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Mirroring or misting:

On the role of product architecture, product complexity,

and the rate of product component change

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Abstract

This paper contributes to the literature on the within-firm and across-firm mirroring hypothesis – the assumed architectural mapping between firms' strategic choices of product architecture and firm architecture, and between firms' architectural choices and the industry structures that emerge. Empirical evidence is both limited and mixed and there is evidently a need for a more nuanced theory that embeds not only whether the mirroring hypothesis holds, but under what product architecture and component-level conditions it may or may not hold. We invoke an industrial economics perspective to develop a stylised product architecture typology and hypothesise how the combined effects of product architecture type, product complexity and the rate of product component change may be associated with phases of mirroring or misting. Our framework helps to reconcile much existing mixed evidence and provides the foundation for further empirical research.

Keywords: Product architecture; Modularity; Organisation structure; Technological change; Mirroring hypothesis

INTRODUCTION

The coordination of complex product development has a long tradition (ie, Galbraith, 1977; Williamson, 1971) and more recently theorists within the modularity tradition have hinted at the potential benefits of a "mirror" between the structure of a product development firm and the technical product it designs (Henderson and Clark, 1990; Sanchez and Mahoney, 1996, Baldwin and Clark, 2000). Despite a growing literature on the so-called "mirroring hypothesis", there remain renewed calls for a more nuanced and contingent view of the phenomenon (Colfer and Baldwin, 2010; Cabigiosu, Zirpoli and Camuffo, 2013; Furlan, Cabigiosu and Camuffo, 2014) especially in terms of not just whether it holds, but when it holds. Put plainly, the mirroring hypothesis seeks to examine two important and pervasive relationships: the extent of an architectural mapping between firms' strategic choices of product architecture and firm architecture – within-firm mirroring - and between firms' architectural choices and industry structures – across-firm mirroring.

In a recent literature review of empirical studies concerning the mirroring hypothesis, Colfer and Baldwin (2010) find that the hypothesis received *uniform support* in 68% of 'within-firm' cases and 47% of 'across-firm' cases, but found notable exceptions[1]. In the case of the within-firm studies, exceptions were classified into two types – where a co-located, interdependent product development team within a single firm designed a modular architecture consisting of mainly independent components, such as Lehnerd (1987) study of Black and Decker and MacCormack, Rusnak and Baldwin (2006) study of browser software. In addition, a single case in software development was noted where interdependent product development was undertaken by geographically-dispersed contributions (Srikanth and Puranam, 2007, 2008). The exceptions to the across-firm mirroring hypothesis were examples of firms developing a modular product without movements of activities to external firms (for example, case studies by Sosa et al, 2004 in aircraft and Hoetker, 2006 in the notebook computers); independent firms developing an interdependent product (for example, Helper,

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[1] Colfer and Baldwin (2010) found uniform support for the within-firm mirroring hypothesis in 68% of studies, but 77% supportive when partial or mixed results were incorporated. Similarly, the across-firm mirroring hypothesis found uniform support in 47% of studies, but 74% when partial or mixed results were incorporated

Macduffie and Sabel, 2000, in the motor vehicle industry and Staudenmeyer, Tripsas and Tucci, 2005, in software), or, where a group of firms depend on extensive information-sharing to resolve complex architectural or system-wide issues (Brusoni, Pencipe and Pavitt, 2000, Brusoni and Prencipe, 2001).

Despite calls for a more nuanced view, the literature review by Colfer and Baldwin (2010), however, doesn't throw any light on whether the product architecture type, its complexity or the rate of product component change is associated with degrees of mirroring or misting. Empirical work has started, however, in this direction with a few studies in air-conditioning and motor vehicle industries. Furlan, Cabiguso and Camuffo examine the across-firm mirroring hypothesis in the air-conditioning industry, and find that the 'mirror' becomes misted by high rates of product component change, with firms engaging in rich collaborative relationships, even where the underlying components had modular characteristics. Writing with Zirpoli, Cabigiuso and Camuffo (2013) in a study of the motor vehicle industry, suggest that the mirroring hypothesis may become misted as firms seek to integrate external sources of innovation into complex product development.

We draw upon these initial contributions. However, many conceptual contributions to the mirroring hypothesis product architecture types as perfectly modular or perfectly integral (ie Sanchez and Mahoney, 1996) – and yet as few product architectures exhibit these 'perfect' characteristics, this conceptual paper aims to offer three important theoretical contributions: firstly, we extend the work of Ulrich (1995), Sanchez (2008) and Sanchez, Galvin and Bach (2012) to develop a stylised product architecture typology that contributes to the existing literature by enhancing our understanding of product architecture types; secondly, we introduce the idea of hybrid product architectures to the mirroring literature; and, thirdly, we hypothesise how the effects of product architecture type may be synthesised with the underlying rate of product component change to associate the joint effects with phases of mirroring or misting.

By doing this, we believe this paper is the first to show how factors at both the product architecture and the underlying component level may influence the degree mirroring and misting. We also draw attention to the potential proxy measures for mirroring or misting used in the extant literature, and highlight the need for uniformity.

We develop a more systematic and contingent view of the mirroring hypothesis that helps uncover when mirroring or misting may emerge or even be beneficial; and hence, it is important for managers to understand how these factors may influence the trade-off between high levels of information-exchange to spur innovation and the possible 'embedded coordination' benefits of modular structures. Our framework helps to reconcile much existing mixed evidence and provides the foundation for further empirical research.

THEORY AND RESEARCH CONSTRUCTS

Typology of product architectures

In any given product market, it is possible that a number of different architectures might be strategically feasible, each with different combinations of performance, quality or cost. A more complete understanding of how different product architectures emerge and then establish themselves, as well as how such architectures correspond to firm and industry architectures is therefore a critical issue for academic research. The concept of products having an *architecture* has been well-established in the literature (Ulrich, 1995; Sanchez and Mahoney, 1996; Baldwin and Clark, 2000). In defining product architecture, many theorists adopt a definition that encompasses the relationship between a product's functions, its components and its interfaces; Sanchez and Mahoney (1996) suggest that a product architecture is " *a way in which the total functions that a design is intended to achieve have been decomposed into specific functional components, and secondly, it defines the way in which the functional components that make up the design will interact when the components function together as a system – known as the interfaces*". (p64) Ulrich (1995) classified product architectures into two 'ideal types' – integral or modular. At one end of a continuum, an integral architecture is where the components, interfaces and their relationship is complex, interdependent and non-standardised. At the other end of the continuum, a modular architecture has relationships between components and interfaces that are simple, independent and standardised.

The integrated - modular continuum

Modularity theory is based upon the notion of the decomposability of a system into subsystems or components (Simon, 1962, Alexander, 1964) and information-hiding and parallelism, (Parnas, 1971, 1972, 1978) which have focused on the potential advantages of partitioning complex systems into smaller modules[2] in such a way that their interdependence with each other is either substantially reduced or fully removed. The characteristics of product architectures, therefore, often differ fundamentally in the degree to which

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[2] We will refer, in this paper, to components rather than modules

components and interfaces are independent or interdependent (Ulrich, 1995). The degree of independence/interdependence depends upon the extent to which a change in the design of one component requires design changes in other components.

Product architectures with significant integrated characteristics are often created to serve a single use or product market (Sanchez, 2008), but often the complexity and interdependence between components in such architectures often means that they cannot be easily adapted without redesigning the entire architecture or many other interdependent components (Ulrich, 1995). Often, an integrated product architecture is one that has been designed for strategic optimisation, such as maximum performance or lowest cost (Sanchez, 2008) resulting in significant interdependencies being 'designed in' to the architecture throughout an often sequential product development process (Baldwin and Clark, 2000). There is often, therefore, a trade-off for firms in deciding between architectural choices for product design: integrated architectures may offer performance or cost advantages in the product market, and they may often be instrumental in enabling firms to reap significant rents from investments in 'specific' assets (Sanchez, 2008; Sanchez, Galvin and Bach, 2013). However, it is often a decision to forego product variety and collaboration with other external firms that may inhibit the eventual widespread adoption of the product architecture, increasing the risk of technological 'lock out' (Schilling, 1998, 2002).

Modular product architectures are a design where components are loosely-coupled – interdependencies exist within components but not across or between components (Simon, 1962; Baldwin and Clark, 2000) - and such architectures can either emerge or be purposely developed through a process of specifying design rules (Baldwin and Clark, 2000, Sanchez, 2008). The design rules establish the 'blueprint' of the product architecture as well as the interface specifications between the architecture and its independent components. The design rules can also determine which properties are 'hidden' within components and which are 'visible' to other components (Parnas, 1972). If the interface specifications between components are open and standardised in a product market and held constant for a period of time, modular product architectures may permit a large variety of components to 'plug and play' (Sanchez, 2008; Sanchez and Mahoney, 2013), such that they are often easily substitutable without compromising the interoperability of other components.

Modularisation often therefore creates 'thin crossing points' in the product architecture, breaking up interdependencies that may generate the potential to use market-based transactions without the need for extensive managerial control (Baldwin, 2008). Modular product architectures, therefore, can often provide a form of "embedded coordination" (Sanchez and Mahoney, 1996; Galvin and Morkel, 2001) that supports in-parallel component development by loosely-coupled teams or even loosely-coupled organisations (Sanchez and Mahoney, 1996).

Many authors have stressed the potential benefits of perfect or near perfect modular product architectures (Sanchez and Mahoney, 1996; Schilling, 2000; Galvin and Morkel, 2001). Modular architectures may often permit significant product variety (Sanchez, 1995; Ulrich, 1995, Baldwin and Clark, 2000) because upgrades can be easily leveraged (Brusoni and Prencipe, 2001) and the mixing and matching of modular components may give a potentially large number of product variations (Ulrich, 1995; Schilling, 2000; Sanchez and Mahoney, 1996; 2013), and, as such, can be a source of strategic advantage (Sanchez, 1995) by enabling a firm to respond more quickly to evolving or segmenting product markets. In addition, modular product architectures can often provide firms with significant positive network externalities (Sanchez, 2008) and mitigate transaction hazards (Schilling, 1998, 2000, 2002), as it supports the increased availability of complementary goods and the convergence of buyers and suppliers around a particular architecture.

The open and closed continuum

Product architectures may also be conceptualised along a continuum of being either open or closed (Shibata, Masaharu and Fumio, Sanchez, 2008, Sanchez, Galvin and Bach, 2013). A perfectly closed architecture is one that is not able to be used by other firms; it is proprietary and a firm may hide, encrypt, patent or copyright components and interface specifications (Sanchez, Galvin and Bach, 2013). When a product architecture is both closed and integrated, there is the potential for a firm to extract significant rents and to sponsor its architecture as a potential dominant design by investing in the creation of its own 'externalities' through pricing, marketing and branding (Sanchez, 2008; Schilling, 1998, 2002). However, a closed product architecture does not always exhibit integrated characteristics. It may also exhibit closed and modular

characteristics if a firm expends significant effort, time and resources to understand and minimise component interdependencies within firm boundaries. This process may involve strategically partitioning and decomposing the integrated architecture into modular components and 'specialised' (or 'firm-specific') interfaces (Schilling, 1998, Fine, Golany and Naseraldin, 2005). Closed and modular product architectures, therefore, may offer a firm the potential to benefit from both rent appropriation, as well as increase product variety through mixing and matching firm-specific or self-manufactured modular components.

In contrast, a perfectly open architecture is one whose interface specifications are open and standard, dispersed across firms in an industry in order to support widespread interoperability, unencumbered by IPR and other means of secrecy, and firms interested in developing components or complementary goods can often 'plug and play'. Sanchez (2008) argues that "*open-system architectures allow firms to access an architecture, they may create gains from trade, as well as significant positive network externalities, both for firms that participate in a product market based on an open architecture and for users or consumers of products and services leveraged from open-system architectures*" (p342). However, use of modular designs may also limit the technological design space for potentially important interactions and interdependencies between and across components, consequently resulting in a failure to optimise performance, quality or cost. As open and modular product architectures may also invite speedy imitation by competitors, differentiation and competitive advantage arising from modularisation may erode quickly for all participants within the value chain perhaps leading to a reversal of gains from trade. Hinting at need for hybridity, Henkel, Baldwin and Shih (2012) sum up, "*controlling too much of a system's IP is problematic if it deters innovation by others. Controlling too little –, or the wrong parts – may prevent the focal firm from capturing value or expose it to the risk of hold-up*" (p1).

Intermediate or hybrid architectures

Product architectures may either be open or closed, integrated or modular, however, some product architectures are not easily classified along these continuums. Firms may often control the degree of openness or modularity of their product architectures, perhaps seeking to control which components are proprietary and which are not, and which interface specifications are specialised and which are open and standardised. In other words, a firm can pursue an architecturally-hybrid product strategy and potentially exert some degree of influence or control over the openness of the product architecture. Such intermediate or hybrid architectural strategies are particularly amenable to product systems (Katz and Shapiro 1994) made up of multiple components, which can be often opened or closed one component or interface at a time.

Hybridity of product architecture may resolve some of the inherent conflicts in the strategy or modularity literature. On the one hand, strategy research (see, Porter, 1991) suggests that complexity deters imitation and sustains competitive advantage. On the other hand, the modularity literature suggests that reducing design complexity can help firms become more flexible and adaptive (Baldwin and Clark, 2000). The hinted-at end result is that although modularity may infer some strategic benefits, particularly over the short-term, it also opens up a firm to imitators and so "ignores the durability of such gains" (Ethiraj, Levinthal and Roy, 2008: p953). Intermediate or hybrid product architecture may also allow a firm to maximise what West (2003, 2007) has called the appropriation versus adoption trade-off. In opening access to selected components and interfaces and exchanging architectural IP with external firms may allow a firm to benefit from gains from trade, positive network externalities and the potential to mitigate transaction hazards involved in market contracting. On the other hand, controlling and restricting access to other proprietary components may capture appropriable rents and maintain sources of differentiation and competitive advantage.

In seeking to balance these trade-offs across the integrated/modular and open/closed continuums, many scholars have argued that intermediate modularity often produces the most useful innovations and argue that nearly modular structures often provide the best trade-off between incremental innovation and imitation deterrence (Fleming and Sorensen, 2001; Ethiraj, Levinthal and Roy, 2008)

>>>insert figure 1 about here<<<

In this section, drawing upon the work of Sanchez (2008) and Sanchez, Galvin and Bach (2013) we have proposed four stylised product architecture types: closed and integrated; closed and modular; intermediate and hybrid; and, open and modular. We tentatively present these four 'types' as a continuum. We have not presented our typology as a two-by-two matrix with axes labelled open/closed and integral/modular as, like Shibata, Masaharu, and Fumio (2005), we cannot envisage a product architecture type in practice that could be classified as open and integral.

We now turn our attention to the idea of mirroring, the assumed architectural mapping between firms' strategic choices of product architecture and firm architecture, and between firms' architectural choices and the industry structures that emerge.

Mirroring or misting

The idea of mirroring has its roots in many different disciples. In organisational design, it has been argued that firms should be designed to reflect the nature of the tasks they perform (Lawrence and Lorsch, 1967) and in the industrial economics literature, firms exist to solve the contractual challenges associated with tasks that possess different levels of uncertainty (Williamson, 1985) such that governance modes should reflect 'discriminating alignment' and that discriminating alignments will be observed much more frequently than misalignments, since misalignments 'invite their own demise' (Williamson, 1996). Weick (1976) and Orton and Weick (1990) were also the first scholars to characterise firms as complex systems with differing degrees of coupling.

To this extent, it is conceivable that firms and products should be architecturally aligned (Von Hippel, 1990; Sanchez and Mahoney, 1996; Henderson and Clark, 1990; Fine, 1998; Baldwin and Clark, 2000). As modularity is a general concept that can be applied to many types of systems (Schilling, 2000), it is a notion that could apply equally to the analysis of firm architecture (Colfer, 2007). In effect, theorists have suggested that the architecture of a firm may often be a mirrored reflection of the underlying product architecture - what has later been termed the 'mirroring hypothesis' (Colfer, 2007). Colfer went on to clarify that the concept of a modular firm architecture "*is one that is partitioned into distinct organisational entities (ie, individuals, teams and firms) that are narrowly specialised, nearly independent and easy to remove or replace because they interact through simple, standardised exchanges*" (p1-2). In contrast, an integrated firm architecture is one that "*lacks partitioning into specialised parts, or is partitioned, but whose parts are tightly integrated and difficult to remove or replace because they interact through rich, tacit interfaces*" (p2). In sum, then, the mirroring hypothesis suggests that an integrated firm architecture is perhaps optimal for developing an integrated product architecture and a modular firm architecture is necessary and perhaps optimal for developing a modular product architecture.

Colfer (2007) identifies four types of architectural structure that are amenable to mirroring: the product; the firm; the division of labour and the division of knowledge (p4). She suggests that the target for modularisation and mirroring is not always the same as it depends upon the architectural layer under examination. For example, in the case of the product architecture, the target for modularisation is often the interdependencies across components. Secondly, in the case of the firm, the target is often the communication patterns and relationships between the organisational actors who develop the product (such as individuals, teams, firms). Thirdly, in the case of the division of labour, the target is the technical interdependencies across the component development tasks of different firms. And, finally, in the case of the division of knowledge, the target is the technical interdependencies across the information/skill sets required to perform the product development tasks. Summarising the different targets for mirroring, Colfer (2007) suggests that we can talk of a 'within-firm' mirroring – the extent of architectural similarities between the product and the product

development firm – and an 'across-firm' mirroring – the extent of architectural similarities between the product and the division of labour and/or division of knowledge across firms.

The mirroring interface

While the mirroring hypothesis examines the relationship between one structural layer of a system and another, Colfer (2007) observes that differences exist in how scholars define the relationship between architectural layers. Colfer and Baldwin (2010) argue that an 'ideal test' of the mirroring hypothesis is one that analyses how product architectures may relate to other layers and would seek to examine organisational ties such as firm co-membership; geographical co-location; or, formal and informal communication, suggesting that it is then possible to see whether "*a technical dependency was correlated with the presence (or absence) of a given type of organisational tie*" (p6). Orton and Weick (1990) suggested that organisational coupling could be assessed along a number of dimensions, such as geographical proximity or shared values, for example, which represent a continuum along which participants will vary. Drawing upon these contributions, one feature of the mirroring literature is that the 'organisational tie' used as a proxy for mirroring is not uniform across empirical studies which may yield inconsistent results. In this paper, we suggest that the degree of mirroring between product and firm architecture could be assessed along a number of dimensions such as firm co-membership, geographical proximity or distance, or the extent of information exchange between individuals, teams or firms, as shown in Figure 2.

>>>insert figure 2 about here<<<

For example, individuals or teams within the boundary of a single firm share co-membership of the firm. As such, the within-firm mirroring literature tends to focus on an 'organisational tie' as the presence or absence of patterns of information-exchange or geographical proximity (Colfer and Baldwin, 2010). This is perhaps entirely logical. For example, extending the usual logic of product modularity to firm modularity then communication should be higher within the component development team (high information-exchange) than with other component development teams (low information exchange), which may permit component development teams to be geographically dispersed. Similarly, where a product component is highly interdependent with other components, information exchange is likely to be high and this often means that individuals or teams need to be co-located.

In the across-firm literature, product development activities takes place across two or more firms, and therefore mirroring has tended to focus on whether the partitioning of development activities across firms mirrors the underlying component independencies/interdependencies of the product architecture. Colfer and Baldwin (2010) argue that "*to make interdependent contributions to a product's design, people must exchange information openly and resolve design conflicts efficiently*" (p13). Often, therefore, interdependent product components are more efficiently designed, and dispute-resolution more easily handled, within the boundaries of a single firm. Information exchange is often easier and more efficient as individuals (or teams) share co-membership and often geographical location. Within the boundaries of a single firm, product development actors are also often compatibly motivated and therefore ease of communication, as opposed to coordination, is the central concern (Colfer and Baldwin, 2010).

It is therefore likely that to move product development activities outside the boundaries of a focal firm requires a modular product architecture with clearly defined component boundaries and visible interface specifications in order to reduce transaction hazards associated with market contracting. Cabigiuso and Camuffo (2012) suggest that a modular product architecture "*reduces the need for "hand-in-glove" supply relationships, because knowledge encapsulation within modules lowers inter-firm interdependence and, hence, coordination and control needs*" (p687). Modular product architectures which support information-hiding within components

may often reduce the need for information exchange between firms, providing interfaces are open and shared. Firms that design modular components with open interface standards do not need to exchange information about the inner workings of a component because the open interface standard ensures it will fit into the overall product architecture and its design will not affect the subsequent design of other components. As a consequence, 'hand-in-glove' supply relationships are often unnecessary and that this makes possible "*the concurrent and autonomous development of components by loosely coupled organisation structures*" (Sanchez and Mahoney, 1996: 64). In sum, the usual logic is that modular product architectures are often associated with market contracting.

As the product modularity literature is grounded in the central notion of information-hiding (Parnas, 1972), and embedded coordination (Sanchez and Mahoney, 1996), we are associating the extent of mirroring between products and firm architectures as dependent upon the amount of information exchange (Furlan, Romano, and Camuffo, 2006; Cabigiousu and Camuffo, 2012; Furlan, Cabigiosu and Camuffo, 2014) between organisational actors – either within or across-firm, and we will call the 'organisational tie' used to assess the extent of mirroring between architectural levels, the *mirroring interface.* In this paper, the mirroring interface is the amount of information-exchange between individuals or teams within firm boundaries (in the case of closed and integrated and closed and modular product architectures) or between contracting firms (in the case of open and modular product architectures). Hybrid product architectures may naturally exhibit both high and low levels of information exchange both within and across firm boundaries characteristics, dependent upon the integrated/modular characteristics of each underlying component in the product architecture.

Nuancing the mirroring hypothesis – product complexity and the rate of product component change

Despite empirical research on the mirroring hypothesis being mixed, it follows two broad streams: holding the product architecture as a given or holding the firm architecture as a given (MacCormack, Rusnak and Baldwin, 2012). The first stream explores how information exchange within a product development team should reflect the interdependencies or independencies within the product architecture design. For example, Hoetker (2006) found that, in the notebook computer industry (1992-1998), changes in the degree of product modularity were accompanied by reconfigurable firm structures. However, contrary to the usual logic of the modularity literature, changes in product modularity and the reconfiguration of firm architecture did not lead to movements of activities outside firm boundaries. In the aircraft industry, Sosa, Eppinger and Rowles (2004) found a correspondence between architectural levels, but that component modularity did not always limit the amount of information exchange over system-wide issues.

The second stream of research suggests that the structure of firms are not easy to change, at least in the short-term, and is based upon Conway's observation that "any organisation that designs a system will inevitably produce a design whose structure is a copy of the organisation's communication structure" (Conway, 1968). Henderson and Clark (1990) argue, in their study of the photolithographic industry, that the architecture of a firm and the product it designs is tightly connected. They suggest that where there is an existing and established product architecture, the definition of product development teams, workgroups and the information exchange patterns between them, as well as the problem-solving routines, are often embedded in the organisational practices of the firm. Their empirical work shows dangers for such tight connections and major setbacks for lead firms faced with architectural change, and argue that a firm that may have been performing well where change is incremental, but find it difficult to respond to the challenge of a new architecture because firm structures and routines are often hard-wired.

Because of mixed empirical evidence and inconsistencies in empirical approaches, the conventional logic on the across- and within mirroring hypothesis has been challenged as too simplistic (Colfer, 2007; Colfer and Baldwin, 2010). Cabigiosu and Camuffo (2012) argue that a modular product architecture can either be associated with the usual logic of a decrease in information exchange across component development teams/firms or alternatively with significant information exchange, positing that modularity may either be achieved with ex-ante information exchange to define component boundaries and interface standards, and then maintaining a low level of ex-post information exchange, or alternatively by exchanging significant information with other firms throughout the product development process (p699).

Furlan, Cabigiosu and Camuffo (2014) find support for conventional views of mirroring in the air conditioning industry for low levels of ex-post information exchange across contracting firms, but only under conditions of product component *stability*. Moreover, they argue that where underlying product components are subject to fast technological change this is often likely to affect the dynamics of the supply relationship, such as increasing market and technological uncertainty, information asymmetry and asset specificity (Williamson, 1985). When product components change, buyers and suppliers may often need to exchange information to achieve effective coordination of the product development activities. Fast-changing product components may have the potential to undermine the existing modular product architecture if the changes arise from technical imbalances that can only be resolved or exploited by significant information exchange between individuals/teams/firms. Furthermore, such technological changes may offer the potential to appropriate rents from the interplay between modularisation and integration that can only be developed by accessing and sharing external sources of innovation. For example, Brusoni and Prencipe (2001) argued that the interplay between modular and integral technologies may offer 'novelties' in such fast-moving product domains. Furlan and colleagues conclude that these effects are often likely to lead to more complex buyer-supplier relationships which may, in turn, result in more complex information exchange. As such, under conditions of fast-changing product components, modularisation may *not* provide a form of embedded coordination and the need for hand in glove supply relationships persist regardless of the level of component modularity.

Cabigiosu, Zirpoli and Camuffo (2013) also argue that it is the level of knowledge held by the firm and its "*ability to predict the technical interdependencies characterising the design of the product over the life of the project*" (p673) that determines product design choices. In other words, ex-post information-exchange can only be minimised if the firm has sufficient knowledge to scope ex-ante the required component interfaces. In other words, in complex product markets (such as motor vehicles and commercial aircraft, for example Ethiraj and Levinthal, 2004; Sosa, Eppinger and Rowles, 2004; Brusoni and Prencipe, 2006; MacDuffie, 2012), it is likely that firms may often lack the knowledge over a broad range of specific components, and how they integrate effectively into the overall system architecture. Cabigiosu and colleagues question firms who "*rely on the component-specific knowledge owned by suppliers and use product architectural choices….to coordinate multiple firms' design efforts*…[as] *firms' knowledge necessarily has to span these boundaries and only car-makers that know more than they do can leverage modularity*" (p673). This highlights the paradox at the heart of their study of air-conditioning systems in the motor vehicle industry that "*the ability to design a highly modular A/C system architecture is contingent upon an in-depth knowledge of both the A/C system architecture and its inner components. Given cars' architectural complexity, only OEMs with high levels of direct involvement in components development can design a more modular system and experience the benefits of this architecture, as coordination and control mechanism. But this is a paradox, since one of the hypothesised benefits of modularisation is to economise on component-specific knowledge by decoupling the OEMs' and suppliers' design activities, ie by making them separable, isolable, and recombinable*" (p673).

Therefore, misting of the mirror may occur under two contingencies. Firstly, in order to remain competitive, firms often need access to external sources of innovation if component technologies change quickly. As a consequence, the ability of firms to integrate external sources of innovation is seen as a paradox to modularity – the modular benefits of information-hiding may be at odds with the need to access external knowledge (Cabigiousu and Camuffo, 2012; Cabigiuso, Zirpoli and Camuffo, 2013). In other words, accessing external sources of knowledge necessarily requires a high degree of information-sharing, even in the presence of modular components. A second broad theme is that 'misting' may arise in complex product markets because of the scope of knowledge domains (Cabigiosu et al, 2013) and that only firms who know more than they

make have the knowledge to invest ex-ante in defining component interfaces; investments in defining modular entities are ex-ante in order to observe any benefits ex-post (Gomes and Joglekar, 2008). Therefore, in complex settings, firms who rely on stocks of external knowledge owned by suppliers may not possess the required component level knowledge to design ex-ante modular components. Despite assertions that modularity is a useful way to manage complexity (Ethiraj and Levinthal, 2004), we argue that in the case of product architectures with high levels of complexity and/or high rates of product component change, modularity may in fact have an inverse relationship to the usual logic of information-hiding and embedded coordination.

PROPOSITIONS

Degree of mirroring in closed and integrated architectures

Product architectures with closed and integrated characteristics are often complex and poorly understood by the people who design them, information exchange patterns are often complicated, and the knowledge underpinning the numerous product component interdependencies is often largely tacit. As firms are often more efficient than markets at resolving conflicts (Williamson, 1991, 1996) and facilitating communication flows (Monteverde, 1995), product development tasks are often encompassed within the boundaries of a single, focal firm.

The usual logic is that firms sponsoring a closed and integrated product architecture tend to internalise production (see for example early works by Stigler, 1951; Chandler, 1977) in the face of perceived opportunities for rent appropriation, as well as to minimise knowledge appropriation through IPR or other secrecy mechanisms. Under these conditions, small numbers bargaining issues (Williamson, 1971) are likely to also impose prohibitive transaction hazards because market, technological uncertainty and asset specificity are high, reducing the perceived benefits of 'supply-side externalities' (Sanchez, 2008). In sponsoring its own product architecture, a firm is likely to deny access to potential collaborating external firms that may exist in the intermediate market due to concerns over contracting hazards which, in turn, may also help the firm focus

on its own integral capabilities. The firm may also seek to develop its own demand-side externalities (Sanchez, 2008) such as using penetration pricing, marketing or branding to create a significant installed user base and propel it towards the dominant industry standard (Schilling; 1998, 1999; Suarez, 2004), thereby increasing its embeddedness in a product market.

Firms that choose to sponsor a closed and integrated product architecture are likely to engage in 'thick' (Baldwin, 2008) information-exchange patterns in order to improve products and processes as changes in one component often have significant and unforeseen changes in other components. Firms are likely to rely on face-to-face information exchange, close geographical proximity or co-location and formal managerial authority to coordinate highly interdependent product development activities. High levels of complex information-exchange that is tightly structured around the interdependencies within the product architecture allows firms to more efficiently manage the interaction effects between technical elements (see for example the semi-conductor industry in Monteverde, 1995) and to exchange information freely without worrying about ex-post opportunism in the intermediate market.

Thus, our first propositions are that there is a mirrored architectural relationship as follows:

P1: Closed and integrated product architectures are positively associated with high levels of information-exchange between product developers within the boundaries of a single product development firm

Degree of mirroring in closed and modular architectures

The process of modularisation within firm boundaries is not easy and straightforward as the product development teams' knowledge and understanding of the interdependencies are imperfect (Baldwin and Clark, 2000). However, a commitment to ex-ante investments in order to define components and interfaces is often needed to identify and clearly delineate component boundaries. The specification of modular components and specialised interfaces within a significantly closed architecture may over time begin to supplant existing interdependencies across the product architecture. This process may initially take seed

where increased component mixing and matching or speed to market may offer a firm competitive advantage in a product market.

Where the closed and modular product architecture can be characterised as *simple*, the emerging modularisation of its components may permeate throughout a significant proportion of it. This is likely as the firm will often possess a broad scope of component level knowledge in order to scope ex-ante component boundaries and specialised interfaces leading to ex-post information exchange being minimised. However, if the product architecture is *complex*, there is often a need for organisational actors to maintain high levels of ex-post information exchange, even where the components are stable. Product complexity may affect how a component interacts with other components increasing the potential for unforeseen design and system integration problems across the architecture.

The architectural mirror may often be influenced by the rate of underlying product component change[3] (Fulan, Cabigiosu, and Camuffo, 2014). Where the modular components within a simple product architecture are *stable* ex-post, the need for rich ex-post information-exchange between component development teams within firm boundaries is often reduced, as the specialised interfaces may begin to provide a form of 'embedded coordination' that replaces overt managerial control (Sanchez and Mahoney, 1996; Galvin and Morkel, 2001; Cabigosu and Camuffo, 2012). This may happen because the design of product components can be isolated and frozen which may make within-firm co-development practices and information-exchange within the firm unnecessary. As a consequence, a firm is often likely to begin to re-architect itself around the underlying modular components into quasi-independent structures such as independent teams, units or divisions under one corporate umbrella (Baldwin and Clark, 2003) that often function based on internal shadow prices (Baldwin, 2008) that may, in future, propel the firm to consider additional ways to increase quality or reduce costs through market sourcing. Where modular components and interfaces are stable, a firm is much more

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[3] Furlan, Cabigiosu and Camuffo (2014) suggest that the rate of product component change may influence the architectural mapping between product and firm in the case of buyer-supplier relationships. We see no reason to extend this reasoning to closed and modular product architectures developed within the boundaries of a single firm

likely to be able to redesign its information exchange needs to obtain a clear mapping between product component boundaries and component development tasks.

However, where the components are fast-changing, either as part of a complex or simple product architecture, ex-ante investments will often be required to understand how the technological changes affect other components. For example, component technological change is likely to increase coordination needs (Galbraith, 1973), affect the performance uncertainty of the components (Parmigiani, 2007), and make it harder for internal buyers and suppliers to monitor each other's performance and value shadow price contracts. Therefore, where a product component is subject to technological change, frequent ex ante and ex-post information exchange may often be required in order to coordinate the integration of the product component into the overall architecture, manage performance uncertainty, and to nurture component-specific knowledge so as to "identify potential novelties" (Brusoni and Prencipe, 2001: p613) that may emerge[4].

Thus, there is a within-firm mirrored architectural relationship only when closed and modular product architectures are simple and component technologies are stable as follows:

P2a: Closed and modular product architectures are negatively associated with high levels of ex-post information-exchange between component developers, only when product architectures are simple and component technologies are stable

However, as modular product architectures are usually associated with market contracting, the across-firm mirror will become misted:

P2b: Closed and modular product architectures are positively associated with product development activities within the boundaries of a single product development firm

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[4] It is notable that in the case of complex product architectures or where product components are subject to fast technological change, which may result in high levels of ex ante and ex post information-exchange, "breaks the knowledge mirror" as described by Brusoni and Prencipe (2001), Colfer (2007) and Colfer and Baldwin (2010). The internal or external division of labour may be said to reflect product component boundaries, but the division of knowledge does not.

Degree of mirroring in intermediate/ hybrid modular architectures

Product architectures with closed and modular characteristics often exhibit thinned-out crossing points that may eventually lead firms to outsource some or many 'internally modular' product components. The re-architecting of the focal firm into quasi-independent product development teams, units or divisions that function based on internal shadow prices may propel a firm to consider ways to improve performance or lower cost through market contracting. Firms sponsoring closed and modular product architectures, once motivated by latent gains from trade[5] (Jacobides, 2005) and the need to access external sources of innovation often transact across firm boundaries for particular product components which leads to the emergence of intermediate or hybrid product architectures. Developing Jacobides' argument, where gains from trade arise from market contracting, product components will be outsourced, whereas where gains from integration persist, they will remain within firm boundaries.

Where a firm decides to open up (parts of) its product architecture, the usual logic then is that contracting firms in a value chain will often recognise the benefits of making ex-ante investments in modularisation, a *"modularisation process that is interaction-intensive and quasi-integrated"*. (MacDuffie, 2012:37). Product complexity and a fast rate of underlying product component change is likely to, however, affect the basis of contracting relationships with external firms such as increasing asset specificity and technological uncertainty (Williamson, 1985) and "*require more complex inter-firm devices (and hence more information-sharing)"* (Furlan, Cabigiosu and Camuffo, 2014: p791). Therefore, as we have noted before, where a product architecture is *complex* frequent ex-post information exchange may often be required in order to coordinate the integration of both insourced and outsourced product components into the overall architecture (see for example, Lau and Yam, 2005; Zirpoli and Becker, 2011; Furlan, Cabigiosu and Camuffo, 2014). Low levels of ex-post information exchange may diminish a firm's ability to orchestrate activity across its intermediate/hybrid product architecture because it represents a challenge of accumulating and consolidating diverse technological developments, both within- and across-firms.

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[5] Jacobides (2005) uses gains from trade as a key concept to argue why intermediate markets emerge

Brusoni, Pencipe and Pavitt (2000) were one of the first to examine the relationship between modularity and technology. They argue that when components are stable, firms often outsource both the design and production of components. However, firms tend to internalise product component specific knowledge for rapidly changing and complex components in order to exploit novelties that may arise from the interplay or modularity and integration. When product components technologically evolve at uneven rates, there is the potential for technical imbalances which often requires a 'cognitive overlap' (Furlan, Cabigiosu and Camufo, 2014) in order to control or exploit them. A cognitive overlap can either be achieved through either keeping some components within firm boundaries or through remaining engaged in thick collaborative relationships with external firms. Where fast-changing components are outsourced, firms need to develop collaborative relationships with external firms in order to absorb component-specific knowledge, even when the component is modular. In sum, in intermediate or hybrid product architectures, modularity does not mitigate the need for high levels of ex-post information exchange, as such architectures often tend to be either complex or subject to fast rates of product component change.

Thus, there is a within-firm mirrored architectural relationship only when intermediate/hybrid product architectures are simple and product component technologies are stable as follows:

P3: Intermediate/hybrid product architectures are negatively associated with high levels of ex-post information-exchange between and across component developers/firms, only when product architectures are simple or where component technologies are stable

Degree of mirroring in open and modular product architectures

As further product components are outsourced to external firms, a product architecture can often be characterised as open and modular. As we have noted, where the product architecture can be characterised as *simple* and where underlying product components are *stable,* contracting firms invest ex ante in high levels of information exchange in order to define product component boundaries and standard interfaces, and then may switch to a low level of ex-post information-exchange. However, in complex architectures, or with fast rates of product component change, firms often rely on rich information exchange in order to orchestrate a diverse range of product component technologies across a number of external firms.

Stated formally:

Thus, there is a within-firm mirrored architectural relationship only when open and modular product architectures are simple and product component technologies are stable as follows:

P4a: Open and modular product architectures are negatively associated with high levels of ex-post information-exchange between product developers/firms, only when product architectures are simple and where component technologies are stable

<<<insert figure 3a and 3b>>>

Concluding remarks

We have hypothesised phases of mirroring and non-mirroring contingent upon the product architecture type, its degree of complexity and the rate of product component change.

The mirroring hypothesis poses the existence of architectural mirror between the product and product development firm (within-firm) and the product development firm and division of labour (across-firm). Despite its intuitive appeal, we hypothesise that the mirroring hypothesis may shift from phases or mirroring and misting as product architectures evolve and change across time. We suggest that where a product architecture can be characterised as closed and integrated, information-exchange will be rich and frequent within the boundaries of a single firm, reflecting a correspondence between the different architectural levels. In all other cases, we hypothesise that that such a correspondence between architectural levels is only likely to be witnessed where the stylised product architecture type can be characterised as simple and where the underlying product components are stable.

Where a stylised product architecture is characterised as complex – such as in the case of empirical studies of the software, motor vehicle and aircraft industries - we hypothesise that firms may not resort to low levels of ex-post information exchange between product developers, either within or across firms as there will be a need to effectively orchestrate the integration of diverse product components, access external sources of knowledge and manage unforeseen integrative consequences as they arise. As such, we hypothesise that even where product components are modular and stable, high levels of information exchange tend to be required to ensure effective integration into complex product architectures.

We suggest that our proposed model helps reconcile existing mixed evidence. For example, our model helps position the studies of the motor vehicle industry in the works of Sosa, Eppinger and Rowles (2004), MacDuffie (2013) and Cabigiosu, Zirpoli and Camuffo (2013) that question mirroring. Similarly, the study of the computer notebook industry by Hoetker (2006) that illustrates how modularity emerged in the industry but did not lead to movements out of firm boundaries can also be positioned.

The overall framework, therefore, is one in which phase-shifts in the character of product architectures may often result in reconfigurations of information-exchange. In particular, many empirical studies focus on whether the mirroring hypothesis may hold, not under which product or component conditions it may hold. Responding to the call for a nuanced theory of the mirroring hypothesis, our paper extends the ideas of writers such as Furlan, Cabigiosu and Camuffo (2014) and proposes how the contingencies of the stylised product architecture type, its complexity and the underlying rate of product component change may either be associated with phases of higher-levels or lower-levels of information-exchange. It may be the case that as product architectures evolve across time, there may be periods where mirroring yields strategic benefits, and yet in other periods a failure to shift the information exchange needs to 'misting' may have negative consequences for competitive sustainability.

Our aim is that these theoretical contributions will provide the foundation for further research in this field.

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Figure 1 – Product architecture typology

Closed and integrated	Closed and modular	Intermediate or hybrid	Open and modular
A proprietary product architecture with many interdependent components, a many – to-one component to function mapping and tacit interfaces Examples: Formula 1 racing	A proprietary product architecture with many independent components, some one to one component to function mapping and specialised interfaces Examples: Commercial aircraft	A proprietary product architecture with a mix of interdependent and independent components, with a mix of specialised and open, standard interfaces Examples: Smart phones Motor vehicles	An open product architecture with many independent components, mostly one to one component to function mapping, with many open, standard interfaces Examples: Bicycles Hi-fi systems

Figure 2: The mirroring interface – potential proxy measures

Mirroring hypothesis	Within-firm	Across-firm
Firm co-membership	Shared	Not shared
Location	Co-located	Dispersed
Information-exchange	Frequent	Infrequent

Figure 3a: Within-firm mirroring hypothesis

Within-firm mirroring hypothesis	Closed and integrated	Closed and modular	Intermediate and hybrid	Open and modular
Simple architecture, low product component change	Mirrored	Mirrored	Mirrored	NA
Simple architecture, high product change	Mirrored	Misted	Misted	NA
Complex architecture, low product change	Mirrored	Misted	Misted	NA
Complex architecture, high product change	Mirrored	Misted	Misted	NA

Figure 3b: Across-firm mirroring hypothesis

Across-firm mirroring hypothesis	Closed and integrated	Closed and modular	Intermediate and hybrid	Open and modular
Simple architecture, low product component change	NA	NA	Mirror	Mirror
Simple architecture, high product component change	NA	NA	Misted	Misted
Complex architecture, low product component change	NA	NA	Misted	Misted
Complex architecture, high product component change	NA	NA	Misted	Misted