suppliers share technological and business information to coordinate their business processes.

We find that high component technological change nullifies the inverse relationship between the degree of the coupling of product architectures (component modularity) and the degree

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of the coupling of organizational architectures (buyer–supplier information sharing). In other words, buyers and suppliers confronting a high rate of component technological change will resort to information sharing even in the presence of highly modular components. On the other hand, modularity reduces the need for information sharing and, hence, for interfirm coordination, only in the presence of low component technological change.

These results offer several contributions for academicians as well as practitioners. First, this study's contribution to the debate on the organizational implications of modularity and its ramifications for the theory of the firm lies in the fact that the rate of component technological change affects the extent to which buyer's and supplier's task networks can be encapsulated and partitioned (Baldwin, 2008) within the boundaries of modules, contradicting the idea of a deterministic relationship between the degrees of the coupling of components and of organizations. Contingent upon the degree of technological change, highly modular components can be designed, produced, and exchanged through either relationships with scant information sharing or relationships based on intense information sharing. Therefore, general statements such as "integral products would tend to be produced by integral supply chains while modular products would tend to be produced by modular supply chains" (Fine *et al.*, 2005, p. 392) or "product modularity positively influences supplier integration" (Jacobs *et al.*, 2007; p. 1051) are somewhat inaccurate.

Second, our findings lead us to question some aspects of the modular theory of the firm (Baldwin, 2008; Langlois, 2002). This theory explains the position of the boundaries of firms and, hence, the vertical contracting structure of industries, as located at the crossing points of task networks, i.e., the locations where the overall task network is divided into more sets of subnetworks, with transactions occurring among them. These crossing points may be thin, requiring low interaction and information exchange between the parties (arm's length transactions), or thick, with many interdependencies to manage, and hence requiring substantial information exchange and coordination via formal and/or relational contracts. Baldwin (2008) asserted that "regardless of its intended purpose, modularization necessarily creates new module boundaries" (p. 179) with associated thin crossing points and low mundane transaction costs. In this paper, we show that in technologically dynamic contexts, characterized by higher uncertainty and supplier's potential opportunism, product modularization may not be a sufficient condition to reduce all types of transaction costs. We acknowledge that while modularization drives down mundane transaction costs à la Baldwin, other types of transaction costs might actually increase due to technological change, and we suggest that future studies must focus on disentangling the combined effect of modularization and other variables (like component technological change) on the diverse types of transaction costs modularization might affect.

Linking Baldwin's (2008) analysis to the theoretical distinction between task and agent interdependencies put forward by Puranam *et al.* (2012), we may assert that task interdependencies largely correspond to "mundane" transaction costs, and that agent interdependencies reflect the other types of transaction costs conceptualized by Baldwin. Consequently, product modularization is a sufficient condition to create thin crossing points, breaking down the overall task network and generating across-firm transactions that can be efficiently governed with little information intercourse (market type). Our study shows that the components characterized by high technological change generate substantial (epistemic) interdependencies among agents even though crossing points among task subnetworks are "thin." In this case, across-firm transactions remain complex, and the corresponding across-firm coordination needs cannot be fully satisfied by product modularization.[11]

Third, our study offers some original insights about the complex relationship between product modularity and technological change. Part of the modularity literature maintains that investment and

[11] The high level of information sharing that characterizes supply relationships for technologically dynamic components, despite high component modularity levels, is also consistent with relational contract theory (Dyer and Singh, 1998). When component technology changes rapidly, buyers and suppliers must use their detailed knowledge of their specific situation and adapt to new information as it becomes available so that "the value of the future relationship remains sufficiently large that neither party wishes to renege" (Baker, Gibbons, and Murphy, 2002, p. 40). These results deemphasize the role of product modularity as a functional equivalent of a high-powered interfirm coordination mechanism showing how technology contributes to shaping vertical interfirm relationships (Mitchell and Parmigiani, 2010; Parmigiani and Mitchell, 2009).

effort in product modularization are worthwhile in complex settings and that modular products better fit technologically unstable environments (Langlois, 2002). More specifically, Langlois (2003) asserted that "in a world of change, modularity is generally worth the cost" (p. 24) because the cost of interfirm communication and information sharing associated with nondecomposable systems would be prohibitive. Therefore, according to this position, product modularity should emerge and prevail in contexts characterized by rapid technological change. However, our findings provide a more nuanced view of the relationship between modularity and technological change. Even under the specific conditions of this study (product architecture stability and technological changes confined to within-component modular or incremental innovation), it appears clear that not all the product components can be/have been modularized (partial and imperfect product modularity) and that interorganizational relations between OEMs and suppliers can be/have not been thinned to minimal information sharing (partial and imperfect organizational modularity), even in the case of highly modular components. Furthermore, the evidence gathered in the aerospace (Brusoni and Prencipe, 2001, 2011), automotive (Cabigiosu *et al.*, 2013; MacDuffie, 2013; Zirpoli and Becker, 2011), and other industries (Staudenmayer *et al.*, 2005) suggests that in more technologically unstable environments, i.e., under conditions of product architecture instability and technological change generating radical or architectural innovations, modularization should be even more difficult and costlier than in technologically stable environments because technological instability always questions module boundaries.

From another standpoint, however, Langlois's (2003) position that "in a world of change, modularity is generally worth the cost" is agreeable, because managers and engineers within organizations, under conditions of bounded, though intentional, rationality (Simon, 1947), will relentlessly continue to pursue modularization. They will continue to make decisions about the design of complex systems (e.g., products and organizations), pursuing the two fundamental properties of flexible complex systems—hierarchy and near-decomposability (Simon, 1962)—and they will do that even more in a world of change.

Fourth, our study illustrates why modularity theory, as located at the crossroads of organizational economics, system theory applied to product design, and the theory of relational contracts applied to vertical interfirm relationships may help us interpret the structure and dynamics of interfirm relationships. Modularity theory complements mainstream organizational economics, which is prevalently a theory of relationships (i.e., of actors, interests, contracts, incentives, etc.), and less a theory of production (i.e., of technology, information, knowledge, and capabilities) (Gibbons, 2006). Modularity theory draws on Simon's (1962) original intuition about the architecture of complexity that the fundamental properties of flexible complex systems (like products and organizations) are hierarchy—the fact that some structures provide constraints on lower-level structures—and near-decomposability—the fact that patterns of interactions among the elements of a system are not diffused, but will tend to be tightly clustered into nearly isolated subsets of interactions (Ethiraj and Levinthal, 2004; Schilling, 2000). Applying this powerful concept, it is possible to explicitly integrate technology (a variable often considered exogenous in organizational economics) into the analysis (albeit, in this study, only in the form of product component technological change), showing how it may constrain (or contribute to shaping) interfirm relationships. From this standpoint, our study also connects the modularity literature to the classic debate about the nature of the relationship between technology and organization[12] (Emery and Trist, 1965; Monteverde, 1995; Pugh and Hickson, 1976; Woodward, 1965).

[12] As discussed in the hypotheses development section, from a microlevel of analysis, there are three mechanisms that can help to explain this relationship. The first microlevel process relates to the logic of vertical cross-firm knowledge partitioning and sharing when component technologies change (Brusoni *et al.*, 2001; Zirpoli and Becker, 2011). In the presence of high component technological change, the buyer needs to learn component and system-specific knowledge to accommodate changes in one field that may have cascade effects on others. The second microlevel process relates to the effect of component technological changes on the interplay between the relative distribution of capabilities between buyers and suppliers and the associated transaction costs (the "resource-based view meets organizational economics" approach). The third microlevel process refers to the increase of epistemic interdependencies caused by component technological change.

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Fifth, mainstream modularity theory tends to focus on architectural changes and technological discontinuities (Langlois, 2002), implicitly assuming that technological change occurring within the boundaries of given modules would not affect the interdependencies between the modules and the corresponding interorganizational relationships. Our findings show that this is not the case. Within a given (and, in our specific case, stable) product architecture, the degree of component modularity plays an important role in shaping interorganizational relations (Hoetker, 2006; Hoetker, Swaminathan, and Mitchell, 2007; Tiwana, 2008) only when component technology does not change. When component technological change is high, buyers and suppliers need to coordinate through information sharing, i.e., use the *ex post* detailed knowledge of their specific situation as it arises and reciprocally adapt their expectations and behaviors.

LIMITATIONS AND AVENUES FOR FUTURE RESEARCH

Our study suffers from some limitations that can provide avenues for future research. First, we conducted our study under specific contingencies, and it has clear boundary conditions: product architecture stability, industry maturity, and focus on modular/incremental technological change confined within components. Only under such conditions are our cross-sectional data and point observations meaningful. Thus, future research should address the potential observable divergence between modularity-as-property and modularity-as-process in order to take into account the distinctions between actual and intended levels of modularity and between visible and hidden interdependencies. This will require the investigation of other, more dynamic industries characterized by radical and architectural changes, the adoption of a longitudinal perspective, and innovative measures of modularity.

Second, besides component technological change, other strategic and organizational variables can moderate the relationship between component modularity and information sharing. For example, other things equal, a collaboration-oriented sourcing strategy can lead the buyer to develop collaborative relationships with suppliers even if the component is perfectly modularized.

Third, our industry setting might have influenced the observed results. Several industry-specific features can affect the results of a one-industry based study. For example, the presence of market power imbalances between buyers and suppliers can change the way that supplier relations are managed. Future research should conduct cross-industry studies to control for industry-specific factors.

Finally, our analysis does not include performance variables. Future research might analyze the performance effects of different triplets' component modularity-component technological change-buyer–supplier information sharing.

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article:

Appendix S1. Items, scales and reliability analysis.
Appendix S2. Endogeneity issues.

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