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When do modular dominant designs emerge?
A theoretical framework

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Abstract. We know that dominant designs affect firms' competitive advantage and firms need guidelines to predict which type of dominant design is more likely to emerge. But while theories about dominant design identify the forces that in general predict the emergence of dominant designs, we still lack studies that specifically address the issue of when modular architectures become dominant. This is a relevant research question because scholars have shown that the rise of modular architectures can greatly affect industry dynamics and firms' competitive advantage.

This study creates a bridge between dominant design and modularity literature and develops a framework that identifies the forces and industry characteristics that help predicting the emergence of a modular dominant design. Interestingly enough, while modularity literature argues that firms develop modular products to reduce product complexity, this contribute suggests that modular architectures become dominant when technology is well known and with a moderated level of complexity, thus somehow limiting the power of modularity. Also the study identifies the conditions under which multiple stakeholders contemporarily select a modular architecture and emphasizes the role of firms producing core components.

Keywords: dominant design; product modularity; product architecture; standards

JEL Classification Numbers: O33, O32

Introduction

During the '90 several authors produced empirical works supporting the hypothesis of a product architecture evolution from integral to modular with remarkable consequences at the industry level and for competitive dynamics (Baldwin and Clark, 200; Langlois, 2002; Sanchez and Mahoney, 1996). Mature industries, after a period of technological sperimentation and fluidity, should move toward modular product architectures, specialized suppliers and disintegrated value chains that all promote incremental and process innovation and favor price-based competition (Galvin and Morkel, 2001). A range of technology-based industries such as personal computers, stereo systems, and household appliances tends to reflect increasing modularity (Argyres and Bigelow, 2010). Nevertheless in the 2000, as Fixson and Park (2008) well explain, a substantial body of literature shows that product modularity does not dominate many industries. For example the automotive industry still has overall integral products (Cabigiosu *et al.,* 2013) as well as the bicycle drivetrain industry (Fixson and Park, 2008) or the watch industry (Jacobides and Winter, 2005). Hence relevant questions are why do we observe modular dominant designs only in some industries and which are the forces that push the market toward a modular dominant design? These are relevant research questions in that modularity is often correlated to specific industry dynamics and affects firms' strategy: technological and strategic decisions are interrelated. Modularity has direct implications for the time and costs of new product development (Henderson and Clark, 1990; Baldwin and Clark, 1997, 2000; Salvador *et al.,* 2002; Lau *et al.,* 2007), inter-firm coordination (Argyres, 1999; Hoetker *et al.*, 2007), the role of formal and informal standards (Garud and Kumaraswamy, 1995), production costs, assembly and testing (Fixson, Ro, and Liker, 2005; Takeishi and Fujimoto, 2001; Sanchez and Mahoney, 1996), and more.

In 2000 Melissa Schilling asked what drives some systems toward increasing modularity and her seminal work helped identifying multiple forces. Interestingly enough some of the forces she identified also drive the emergence of a dominant design but many forces considered by the dominant design literature are not discussed in the Schilling's framework. Also, the debate about modularity after the 2000 is of help in revising and updating Schilling's framework. In this paper we seek to understand when modular design emerge and become widespread in the market by analyzing the modularity literature and by integrating it into the dominant design literature.

Overall this paper contributes to the dominant design and modularity literature by emphasizing how the emergence of a dominant design requires dedicated frameworks for different types of product architectures. Accordingly this article develops testable propositions that help explaining when modular dominant designs emerge. Particularly this article suggests that often product complexity and technology dynamics limit the power of modularity. This study also emphasizes the role of multiple stakeholders and network dynamics. The existence of leading firms producing core components with a low level of vertical integration and high appropriability of rents all favor modular dominant design. Finally competition based on mass customization, network externalities, the availability of complementors and imitation strategies also promote modular designs. The remaining of the paper is organized as follows. The next section synthesizes the concept of dominant design and identifies the key variables explaining the emergence of a dominant design. Then the paper presents the concept of product modularity and the Schilling's framework of system modularity (2000). Building on the dominant design literature, the Schilling's model, and the most recent contributes of the modularity literature the paper presents the framework of modular dominant design. The framework identifies the forces that are expected to push the industry toward a modular dominant design and provides testable propositions. Finally the discussion and conclusion section compares the new framework with the Schilling's model and identifies the main contributions of the paper and future avenues of research.

1. Theory

1.1 Dominant design

Many scholars have so far analyzed the concept of dominant design, its level of granularity, under which conditions dominant designs emerge and the subsequent implications at the firm and industry level (Argyres *et al.,* 2015; Murmann and Frenken, 2006; Srinivasan *et al.,* 2006). Abernaty and Utterback (1978) and Anderson and Tushman (1990) define the dominant design as a single architecture that dominates a product category with a market share higher than 50%. Henderson and Clark (1990) explain that "the elements of a dominant design that are most salient to a company's survival are architectural in character: they are the concepts that define how the components within the product interact or relate to one another." (p. 208). Murmann and Frenken (2006) emphasize that dominant designs may affect different levels of the product hierarchy and components that display different levels of relevance. The authors focus on core components that are located at a high level of the product architecture, perform crucial functions and affect other components' functioning. When dominant designs emerge for the technology and interfaces of core components then we observe the most relevant effects at the industry level. Dominant designs matter because firms that adopt the dominant design architecture and technology will be less likely to exit from the industry and are more likely to survive (Christensen *et al.,* 1998; Utterback and Abernathy, 1975; Suarez and Utterback, 1995). In many industries technological evolution lead to the emergence of a dominant design. The literature identified multiple factors influencing the emergence of a dominant design: appropriability, network effects, the number of firms in its value net, the type of standards-setting process (de jure versus de facto), its radicalness, and its R&D intensity (Srinivasan, Lilien, and Rangaswamy, 2006).

Appropriability refers to firms' ability to capture innovation rents in the product category (Teece 1986). Weak appropriability (innovation rents) enables knowledge sharing among firms and the coevolution of networks of cooperating competitors. With weak appropriability, all firms in the network can share the innovation rents. Such rent-sharing reduces firms' incentives to innovate independently. The weaker the appropriability of the product design, the more probable is the emergence of a dominant design (Srinivasan *et al.,* 2006). Positive network effects exist when a customer's utility from a product increases as the number of customers who use the product increases (Katz and Shapiro 1986). Several authors suggest a positive effect of network externalities on the emergence of a dominant design other suggest that clients, in this context, adopt a wait and see strategy that constraints the emergence of a dominant design. A firm's linkages with suppliers and producers of complementary products are important sources of relational rents for the firm and utility for its customers (Dyer and Singh, 1998). Suppliers and producers of complementary goods deliver utility to customers and increase the firms' incentive to support a dominant design (Amit and Zott, 2001). Furthermore a dominant design permits firms to suspend further investments in product development, to compete within the dominant design, and to achieve supply-side and demand- side efficiencies. Nevertheless some authors are more cautious in emphasizing the number of complementors that can increase transaction and coordination costs and could potentially delay a dominant design's emergence (Bergen *et al.,* 1992). Radical products, which offer a low initial performance-to-price ratio, face limited market acceptance (Christensen, 1997; Utterback, 1994). The evolution of a radical product occurs over several years. The greater the radicalness of the product category, the less probable is the emergence of a dominant design. Radical and competence destroying innovations reduce the probability of having dominant designs. Also, the greater the R&D intensity of the product category, the higher is the pressure for the emergence of a dominant design.

Murmann and Frenken (2006) also well synthesize the casual mechanisms that explain why and when dominant designs emerge. First, dominant designs are established if they are the best technological compromise among different options and constitute a Nash equilibrium at which players producing different technologies and components have not the convenience to move from.

Second, firms have convenience in converging around a dominant design when this selection process increases product standardization and economies of scale. Third, a dominant design is established when the number of users is big enough to outperform the value of a competing design. A high number of users positively affect network externalities and the availability of complements. Fourth, firms' tactics and strategy are aimed at favoring a design, for example through alliances, in order to benefit from being the owners of the industry dominant design. In this case the perceived high appropriability favors dominant designs. Finally, dominant designs are the outcome of complex socio-political negotiation processes among firms. Economic, social, cognitive, political, and institutional forces influence the industry convergence process on a particular dominant design. Particularly increasing returns arising from economies of scale, learning curves and network externalities can tip the industry toward a particular technology. Socio-cognitive forces also drive convergence as actors develop a common set of beliefs about the industry as well as coordination mechanisms rooted on how firms divide and manage supply relationships (Tripsas, 2008).

Furthermore the authors enrich the extant literature by emphasizing other variables that affect the emergence of a dominant design. Product complexity favors local and sequential search hence learning curves play a relevant role. In R&D-intensive product categories, widespread integration of interdisciplinary technologies across diverse firms may be necessary to achieve the technology fusion that is critical for product development. High central and core components play a crucial role in the definition of a dominant design because once performing solutions are reached for such crucial components these solutions are difficult to overt. Also platforms and product families are often developed around dominant designs and the benefits of economies of scope may push firms toward the establishment of a dominant design.

Dominant designs have a powerful impact on the development of industries and firms. The firms that produce the emerging dominant design flourish, whereas firms that invested in the failing designs will face a complex landscape. Consequently the knowledge of driving forces explaining the emergence of dominant designs and their nature will allow scholars to make predictions about the nature and structure of industrial organization and production systems. Table 1 synthesizes these forces.

Tab. 1: List of the main forces that favor (+) or not (-) negative the emergence of dominant designs

Efficiency/strategy
Appropriability (-/+)
Network externalities (+)
Availability of complementors (+)
Economies of scale, learning curves, platform design (+)
R&D intensity (+)
Network management toward a technological compromise
Number of firms in the value chain, coordination costs, agency and negotiation costs (-)
Alliances diffusion (+)
Existence of core components (+)
Availability of technological compromises (+)
Radical and competence destroying innovations (-)

Source: our elaboration

Overall dominant designs emerge when firms have the strategic convenience in sharing the same design and are able to identify a convenient technological compromise. Firms must have strategic convenience due to efficiency reasons (economies of scale, learning curves, R&D costs, network externalities, availability of complementors) and must be able to coordinate the network and identify a convenient technological compromise (availability of a satisfying and quite mature technology that ensures a diffused appropriability of rents, reduced coordination and agency costs, alliance diffusion and availability of core components and leading firms that can act as coordinators). These considerations all emphasize the relevance of networks coordination and that of diffused strategic convenience.

2.2 Modularity in product design

The modularity concept is wide and applied to different research fields: products design and re-design, modular production forms and modular organizations (Takeishi *et al.,* 2001). The modularity concept is not new and was originally developed by H. Simon (1962), who defined modularity as a property of complex systems "nearly decomposable". Modularity is a property that allows representing products not as complex and indivisible units, but as the sum of independent units. In this paper we analyze modularity of the full product (level zero of the product hierarchy. In this case a modular product is characterized by the separability of its components (or chunks) at the first level of the product hierarchy, by the possibility to manage and develop them independently one from another, and by the re-combinability of the components into the final product. These properties allow managing the product not as a complex whole, but as a sum of smaller units, easier to manage than the whole product, and then easily re-combinable. The reduced product complexity is symmetrically translated in a lower complexity in developing modular or incremental innovations (Henderson and Clark, 1990), and in managing several production activities (as the components assembly and test) (Fixson *et al.,* 2005; Takeishi *et al.,* 2001; Sanchez and Mahoney, 1996).

Modularity is a relative property meaning that products can be more or less modular (Cabigiosu and Camuffo, 2017). Modularity is achieved maximizing the independence across modules and the interdependencies within modules (Baldwin *et al.*, 1997, 2000). Sosa *et al.* (2007) define component modularity as the level of independence of a component from the other components within a product. The authors suggest that components lose design independence because of their connections with other components. Connections are due to functional interdependencies and physical interfaces. Ulrich's definition of modularity (1995) well captures and emphasizes the role of functions and interfaces by stating that a product is modular if each element wholly implements one or few functions and interactions among components are well defined. In a modular product, interfaces among components are well known, desired, and without residual interactions. These properties bring to the codification of such interfaces, and then to their repeated use. This is why they are labeled standard interfaces (open if the standards have been accepted by the whole industry, or close if they are proprietary standard (Fine *et al.*, 2005)). Products with open standard interfaces are labeled open modular: open to a network that work following given rules, which might offer externalities achievable using open standard interfaces. Among those externalities there are: the opportunity to have a lager supplier park usually made of bigger global suppliers, the chance of quickly and economically incorporate someone else innovations in the product, the chance of increasing the product's variety having different suppliers for the same component, and the opportunity to invest less resources in supply relationships thanks to the reduced level of components' customization. Of course, sometimes open standards do not exist, or an open strategy might be not compatible with firms' strategy. Sometimes, the competitive advantage is strictly related to product architecture that has to be protected, and the standards have to be close, as for the Apple's strategy or the most of carmakers.

Overall, only in few industries we observed that the product system design efforts of firms go in two directions: the simplification of the mapping from functional elements to structural elements, and the establishment of open standard interfaces. In other words, product architecture gradually becomes widespread and modular. In those industries we observe modular dominant design with open standard interfaces and functionally isolated components.

2. Modular dominant design

Schilling (2000) and Schilling and Steensma (2001) where the first suggesting a framework identifying multiple forces that push products toward higher levels of modularity. Summarizing both contributes the key forces they identified are: a) synergistic specificities of modules that occur when product functionalities are achieved through components implementing specific functions that clients can easily evaluate in their performance and assemble; b) heterogeneity of inputs: the more heterogeneous the inputs are that may be used to compose a product or service, the more possible configurations there are attainable through the recombinability enabled by modularity and the higher will be the industry convenience in converging toward modular configurations and symmetrically; c) the more heterogeneous the demand is the more valuable becomes the heterogeneity and recombinability of different inputs. Schilling (2000) also recognizes that while recombinability has advantages related to an easier product differentiation it may also have drawbacks concerning product integrity, quality and performance; d) the urgency that captures the responsiveness of a system to the above stimulus. Particularly the higher the urgency correlated to competitive intensity, time constraints and technological change the more firms may be willing to converge around a modular design that eases and speed modular and incremental innovations. In this setting the availability of industry standards eases the modularization process. Finally, the framework acknowledges constraints toward modularization that in the following years have been widely discussed by modularity literature (Brusoni and Prencipe, 2001). The framework emphasizes that the gains achievable through recombination may be lower than the gains achievable through components specifically designed to suit each other needs and that customers may have difficulties in assembly components and evaluating their quality. Integral design may have superior performance. In this scenario firms may not have pressure for the decomposition of the system. Table 2 synthesizes the above forces. Overall the framework suggests that strategic pressures toward mass customization and incremental innovations positively affect modular designs.

Tab. 2: List of the main forces that positively (+) or negatively (-) affect the emergence of modular design. The list is based on Schilling (2000) and Schilling and Steensma (2001)

Synergistic specificities (+)
Input heterogeneity (+)
Demand heterogeneity (+)
Competitive pressure (+)
High technological change (+)
Radical and highly performing innovations (-)

Source: our elaboration

The modularity literature has strongly emphasized the connection between product architecture and technology, firms' performance and industry structure as well as dynamics (Langlois and Robertson, 1992; Baldwin and Clark, 2000). Comparing Table 1 and table 2 it emerges that modular dominant designs may be favored when pressures toward efficient innovation and mass customization is coupled with the availability of heterogeneous input or complements.

Nevertheless, the Schilling's framework of modularity does not acknowledge the complexity of network coordination that leads to the selection and convergence toward a dominant design and this complexity may be one of the reasons why we observe modular dominant design only in some industries. Hence, a model of modular dominant design, which builds on dominant design theory, should also consider the role of stakeholders and their strategic convenience in converging around a modular design. Furthermore, modularity literature has more recently disentangled the question of under which circumstances can modular design be technologically feasible and performing. Building on the need of expanding the Schilling's framework relying on the dominant design literature we also decided to increase our understanding about the forces enabling the diffusion of modular dominant design by analyzing the existent literature in search for articles documenting the existence, and describing the emergence, of a modular dominant design in a given industry or describing the key attributes of industries in which a modular dominant design emerged. We began in 2017 by conducting an electronic search for relevant scholarly works across the full digital publication lives of 19 major journals spanning multiple disciplines (Colfer and Baldwin, 2016). These journals are listed in Table 3. To identify the relevant articles we used the combinations of the following keywords: “dominant design” and modular or “product architecture” and modular.

Tab. 3: Journals analyzed

Academy of Management Journal
Academy of Management Review
Administrative Science Quarterly
California Management Review
Harvard Business Review
IEEE Engineering Management Review
IEEE Software
IEEE Transactions on Engineering Management Industrial and Corporate Change
Industry and Innovation
Journal of Management Studies
Journal of Product Innovation Management Management Science
Managerial and Decision Economics Organization Science
Organization Studies
Research in Engineering Design Research Policy
Strategic Management Journal

Source: Colfer and Baldwin (2016)

We obtained 141 articles and expanded the sample by scanning the retained articles for relevant studies that were not yet included. We also added studies with which we were familiar. We removed the articles that only mention the selected keywords without investigating or contributing to this paper research question. The resulting sample included 54 articles. These articles are representative of scholarly work through the middle of 2017 and suggest that several relevant studies can undoubtedly contribute to the topic of this paper. These contributes do not explicitly have the aim of identifying the forces and conditions under which dominant designs become modular but present interesting insights, theory findings and empirics that improve our understanding of the topic. In the next sections, building on this literature, we describe the main forces that have so far eased the emergence of modular dominant designs. In Table 4 we list these forces and we emphasize their correlations with the dominant design literature and the Schilling (2000) and Schilling and Steensma (2001)’s frameworks.

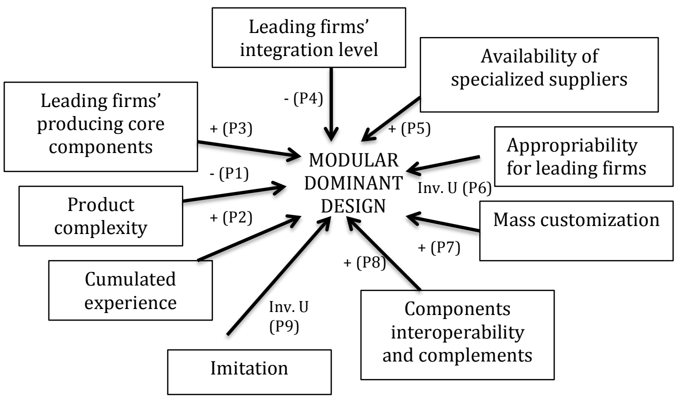
The first two forces discussed regard the technological characteristics and knowledge held for a given product architecture and technology. Modularity is an attribute of the product architecture and the first requirement for modularity to become widespread is it’s technologically feasibility. The second set of forces identifies the network actors and structure (propositions 3, 4 and 5) and the conditions under which buyers and suppliers have the convenience to converge around the same modular dominant design (proposition 6). Third, we identify the competitive landscape in which modular architectures are perceived as being strategically convenient for all the stakeholders (propositions 7, 8 and 9).

Tab. 4. List of the main forces affecting the emergence of a modular dominant design and comparison with the forces identified by the dominant design literature and by Schilling (2000) and Schilling and Steensma (2001)

	Dominant design	Schilling's framework	Original contribute
P1. Product complexity (-)		Synergistic specificities (+)	Under which conditions modularity is technically feasible.
P2. Firms' accumulated experience and knowledge, concerning both system design and components' technology development (+)	Radical and competence destroying innovations (-) R&D intensity (+) Availability of technological compromises (+)	High technological change (+) Demand for radical and highly performing innovations (-)	Modularity prefers incremental innovations only, both system and component specific knowledge is required to manage modular products.
P3. The existence of leading firms producing core components (+)	Number of firms in the value chain, coordination costs, agency and negotiation costs (-) Existence of core components (+)		Recognize the issue of network coordination for modular products and the role of leading firms.
P4. Leading firms' level of vertical integration (-)			The existence of leading firms favors modularity when leading firms have a low level of vertical integration.
P5. The existence of a network of specialized suppliers producing system components and complements (+)	Availability of complementors (+)	Input heterogeneity (+) Alliances diffusion (+)	In line with previous contributes.
P6. The appropriability of rents of leading firms has an inverted U-shaped relationship with the diffusion of modular dominant designs (inverted U)	Appropriability of rents (-/+)		Contrary to dominant design literature we focus on the appropriability of rents of leading firms, which is crucial in explaining if and how they protect their standards.
P7. Competition based on mass customization of final products (+)	Economies of scale, learning curves, platform design (+)	Demand heterogeneity (+) Competitive pressure (+)	In line with previous contributes.
P8. Competition based on components interoperability and availability of complements (+)	Network externalities (+)	Competitive pressure (+)	We emphasize that not only firms but also clients favors platforms and interoperability.
P9. Imitative behavior of stakeholders (inverted U)			Imitation is a strategy previously neglected: imitators can more easily copy a modular architecture and imitation may favor the diffusion of standards.

Source: our elaboration

Fig. 1. List of the main forces affecting the emergence of a modular dominant.



Source: our elaboration

3.1 Product complexity and technological knowledge

Modular dominant designs require an in-depth understanding of both the product architecture and of the components' inner technologies. In modular products functional interdependencies should be clustered within modules boundaries and managed via open standard interfaces. When products are complex, i.e. characterized by multiple components and technologies with frequent innovations and continuous introduction of changes in system components and subsystems (Teece, 1986; Davies, 1997), it becomes more difficult to design a modular architecture. In complex product systems open modular architectures are less likely to emerge because for innovation to proceed, high system integration skills (both at the technological and organizational level) are required (Bergek *et al.*, 2008; Prencipe 1997, 2000; Brusoni *et al.*, 2001; Furlan *et al.,* 2014; Cabigiosu *et al.*, 2013). In these products the emergence of a dominant design does not signal a decrease in the rate of technical development (Bergek *et al.,* 2008). Examples of industries producing complex product systems include the gas turbines industry, telecommunication, aircraft engine, high-speed trains, cars, flight simulators (Bergek *et al.*, 2008).

The development of complex product systems requires both breadth and depth in underlying knowledge bases (Prencipe, 2000; Magnusson *et al.*, 2005). In this context system integration capabilities and higher levels of vertical integration in the knowledge domains of most crucial and complex components are necessary. While modular architectures emphasize components decomposability, product complexity and technological change emphasize engineers' difficulties in forecasting and managing up-front via standard interfaces all components interdependencies. Product complexity and technological change require high components integration and reciprocal and continuous adaptation. Hence when product complexity is high and coupled with a continuous technological change, modular architectures are less likely to emerge. Modularity is effective to cope with some but not all levels of complexity (Cabigiosu *et al.*, 2013; Furlan *et al.*, 2014). Empirical evidence shows that PCs have been modularized but not cars or airplanes that embody, among many others, also on-board computers. Furthermore, complex systems products that are new to the world are often built using idiosyncratic components and dedicated technologies (Siggelkow, 2002). Some of these new components may show impediments, technological glitches or undesired interactions that were not anticipated at the beginning of the innovation process. Brusoni *et al.* (2001) analyzed the development of aircraft engine control systems and show that multi-technology firms need to have more knowledge than is required for manufacturing, to cope with the imbalance resulting from uneven rates of development of the respective technologies of different components and unpredictable product level interdependencies.

Nevertheless, several scholars argued that in complex products the product architecture could still evolve from an integral architecture to a modular architecture, through a learning process at the design stage. For this kind of products, the accumulation of experience, knowledge and expertise concerning system product design is necessary. Product system design efforts of companies can eventually proceed via the simplification of the mapping from functional elements to structural elements, and the establishment of standard interfaces. In other words, product architecture may gradually shift to modular architecture if the enterprise has accumulated enough design capability (Shibata *et al.,* 2005). Henderson (1992) also claims that modular architectures require enough problem-solving experience to be able to fragment a complex issue into elements without loose of functionalities. As Baldwin and Clark (2000) have noted only after firms have accumulated sufficient knowledge and experience about the product architecture and core components' technology of a system it becomes feasible and advantageous to modularize the system. Only over time, as engineers improve their understanding and knowledge of the ways in which product components function and interact they can develop codified, well known and performing interfaces. Hence, interfaces standardization at the industry level is a gradual output of the knowledge accumulated at the component and at the product system level (Argyres and Bigelow, 2010).

But experience in system design may not suffice to develop modular products when multiple components are affected by innovations at different times thus creating the risk of technological imbalances. In fact interfaces stabilization and predictability becomes more difficult to achieve when technological innovation is distributed, relevant and displays an uneven rate of change across components. The higher the technology complexity and dynamism the more leading firms' technological competences must span different technological fields in order to ensure a dynamic integration of different components technologies and configurations. Hence technological complexity and dynamism may negatively affect the system integrators' attempt to modularize product architectures. Brusoni, Prencipe and Pavitt (2011) suggest that the maturity of the technology enables engineers to better understand and then modularize components, as in the case of the hydro mechanical aircraft engine control system. On the contrary, when digital electronics emerged it initially displayed systemic interdependencies and uneven rate of component technological change that challenged modularization efforts. Furlan *et al.* (2014) show that in the air conditioning industry, component technological change may limit modularization benefits in terms of supply chain management. Also performance gap generated by new technologies reduce the likelihood of having modular dominant designs. As Christensen *et al.* (2002) explain when clients ask for increased and improved functions these may more easily offered by integral product architectures that embody radical innovations.

Overall, in complex product systems characterized by multiple components, different technologies and a high pace of technological change, open modular architectures are complex to be developed because they require an in-depth knowledge and understanding of both product architecture and components' technology. Particularly, in an era of high technological change, it becomes difficult to fix and freeze the product architecture and components' technologies. OEMs need to be very skilled at the architecture and technological level and to be good integrators of suppliers' knowledge bases (Furlan *et al.*, 2014; Shibata *et al.,* 2005; Wolter and Veloso, 2008). The first propositions follow:

P1. Product complexity has a negative effect on the development of modular dominant design.

P2. Firms' accumulated experience and knowledge, concerning both system design and components' technology, have a positive effect on the development of modular dominant design.

Modular products are characterized by the functional isolation of components that interact via open standard interfaces. Baldwin and Clark (1997) well documented how modularity became widespread in the PC industry when the Wintel technology and the related standards became dominant. These standards emerge when stakeholders are interested and favor their diffusion. Stakeholders include a) leading firms producing core components at a high level of the product architecture that more than other affect the product functioning and performance, such as the microprocessor in a PC, b) suppliers of complementary components that adopt the standards and c) the clients that prefer products or components with compatible interfaces. d) Finally, other stakeholders, such as public institutions or other organizations, may favor the standards promotion.

In the bicycle industry, Galvin and Morkel (2001) well document the relevance of standards that were favored by the existence of few big firms specialized in few components produced in limited variants due to high pressure on costs competition. Crespo *et al.* (2016) analyze the European mobile phone industry and emphasize the modularity of its products. They also acknowledge that European organizations and public authorities have been crucial for the establishment of common standards, such as the GSM standard, that enhanced the diffusion of a modular dominant design and of mobile phones. Also organizations and associations of buyers and suppliers may be willing to promote the diffusion of particular architectures and standards thus favoring modularity (Vakili, 2016).

Hence, an important question is what drives the dissemination of modular architectures with open standard interfaces. While the above forces, described in propositions 1 and 2, explain under which conditions modularity is technically feasible, the following forces explain in which networks modularity is more likely to diffuse and under which conditions modularity is a convenient strategy for the main stakeholders. Modular architecture diffusion is correlated to firms' network structure, appropriability and strategy issues (see table 4).

3.2 Leading firms and network structure

Modular dominant designs are more likely to emerge in industries where leading firms exist and dictate the architecture of products acting as focal firms in networks. Leading firms produce core components and core subsystems that have the greatest influence on the overall product performance and design. These firms produce components higher up in the hierarchy and have the highest control over products' technology performance and development. Leading firms produce one component within the architecture that is central for the architecture itself and the performance of the product. Leading firms are not necessary OEMs (Murmann and Frenken, 2006).

When core components exist and become dominant then leading firms dictate product architecture features. In this context suppliers and firms producing complementary components have the incentive to adapt their components' architecture to that of core components. This process promotes the diffusion of core components' standards and freezes tasks portioning between components. This happens in the PC industry where we have leading firms producing core components that dictate the standards ensuring components' compatibility, i.e. Intel and Microsoft (Baldwin and Clark, 1997; Tegarden *et al.*, 1999). A similar concept is suggested by Gawer and Cusumano (2008) who write that platforms, which share some properties with modular design, become widespread at the industry level when other firms are convinced of adopting this technology because it performs a function essential for the whole product or technological system. At the same time leading firms may have relevant benefits by modularizing and hence by standardizing core components or core interfaces of the system: without standardization designers may become overwhelmed by the need of developing new technologies and the parallel need of ensuring compatibility with peripheral components produced by external suppliers.

Crespo *et al.* (2016) analyze the European mobile phone industry and emphasize as mobile phones have undergone a process of technological convergence and today they integrate similar functions and technologies, such as digital camera, music player, GPS, Internet services and they display a modular architecture. The authors also emphasize the relevance of networks and of leading firms in this setting. For example in Europe leading firms, such as Nokia or Ericsson, were able to coordinate the network of suppliers holding complementary knowledge and were able to integrate them in a systemic and complex technology. Also Funk (2003) and Funk (2008) show that the success of mobile phone OEMs in the definition of a modular dominant design were strictly related to their ability to coordinate a critical mass of complementary products and partners. In the low end of the bicycle industry leading firms, such as Shimano, produce core components that belong to the category of mechanical parts, such as the gear, that affect crucial interfaces with other subsystems (Galvin and Morkel, 2001; Fixson and Park, 2008). Also in the air conditioning industry there exist core components, such as the compressor, that dictate multiple interfaces within the product architecture (Cabigiosu and Camuffo, 2012).

But when leading firms opt for high levels of vertical integration, we do not expect the emergence of a modular dominant design because leading firms have fewer advantages in modularizing their products and opening their standards: firms risk loosing the control of their standards, as happened for IBM, and face the costs of modularizing an architecture whose benefits in terms of performance and coordination are somehow limited by the fact that integration and hierarchy ensure a better coordination between development teams than the market. Modularity is favored when leading firms have a lower degree of vertical integration and rely on innovative suppliers producing complementary components. In this context modularity eases the collaboration and integration of external sources of innovation and leading firms are more willing to open and share their interfaces (Hoetker, 2006; Sanchez and Mahoney, 1996; Wolter and Veloso, 2008). Also modularity and open standard interfaces increase leading firms' core components compatibility with multiple complementary components.

P3. The existence of leading firms producing core components, which are widespread at the industry level, positively affects the development of modular dominant designs.

P4. Leading firms' level of vertical integration has a negative effect on the development of modular dominant design.

P5. The existence of a network of specialized suppliers producing system components and complements positively affects the development of modular dominant designs.

Propositions 4 and 5 emphasize that modular dominant design emerges in an industry characterized by high division of tasks and specialization. While these propositions are in-line and consistent with the majority of the modularity literature, the dominant design literature also argues that appropriability is a relevant variable explaining the convergence of multiple firms around the same design. Firms must have the convenience of adopting modular architectures.

3.3 Leading firms and appropriability

In the above sections, building on the dominant design literature, we have suggested as leading firms play a crucial role in explaining when modular dominant design emerge. Hence in this section we debate the appropriability issue focusing on these firms. Leading firms have a competitive advantage compatible with a modular architecture if they provide core modules for a network of compatible components and at the same time they are able to protect their technology, architectures and rents. If the appropriability (the firm's ability to capture the profits generated by innovation (Teece, 1986)) of rents deriving from individual/components innovation is high hence modular design is more likely to emerge. If the appropriability is risky, hence vertical integration and proprietary standards are more likely to emerge. But modular dominant designs do not emerge if market leaders introduce and base their competitive advantage on integral and closed designs. This is especially true after the IBM case, which shows how appropriability issues affect the convenience of pursuing a modular strategy in system design. In the PC industry leading firms started making extraordinary profits while IBM, which generated the modular architecture, lost the control of its standards. Today, Microsoft and Intel make supernormal profits by controlling key software and hardware standards (operating system and processor architecture, respectively). In fact, a change in microprocessor lead to high switching costs for the PC manufacturer because semiconductor manufacturers often produce unique and incompatible designs. PC software and drivers for peripherals are designed around the microprocessor (Baldwin and Clark, 1997). Therefore, PC makers face high switching costs that increase Intel's bargaining power (Tegarden *et al.*, 1999). Possessing tremendous bargaining power, Intel and Microsoft capture a large share of PC industry profits. Microsoft and Intel's bargaining power and defense of valuable standards make it harder for systems vendors, like HP or Lenovo, to differentiate their computers and develop new competing architectures. When leading firms have a high bargaining power they impose their standards. Hence while appropriability matters for all networks participants, as suggested by Murmann and Franken (2006), here we emphasize how appropriability is crucial for leading firms.

In fact leading firms may opt for alternative strategies if they perceive that closed architecture can be more easily defended and generate higher profits. In the same industry, Apple opted for a closed architecture and a tight coordination between its hardware and software platforms and between its on-line services. Apple decided to control user interfaces to benefit from network externalities between its proprietary products such as IPod, ITune software and iTunes store (Dedrick *et al.*, 2009, p. 99). This strategy increased Apple control over its products' architecture and the related appropriability but it also reduced the differentiation of its products (less combinability options and less complements available), reduced product variants and increased prices. This was also the case of the automotive industry which at the end of the twenty century invested in modular architectures but when carmakers faced appropriability issues they make a step back and being the leading firms they dictated the dominance of closed architectures and standards. While platforms are widely diffused carmakers maintain the control and the property of its own designs (Jacobides *et al.,* 2016). Therefore, modularity emerges when leading firms producing core components do not integrate in the production of multiple complementary components and leave space to other specialized players. If leading firms benefit from innovation at the core components level the requirement of appropriability is satisfied (Gawer and Cusumano, 2014). Under these circumstances, focal firms act as the architecture leaders enabling the development of modular dominant designs at the industry level. Finally, the high appropriability of leading firms should not overt the economic convenience of the other network partners. As Gawer and Cusumano (2014) explain, once leading firms have established their technologies, then networks effects are crucial in explaining their success. Modularity may facilitate third-party innovation generating relationships that are beneficial for all networks participants that remain stick to that architecture and have limited incentive to change it. Suppliers and firms producing complementary components will converge around a modular design if this is an economically and strategic convenient compromise: they will be more likely to adopt a modular product architecture based on the leading firms' standards if they have both economic and strategic convenience. This usually happens when development costs are high and the break-even difficult to reach and clients ask mass customized products. All in all these arguments suggest an-inversed U-shaped relationship between appropriability of leading firms and the emergence of a modular dominant design.

P6. The appropriability of rents of leading firms has an inverted U-shaped relationship with the diffusion of modular dominant designs.

The competitive landscape in which firms have the economic and strategic convenience to adopt modularity is described in the following paragraphs.

3.4 Complements, mass customization, and network externalities

Firms have the convenience to adopt a modular dominant design if there is a wide segment of clients that asks differentiated products at low price (mass customization and not pure customization). In this context modularity allows a more efficient division of labor. Firms aiming to compete on cost and differentiation will seek to increase the variety and number of product variants and complementors by relying on modular architectures and open standard interfaces (Sanchez and Mahoney, 1996). As Campagnolo and Camuffo (2010) argue modularity is based on the notion of mix and match of modules to obtain new and multiple product configurations without loss of functionality across modules and platforms of multiple firms (open modularity). Clients favor modular architectures because they ensure multiple applications of modules and their compatibility to multiples platforms in time (future and backward compatibility). In many industries consumers expect interoperability of components and high speed of change. In markets where customers assemble their own products, such as stereos, the locus of sustainable advantage may shift from individual product positions to product platforms or families (Pil and Cohen, 2006).

Hence even the largest firms often work with wide supply networks to bring new ideas to the market. Innovators need to coordinate to varying degrees with a large number of firms to ensure a supply of complements in order to maximize the total value proposition, while also positioning themselves to capture as much as possible of the value that is created by the network (Dedrick *et al.*, 2009). In these industries, modular dominant design may ease such coordination process via the adoption of the same architecture and standards. Also in these networks modular dominant designs ensure higher modules interoperability and compatibility across multiple platforms thus leveraging firms' economies of scale as well as learning curves at the component level (Shibata *et al.*, 2005). In these contexts modular architecture may exploit to the fullest the network externalities typically correlated to dominant architectures (Dowel and Swaminathan, 2006). In this case firms may be willing to produce for open product platforms and modular designs. In this context modular dominant design may increase the convenience of managing specialized and eventually small segments or niches, as happened in the regional jet industry (Vertesy, 2017). Modularity is also relevant to ease after sale services and the development of substitutive components (Argyres and Bigelow, 2010).

P7. Competition based on mass customization of final products has a positive effect on the diffusion of modular dominant design.

P8. Competition based on components interoperability and availability of complements has a positive effect on the diffusion of modular dominant designs.

3.5 Imitation as a strategy

An additional explanation to modular architecture diffusion may be found in the imitation literature. Modularity eases reverse engineering (Ethiraj *et al.,* 2008; Pil and Cohen, 2006; Schulze *et al.,* 2015) and firms willing to imitate competitors may favor this architecture.

Lieberman and Asaba (2006) suggest that firms imitate competitors with similar size and resources to maintain competitive parity, i.e., rivalry-based imitation, or imitate the most successful competitors when environmental uncertainty is high, because they are perceived as having superior information about future market trajectories, i.e., information-based imitation. Coherently, Burganza and Vergati (2006) suggest that in uncertain and turbulent environments, open modular architectures and platforms increase firms' opportunity to benefit from externally defined technologies. Lieberman and Asaba (2006) also suggest that managers imitate to legitimate their actions in uncertain and turbulent environments. In all these cases followers may favor modular architectures, which are among the easiest to imitate, and modularity may dominate the industry, as happened in the PC or mobile phone industry.

Also clients may prefer modular products in uncertain environments. With modular architectures it is easier for clients to find expert users that experienced either the platform and/or the new module thus further reducing the perceived uncertainty. Furthermore modular architectures ensure the possibility to more easily integrate and mix and match innovative modules in multiple platforms, old or new, thus reducing clients' efforts to buy the new technology and to learn how to use it (Afuah and Bahram, 1995). The components of a modular system usually more easily accommodate functional substitutes that allows modifying or up-grading the existing product (Jacobides, Knudsen et Augir, 2006).

Overall, modularity may favor the bandwagon effect not only of firms that imitate competitors but also of clients that imitate lead users. In this context stakeholders, other than leading firms, play a central role in the diffusion of an architecture and the related standards. This is the IBM case that developed the first modular PC, the system 360, that was soon copied by competitors and IBM was not able to protect its standards (Baldwin and Clark, 2000). Consequently we argue that modular products higher imitability, flexibility and adaptability during product life-cycle better fit uncertain environments and contexts in which stakeholders favor imitation strategies. This also explains why we predict in proposition 6 an inversed U-shaped relationship between appropriability of leading firms and gains of other stakeholders. While leading firms may willing to favor modularization process if they can maintain some control over their architecture, at the same time some level of imitation may favor the diffusion of modular architectures. Hence our last proposition follows:

P9. Imitative behavior of stakeholders has an inverted U-shaped relationship with the diffusion of modular dominant designs.

4. Discussion and conclusions

Dominant designs are relevant in explaining competitive dynamics and several authors predicted that modular designs, in particular, would play a crucial role. In this context Melissa Schilling (2000) identified the forces that better than other explain when modularity emerges. Particularly she suggests that modularity allows better answering to clients' quest for variety and innovation when multiple inputs are available. She also suggests that technological change may push toward modular architectures. But the analysis of the dominant design literature shows that not only variables associated with the competitive landscape and the technology affect the likelihood that a dominant design emerges. Network dynamics and appropriability issues are also crucial. For a dominant design to emerge, firms in an industry must have the convenience to adopt such design and must converge around the same architectural and technological solutions. Furthermore, recent contributes offer a deeper understanding of the interplay between product architecture and innovation management by suggesting when engineers are more likely to modularize products.

The Schilling's framework emphasizes the attributes of modules that favor their diffusion, such as functional isolability, but scholars made a step back asking under which conditions technologies and products can be modularized. This is probably the wider reflection performed by the modularity literature asking why only in some industries modular designs emerge. Propositions 1 and 2 suggest that in case of highly complex products and a high pace and level of technological change, modular dominant designs are less likely to emerge due to system integration and performance issues that limit the possibility to develop functionally isolated modules with standard interfaces. Such issues exist also when engineers aim at developing modular and incremental innovations because they strive to cluster components interdependencies within modules' boundaries. Contrary to many predictions about the relevance of modularity to ease modular and incremental innovations (Sanchez and Mahoney, 1996), the most recent contributes show that even such innovations may generate technological imbalances and firms must be cautious in swapping modules that embody new technologies (Furlan *et al.* 2014). Modularity is more likely to emerge when technology is mature and well known, innovation is mainly incremental and for low complex products. Only under these circumstances engineers are effective in innovating modules independently one from another.

Second, technological feasibility of modular architectures does not ensure that stakeholders will embrace modular architectures because network dynamics and firms' appropriability issues also matter. Building on the dominant design and modularity literature we argue that leading firms producing core components play a crucial role in explaining when modularity becomes widespread (P3). Leading firms are the network orchestrators that design and produce the product core components that more than others affect the product architecture and the overall product performance. Hence, leading firms' propensity to modularize their components and opening up their architecture to a network of specialized suppliers favor the diffusion of industry standards and that of modular architectures. In this respect we suggest that leading firms are more willing to modularize their components when they need external and specialized partners (P4 and P5) and they can protect their rents (P6). Leading firms will be more prone to open their architecture and standards if they do not fear to loose their control and the related rents. Symmetrically, external partners will favor the diffusion of modular architectures (by employing leading firms' product architectures) if they still have positive rents (P6). Especially after the negative experience of IBM, which modularized the PC architecture but then lost the control of its standards, leading firms are now more cautious as documented in the automotive industry. The IBM case recalls the relevance of another force that may shape industry dynamics: imitation (P9). If stakeholders, such as competitors, clients and institutions, perceive that imitation of an existing architecture provide them benefits, they will favor the diffusion of that architecture and modular architecture are easier to imitate. But a too high imitability can discourage leading firms (P9).

Finally, in this study we also emphasize as both the dominant design literature and the Schilling's framework are coherent in suggesting that leading firms and suppliers will be more likely to favor modular architectures when competing in environments where mass customization, network externalities, and the availability of complementors are all relevant (P7 and P8).

Overall, this article has the merit of having clearly emphasized how modularity diffusion is technologically constrained. While modularity literature argue that modular architectures reduce product complexity this contribute ads that this happens for products with a mature technology and a moderated level of complexity, thus somehow limiting the power of modularity. Second this study creates a bridge between dominant design and modularity literature by emphasizing their points of connection and the role of multiple stakeholders and network dynamics. Particularly in this study we emphasize as multiple stakeholders must have the convenience to opt for a modular architecture and among them we underline the role of leading firms producing core components that heavily influence product architecture and, under specific circumstances, may favor open modular architecture and the division of labor across firms. The existence of leading firms producing core components with a low level of vertical integration and high appropriability of rents all favor modular dominant design. Finally, we add that modular architectures higher imitability, which has been seen as a limit of modular architectures, may in turn favor their diffusion exactly in those contexts in which imitation as a strategy is valuable for firms and clients.

It is our hope that the broader conceptualization and comprehensive model presented here will stimulate additional interest in this topic and will encourage more research that tests and explores under which circumstances modular designs are effective and become dominant in an industry. Furthermore most of the analyzed studies are still focused on a limited number of industries and employ constructs, such as the definition of product modularity, that should be compared cautiously. Future studies may empirically test the propositions presented and also consider interaction and casual effects between the forces identified in this study.

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