COMPONENT COMPLEMENTARITY AND TRANSACTION COSTS: THE EVOLUTION OF PRODUCT DESIGN

ABSTRACT

The issue of whether firms design and develop products with modular product architectures that benefit from the efficiencies of using the market, or integrated product architectures that allow for leveraging firm capabilities is a central question within the product architecture literature. Empirical results show that product modularisation increases over time across a range of industries. However, evidence of increasing (re)integration at the product and industry level has also been hinted at in a limited set of studies. The fact that product architectures potentially oscillate between the modular and integrated designs, as well as often adopting a hybrid form, highlights the need for an integrated explanation concerning how and why this evolution occurs. On this basis we use draw upon the notions of *synergistic specificity* and *product component complementarity.* By considering the trade-offs between different types of value capture that are possible in modular and integrated architectures we are able to build a basic explanation for the evolution of product architectures and their governance choices over the long-run. The proposed typology and discussion helps to synthesise existing evidence and provides the foundation for further empirical research.

Keywords: product architecture; modularity; transaction costs; capabilities; complementarity.

INTRODUCTION

Product architectures articulate the manner in which functional components are structured and integrated into the final product and how the components will interact and function (Sanchez & Mahoney, 1996). In any given product market, it is possible that a number of different product architectures might be strategically feasible, each with different combinations of performance, quality or cost (Burton & Galvin, 2018; Sanchez, 2008; Sanchez, Galvin & Bach, 2013). For example, all electricity power generation systems will produce electricity, but they may be made up of a series of components that will vary significantly in respect of form and function depending upon whether the generation system is based upon coal, gas, wind, solar or some other alternative system. Even within solar power generation systems as one specific choice, there will be a variety of architectures available with different components and the manner in which the components interface with each other. Initial research concerning modularity sought to understand modularity as a phenomena (e.g. Ullrich, 1995), the drivers of modularity (e.g. Schilling, 2000) and its impact upon a range of dependent variables (e.g. Sanchez & Mahoney, 1996). More recently, how different architectural levels align (ie the mirroring hypothesis) and change has become a central theme (e.g. Burton & Galvin, 2018; Colfer & Baldwin, 2016). Building on this theme, this paper makes a clear contribution to our understanding concerning the dynamism of product architectures. This paper views product architectures from the perspective of their *evovlability.* Product architectures are rarely, if ever, stable, and we draw upon the ideas of synergistic specificity and complementarity[1] as lenses to understand the evolution of product design towards and away from modular architectures, and subsequently, the extent to which firms use markets versus hierarchies[2] for different components.

Given the potential benefits of product modularity (greater component level learning and innovation, rapid determination of consumer preferences, flexibility to adapt to new component offerings and market demands, etc) it has been suggested that product architectures naturally tend towards greater levels of modularity over time (Galvin, 1999; Hoetker, 2006; Sanchez, 2008). Empirically this has been observed with increasing product modularity and industry fragmentation occurring in industries such as stereos (Langlois & Robertson, 1992), fanuc numeric controllers (Shibata, Kodama and Yano, 2005) motor vehicle production (Argyres & Bigelow, 2010) computers (Baldwin and Clark, 2000), mortgage banking (Jacobides, 2005) and semi-conductors (Funk, 2008). However, limitations to architectural or radical innovation, the ex-ante cost of designing a modular product

[1] The ideas of complementarity draws heavily on the work in the papers by Teece (1986) and Argyres and Zenger (2012) and Schilling's (2000) work on synergistic specificity.

[2] Transaction cost economics recognises the intermediate form of networks (or alliances) as a governance mode between markets and hierarchies. In this paper, we tend to focus on just the binary choices of markets and hierarchies to keep the discussion simple. In reality, there may be a number of reasons a firm may use networks to source components. For example, there may not be a sufficiently well-formed intermediate market or there may be some asset required that at least partially meets the criteria as a specialised asset and thus a fully functioning market is unlikely to exist. We do not build networks into our analysis as a separate governance choice as such analysis would add significantly to the complexity of the paper.

architecture and the challenges that come with trying to develop competitive advantage based around open product functionality can make an integrated architecture more attractive (Fixson & Park, 2008; Galvin & Rice, 2008). A limited number of scholars have examined how 'reintegration' might emerge in products or industries (Cacciatori & Jacobides, 2005; Christensen, Verlinden & Westerman, 2002; Fixson & Park, 2008; Galvin & Morkel, 2001; Jacobides & Winter, 2005).

Despite this recognition that product architectures evolve over time between integration and modularisation we have little understanding of why this may be the case other than this evolution occurs in "response to changes in their context, or to changes in their underlying components in the pursuit of better fitness" (Schilling, 2000: 314-5). To build a potential explanation for changes in product architectures over time, we look to the concepts of synergistic specificity complementarity. We follow Schilling (2000) to argue that synergistic specificity is the property of a system, in our case a product architecture. Schilling (2000, 316) highlights that synergistic specificity is defined as "The degree to which a *system* [emphasis added] achieves greater functionality by its components being specific to one another can be termed its synergistic specificity; the combination of components achieves synergy through the specificity of individual components to a particular configuration". On the other hand, according to Argyres and Zenger (2012:1647-8), complementarity is grounded in the idea that the assets and activities of a focal firm are acquired or accessed in markets, and managers seek to build positions to capture value through the discovery of complementary and heterogeneous asset bundles. Our idea of 'product component complementarity' assumes that product components or sub-systems within a given product architecture are bundles of 'assets and activities' each with its own complementary characteristics to the firm's other product components (and hence 'assets and activities'). Thus, product component complementarity is the characteristic of a sub-system, in our case bundles of product components within a given product architecture.

Using these concepts, are able to investigate the potential for firms to capture different types of value with different product architectures (integrated, closed modular, hybrid and open modular) given differing sets of transaction costs and potential for opportunistic behaviour from suppliers. Within the product architecture literature, value capture is often conceptualised as a paradox between value capture through diffusion versus value capture through protection (Schilling, 1999, 2000). Schilling (2000, 329) argues that "[there is]…a dilemma for the firm about whether to protect or diffuse its technology: although a firm might wish to protect its proprietary technologies in order to appropriate rents, product systems based on open standards might more rapidly accumulate an installed base and be compatible with a wider range of complementary goods". Similarly, West (2003) conceptualises the trade-off as one of adoption versus appropriation, positing that when a firm pursues a fully open product strategy it is likely to reduce rent appropriation as it opens up competition and lowers entry barriers. On the other hand, opening up a product architecture may encourage user adoption as it reduces consumers' fears of being locked in to a single technology manufactured by a single firm. Ethiraj, Levinthal & Roy (2008) also note the duality between innovation and imitation and show how integrated product designs are often associated with imitation deterrence, whereas modular product designs are often associated with a diversity of 'plug and play' complementary product components that may serve to facilitate quicker and easier imitation. Kilmas & Czakon (2018) also suggest opening up a product architecture may encourage user adoption as it reduces consumers' fears of being locked in to a single technology manufactured by a single firm. On the other hand, such an understanding provides managers with a better appreciation of the trade-off between the potential appropriation of rents versus the efficiencies that may come with access to the market (Pil & Cohen, 2006; Bourdeau, 2010). Assuming utility maximisation on the part of managers, such an understanding provides a basis for choosing alternative product architectures, and approaches to value capture, at different points in time.

This paper is set out as follows: (i), prior modularity literature is discussed to suggest a stylised product architecture typology that encompasses 'imperfect' product architectures thereby extending the prior typologies developed by Shibata, Kodama and Yano, (2005) and Sanchez (2008) and propose a stylised product architecture typology which characterises four stylised product architecture types; (ii) we then explain how synergistic specifity and product component complementarity may propel a product architecture in either one direction or another on the basis ofdifferent approaches to value capture ; and, (iii) we conclude with a discussion of how this fits within the broader modularity research agenda and provide suggestions for future research.

PRIOR CONCEPTUALISATIONS OF PRODUCT ARCHITECTURE

The concept of a product architecture can be traced back to Herbert Simon's (1962) seminal paper *'The Architecture of Complexity'*. A product architecture is a schematic, "the scheme by which the function of a product is allocated to physical components" (Ulrich, 1995:419), and encompasses three distinct features: (i) an architecture that acts as the blueprint for the way in which product components are arranged; (ii) product components which contribute to the products' function, and, (iii) interfaces which document how components connect together (Baldwin & Clark, 2000). Product architecture has been stylised as two ideal types: integral or modular (Ulrich, 1995) whereby an integrated product architecture is one where product components, interfaces and the nature of their relationship is complex, interdependent and non-standardised, whereas, a modular product architecture has relationships between product components and interfaces that are simple, independent and standardised.

For the purposes of this paper, we focus upon the architecture of a product component bundle or sub-system and use this as our unit of analysis. An entire product such as an air-conditioning system or bicycle – to use examples of products that have previously been popular foci in modularity research – is likely to be made of up a series of component bundles or sub-systems. And in many cases, the overall product will consist of some component bundles or sub-systems which are modular and others that are integrated. There are times in the paper where we refer to an entire product architecture to discuss how the bundles of components may have different architectures, but when we do this we refer to this unit of analysis as an entire or overall product architecture.

Integrated-modular continuum

Integrated product architectures usually incorporate product components that are tightly-coupled and interdependent, connected together via interfaces that are closed, often idiosyncratic, (Sanchez, 2008) or even non-existent (Mikkola, 2003; 2006). They are often created to serve a single use or market purpose (Sanchez, 2008), statically-optimised along some dimension (Sanchez & Mahoney, 2013) such as maximum performance or the lowest cost (Sanchez, 2008). Integrated product architectures are usually very difficult to re-architect to new uses without significant re-engineering (Sanchez & Mahoney, 2013), and hence product component or sub-system level innovation is often hindered, often requiring more difficult, expensive and time-consuming architectural innovation (Henderson & Clark, 1990) to untangle the intricate web of interdependence and complexity. Following on, the design characteristics of integrated product architectures can act "as a strong force against the system shifting to a more modular design" (Schilling, 2000:316).

Integrated product architectures are often designed to maximise value capture through its synergistic specificity (Schilling, 2000). However, an integrated product architecture, is potentially subject to diffusion risks arising from its non-compatibility with external complementary product components, and are often more expensive and time consuming to develop and improve than more open or modular products (Schilling, 1999). Therefore, Schilling (1999:269) contends that integrated product architectures often have a "high risk of rejection under conditions of strong network externalities" as a firm would need to generate its own firm-specific externalities through branding and marketing in order to generate a sufficient installed user base around its product architecture.

In a modular product architecture, the design characteristic that lies at its heart is greater interdependence within product components than across different components (Ulrich, 1995) permitting product components and sub-systems to be designed and produced independently by separate individuals, teams, divisions or firms (Sanchez, 2008), resulting in a reduction in development cycle time and an increase in speed to market (Sanchez & Collins, 2001). The architectural 'design rules' (Clark, 1985) dictate which parameters are 'hidden' or encapsulated and which parameters are 'visible' to other product components. According to Baldwin and Clark (2000), proprietary knowledge and intellectual property rights can be encapsulated within the inner-workings of a product component, whereas the design rules of the architecture and its interface specifications remain visible to external firms and are widely-shared. Interface standardisation is also a key design characteristic (Sanchez, 2008), and can occur either within firm boundaries via the creation of firm-specific or 'specialised interfaces' (Fine, Golany & Naseraldin, 2005; Schilling, 2000), or interfaces may emerge and permeate across firm boundaries to eventually to become an industry-standard. Standardised interfaces often increase product component variety through easier substitution (Garud &

Kumaraswamy, 1995) to give a potentially large number of product variations (Ulrich, 1995; Sanchez & Mahoney, 1996), which may be a source of strategic advantage or option value (Baldwin & Clark, 2000). Modular product architectures may, therefore, help mitigate transaction hazards and benefit from network externalities (Galvin & Rice, 2008; Schilling, 1999; 2000).

Closed-open continuum

Product architectures can also be conceptualised along the dimension of being either open or closed (Sanchez, 2008; Shibata, et al., 2005). A closed product architecture is proprietary, not able to be used by other firms, and a firm may choose hide its intellectual property through formal mechanisms such as patents, trademarks, and copyright, or informal mechanisms such as secrecy, encryption, or complexity (Sanchez, et al., 2013). As a consequence, firms who choose to sponsor closed product architectures may be unable to plug and play external complementary product components from other external firms, owing to the specificity and idiosyncrasy of their own designs.

Not all closed product architectures are integrated, however. Takeishi (2002) and Takeishi and Fujimoto (2003), for example, refer to the motor vehicle industry as a form of 'closed modularisation' and Langlois (2002) distinguishes between forms of internal modularity and external modularity. The idea of a closed and modular product architecture has also been formalised by Shibata, et al., (2005) and Sanchez (2008) in typologies and argue that they may offer firms the potential to respond to external demands for variety and hence capture value from developing internal modular product components and firm-specific interface specifications via their own capabilities, but it is also a decision to forego network externalities (Schilling, 1999), technical advances that may emerge with a diversity of contributions from external firms (West, 2007) and the option value of seeking the best quality or lowest cost product components (Baldwin & Clark, 2000). On the other hand, an open architecture has high levels of commonality (Sanchez, et al., 2013) and interface specifications that are standardised, unencumbered by intellectual property or other means of protection. Open product architectures are often used by many firms and are associated with the presence of significant network externalities and gains from trade and/or specialisation where interoperability between diffuse and externally-sourced complementary product components is desired or essential.

The modular-integral and open-closed continuums presented indicate a stylised 2x2 product architecture typology comprised of closed and integrated, closed and modular, open and integrated and open and modular product architecture types (as described by Sanchez, 2008; Shibata, et al., 2005). However, such static typologies[3] seem to suffer from a weakness relating to the evolvability of product architectures in either direction – either towards or away from modularity. In practice, the terms integral and modular are relative terms, and many product architectures often exhibit 'non-perfect' characteristics, especially evident in the stylised types of closed and modular and hybrid product architectures. Semi-open or 'hybrid' architectures have been discussed in platform literature (ie, Boudreau, 2010) but have received comparatively little attention in the product architecture and modularity literature.

Hybrid product architectures

Considering complete products, the product architectures often incorporates a blend of both modular and integrated product components, a blend of both specialised and industry standards, and ownership varies across different product component types. Hence our unit of analysis in the following sections is a bundle of components or sub-system within a larger architecture. Certainly Baldwin (2008) discusses modularity in respect of the local characteristics of a sub-system within a larger and often complex architecture. As such, the architectural characteristics of different sub-systems may vary between being modular and integrated across these different sub-systems within a larger product architecture. Similarly, Boudreau (2010) argues that product architectures, as complex and nested systems, are made up of multiple product components, and can often be 'opened up' one component at a time

[3] Shibata, et al., (2005:15), argue that a stylised open and integrated product architecture is very unlikely to exist in practical terms, because "there are virtually no products for which the mapping relationship is complex and for which standard interfaces have been established. Accordingly we may assume that as a rule, open architectures are [always] modular architectures". For conceptual clarity, we adopt the same position in this paper.

(Boudreau, 2010). West (2003) identified two types of hybrid product strategy: (i) opening parts of the architecture by waiving control of the commodity layer, while retaining full control of other layers that may offer a source of potential differentiation along some lines; or (ii) disclosing technology under restrictions so it cannot be easily coped or appropriated by competitors. West suggests that the first strategy is likely to be advantageous to stimulate demand and supply side adoption and so facilitate interoperability, as, he argues, without some approach to innovation, differentiation or some form of lock-in, incumbent firms will find it very difficult to capture value unless there are significant advantages to be gained through marketing, customer service, or leveraging brand names. As we have argued, opening up a product architecture is often characterised as a crucial strategic decision because "opening has the potential to build momentum behind a technology, but could leave its creator with little control or ability to appropriate value" (Boudreau, 2010:1849). Boudreau (2010:1852) goes on to posit that the risks can be conceptualised as a 'balance of power' between the product architecture owner and external contracting parties. For example, if a firm gives up some control over a closed and integrated architecture, it can stimulate the intermediate market for external complementary product components and firms can benefit from an increase in technological diversity.

Hybrid product architectures can, therefore, be conceptualised as a stylised product architecture that fosters a balance of power between the owner of the product architecture and external providers of complementary product components. In other words, the degree of hybridity a product architecture exhibits is inherently unstable and dynamic. On the one hand, if the product architecture owner demands increased control, or identifies opportunities to capture value through integrative innovation, the product architecture may 'close' or become more integrated. On the other hand, increased openness may propel a product architecture towards an open and modular design. Boudreau (2010:1850) cites the example of Apple in its development of the iPhone, where Apple tightly-controlled the operating system, but allows thousands of external firms to develop software applications. The degree of hybridity is a fine balancing act, the trick being to determine which product components to open up and which to retain proprietary control.

We turn now to propose a range of different product architectures that may be observed as products evolve and the different set of components or sub-systems vary between being integrated and closed to the wider industry, through to hybrid architectures whereby some bundles of components are open and modular and others may be closed and modular or closed and integrated, and possibly product architectures being entirely open and modular.

<<<< Insert Figure 1 about here >>>>

In Figure 1, a *closed and integrated product architecture* is proprietary. It is designed and used by one controlling firm and a high number of product components are integrated. A low number of product components may be modular. The product architecture may be protected by either formal or informal mechanisms and interface standards are either idiosyncratic to the controlling firm or non-existent.

A *closed and modular product architecture* is proprietary. A high number of product components are modular. A low number of product components are integrated. A high number of interface specifications have been specified by the controlling firm. A low number of interfaces may remain non-existent, or have been adopted as the basis of exchange with a low number of external suppliers.

A *hybrid product architecture* has elements that are proprietary and controlled by a single firm, and other elements that are controlled by two or more firms. It has an intermediate *mix* of integrated product components and modular product components, and an intermediate mix of firm-specific and industry-wide standards.

Finally, an *open and modular product architecture* does not have one controlling firm, and is typically non-proprietary, unencumbered by formal or informal mechanisms. A high number of product components are modular, interacting and connected through a high number of industry standards. A low number of integrated product components and firm-specific interfaces may be present.

EVOLUTION OF PRODUCT ARCHITECTURE

Product architectures are rarely static in nature and may often evolve in the long-run (Burton & Galvin, 2018; Fine, 1998; Fixson & Park, 2008; Schilling, 2000). It is often assumed that they evolve towards increasing openness and modularity – from left-to-right in the figure – initially designed as closed and integrated, and then progressing through 'imperfect' periods until they exhibit more or less open and modular characteristics. Empirically, increasing product modularity and associated industry fragmentation has been noted in a number of product market settings from computers to motor vehicles (Argyres & Bigelow, 2010; Baldwin & Clark, 2000). In a similar vein, the dominant logic in explaining shifts in industry architecture is conceptualised as a set of 'centrifugal forces' (Jacobides, Knusden & Augier, 2006) that push towards disintegration and 'modular organisations' whereby "the role of a tightly-integrated hierarchy is supplanted by loosely-coupled networks of organisational actors" (Schilling & Steensma, 2001:1149-1168). In other words, scholars have also argued that industry architecture tends to 'mirror' the evolvability of products towards a modular organisational form and disintegrated product markets populated by highly-specialised firms.

A few scholars, however, have hinted at the possibility that product architectures may resist a modular design (Chesbrough, 2003; Chesbrough & Kusunoki, 2001; Chesbrough & Prencipe, 2008) and progress from right-to-left in the figure. Empirically, however, only a few studies have examined 'reintegration' (Cacciatori & Jacobides, 2005; Christensen, et al., 2002; Fixson & Park, 2008; Jacobides & Winter, 2005). The lengthy historical review by Galvin and Morkel (2001) has shown how the product architecture in the bicycle industry evolved towards modularity, back towards integration and then back towards modularity. In explaining the drivers for reintegration, Christensen, et al., (2002) highlight the role of technology and demand-side factors, and argue that increasing integration as associated with a 'performance gap' in modular product markets.

In their study of Shimano in the bicycle industry, Fixson and Park (2008) foreground the role of product designers in '*seeking value*' [emphasis added] through reintegration. According to Fixson and Park (2008:1310), "knowledge across several segments appears to have been a necessary ingredient for maintaining competitiveness in the wake of [a] architectural shift". Prior broad product component scope, they contend, helped firms avoid the modularity trap (Chesbrough and Kusunoki, 2001) and retain the knowledge required to engage in reintegration. In other words, a broad scope of knowledge may assist firms in identifying new architectural shifts and perhaps initiate a new integrated dominant design.

To better understand these shifts in levels of modularity in the product design, especially in those cases that move back towards reintegration, we draw upon ideas of synergistic specificity (Schilling, 2000) and complementarity developed in the work of Teece (1986) and latterly extended by scholars such as Jacobides, Knusden and Augier (2006), and Agyres and Zenger (2012). While Schilling (2000, 320) notes that synergistic specificity is a design property of integrated systems, Schilling does not directly discuss the transaction costs associated with such designs. Given that integrated product architectures are non-decomposable – at least unless ex-ante investments to decompose the product architecture into components and sub-systems and define interface standards are considered valuable by the sponsoring firm –such designs are often enveloped within firm boundaries given the potential for ex-post opportunism in market exchanges. Moreover, according to Argyres and Zenger (2012:1647-8), complementarity is grounded in the idea that the assets and activities of a focal firm are acquired or accessed in markets, and managers seek to build positions to capture value through the discovery of complementary and heterogeneous asset bundles. In addition, firm boundaries are then enveloped around the bundles of complementary assets that are owned. Furthermore, assuming markets match buyers and sellers of heterogeneous assets, the value assigned to assets will differ between firms to the extent that the degree of complementarity to the firm's other assets differ. Put another way, the degree of complementarity is relative and firm-specific. Value-added, then, is the value created by the firm with the complementary asset included in its bundle. Using this logic, the role of strategizing managers is to identify "under-priced" unique complementary assets to the extent that its 'unique' complementarity is not evident to others.[4] On the reverse side of the coin, should assets be or become generic or homogenous, and thus freely available in markets, then strategizing managers are much more likely to access such assets through market contracts with suppliers as the risk of ex-post opportunism has been effectively minimised. Stated formally, Argyres and Zenger (2012:1649) suggest that "…firms are unlikely to integrate generically complementary assets and activities as well as highly capable but non-complementary assets and activities.

[4] Like much of the work that is considered within the field of strategic management, there is an assumption here that managers behave in a manner is utility maximising on the part of the firm. However, we do not assume true rationality as per an economic definition whereby all managers possess the same information, assess threats and opportunities the same or reason in the same way (Stubbart, 1989). In this respect, some managers will note opportunities for unique complementarity due to either their exclusive knowledge of internal bundles of components or their unique processing of the benefits that may accrue through externally available bundles of components available through the market.

However, firms are likely to integrate assets and activities … that are uniquely complementary to the other assets and activities of the firm".

There are some notable differences between the arguments posed by Teece (1986) and Argyres and Zenger (2012) relevant to this paper. Argyres and Zenger (2012:1652) note that Teece and TCE more generally has often concerned itself with bi-lateral market transactions, whereas heterogeneous and uniquely complementary asset *bundles*[5] are concerned with multi-lateral exchanges, or concerns with how firms can profit from innovative activities at the industry architecture level.[6] According to the authors, "When multiple transactions are interrelated and are occurring simultaneously…the holdup risk for a focal transaction involving a uniquely complementary capability will be considerably greater than for a single bi-lateral transaction" leading to the potential for opportunism in respect of one uniquely complementary asset to affect all assets within the bundle, further promoting vertical integration. By extension generic or homogenous complementary assets are much more likely to be characteristic of bi-lateral exchanges and, so, less likely to incur such opportunism risks.

The modularity literature has taken up the ideas of transaction costs (ie, Baldwin, 2008; Sanchez, 2008;) and capabilities (ie, Aryres & Bigelow, 2010, 2006; Jacobides, 2005) to explain how product architectures and their associated governance modes may evolve towards greater openness and modularity. Complementarity, by comparison, has received little attention despite its promise. In the section that follows, we attempt to show how ideas of synergistic specificity and complementarity may be a key mechanism in the *evolvability* of product architectures and governance modes in the medium to long run.

To develop the synthesis, we begin with two basic assumptions, (1) synergistic specificity is a design property of integrated systems (product architectures), and (2) that product components within a given decomposed product architecture are bundles of 'assets and activities' each with its own complementary characteristics to the firm's other product components (and hence 'assets and activities'). Put simply, each product component is seen as emerging out of a bundle of assets and activities. Second, we assume that strategising managers seek to build positions to capture value either through synergistic specificity at the

[5] Emphasis added
[6] Jacobides, et al., (2006) adopt an industry-level analysis of complementarity in their reinterpretation of Teece

product architecture level or through the discovery of uniquely complementary product component bundles within decomposed product architectures. Third, in the case of product architectures with synergistic specificity, firm boundaries are then enveloped around the entire product architecture, whereas for decomposed product architectures firm boundaries are enveloped around bundles of uniquely complementary product components that are owned, and market exchanges are the preferred governance mode for generic or homogenous complementary product components.

LINKING PRODUCT ARCHITECTURE EVOLUTION AND PRODUCT COMPONENT COMPLEMENTARITY

Closed and integrated architecture

Closed and integrated product architectures are often developed in the emergent stages of a product market as firms experiment with idiosyncratic and unique product designs (Sanchez, 2008). The prevailing logic is that in many new and emerging product markets, firms often develop "product architectures that are idiosyncratic to the firm and that feature customised and highly interdependent components" (Argyres & Bigelow, 2010:853). Given the ex-ante investments required to design and develop integrated product architectures, value capture from integrative innovation is a key concern for firms. Thus, if a firm can establish and protect its own, idiosyncratic and integrated product design as a 'dominant design', a firm "…may be able to earn near-monopoly rents" and be in "a good position to shape the evolution of the industry" (Schilling, 1999: 266).

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TCE logic supports the rationale of enveloping entire integrated product architectures within firm boundaries due to significant ex-post opportunism risks associated with high levels of asset specificity (Williamson, 1975; 1985). Furthermore, given the high levels of synergistic specificity in closed and integrated product architectures, it is much more likely that any possible exchanges across firm boundaries would be multi-lateral, further compounding the risk of ex-post opportunism by the supplier.

Despite the potential value capture arising from synergistic specificity, , the sponsorship of such architectures is not without risks as product markets evolve in the medium-run (for instance, increased demand, emergence of a more comprehensive intermediate market, lower entry barriers, etc[7]). For example, the decision to invest in synergistic specificity is also a decision to forego product variety associated with product component mixing and matching, as well as compatibility with external complementary product components offered by suppliers which may lead to "…a high risk of rejection under conditions of strong network externalities" (Schilling, 1999:269). For example, early versions of hand-held devices were largely closed and integrated. The Palm hand-held device was designed and manufactured by Palm who sold a bundled package of hardware, operating system and applications, but it was later rejected by the market under conditions of strong network externality effects.

According to Schilling (2000), drivers such as customer demands for variety and speed of technological change act as forces towards modularisation and less synergistic specificity, which compete against the higher-levels of system performance that synergistic specificity often enables. For Schilling (2000: 317), "the balance between the gains achievable through recombination and the gains achievable through specificity determines the pressure for or against the decomposition of the system".

Closed and modular product architecture

Should the forces towards modularisation win out, firms may choose to invest ex-ante in decomposing the product architecture into components and sub-systems, and designing standardized interfaces that connect the various part of the product architecture together. This modularisation process minimizes synergistic specificity within the product architecture system, requiring product designers to identify particular bundles of uniquely complementary product components that confer a source of competitive advantage and/or differentiation and, hence, appropriable protective value capture.

[7] Sanchez (2008) provides an interesting discussion of the characteristics of the typical transition from integrated products to near-modular products.

At the same time, other product components within the product architecture are made much more generic and homogenous, and strategizing managers should be better able to gain access to these product components through market exchanges without the risk of ex-post opportunism. However, contra-dominant logic, closed and modular product components may be retained within vertically-integrated firm boundaries. The prediction from the TCE literature is that when assets are made either non-specific or generic, the risk of ex-post opportunism is minimised which would normally lead to market-based contracts; in other words, ex-ante investments in modularisation trade-off against the risks of ex-post opportunism (Sanchez, Galvin & Bach, 2013). Furthermore, decomposition into product components eliminates interdependence with other product components, and hence market exchanges may revert to bi-lateral contracting arrangements, further reducing risks of ex-post opportunism. So, at this stage in the evolution of product architectures, why would a modular product architecture be retained within firm boundaries?

We can turn to a number of possible arguments. First, closed and modular product architectures offer firms the potential to respond to external demands for variety (often through experimentation at a component level) and hence the opportunity to capture value through the discovery of uniquely complementary product component bundles. Any unique complementarity developed through developing a variety of components is best protected within firm boundaries. To do otherwise runs the risk of a loss of unique complementarity and a transition to homogenous complementary product components designed and developed by suppliers. Second, valuable intellectual property relating to the inner-workings of the modular product component remains hidden within the boundary of the component and its interface standards remain firm-specific (ie, unique) to the focal firm promoting vertical integration. Such outcomes have been seen through the mix and match approaches that led to a variety of Walkman products (Sanderson & Uzumeri, 1997), Black and Decker family of power tools Utterback (1994) and even a range of second generation phones from Nokia and Ericsson (Galvin & Rice, 2008).

The knowledge-based lens may also be instructive. Closed and modular innovation requires decomposition schemes to be codified. According to Ulrich (1995), modular decomposition reduces cognitive complexity and it is often a gradual and recursive process (von Hippel, 1990). Codification of decomposition schemes – and the underlying knowledge - however, is often likely to happen within firm boundaries initially, before perhaps eventually permeating across firm boundaries (Hoetker, 2006; Tee, 2011). Hoekter (2006), in studying the display screens in the computer industry, found that modularisation of components did not lead to task activities moving beyond firm boundaries due to communication and governance advantages of continuing to use internal suppliers. In essence, the modularisation of the product architecture may not mirror the architecture of organisational capabilities. While the mirroring hypothesis (Colfer & Baldwin, 2016) suggests that in time the architecture of organisational capabilities will align with the product architecture, the actual capacity to decompose architectures through codification is in itself an important capability (Jacobides, 2006) and as such firms may be able to modularise product architectures before they develop the organisational capabilities around communication skills, supplier management and other such skills that would be required to effectively shift the procurement of components from internal operations to an external market.

However, many scholars, such as Galvin & Rice (2008) Sanchez (2008), Shibata *et al.,* (2005) and Tee (2011) argue that in time, the eventual emergence of intra-firm and industry standards for connecting modular product components makes them more homogenous and much more likely to move across firm boundaries. Shibata, *et al.*, (2005), for instance, summise that in most cases the evolution of product architecture shifts from one of "complex, non-standard interfaces, through simple company-wide standard interfaces and ultimately to industry-wide standards" (2005:15). Many scholars have argued that once closed and integrated product architectures are decomposed and interface standards developed, it is difficult to maintain transactions entirely within firm boundaries (ie, MacDuffie, 2013; Sanchez, 2008; Sanchez, *et al.*, 2013) and the activities associated with modular product components may leak across firm boundaries, especially in the presence of reduced ex-post opportunism. Indeed, proponents of the benefits of modularity have suggested that moving activities across firm boundaries is associated with accessing external capabilities associated with technological diversity (West, 2003) and positive network externalities (Schilling, 1999; Sanchez, 2008).

It is therefore probable that a closed and modular product architecture is a short-run phenomenon on a more general evolutionary path towards greater openness, modularisation, and market-based exchanges as value capture shifts from protection to diffusion.

Hybrid product architecture

For closed and modular product components to move across firm boundaries, prior investments in ex-ante transaction costs to decompose product components and interfaces must have occurred, setting in motion the often-described evolutionary forces towards open and modular product architectures. Drawing on Argyres and Zenger (2012), for those generic or homogeneous complementary product components that are abundantly available in an intermediate market, where ex-post opportunism reduces, market-based exchanges will come to be the preferred governance mechanism. This modularisation process may promote bi-lateral dyadic exchanges between buyer and seller as transactions that may be contained at the product component boundary (a thin crossing point), further reducing the risk of ex-post opportunism and supporting the operation of an open and functional market.

Not all complementary product components, however, migrate across firm boundaries. One of the drawbacks to a form of modularisation that extends across firm boundaries is that "… firms consisting of assets that are less uniquely complementary to each other … earn average long-run returns at best" (Argyres & Zenger, 2012: 1648). As a response, strategizing managers may choose to resist the forces towards increasing openness and modularisation, maintaining, or creating new - perhaps through superior perception or luck - particular bundles of uniquely complementary product components that confer a source of competitive advantage and/or differentiation and, hence, appropriable value capture. For some uniquely complementary product components, managers with superior foresight may identify gains from integrated bundles, and yet, at the same time, identify gains from trade in the market in respect of contracting for generic or homogeneous complementary product components. The trick, of course, is to identify which strategy is optimal at the product component or 'bundle' level of the product architecture systems hierarchy. The varied complementarity characteristics of product components lie at the heart of the notion of product architecture hybridity.

Extending this, generic or homogeneous complementary product components confer weak appropriability regimes and are much more likely migrated across firm boundaries as the risk of ex-post opportunism is low. On the other hand, bundles of uniquely complementary product components (which may consist of integrated or modular product components) are more likely to remain integrated within firm boundaries. In other words, the pressures for and against a product architecture becoming more open and modular – or remaining hybrid (or perhaps even reverting back towards closed and modular) – is related to the ability of strategizing managers to continually perceive value through bundles of uniquely complementary product components.

Some other clues are available in the literature to guide firms to decide in which product components to promote modularisation and homogeneity, and in which components to resist it. For example, Baldwin and Woodward (2008) identify that many contemporary products are partitioned as bundles of core and peripheral product components. West (2003), on the other hand, suggests that control can be waived over the core commodity layer, and product components that confer some kind of differentiation are retained under tight control. In the platform literature, Boudreau (2010) argues that product architectures, as complex and nested systems, are made up of multiple product components, and can often be 'opened up' one component at a time (Boudreau, 2010). Boudreau (2010: 1852) also suggests that hybrid product architectures can vary along a number of dimensions; for example, its "…treatment of property rights, contracts, and rules, as well as their procedural characteristics". These bundles of components that remain integrated whilst others are made modular are examples of unique complementarity at play, and practical examples of this can be seen in the example of Apple in its development of the iPhone, where Apple tightly-controlled the operating system, but allows thousands of external firms to develop software applications. Apple initially bundled Google Maps as part of its iPhone, but then replaced it with its own Apple Maps application as part of iPhone 5. Similarly, Netscape began life as a provider of a complementary product to Microsoft, who later enveloped the browser component within Internet Explorer (Boudreau, 2010).

Open and modular product architecture

Sanchez, et al., (2013) suggest that a firm's choice of product architecture and governance mode is likely to be associated with its ability to capture value from its product development activities. Within an overall product architecture that contains both integrated and modular bundles of components (ie a hybrid architecture), for a (mostly) open and modular product architecture to emerge, opportunities for value capture from gains from trade will exceed value capture from unique complementarity, or value capture from unique complementarity must be eroded – or at least not perceived by firms - and the vast majority of product components will be much more generic and homogenous (often leading to a level of commoditisation in the market). Market dynamics may offer one explanation of why hybrid product architectures transition towards an open and modular architecture. Langlois and Robertson (1995) assert that the emergence of intermediate markets for product components requires modes of interaction which enable newly specialised buyers and sellers to interact through a market interface. The emergence of standardised or industry-wide interfaces to connect product components together may enable further reductions in ex-post opportunism that make market contracts much more attractive. Thus as per the arguments in the previous section as to why integrated components may become modular, the unique complementarity that provided opportunities for added value no longer outweigh the benefits that may be available via gains from trade in cases featuring homogeneous components and limited potential for opportunism.

Sanchez, et al., (2013) adopt a TCE perspective to make a similar argument. Where firms engage in an open and modular product architecture, it is likely that both ex-ante and ex-post transaction costs are reduced (Sanchez, et al., 2013) tempting new entrants to adopt the existing product architecture. Ultra-low[8] ex-post transaction costs may be available as the presence of industry standards often define the parameters of bilateral exchanges between firms. Open and modular product architectures offer opportunities for suppliers to specialise in specific types of generic or homogeneous modular product components. Sanchez, et al., (2013) suggest that assembler firms can also benefit from both gains from specialisation and gains from trade via sourcing lower-cost modular product components from specialist firms owing to the economies of scale advantages the specialist firm has, or a firm may source

[8] Ultra-low transaction costs may be available due to market dynamics such as the significant presence of industry standards throughout the entire product architecture, as well as the intermediate market moving from a supplier base to a complementor base, for example.

higher-quality product components that may earn it a price-premium for the final, assembled product. However, as West (2003) reminds us, without innovation, differentiation or some form of lock-in, it will be very difficult for assembler firms to appropriate value in the long-run. Furthermore, it is possible that value can only be captured through retaining (or regaining) control of critical aspects of the architecture, such as the ownership and property rights of critically important product component technologies that confer some kind of differentiation or competitive advantage (Thomas, Autio & Gann (2014; Helm, Endres & Hüsig, 2017) which acts as a strong force against evolution to a fully open and modular product architecture..

Reintegration

The canonical shift towards ever increasing openness and modularity is not without its limits, and such products are often characterised as suffering from high levels of inter-firm competition, commoditisation and easier imitation (ie, Ethiraj, Levinthal & Roy, 2008). Furthermore, the modular properties of generic and homogenous complementary product components may serve to constrain innovation over the medium to long-run. Innovative activities within an open and modular product architecture need to occur within the constraints of the industry standard, and so eventually the product architecture will fall away from an 'efficient frontier' of what is technologically possible (Christensen, et al., 2002). In response, the pressures for managers to rediscover value from investing in uniquely complementary product component bundles is amplified. (ie, designers seeking value through reintegration, see Fixson & Park, 2008). Ultimately, this type of integrative innovation may reverse the pendulum away from open and modular product designs and back towards at least some bundles of components being integrated, thereby increasing transaction costs.

Integrative innovation may take a number of forms. For example, in line with West's (2003) assertion, firms may initially focus on bundling generic or homogeneous complementary product components, foregrounding, via marketing or branding, product or service bundles that offer the opportunity for value capture. This is unlikely to generate above-average returns in the long-run. An alternative reintegration mechanism is to focus innovative attention on investments in uniquely complementary product components, while retaining an outsourced relationship with suppliers.

It is possible that firms will not have the capability to develop uniquely complementary assets within firm boundaries. Many scholars in the systems integration tradition have recognised the benefits of firms maintaining a broader knowledge than task boundary in order to capture value from outsourced activities. However, Argyres and Zenger (2012) note that the desire to possess uniquely complementary assets may be so strong that firms without at least comparative capabilities will still seek opportunities for value capture through acquiring and integrating (via acquisition) appropriate assets. In other words, even in the presence of ultra-low transaction costs associated with open and modular product architectures, re-integration of uniquely complementary product components will be perceived as worth the cost, effectively re-introducing the hybrid characteristics of the product architecture. It is feasibly possible that, eventually, as bundles of uniquely complementary product components are acquired, invested in and re-integrated, the previously open and modular properties of the product architecture may be undermined to the extent that its hybridity is diluted to an extent whereby a closed and modular and/or closed and integrated product architecture re-emerges as a dominant design, perhaps serving to reignite further cyclic pressures for decomposition again. This process of product architecture potentially evolving towards more modular architectures or moving in the opposite direction through reintegration, along with the drivers of such evolutionary paths is illustrated in Figure 2.

<<<< Insert Figure 2 about here >>>>

CONCLUDING REMARKS

The aim of this paper was twofold: (i) to outline the different forms that product architectures may take as these architectures evolve over time; and, (ii) to explore how the dynamic effects of synergistic specificity and product component complementarity may create forces that propel a product architecture either towards or away from increasing integration or modularity.

As previous stylised product architecture typologies tended to focus on a stylised 2x2 matrix (ie, Shibata, et al., 2005; Sanchez, 2008), one contribution of this paper is to argue that there is an evolutionary cycle that shifts product architectures towards or away from modularity and that often the different bundles of components that make up the overall product architecture may be hybrid nature. Second, these different architectures are then linked to the idea of synergistic specificity at the product architecture level and complementary at the product component level, and, hence, to its governance mode, providing a fuller picture of how managers, in trying to discover how to capture value typically decide to govern transactions in terms of the use of markets versus hierarchies. Thirdly, the evolution of product architecture explicitly suggests that reintegration is not only feasible, but probable as ever increasing product modularity may erode long-run returns to average at best. The evolution of different product architectures can therefore be seen as one in which product architectures, over the long-run, may evolve back and forth between integrated and modular forms, and a product architecture that makes sense in terms of value capture in one time period may be strategically sub-optimal in a subsequent time period.

The second part of the paper uses the different product architectural forms as a foundation for exploring the extent to which synergistic specificity and product component complementarity are key mechanisms in the transition between one product architecture type and back again. Given the premise that ownership of assets and activities is determined by reference to the degree of complementarity of an asset or activity to a firm's other assets and activities (Argyres & Zenger, 2012), assets and activities are much more likely to be vertically integrated when they are uniquely complementary, owing to ex-opportunism risks in the intermediate market. However, exogenous factors in a typical industry life cycle suggests that market characteristics such as demand, entry barriers, and competitive intensity, for example, is likely to propel managers to perceive value capture through modularisation efforts. Initially, managers will strive to protect the unique characteristics of its synergistic specificity or unique complementarity, despite the emerging modularisation of the product architecture, specifying firm-specific interfaces and maintaining design and production in-house. However, once started, the increasing modularisation attracts new entrants with specialised capabilities and scale economies to intermediate markets that cause the unique complementarity of closed modular product components to be eroded and transaction costs to fall as some bundles of product components become much more abundantly available, generic and homogenous.

Hybrid product architectures emerge as managers seek to protect value in some uniquely complementary product component bundles that are perceived to confer a source of competitive advantage through integration, while for some other product components there are potential gains from trade in the intermediate market in respect of contracting for generic or homogeneous complementary product components, owing to ultra-low transaction costs linked to the emergence of intra-firm or industry-wide standards. In some product markets, hybrid architectures may be eroded to a significant extent as the emergence of industry-wide standards that define independent and bilateral exchanges may enable further reductions in ex-post opportunism that make market contracts much more attractive and as such, open and modular product architectures evolve.

Without unique complementarity, generic and homogenous complementary product components (which are characteristic of open and modular product architectures) are unlikely to generate above-average returns in the long-run, as competition, commoditisation and imitation erode value capture. Moreover, standards constrain innovation (Galvin, 1999), pressurising managers to rediscover sources of value capture through investment in assets and activities that deliver unique complementarity. Ultimately, this type of integrative innovation may reverse the pendulum away from open and modular product designs and back towards hybrid product architectures.

In our view, synergistic specificity and product component complementarity are key mechanisms is explaining how and why product architectures transition from one design type to another – and back again – creating a cyclical process over the long-run. The cyclical characteristics of product markets have been alluded to before (Christensen, *et al*., 2002; Fine, 1998; Fixson & Park, 2008; Galvin & Morkel, 2001; Schilling, 2000; Shibata, *et al.,* 2005) and evolve "in response to changes in their context, or to changes in their underlying components in the pursuit of better fitness" (Schilling, 200:314-5). However, exploring the relationship between integration-modularisation and the dynamism of capabilities and transaction costs – and hence complementarity – over the long-run adds a new perspective to prior scholarship. Thus, by drawing on Schilling (2000) and Argyres & Zenger (2012), we offer a first step in offering an integrated explanation of the evolvability of product architectures and associated governance mode.

From a management perspective, understanding the forces and thus the likely evolution of product architectures either towards or away from modular designs in critical. For example, early movers towards modular components may be in a position to establish the dominant design in select components that aligns to the firms strengths, or in open and modular industries that have reached a point of commoditisation of the product, those firms that make the early moves back towards a partially integrated architecture are likely to be rewarded both in terms of market positioning as well as the opportunities in reintegrate components of their architecture through the acquisition of firms producing the best and most complementary components for their operations. For example, a building firm (that uses sub-contractors for all of its work) may seek to integrate quantity surveying into its operations as a point of differentiation and because of its capacity to provide a greater level of predictability over its cost structure. Being a first mover in this respect will (a) provide a basis for differentiation relative to competitors and (b) allow them to acquire the most appropriate quantity surveying firm in respect of complementarity.

This paper paves the way for a number of suggestions for future research. Whilst we have stopped short of offering suggestions of different hybrid product architectures types, this work is important to aid our understanding of how hybrid product architectures evolve. We still know relatively little about the reasons for different forms of hybrid architectures. West's (2003) assertion that firms might open parts of the architecture by waiving control of the commodity layer, while retaining full control of other layers is a start, however further research is required to understand how firms may perceive unique product component complementarity in terms of different architectural designs, such as core and periphery component structures.

Furthermore, this paper raises important questions for proponents of the mirroring hypothesis (Colfer & Baldwin, 2016). Despite the call for a 'nuanced' view of mirroring (Colfer, 2007), product component complementarity has not featured in this literature. Recent contingent contributions that examine contingencies such as product complexity and the rate of product component/technological change (Furlan, Cabigiosu and Camuffo, 2014) have been helpful in addressing the conditions under which mirroring may be challenging – or even ill-advised – however, the relationship between different types of product component complementarity and mirroring offers a new terrain for this stream of research. The link between different architectural levels has the potential to impact the way that organisations are structured, the composition of industries and even the nature of competition – issues that sit at the heart of strategic management research (Zubac, 2018).

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FIGURES

Figure 1: Potential evolution of product architectures

Degree of openness →

Closed and integrated product architecture	Closed and modular product architecture	Hybrid product architecture	Open and modular product architecture
Designed and developed within a single firm		Designed and developed across two or more firms	
← →			
Path of product architecture evolution			
Example: Couture wedding dress	Example: Boeing 787	Example: iPhone (including apps)	Example: Personal Computer (based around 'Wintel')

Figure 2: Drivers of product architecture evolution

	Closed and integrated product architecture	Closed and modular product architecture	Hybrid product architecture	Open and modular product architecture
Drivers towards more modular architectures	Perceived value for modularization such as providing a ‘mix & match’ capability	Perceived benefits from trading with the market for generic components	Perceived gains from trade and participation in industry standards	

	Closed and integrated product architecture	Closed and modular product architecture	Hybrid product architecture	Open and modular product architecture
Drivers towards more integrated architectures		Perceived benefits available via unique product features and synergistic specificity	Perceived benefits from developing the entire architecture in-house to increase differentiation and reduce risk of replication	Perceived benefit from bringing some core components in-house as a basis for differentiation