HOW THE RATE OF CHANGE AND CONTROL OF A MODULAR PRODUCT ARCHITECTURE IMPACT FIRM-LEVEL OUTCOMES[1]

Article Running Head: Modular Product Architectures

Peter Galvin, School of Business and Law, Edith Cowan University, Australia

Nicholas Burton, School of Business and Law, Northumbria University, United Kingdom

Norbert Bach, TU Ilmenau, School of Economic Sciences and Media, Germany

John Rice, College of Business, Zayed University, United Arab Emirates

Who controls a product architecture and the rate at which this architecture changes, impacts the type of outcomes a firm can expect to derive from utilizing a modular product architecture.

Key Points

Advantages such as increased levels of innovation, quick determination of consumer preferences and lower production costs have been linked to modular product architectures. However, such architectures have also been linked to detrimental outcomes such as high levels of competition and commoditization along with higher development costs. It is via the introduction of two key moderating variables that we better understand the impact that a modular product architecture has upon different firm-level outcomes.

[1] JEL Classification: L22, L23, L25

Introduction

The standardization of components within products to allow for the efficient division of labour as a basis for economic efficiencies goes back to the work of Adam Smith. By the 19^{th} Century, standardization of components had moved from underpinning elements of the Victorian factory system to driving true large scale production as a precursor to the Scientific Management approach of Taylor and the mass production principles of Fordism. Standardization literally changed the way manufacturing firms went about conducting business and had significant flow-on effects across society (Shapiro & Varian, 1998). For example, prior to the introduction of Winchester rifles, all firearms were crafted individually. The bolt on a rifle was built for a specific rifle and could not be interchanged with any other rifle, even those of the same brand. Standardizing parts and allowing for parts to be interchanged was a key part of the success of the Union Forces in the US Civil War. By the early 20^{th} Century industries such as the automobile industry were establishing industry-wide standards in basic components allowing for some level of interchangeability (Epstein, 1928). As competitive pressures increased various industries were driven, or chose to move towards modular product architectures for a variety of reasons (Schilling & Vasco, 2000). In the computer industry, the modular IBM PC was a result of IBM trying to quickly catch up to Apple and thus using a series of components from other companies (Baldwin & Clark, 2000). In the aircraft construction industry Boeing introduced a modular structure as way to reduce costs in the development of the 777, and in the automobile industry utilizing the same engine or platform was one way to spread the huge development costs across a greater number of cars (MacDuffie, 2013; Cabigiosu, Zirpoli & Camuffo, 2013). Sony moved to modular product architectures to gain a better understanding of consumers' needs and the mobile telecommunications industry has introduced elements of modularity to the mobile phone industry to ensure compatibility for users and to encourage the development of complementary products and services (Galvin & Rice, 2008).

While the initial shift towards standardization eventually led to a growing interest in modular product architectures, the basic principles of modularity are not limited to physical products. Modularity builds upon the principle of decomposition of artefacts into components and defining the manner in which these components interface. Sanchez and Mahoney (1996) recognized that modular products tended to be produced by firms with a modular organization architecture – in what has subsequently been termed the mirroring hypothesis (Colfer, 2007). Today, the mirroring hypothesis suggests a mirroring across differing levels of architectures such that we may consider how modular products may be developed by modular organizations and the corresponding division of labor and the division of knowledge (Colfer & Baldwin, 2016).

The effect on firms of introducing modular architectures has been inconsistent in terms of any benefit obtained. For IBM, the PC was in many ways their first step to losing their position of dominance in the computer industry, yet the modular System/360 was hailed as one of their great successes (Baldwin & Clark, 2000). For the bicycle industry as a whole, modularity principles sat at the heart of component level innovation, cost reductions and an ability to 'mix and match' components within the larger product architecture (Galvin & Morkel, 2001). However, the specialization of firms at the component level reduced the number of architectural and radical innovations (Galvin, 1999) and more recently there has been some shift back towards an integrated architecture to allow for performance improvements in the way that certain components function together (Fixon & Park, 2008). The flexibility that modular designs bring (Sanchez, 1995; Worren, Moore & Cardona, 2002) may also bring with it a level of commoditization and imitation that limits the capacity for a firm to achieve competitive advantage (Pil & Cohen, 2006). To date, the extant literature tends to look at the various advantages that firms may achieve in adopting modular product architectures. Less well covered are the potential downsides or drawbacks that come with a modular product architecture. It is on the basis of these inconsistent outcomes concerning the adoption of modular product architectures that we look to those contextual factors that may impact various outcomes. Drawing upon prior research, we consider various outcomes including learning at the firm level, barriers to entry, the nature of competition and prevalence and type of innovation.

This step towards understanding the conditions under which firms may benefit (or be disadvantaged) through adopting the principles of modularity aligns with other foci in respect of modularity research. Research in respect of the mirroring hypothesis has moved away from testing whether the mirroring hypothesis holds to the conditions under which mirroring does not occur. As such, recognizing that high levels of product complexity (e.g. MacDuffie, 2013; Zirpoli and Becker, 2011) and the rate of component change (Furlan, Cabigiosu & Camuffo, 2014) will 'mist the mirror' assists our understanding of what may constitute appropriate design choices in the case of modular product architectures under particular conditions. In the same vein, we introduce two key contextual variables through which to consider the likely outcomes when firms move to a modular product architecture. In-line with the recognition that the rate of change that restricts mirroring (Furlan et al., 2014), we similarly highlight how the rate of change will influence the impact modular designs may have upon a firm in terms of the benefits it may accrue. The other dimension we consider is who controls the architecture and the underlying knowledge of how the components work. Some modular designs constitute industry standards and others are firm-controlled. Whether or not a firm has control of the architecture and the underlying component-level knowledge is likely to impact how firms compete and the manner in which they can may benefit (or be disadvantaged) through the use of modular architectures. Before we introduce a more detailed discussion of these two contextual factors in the paper, we initially consider modularity as a concept, and then look to the literature to highlight the key advantages and disadvantages that have been presented concerning using modular product designs. Following the discussion concerning our two contextual factors, we discuss how the various advantages and disadvantages may vary within the different environments that may exist as per the two contextual factors. The result is a more fine-grained understanding of when the adoption of a modular product architecture is likely to lead to benefits at the firm level, and the form that these benefits may take.

What is Modularity?

Modules are parts within a larger system that are structurally independent, but work together. Where the system is a product, the modules are components. "A component in a product design performs a specific function or functions within a system of interrelated components whose collective functioning creates the overall functionality of the product" (Sanchez & Mahoney, 2000: 160). Thus a complex product such as a watch is made up of a series of components. Beyond the way that components interface with each other, these components are structurally independent, but they work together to provide an operational product. What differentiates modular product architectures from non-modular product architectures is the way the various components interface. Modular products have defined interfaces whereby each component connects and interacts with every surrounding component in a predefined manner. Thus, the deconstruction of systems such as complex products into a series of components and an architectural map of how they fit together provide us with the building blocks for modularity – components and defined interfaces (Schilling, 2000). The same principles apply to modular architectures of other artefacts. For example, a modular organizational architecture would see the organization design decomposed into organizational units that perform various functions (functional components) and these units would interface in a defined manner to determine how these units would interact and thus function together as a totality (Sanchez & Mahoney, 2013).

The result of adopting a modular architecture is that single components can be developed and operated independently of what occurs in respect of other components. Thus, modular products have advantages in that they, "allow each functional element of the product to be changed independently by changing only the corresponding components [whereas] ... fully integral components require changes to every component to effect change in any single functional element" (Ulrich, 1995: 426). Elements of modular systems can therefore be constantly changed or upgraded without the need to make changes across the entire system (Burton & Galvin, 2018a). The result is the modular products and the organizations that sit behind them may be loosely coupled due to the embedded coordination that modular architectures bring with them. Firms require less interdepartmental communications, they can move away from co-locating different departments responsible for different components and may even move towards using the market to acquire components rather than developing them internally. In essence, modularity is built around a series of architectural 'design rules' (Baldwin & Clark, 2000) that dictate which parameters are 'hidden' or encapsulated and which parameters are 'visible' to other product components. These design characteristics bring with them the potential for significant benefits, but also a series of downsides that are outlined in the following section.

Key Advantages and Disadvantages of Modularity

As product modularity occurs when component interfaces are standardized allowing for components within a product to change without affecting other components, modular designs allow for firms to 'mix and match' components within the product to increase the number of product variations available in the market (Ulrich, 1995) through what Garud and Kumaraswamy (1996) refer to as economies of substitution. Extending this line of reasoning, firms are able to more quickly determine consumer preferences by releasing multiple versions of a product in a short space of time that go to market with different combinations of components. A good example of this was the Sony Walkman which saw over 160 variations of the product released using a modular product architecture (Sanderson & Uzumeri, 1995).

The capacity to vary components while keeping the product architecture stable has also been linked to increased component level learning (and subsequent component level innovation) as firms are able to focus on a single component at a time. Due to the embedded coordination that is inherent in modular designs, teams are able to specialize and operate independently of other teams within a firm's structure or between independent firms, providing opportunities for specialization and develop capabilities at the component level (Sanchez & Mahoney, 1996). For example, in the computer industry, the large integrated manufacturers such as IBM and DEC have given way to specialist hardware and software producers, whereby most firms today compete in just one small segment of the industry. Similarly, in the UK pension industry, the large integrated pension companies undertake little activity in the value chain outside of retail and coordination as components such as the IT systems and funds management are undertaken by specialist firms (Burton, 2018). With the focus at the component level there are risks concerning the ability to adapt to future change. With task and knowledge specialization, there may be a specialization of capabilities (Jacobides & Winter, 2012) and thus firms may fail to build a broader set of capabilities that can cope with rapid technological and product related change.

In addition, whilst being able to focus on single components stimulates component level learning and innovation, the potential for more radical forms of innovation where component interfaces must also change is limited. Galvin (1999) highlighted how industry standards for components in the bicycle industry had allowed for considerable innovation at the component level, but had severely restricted architectural and radical forms of innovation. Firms have found ways around this – normally through dominant firms exerting control over the architecture. For example, systems integrators develop and control the product architecture, but use external providers for many of the components (Brusoni, Prencipe & Pavitt, 2001).

If choosing a modular architecture provides opportunities for learning and innovation (at least at the component level) as a basis for differentiation, then the other generic strategy (Porter, 1980) to consider is low cost. As modular designs create a level of embedded coordination, they remove the need for integrating mechanisms to coordinate activities (Sanchez & Mahoney, 1996). Such integrating mechanisms are costly to operate and create potential bottlenecks in respect of decisions regarding design and development – thereby providing firms with modular architectures a potential cost advantage due to the removal of these cost drivers. Modular product architectures may also lead to lower cost structures as it is likely that both ex-ante and ex-post transaction costs are reduced (Sanchez, Galvin & Bach, 2013). At least in the case of industry standard architectures, firms can limit their ex-ante transaction costs associated with sourcing components from the market as such components will already be defined through the industry standard. And ex-post transaction costs are similarly reduced on the basis of such standards reducing the costs of maladaptation and other disputes (Williamson, 1985). Modular architectures with standardized components may also provide opportunities for gains from specialization (when firms build capabilities to be more efficient at producing one or more components for sale into the market) and gains from trade (where firms acquire other components from firms that have a comparative advantage in this area) (Jacobides & Hitt 2005, Baldwin 2008). Combining these three drivers of potential sources of lower costs – embedded coordination, reduced transaction costs and gains from specialization and trade – it is likely that under certain circumstances, modular architectures reduce the cost of design and manufacture of components internally and increase the efficiencies associated with sourcing components from the market.

As the creation of a standardized product architecture across an entire industry shifts the focus of competition to the component-level, most players will produce one or a small range of components that will then be assembled by specialist assemblers or a small number of firms at one stage of the value chain (as is seen in the computer, bicycle and financial products industries). As components are developed that can simply 'plug and play', the barriers to entry to the industry are reduced as firms can become highly specialized in respect of a single component. However, as West (2003) reminds us, without innovation, differentiation or some form of lock-in, it will be very difficult for assembler firms or non-differentiated component developers 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).

These low barriers, while beneficial for new entrants, simultaneously limit the potential for a product based competitive advantage. Numerous researchers highlight that highly modular architectures bring with them significant threats of high levels of inter-firm competition, imitation and commoditization on the basis that the overall product architecture is consistent across the industry (Chesbrough & Kusunoki, 2001; Ethiraj, Levinthal, & Roy, 2008; Pil, & Cohen, 2006). The realization of all of these threats in the UK pension industry saw profitability in the industry severely reduced and this was the catalyst for a degree of reintegration that shifted aspects of the product architecture away from a modular design (Burton, 2018).

Finally, having a modular architecture whereby separate departments within IBM as well as other firms each worked on specific parts of the product significantly boosted the rate of component level innovation in the System/360. However, this same product is famous for the initial cost over-runs incurred (Baldwin & Clark, 1997) as developing various modules of the product independently was very difficult. What we see across different examples, is that the costs of initially developing an architecture can be very high as the operation and interfacing of components in an integrated product do not need to be defined up front and so teams work sequentially on different components of the product. However, in a modular architecture where teams work independently and often simultaneously, this cost of defining interfaces is a necessary operational cost. This perspective can be traced back to the ideas of Parnas (1972) who stressed the potential benefits of 'information-hiding'. His view is grounded in the notion that high levels of information-sharing can overwhelm a product development project, and it would be more efficient to hide or encapsulate information within a component boundary so that it cannot affect other parts of the system. However, this information hiding cannot occur to the same level in modular architectures due to the need to specify the interfaces and how the component will operate to other parts of the development team. It is this additional work that increases the time and costs involved in developing a modular architecture.

Taken together, we see from the prior literature that the key advantages associated with a modular architecture include; (a) higher levels of component level learning/innovation, (b) quick determination of consumer preferences, (c) reduction in production costs/costs of using the market, and (d) the lowering of barriers to entry within an industry.

Similarly, prior research suggests the key disadvantages of adopting a modular architecture are; (a) the low levels of architectural and radical innovations, (b) the high cost of developing a modular architecture, (c) limited capacity to react to change due to highly focussed capabilities, and (d) the high potential for inter-firm competition, imitation and commoditization.

Key Variables Determining the Effect of Modularity

Product modularity is built around two forms of knowledge; component level knowledge of how components operate and interact, and architectural knowledge as to how components fit together to form a functional system. Component level knowledge is required to understand how different parts within a system operate. For example, in a DVD player the digital data is read by a laser and is processed via a chip (microprocessor) that is at the heart of the system. Changing the capabilities of this chip has led to the advances seen in DVD players in terms of their reading capabilities. However to change the chip, it is necessary to know both what the chip does (component level knowledge) and how it links with the other components as per the spatial interface (physical location of component relative to others), the communication interface (how signals are exchanged) and the attachment interface (how the components actually connect). Characterizing product architectures in terms of these two forms of knowledge is not new. For example, Henderson and Clark (1990) discuss both component level knowledge (how a component operates) and architectural knowledge (how components fit together to form a functional system).

Integrating these two forms of knowledge as to how a component operates and links to others to create a functional system has been termed in the product modularity literature as the visible design rules (Baldwin & Clark, 2000) or 'the glue' that allows a functional product to emerge from a series of interlinked components (Sanchez & Mahoney, 1996). However, much of the literature suggests that a product architecture covers both how individual components operate within a system together to form a functional product as well as how the different components interface with each other. This product architecture and its underlying knowledge or 'glue' can act as an embedded form of coordination mechanism for loosely coupled organizational structures (Sanchez & Mahoney, 1996). In essence, firms that manufacture different components can operate autonomously because the critical task of coordinating the product development process no longer needs to occur as a functioning product architecture provide the coordination function ensuring that all components will operate effectively within the finished product.

Product architectures are particularly important in modular products as they provide a knowledge map of how and why each component must link with others in the system to create product functionality. This knowledge of component operations and interfaces allows for a firm to focus upon a single component independently, the backbone of both the advantages and disadvantages associated with modularity.

Thus we propose that the first of the critical contextual factors to consider in modularity studies is who actually controls the product architecture. The product architecture can be controlled by a single organization or the product architecture may be broadly diffused to form an industry standard. Where the product architecture is modular but is controlled by a single organization Takeishi (2002) and Takeishi and Fujimoto (2003), refer to this as 'closed modularisation' and

Langlois (2002) presents is as internal modularity (as opposed to external modularity). The idea of a firm-controlled or closed yet modular product architecture has also been formalised by Shibata, et al., (2005) and Sanchez (2008) in typologies 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 architecture that is open (and often relies upon industry standards) may be used by many firms and is often associated with the presence of significant network externalities and gains from trade and/or specialisation where interoperability between externally-sourced complementary product components is essential.an open architecture has high levels of commonality (Sanchez, et al., 2013). In such cases, interface specifications are standardised and the overall product architecture is unencumbered by intellectual property or other means of protection.

We posit that the second key contextual variable is the rate of change across a product architecture. A high rate of change across a product architecture was identified as a factor that limits mirroring across architectural levels (Furlan et al., 2014) as firms needed to have a more integrated structure that would allow for communication (and adaptation) to support technological change. We suggest that the product architecture can vary from being passive where virtually no change occurs through to active where change occurs on a regular basis. Passive product architectures see the component interfaces remain constant over time. For example, in the bicycle industry a dominant design has existed for over 100 years and while there is regular change at the component level, relatively few changes have occurred at an architectural level (e.g. in the 1980s the rear axle changed from being 130mm to 135mm to accommodate more gears). However, most component interfaces have been constant for at least 50 years (Galvin, 1999). At the other extreme is an active product architecture such as that found within the PC industry where standards for removable storage have shifted from 5¼ inch floppy disc to the 3.5 inch 'floppy' disc to the zip drive alternative to different DVD formats to USB and updated versions of this standard. Applying these two contextual dimensions will now allow us to discuss the scenarios under which modularity advantages or disadvantages may arise.

The Role of the Contextual Variables

Incremental and Radical Innovation

Increased component level learning (and subsequent component-level innovation) would seem to occur under all conditions affecting modularity. Irrespective of whether the product architecture is firm controlled or exists in the form of standards, entire firms or departments of firms are able to focus on just one component at a time without having to alter any other part of the product. Sanchez and Mahoney (2000: 166) suggest that the application of modular product architectures "enables more efficient learning and innovation at the component level to occur within widely dispersed, loosely coupled development organizations". Development of specialized capabilities built around a single (or limited range of components) allows firms to focus on component development built around such capabilities. Incremental innovation levels are high when the architecture is controlled at the firm level and the rate of change across the product architecture is high, eg jet engine control systems (Brusoni, et al., 2001). But incremental innovation is also high when the architecture changes minimally and has adopted industry standards such as in the bicycle industry (Galvin, 1999).

In relation to the disadvantages generated by modular product architectures, firm controlled product architectures are unlikely to suffer from low levels of architectural and radical innovation. While there may be a specialization in respect of capabilities (Jacobides & Winter, 2012), the control that such firms have over the entire product architecture either as systems integrators (Brusoni et al., 2001) or simply on the basis of their ability to bring different components from different suppliers into the system (MacDuffie, 2013). Thus, radical and architectural innovation is not a problem when the firm controls the product architecture.

In comparison, levels of architectural and radical innovation are believed to be very low when the product architecture is broadly diffused to create international standards. The existence of international standards replaces active coordination between firms within the industry. As has been seen in the computer and bicycle industries, this in turn is likely to cause the industry to be less conducive for vertically integrated firms and see more firms specialising in a single segment of the industry, communicating only with those firms to whom they send their finished components (Baldwin & Clark, 2000; Galvin & Morkel, 2001). As architectural and radical innovations require changes to occur in the way the components are linked together for a modular product this is only possible when the component interface specifications change. Thus it is necessary for the manufacturers/developers of adjoining components to work together to institute the innovation. But with communication and collaboration between manufacturers of adjoining components not occurring, it is very difficult to introduce architectural and radical innovations unless a manufacturer makes a number of adjoining components. This (lack of) impact by the contextual variables is shown in Figure 1.

<< INSERT FIGURE 1 ABOUT HERE >>

Establishing consumer preferences and barriers to entry

The rapid determination of consumer preferences is generally more common when the product architecture is firm controlled. For example Sony has used modularity for this purpose with both their Walkman product and their Hi-8 video cameras (Sanchez & Sudharshan, 1993). The basic platform remains constant and different components are trailed (such as different volume control systems) to determine the most popular designs and functions for the system. The same principle is being applied in relation to modular services such as where different financial products are packaged together under a single banner. Launching a number of these packages in short succession allows for consumer preferences to be determined in terms of the make-up of these packages and the level of complexity that they may contain (in terms of number of products).

It is possible to gain to determine consumer preferences where product architectures exist as standards. For example, an assembler such as Dell Computers can offer a range of options to the market (Magretta, 1998). However, the focus here seems to be on increasing the product range rather than determine consumer preferences as a way of establishing the focus for future production. Whether a product architecture is passive or active does not affect the ability of a firm to derive this advantage from modularity, however, this advantage makes more sense when the product architecture is changing.

If the advantage of determining consumer preferences through a process of mix and match different component combinations comes with a firm controlled architecture firms control the product architecture, then this presence of an established set of consumer preferences keeps barriers to entry very low. Thus, where product architectures take the form of international standards and products vary between producers is only limited ways, barriers to entry are lowered, such as in the computer hardware and software industries (Baldwin & Clark, 2000). Here there is a continual move of firms both into and out of the industry. When supplier oriented individual firms sell to assemblers or other firms that control the product architecture, they are not in a position to access the entire product architecture and thus it cannot be easily transferred from assembler firm that acts as the product architecture gatekeeper. As an example, in the pension industry, new small players were able to enter the industry post 2000 with a highly specialized component offering (Burton, 2018).

In cases of international standards, passive product architectures may allow for barriers to entry to be at their lowest (as firms do not need to collaborate in any way and the industry is at its least integrated). For example in the case of the bicycle industry Galvin and Morkel (2001) showed how the industry had fragmented into a number of sub-industries such that 90 percent of part manufacturers were producing only one type of bicycle part (Chu, 1997). When product architectures are changing, there may need to be some collaboration between major players in the industry to enact component interface changes, and exclusion from this key group can cause firms to be far more reactive and this alone may form some form of entry barrier. For the creation of the next generation of wireless short-range communications, a group of large players came together to determine the specifications for what would eventually become known as 'Bluetooth' and major mobile phone manufacturers worked (with support from the International Telecommunications Union) to ensure that the 3G systems were more unified than what was the case with 2G systems (Glimstedt, 2001). These relationships are shown in Figure 2.

< < INSERT FIGURE 2 ABOUT HERE > >

Production cost and development costs

In cases where the product architecture is controlled by the firm, there is likely to be a higher degree of internal production. This will not occur in respect of all components, as many may be somewhat generic and be able to be sourced from the market, but for unique components, to utilize the market is to be subject to opportunism on the basis of small numbers bargaining (as the components is unique) or possibly even feature specialized assets (Williamson, 1975). Lower costs are likely to be possible due to the embedded coordination that the modular architecture provides. But this lower cost structure is only possible if the product architecture is relatively passive. Once the technology starts changing rapidly, as has been shown in respect of the mirroring hypothesis, firms need to create integrating mechanisms to allow for different departments to coordinate their activity. Thus in a study of the laptop industry, firms were unable to benefit from modular structures, even when they were producing a modular product (Hoetker, 2006). In comparison, the air-conditioning industry is slow to develop with products with a product line-up unlikely to develop for five or more years. In such cases firms can use the market (and produce some components internally) whilst benefiting from the reduced coordination costs that come with modularity (Cabigiosu & Camuffo, 2012).

Where product architectures exist as industry standards, firms are able to take advantage of the potentially lower costs associated with the market on the basis of the gains from trade and gains from specialization (Jacobides & Hitt 2005; Baldwin 2008). Relatively passive product architectures such as pension products saw the ‘assemblers’ of the different financial products benefit from low transaction costs and gains from trade (Burton, 2018). However, active product architectures are not able to benefit as much from the lower costs structures due to the need for some form of coordination or supra-governance type arrangements that need to be in place to cope with changes in technology and thus may counter the efficiencies that are otherwise available through sourcing components from the market. This has been seen in the coordination of wireless communication standards such as Bluetooth or various mobile phone standards for certain generations of mobile phones (Galvin & Rice, 2008).

While the reduction of production costs has been associated with adopting modular product architectures, this design choice will likely lead to higher development costs. At a base level, firms make ex-ante investments to create a modular product architecture which then reduces ex-post transaction costs via the inherent embedded coordination that modular architectures bring with them (Burton & Galvin, 2018b; Sanchez, Galvin & Bach, 2013). Thus high production costs become an issue when product architectures are firm controlled and thus an individual firm needs to develop the entire architecture. The very high costs involved in developing new motor vehicle platforms are a case in point. Every new platform involves a series of new interfaces and considerable development work. In an empirical study of the motor vehicle industry MacDuffie (2013) considered the speed of modularization, and while development cost was not directly assessed, the research points to the complexity and high costs of instituting modular architectures. There is no difference in the development costs in terms of the rate of change of the product architecture as the more architectures that change more often simply require firms to make these ex-ante investments more frequently.

In comparison, when industry level standards exist, product development costs are relatively low as existing components can be combined to form the product. As a contrast to MacDuffie's (2012) study of some major motor vehicle manufacturers, the development of the different generations of personal computers (featuring the 'Wintel' standard) is a case in point. Different suppliers purchase existing components/software from the market to build their new products. Similarly, in the mortgage banking industry, Jacobides (2005) presents how what was a vertically integrated industry became disintegrated as smaller firms picked up parts of the value chain (such as the sales function). In respect of the second contextual dimension, the rate of change in the product architecture, active product architectures simply mean that redevelopment has to occur on a more regular basis, whereas passive product architectures limits the frequency of these investments. These relationships are shown in Figure 3.

< < INSERT FIGURE 3 ABOUT HERE > >

Product based competitive advantages, imitation and commoditization

In the same way that barriers to entry are kept high when firms control the product architecture because of their integrated nature, firms are able to keep a tight rein on their technology and maintain any product derived competitive advantage under these same conditions. This is probably best seen in the motor vehicle industry and in aircraft production. Even firms that are brought into the production systems as manufacturers have access to only a small part of the product architecture and they are thus less important than the product architecture controlling firm.

Where industry standards exist, there are limited opportunities for products to be differentiated on the basis of the entire product. Instead, differentiation must occur at the component level. Hence most computer manufacturers/assemblers have to compete on price and service. To most consumers, Dell can probably provide the same product as Lenovo, Acer or HP. Differentiation is reduced to the component level, such as Intel versus AMD chips and Soundblaster versus Creative Labs sound cards.

The rate of change in the product architecture has no bearing on the extent to which a product based competitive advantage may be maintained as it is all entirely dependent upon the industry. That is passive product architectures and no more or less likely to be able to support a product based competitive advantage than an active product architecture.

Similarly, high levels of inter-firm competition, imitation and eventually commoditization are most likely to occur in cases where industry standards are in place. Products are invariably very similar with some possible differences at the components level. Certainly this is the case in the PC industry where most of the key components are very similar and this high level of competition saw firms that dominated the industry early such as IBM leave the industry by selling their PC operations to Lenovo or Hewlett Packard lose considerable market share. While this extreme level of competition and eventual commoditization may be most extreme in respect of passive product architectures (e.g. pension products) it is clearly also present in the case of active product architectures such as shown in the PC industry discussed above.

In comparison, very high levels of inter-firm competition, imitation and commoditization is not a significant issue where the product architecture is firm controlled. The potential for firms to differentiate on the basis of one or more components is high as seen in the cases of air-conditioning systems (Cabigiosu & Camuffo, 2012) or motor vehicles (MacDuffie, 2013). This is irrespective of whether the product architecture is changing rapidly or not as shown in Figure 4.

< < INSERT FIGURE 4 ABOUT HERE > >

Concluding Remarks

Modularity brings together brings together a range of different theoretical areas from organization design through to engineering management. And in considering how various phenomena may vary under conditions of modularity (and not just necessarily product modularity) researchers have drawn upon a wide range of theory including various strategy-related theories such as resources, capabilities, knowledge, competitive dynamics, transaction cost economics and generic strategies. Outside of strategy, the field has brought together organization theory, innovation, operations management, marketing and management history. With such a diversity of research occurring with such varied theoretical grounding it is perhaps unsurprising that core themes outside of the mirroring hypothesis have been slow to emerge. Certainly, modularity has been linked, either implicitly or explicitly to a variety of benefits, and less frequently to some potential downsides. However, in the same way as the mirroring hypothesis prior to the work of Colfer and Baldwin (2016) has previously lacked systematic study as to when modularity at one architectural level is then mirrored by modularity at other architectural levels, there is still a general lack of research concerning the conditions under which modularity may bring with it certain advantages and disadvantages. In essence, this paper hopes to provide the starting point for a discussion concerning some of the contextual factors that determine whether the choice of a modular architecture will bring with it a series of benefits or disadvantages.

Certainly as areas of theory mature, research shifts from universal, generalist theory towards more context specific theory whereby we recognize that well-established cause and effect relationships may well be moderated or mediated by other variables. Specific journals have evolved to cater to this understanding of the role of context (e.g. Galvin, 2014). In respect of the modularity literature, this can be seen in the trend concerning when the mirroring hypothesis does not hold (Sorkun & Furlan, 2017). Other authors have taken similar approaches (eg Sanchez, 2008) and presented other contextual variables. Thus, theoretically, this work falls into a well-established pattern of building our understanding concerning divergent outcomes via the introduction of specific contextual factors.

We have based our analysis of the important contextual factors that may affect the extent to which modularity may form something of a strategic tool around the concept of the product architecture. As product architectures are essentially a knowledge map of how and why each component must link with others to create a functional product, they capture the key dimensions of what differentiates modular products – defined component interfaces and thus interchangeability of components without altering other elements in the system. In asking who, what, where and how questions in relation to this fundamental underlying construct, we suggest that the, 'who controls the product architecture?' and the, 'how often do they change?' are the questions that make the most sense in that they show how different manifestations of a product architecture produce a range of outcomes under different conditions. In discussing whether the product architectures that drive modularity are active or passive, and whether they are firm controlled or industry wide standards, we acknowledge that these are not the only possible contextual variables that need to be considered. They are however, in our opinion, relevant, in that on the basis of our research of the field and our own work in the area of modularity, they are capable of explaining some of the circumstances under which product modularity will lead to the previously discussed advantages or disadvantages. Thus, we believe that such a debate regarding these and other contextual factors is critical for further development of the field.

From a management perspective, this research highlights that modular product architectures are unlikely to be the universal panacea to a raft of strategic issues that perhaps initial research made them out to be. Appreciating that the rate of change across the product architecture and whether the architecture if based upon firm-developed standard interfaces or industry-wide interfaces should provide some level of insight into the potential benefits or challenges that may eventuate when adopting a modular product architecture. In reality, different managers will have different priorities according to the prevailing competition, stage of industry development and perceived importance of innovation. Thus for some managers, certain downsides associated with modular architectures (eg low levels of radical innovation) may not be of concern, whereas others (eg high product development costs) may be critical. Thus, the introduction of two contextual factors and addressing their potential impact on different outcomes provides a starting point for managers to assess the appropriateness of a modular architecture.

This research is perhaps one step closer to what some have suggested as being the unresolved issue facing much of the modularity research – how does the choice of a modular design impact performance (Colfer & Baldwin, 2016; Sorken & Furlan, 2017)? To date, research has addressed questions such as what drives modular architectures, whether and when the mirroring hypothesis holds and the impact of modularity upon a range of variables from strategic flexibility to different forms of innovation. The impact of choosing a modular architecture has not been addressed other than indirectly such as the 'modularity trap' that may result in high levels of imitation and commoditization (eg Pil & Cohen 2006). We have considered some of the specific circumstances under which various advantages or disadvantages may accrue to the firm, but the next step is to empirically consider how the rate of change in a product architecture and who controls the product architecture on the performance of firms.

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ALL FIGURES ARE PROVIDED IN THE ATTACHED DOCUMENT

Peter Galvin is Professor of Strategic Management at Edith Cowan University. He has research interests in modular architectures, boundaries of the firm and dynamic capabilities. He takes a particular interest in non-traditional industries.

School of Business & Law, Edith Cowan University

Ph: +61 406 434 760

p.galvin@ecu.edu.au

Nicholas Burton is a Senior Lecturer in Strategic Management & Corporate Responsibility at Northumbria University in Newcastle, UK. He holds a PhD in strategic management from Northumbria University. His research interests include strategic management, corporate responsibility and thematic coding methods.

Faculty of Business and Law, Northumbria University

Phone: +44 191 227 3319

n.burton@northumbria.ac.uk

Norbert Bach is Professor of Management and Organization at TU Ilmenau since April 2008. He holds a Ph.D. from Justus-Liebig-University Giessen and held visiting appointments at Curtin University in Perth and National University of Ireland, Galway (NUIG). His research interests include strategic management, organizational identity, and entreprenurship.

Institute for Business Studies

TU Ilmenau

Ph: +49 3677 69 4066

Norbert.Bach@tu-ilmenau.de

John Rice is Professor of Strategic Management at Zayed University in the United Arab Emirates. His PhD is from Curtin University. He has held academic appointments at the University of New England and Griffith University. His research interests span strategic management, sustainability and organizational capabilities.

College of Business, Zayed University

Phone: +971 501781053

john.rice@zu.ac.ae