UNDERSTANDING CROSS BORDER INNOVATION ACTIVITIES: THE LINKAGES BETWEEN INOVATION MODES, PRODUCT ARCHITECTURE AND FIRM BOUNDARIES

Global value chains are a complex and nested system to do with how a firm sets its firm boundaries (across two or more national boundaries), and manages its task allocation, its knowledge assets, and its product design and innovation (Rezek, Srai & Williamson, 2016; Srai & Alinaghian, 2013). A significant stream of the international business literature has examined firm boundaries and the way in which a firm manages its global value chain (eg. Casson & Wadeson, 2012; Mudambi & Venzin, 2010; Srai & Alinaghian, 2013). However, few empirical studies, with some notable exceptions (Burton, Nyuur, and Amankwah-Amoah, forthcoming; Elia, Massini, & Narula, in press; McDermott, Mudambi, & Parente, 2013; Parente, Baake, & Hahn, 2011; Rezek, et al., 2016) have examined the role of a firm's product design choices and how they relate to and inform global value chain choices. As Khurana and Talbot (1998) noted some time ago, this is rather puzzling given that product design choices have crucial implications for the flows of inputs, design and development, and the knowledge that underpins value creation and capture (Rezek, et al., 2016).

To better understand how product design choices inform the location (within or across national boundaries) of different activities in a global value chain, we rely upon modularity theory to discern between integrated product designs and modular product designs. In any given industry it is feasible that a number of different product designs might be possible, each with different combinations of performance, quality or cost (Burton & Galvin, 2018a). Modular designs are partitioned and decomposed so that there is a one-to-one mapping between components and product functions, whereas integrated product designs are less easily partitioned and decomposed into independent components and feature a many-to-one mapping between components and product functions (Ulrich, 1995; Schilling, 2000). Recently, modularity theory has also been utilized to consider how firm architecture (eg. Schilling & Steensma, 2001) and industry architecture (eg. Jacobides, 2005; Jacobides & Kudina, 2013) are configured, and the extent to which the configurations relate to product design. Such scholarship has posited that, in some circumstances, firm architecture and the surrounding industry architecture come to mirror the architecture of the technical product (eg, a mirroring hypothesis is said to be present) (Burton & Galvin, 2018a; Colfer & Baldwin, 2016).

The mirroring hypothesis predicts that where a product architecture is decomposed into independent components, the associated task, knowledge, and firm boundary will correspondingly be decomposed and specialized, and mirror the technical architecture of the product. In contrast, where a product architecture is integrated, components remain interdependent with each other, and the associated task, knowledge, and firm boundary will favour vertical integration within a single firm. In other words, modular product architectures are often designed and developed by groups of specialized firms, whereas integrated product architectures are often designed and developed by a single firm. In the literature, mirroring is associated with firm efficiency, such as reduced costs of communication and coordination (Querbes & Frenken, 2018), efficient product design and development (Sanchez & Mahoney, 1996), reduced sourcing costs (Hoetker, Swainathan & Mitchell 2007) and gains from specialization and trade (Sanchez, Galvin & Bach, 2013). These benefits accrue to firms because where the structure of specialization mirrors the technical architecture, communication and information exchange needs *ex-post* are few, and R&D activities can be more efficiently distributed across firm boundaries. Conversely, where vertical integration mirrors the technical architecture, communication and information exchange needs are significant, and R&D activities will benefit from co-location. Given that mirroring has significant implications for organization design, firm efficiency, and the structure of industries, it is puzzling that these ideas have not gained the same attention in the international business literature. Thus, the relationship between product design choices and the location of R&D tasks has yet to be addressed. An exception is the recent study by Elia, Massini and Narula (in press) who adopted an operations perspective to examine business services offshoring, and noted that the mirroring hypotheses was generally supported, but that it was 'misted' where there was a wide cultural distance between home and host country, and political instability in the host country. However, how product design informs the location of firm boundaries within or across national boundaries has otherwise been neglected. We respond to the call by Colfer and Baldwin (2016) and Elia, et al., (in press) for empirical work that offers further explication of the mirroring hypothesis. Our approach is embedded within the innovation literature, and draws upon innovation types discussed by Henderson and Clark (1990) and the later connected between innovation types and firm boundaries elaborated by Wolter and Veloso (2008). Specifically, we consider the extent to which modular/incremental and radical/architectural innovation types inform the geographical location of firm boundaries, and whether those boundaries either reinforce or destabilize the mirroring hypothesis. In essence, given that modular and incremental innovations can be isolated at the component level, and that modularity embeds coordination and communication in its design, it is probable that there is the potential for such types of innovation to span across national boundaries. However, for radical and architectural innovations, given that such kinds of innovation involve design changes across multiple and complementary components, the extensive coordination and information exchange required across different activities may limit the potential for spanning both firm and national boundaries. The extent to which innovation modes interact with the location of firm and national boundaries is both non-trivial and pressing - as supply chains become ever more global, strategizing managers face critical decisions regarding which elements of the product design to modularize and outsource to other firms, which tasks to locate within national boundaries, and which to locate across international boundaries.

To explore the linkages between innovation modes and the geographical location of firm boundaries, we examine the global bicycle industry since the 1990s. We chose the global bicycle industry because it is well-known for its modular architecture that connects together via a series of international standards (Galvin, 1999; Galvin & Morkel, 2001), but also that there is evidence of sets of components becoming less modular following architectural or radical innovation (eg. Fixson & Park, 2008). The novelty of our paper is that we bring the literature on global value chains into a much deeper conversation with product design, innovation modes, and modularity theory. In other words, we put choices of product design at the heart of global innovation and sourcing decisions. In line with the idea that 'products design organizations' (Sanchez & Mahoney, 1996), we argue that the role of product design is central to a fuller understanding of how and where to innovate, and we provide a test of the mirroring hypothesis that encompasses not only firm boundaries, but also national boundaries. By doing so, we contribute to both the extant modularity literature and international business literature by enhancing existing explanations of the drivers behind the location of R&D activities across a global industry value chain.

MODULAR ARCHITECTURES AND INNOVATION

As a general systems theory (Schilling, 2000), modularity supposes that a system can often be decomposed into smaller sub-systems or components (Simon, 1962). Modularity has been applied by scholars to many kinds of systems across multiple industries (Fixson, 2003) and there is a growing literature that illuminates how modularity has contributed to our understanding of how various systems – such as products, firms and entire industries – are configured and evolve (eg. Burton & Galvin, 2018b; Fixson & Park, 2008; Jacobides, Knusden & Augier, 2006; Sanchez & Mahoney, 1996; Tee, 2019). Recently, scholarship has shifted to examine the way in which different industries have differing propensities to modularize

(Cacciatori, Tamoschus, & Grabher, 2012; McDermott, et al., 2013) and the extent to which they fragment (Lall, Albaladejo, & Zhang, 2004). A further stream of research has examined the extent to which nested systems may correspond to each other (eg. Colfer & Baldwin, 2016), and subsequently, the extent to which certain contingencies – such as product complexity and the rate of technological change – may 'mist' the mirror (Burton & Galvin, 2018a; Furlan, Cabigiosu & Camuffo, 2014; Sorkun & Furlan, 2017).

Given that products are technological systems, modularity has featured strongly as a theoretical lens from which to examine product design and its relationship to firm structure and the nature of competition between firms within an industry. Ulrich (1995) argued that products have an 'architecture', and when these are composed of independent sub-systems and components featuring standardized interfaces, the architecture is considered 'modular'. In comparison, interdependent sub-systems and components, with closed interfaces, are described as integrated product architectures. Chung, Han and Sohn (2012) note that the choice of a modular product architecture or integrated product architecture is one between flexibility and complexity. Modular product designs, according to McDermott, et al., (2013), are becoming more ubiquitous as the global economy becomes more networked and fewer products and services are used as integrated units.

Given high-levels of component interdependence, integrated product architectures are much more difficult to re-engineer to new uses without significant architectural redesign (Schilling, 2000). Modular product designs, on the other hand, are more easily manipulated to create multiple product variations (eg, Sanchez, 2008; Sanchez & Mahoney, 2013). However, modular products are enabled by the presence of stable interface standards that reconnect independent components together. Given independent components and stable and standardized interfaces, the architecture of a modular product enables distributed R&D teams to isolate design changes within the technical boundary of a component without requiring modification to other components or the architecture itself (Sanchez & Mahoney, 1996). Isolating design changes at the component level has a number of potential benefits for both 'lead' firms and other specialized firms in the value chain. It permits upgraded components to be substituted into the product architecture or into product families (Garud & Kumaraswamy, 1995), and enables wider mixing and matching of components to offer new product variations (Sanchez & Mahoney, 2013), and this type of flexibility may be a source of differentiation and strategic advantage (Sanchez, 1995). It may also result in reduced product development cycle times and increased responsiveness (Bouncken, Pesch & Gudergan, 2015; Sanchez & Collins, 2001), increased effectiveness of new product development (Parente, Baack, & Hahn, 2011), and offer opportunities to enter multiple international product markets, subject to the presence of international standards, via exporting (Burton, et al., forthcoming). Thus, in an international context, modularity may be a strategic design option to manage cooperation with specialized firms and alliance partners during the R&D process (Bouncken, Pesch & Gudergan, 2015; Tiwana & Konsynski, 2010).

Whether an innovation is architectural/radical or modular/incremental has significant implications for the location of firm boundaries. Wolter and Veloso (2008) explored the effects of Henderson and Clark's (1990) innovation typology on the degree of vertical integration in a product market. They argue that incremental innovation is unlikely to affect the degree of vertical integration in an industry as transaction costs and the existing knowledge boundaries are non-disrupted. However, for modular innovation the degree of vertical integration would be expected to decrease due to falling transaction costs and reduced coordination needs. Finally, architectural and radical innovations have the potential to increase the level of vertical integration owing to the reintroduction of transaction costs and coordination needs. Modularity has also featured in scholarship related to firm boundaries (eg. Burton & Galvin, 2018b; Sanchez, 2008). For example, Baldwin (2008) recognizes that firms that adopt modular organizational designs are more able to engage in transactions with other parties as the firm has invested in aligning with market standards. Adopting a modular product design and aligning with industry standards provides significant opportunities for firms to engage with the market and benefit from gains from specialisation and gains from trade. Extending these ideas to the international domain has received scant attention, however. The location of firm boundaries presents incumbent firms with significant coordination challenges across a global value chain (Patel, et al., 2018; Srai & Alinaghian, 2013). Firms often engage in national and international collaborations to design new products, but when collaboration is distributed across national boundaries it presents significant challenges to effective communication and information exchange (Manning, 2014) as R&D teams from different institutional and cultural backgrounds try to integrate information to progress design and development (Patel, et al., 2018). Martens, Matthyssens, and Vandenbempt (2012) highlight that internationally-distributed collaborations must often develop shared interpretations and establish new collaborative knowledge and routines (Jensen, Larsen, & Pedersen, 2013). Thus, unforeseen challenges in coordination and control often stall the efficiency with which such tasks can be accomplished (Larsen, 2016; Steinberg, Procher, & Urbig, 2017).

Wolter and Veloso (2008) argued that modular and incremental innovations are often governed through bi- and multi-lateral contracts, and the embedded and codified knowledge within modular components can be more easily transferred (Christensen, Verlinden, & Westerman, 2002). Baldwin (2008) contends that the features of modularity are akin to thin crossing points in the product architecture that break-up complexity and interdependence. Extending this argument, a modular product design opens up a strategic choice regarding whether to pursue modular or incremental innovations within firm boundaries and/or to utilize R&D teams in specialized firms across global value chains, with few ex-post requirements for communication and information exchange. Once modularization has permeated much of a product architecture – and assuming the 'mirroring hypothesis' holds – much of an industry value chain may decompose into specialized firms mirroring the technical architecture. Given R&D can be isolated at the component level, modular components can be designed (and produced) independently by separate individuals, teams, divisions or firms (Sanchez, 2008) and alliance partners (Bouncken, Pesch, & Gudersgan, 2015). The interface standards within modular product architectures provide a form of "embedded coordination" (Sanchez & Mahoney 1996) that provides the opportunity for in-parallel component development by distributed R&D teams (Baldwin & Evenett, 2015; Galunic & Eisenhardt, 2001). Embedded coordination acts as a substitute for high-levels of ex-post communication and information-exchange between R&D teams, and removes or significantly reduces the need for overt managerial authority and control (Baldwin, 2008). As R&D teams working on different components are able to operate independently and remotely of each other, the resultant firm structures may also become 'modular' and mirror the technical architecture.

In contrast, vertical integration emphasizes control and coordination of the global value chain and is often a preferred governance mode to overcome transaction inefficiencies in market-based transactions, protect and develop tacit knowledge, develop productive capabilities (Jacobides & Hitt, 2006) and resolve issues to do with communication and control (Lawrence & Lorsch, 1967). In an international context, vertical integration may also have advantages in overcoming issues to do with geographical and cultural distance. Internalization theory (eg. Buckley & Casson, 1976) also assumes that internalization of tasks enables a firm to benefit from ownership advantages through investments in, and protection of, assets, capabilities and knowledge. Moreover, it may also help firms develop or respond to architectural and radical innovation (Wolter & Veloso, 2008). Following, architectural and radical innovations are characterized by the need for high-levels of communication and information exchange between R&D teams as the existing stable product architecture and interface standards are subject to disruption. Thus, such innovations often feature team co-location in order to minimize information asymmetries (Jacobides & Hitt, 2006) and to potentially leverage tacit knowledge and productive capabilities through which the firm achieves competitive advantage (Jensen & Petersen, 2013).

In international business scholarship, the mirroring hypothesis has yet to gain significant traction, and has yet to adequately explain the efficiency benefits of locating product design across both firm and national boundaries. In this paper, unlike Elia, et al (in press), we take an innovation perspective rather than a production or operations management perspective. While Elia, et al (in press) found qualified support for the mirroring hypothesis in business services offshoring, the extent to which the mirroring hypothesis may hold across national boundaries for R&D activities has not been explored. In doing so, we consider the extent to two different types of innovation - radical/architectural and incremental/modular – inform the location of firm boundaries, and whether those boundaries extend across two or more national boundaries. Thus, for the mirroring hypothesis to hold, the prediction would be as follows:

P1: Incremental and modular innovations in a global value chain will feature geographic dispersion of R&D teams across both firm and national boundaries.

P2: Radical and architectural innovations in a global value chain will feature geographic co-location of R&D teams within both firm and national boundaries.

RESEARCH METHOD

The data used in this paper comes from a study of the global bicycle industry that considered innovations developed in the industry since the 1990s. We selected the global bicycle industry because the modular character of the product artefact is well-known, and it features significant geographical dispersion. Of the industries that are known for modular product designs (eg, personal computers, bicycles, air-conditioning units and white-goods), the bicycle industry is the most global in nature (eg, manufacturing occurred across numerous countries and was significant in five continents), and is dominated by relatively small specialized firms, and thus making across-firm collaboration more likely. The bicycle industry has also featured a constant flow of innovations emanating from a range of firms, often originating from the defense, aerospace and chemical industries, and furthermore, the innovations often rely upon new processes such as bladder molding and computer numeric controlled (CNC) machining.

One of the challenges concerning innovation studies that track the development of innovations is that innovation is a process as well as an outcome. The innovation process often begins well before the final product or service is released to market. The informal linkages that exist between people (rather than formal organizational links) and the original source of ideas can be difficult to trace without a detailed investigation of each innovation and so while it is possible, for example, to compile data concerning particular variables such as formal alliances, those formal alliances may represent just part of a much richer story. Our data was collected through an ‘analytically-structured history’ (Rowlinson, Hassard & Decker, 2014) of the global bicycle industry. Case studies and histories are often used in research in the field of industrial change (Dubois & Gadde, 2002). We examined the relationship between innovation type, following Henderson & Clark's typology, and the geographic distribution of the relationships between firms engaged in different types of innovation. Following Fixson and Park (2008) in their study of the relationship between product and industry architecture in the bicycle industry, our approach established separate domains for the innovation type and the location of innovation activities. In the innovation type domain, we classified each innovation in the industry as incremental, modular, architectural or radical. Similarly, the physical location and distribution of innovation activities, and whether the innovation involved multiple firms, was also identified. Of the 186 innovations identified, detailed information concerning the innovation process could be sufficiently tracked for 121 of these.

To create the case history of innovations in the global bicycle industry, we collected both quantitative and qualitative data which we triangulated using multiple data sources. We collected archival data from a range of trade journals, enthusiast magazines and web-site reviews. To add further richness to our archival research, we also supplemented this with oral history data (eg, Haynes, 2010) through interviews with industry observers and technical experts that also provided a useful checking mechanism (King & Horrocks, 2010). The types of innovations across the industry tended to be skewed towards the 'performance' end of the industry. This is because innovations in the industry tended to originate in the 'performance' segment before diffusing to other value-based segments across time. For example, increases in the number of gears were initially targeted towards race-level bicycles but slowly spread through lower priced alternatives. Second, the trade literature and other data sources available in English tended not to cover technical advances made by Chinese and Taiwanese firms that tend to target the more price-sensitive market segments. Thus, it is possible that there may be innovations by firms in the Far East that were not captured within this study.

The data is presented in two blocks. The first set of cases cover incremental and modular innovations. The second set of cases considers architectural or radical innovations. The breakdown of innovations across the different categories is shown in Table 1 below.

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While the frequency of the different types of innovation mode within the total sample is provided, our analysis was focused on the process by which innovations were developed. As discussed, we consider three different location modes: a) within firm boundaries; b) via collaboration with other firms in the same country; and, c) where international collaboration occurred as part of the innovation process.

FINDINGS

Industry Background

The bicycle industry grew very quickly following the introduction of the 'safety bicycle' in 1884 and by 1899 sales reached 1.2 million units in the US alone (Petty, 1995). However, with a dominant design in place, a shake-out of the industry saw hundreds of players exit the industry such that only 12 manufacturers remained in the US by 1905 (Hounshell, 1984). With few suppliers of components left in the sector, larger manufacturers shifted to a vertical integration model. For example, Raleigh (UK), Peugeot and Mavic (France) and Schwinn (USA) started to produce their own range of components in the mid-twentieth century as a way to create product variety and drive innovation across products (Beeley 1992).

As the industry started to grow rapidly again from the 1960s onwards, smaller specialized players started to develop a range of components to sell to frame-manufacturers. These needed to be able to ‘mix and match’ with as many frame-manufacturers as possible and so the industry started to shift towards a range of industry standards to connect components together. These industry standards reduced over time such that today the bicycle has a modular architecture with components linked together via a limited number of industry standards, such as three standard widths for the rear axle, and two types of screw for bottom brackets (Galvin & Morkel, 2001). There has been some movement back towards reintegration of components such as the drive train in the case of Shimano (Fixson & Park, 2008), however, the current product architecture remains largely modular. With no single firm able to produce an entire bicycle, the industry is populated by highly specialised firms that are spread across a wide range of countries. While production of higher-end components is dominated by firms in Western Europe, Japan, USA and Taiwan, there are manufacturers in other regions such as South America, Oceania and Eastern Europe, along with a very considerable number of value-based producers through China and other parts of Asia.

Incremental and Modular Innovations

The vast bulk of innovations within the bicycle industry occurred at the component level. Incremental innovations (constituting 89 of the total sample of 121) often took the form of using advanced materials to improve the performance of the specific component, e.g. reduced weight, increased strength or durability. There were also technical advances in the way in which the component functioned, such as increasing the number of gears, improved biomechanics, or increased strength/durability. Modular innovations were less frequent (25 out of the sample of 121) and do not involve changes in the way that components interact, but alter the core operating principles of the component itself. For example, spokes where the nipple adjusts the tension adjoins the hub rather than the rim.

The vast majority of these incremental/modular innovations (114 in total) were developed within the boundaries of the developing firm. For example, a tyre manufacturer developed tyres that were designed differently for front and rear wheels (given steering occurs through the front wheel and power is delivered through the rear wheel). There was some collaboration with users (such as professional race teams) to test and adjust the component, but collaboration with other firms was not evident. The ZAP electronic gear changing system developed by Mavic was developed with input from, and subsequently tested by, the professional race teams sponsored by Mavic, but no external design collaboration was evident. In other cases, separate firms were established for the specific purpose of bringing a new component to market. For example, specialized firms were established to develop advanced materials such as components that draw upon carbon fibre, titanium or composite materials within the aerospace, defence or chemical industry (eg Kestrel's monocoque frames or Actiontech's titanium chain rings) and thus innovation occurred within the boundary of a single firm. In three cases, we noted that multi-divisional firms leveraged knowledge and capabilities from other parts of the organization to apply to a bicycle component, for example the French firm Corima primarily operated in the defence industry, but used its capabilities in carbon fibre to create a four-spoked carbon fibre wheel.

Where firms did collaborate in design, the collaboration often took place within national boundaries (total of 19 cases where the innovation was incremental or modular). One example is the aero-bar which allows riders to adopt a more aerodynamic position. There is some controversy as to who developed the initial idea but the first version that was commercialized originated through the US company, Scott, and their developer Boone Lennon, who was a down-hill ski coach, and also a keen cyclist and aerodynamics consultant to three-time Tour de France winner Greg Le Mond. Boone Lennon applied his knowledge on wind resistance and aerodynamics to cycling to develop the idea of reducing resistance through replicating the 'egg-tuck' position used in skiing. He then worked with the ski company to develop the product for commercial sale. Scott was a logical choice as their focus was on ski poles (eg. experience in manufacturing tubular aluminium products) and Boone was well-connected in the ski industry. Also in the US, Yeti worked with Kaiser Aerospace to create a thermoplastic composite frame. In Italy, Colnago developed a frame that did not include a seat-tube through collaboration with engineers in the design area of Ferrari. Finally, in Germany, Sachs (a manufacturer of drive train and brake systems) worked with Magura (originally a manufacturer of brakes for motorcycles) to create hydraulic brakes for bicycles.

There were 11 incremental/modular innovations that involved design collaboration across national boundaries. In the first group, there were a number of examples of advanced materials manufacturers that did not have an extensive history in developing components for the bicycle industry. Thus, these firms developed collaborative relationships to enable the development of a component that would specifically meet the needs of the bicycle industry. For example, EDO Fibre Science operated in the defence industry, but with the slowdown in defence in the 1990s, they created a subsidiary – EDO Sports – to leverage some of their expertise around carbon fibre technology into sports industries (most notably golf clubs and bicycle components). EDO Sports focussed on developing carbon fibre spokes which are vertically very strong, but are liable to break (and the wheel collapse) should the wheel be subject to even moderate side loads. To better understand the types of loads to which bicycle wheels are subject – especially in respect of different types of hubs and rims – EDO Sports worked with French bicycle component manufacturer Mavic. The resulting carbon fibre spokes (sold under the brand name of Fibre Flight) were then incorporated into select Mavic race wheels. Another case was the development of a carbon fibre frame that featured the lack of seat stays and seat tube (the saddle is positioned on a beam attached to an oversized downtube near the handlebars). Developed out of a joint venture between LeMond Bicycles and Mitsubishi Rayon, the frame reduces wind resistance, but has subsequently been banned from competition.

Our second group included innovations that were based upon engineering solutions, and these also tended to be collaborative across firms. One case concerned the headset which connects the frame to the stem and handlebars. Traditionally, the headset is threaded to allow it to connect to the steerer tube. The threadless Aheadset was initially designed by John Rader and then developed into a marketable component by Dia-Compe (a Japanese firm with production in the USA and Japan). In another case, the Swiss firm, Edco, created a high performance hub featuring direct lubrication points. This involved a shift away from cartridge bearings, and the firm collaborated with Swedish bearing company SKF to create the necessary sealed bearing system that sits at the heart of the performance of the Edco hub.

Our third group of incremental/modular innovations that originated via collaboration were with parties external to the bicycle industry. For example, front suspension forks using a combination of oil and air were developed for mountain bikes, originating from ideas in the motorcycle industry. Paul Turner had a background in motocross (including working for the Honda motocross team) and he established his own company selling motorcycle components and then brought in Steve Simmons (also from motocross) to expand the business via developing suspension forks for bicycles. They took their design ideas to Japanese company Dia-Compe who provided not just the capital, but R&D and engineering support, along with testing facilities. The product was later manufactured by Rock Shox which was partially owned by all three parties. A further example is the development of saddles that would mould to a rider's shape and maintain absorptive characteristics. Italian company Selle Royal worked with German chemical company Bayer to incorporate a unique gel into parts of the saddle. The distribution of these various innovations are shown in Table 2 below.

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Architectural and Radical Innovations

Architectural and radical innovations tend to occur less frequently across industries relative to incremental and modular innovations. However, the case of Shimano (featured in Fixson and Park, 2008) highlighted how the firm created a more integrated set of components in the drive train (brakes and gears) such that the gears would change with more precision through the use of integrated brake and gear levers that worked with a specific Shimano chain, derailleurs and chain rings. The innovation took place entirely within firm boundaries. Shimano also developed the cassette hub. As the number of gears in the screw-on cluster on the rear wheel increased from five to six there were no technical issues. However, the shift to seven and later eight gears made for longer axles and these would break more easily. Shimano therefore developed the cassette hub that built the ratchet mechanism into the hub and created additional lateral strength. As a leading producer of both types of hubs, the older style screw-on clusters and the cogs that would fit on the cassette hub, Shimano was able to successfully drive this innovation to be a new industry standard. As Shimano moved towards more integrated components, other manufacturers were forced to follow suit. SRAM initially developed a rotational gear changing system. While it can work with Shimano gear systems, it does so in a sub-optimal manner and, as such, they have developed their own complete drive-train set of components that are less modular and thus act as a direct competitor to Shimano. Even smaller specialized firms with limited resources tended to innovate within firm boundaries. A design for suspension forks that dissipates energy in a lateral manner through a parallelogram design (known as horizontal suspension forks) was released by Japanese company SU21 R&D Group. It required a much deeper wheel rim as the brakes would move up and down relative to the wheel limiting the attractiveness of this architectural innovation in the market.

Not all architectural and radical innovations have occurred within the boundaries of a single firm, however, The bicycle designer Mike Burrows (based in Norfolk, UK) conceptualized a frame featuring single wheel stay (eg, both front and rear wheels are held in place on just one side). The design was taken to Lotus (the British sports car company, also based in Norfolk, UK) and the component was then developed through this collaboration with the support of the British Cycling Federation (for wind-tunnel and other testing). Given the single sided fork and rear stay, the hub also had to be redesigned as part of this process. Similarly, the US company Fallbrook Technologies developed a continuous variable transmission drive that essentially replaces the need for gears through an automatic system that controls the level of torque according to the power produced through the pedals. The initial concept was developed by Donald Miller through Motion Systems Inc. He then collaborated with Robert Smithson, before he later joined the company. Later, the engineers from the testing company also joined the enterprise. Thus, rather than independent specialized firms collaborating, the company worked with either individual specialist engineers or small firms and when possible (and appropriate) brought these people into the organization.

DISCUSSION AND CONCLUSIONS

Across established industries, incremental and modular innovations occur in far greater numbers than radical and architectural innovations. Unsurprisingly, of the 121 innovations identified across the product architecture, only 7 were architectural or radical innovations. As modular product architectures are argued to create embedded coordination (Sanchez & Mahoney, 1996) in design and production, the prevailing logic is that the industry value chain would be expected to be highly specialized, with firms designing and producing independent components without reference to other industry participants. The embedded coordination in modular products also provides opportunities for utilizing the capabilities of other firms in the industry value chain (and from other industries), and given the purported reduced need for ex-post communication and information exchange, the migration of design task activities may occur across both firm and national boundaries. In other words, the expectation is that the mirroring hypothesis would hold, given the efficiency benefits associated with mirroring product and firm architecture. However, while Elia, et al (in press) found general support for this idea in respect of business services offshoring, our case analysis highlights only partial support.

In the case of incremental and modular innovations, where the product architecture remained constant and design changes occurred only at the component level, specialized firms were surprisingly often able to innovate within their own firm boundaries, owing to their comparable advantage in either technical or engineering-based design. In contrast to our first proposition, we find that incremental/modular innovations did not always migrate across both firm and national boundaries, breaking the mirroring hypothesis, and therefore our first proposition requires further qualification. Of the 114 incremental/modular innovations, we found only 30 that migrated across firm boundaries. Of those, 19 examples collaborated across firm boundaries, but within national boundaries, and only 11 cases of collaboration extended across both firm and national boundaries. Given the prevailing arguments advocated by modularity theorists, our case analysis highlights that while the modular product architecture supported a distributed industry structure (with hundreds of firms across multiple continents) where different players *could* engage with others in search of innovation at the component level, irrespective of their physical location, few firms located design activities across firm boundaries, and fewer still across national boundaries. In contrast, we found 84 examples of incremental/modular innovations being designed within firm boundaries. While this is not consistent with our first proposition, an important point to highlight is that a modular product does not make it a prerequisite that firms pursue innovation across firm boundaries, but rather that they *may* do so. Our case highlights that firms with a comparable advantage in design capabilities maintained design tasks within firm boundaries, despite low ex-post transaction costs associated with modular product designs. In other words, transaction cost explanations for firm boundaries are inadequate to explain firm behaviour, rather transaction costs acted as a 'tax' on market contracts (eg, Jacobides, et al., 2006). Thus, despite low 'taxes', the benefits of utilizing internal capabilities and knowledge exceeded the benefits of utilizing the market. In contrast, firms who collaborated with external partners faced the opposite problem. A comparative disadvantage in design or engineering capabilities, coupled with low transaction costs, led those firms to outsource design tasks to other firms within national boundaries. This extended across national boundaries where the benefits of accessing the design capabilities of an international firm exceeded an additional 'tax' of using a firm with significant cultural differences and/or different institutional environments (Jacobides & Hitt, 2005). In other words, we find that moving incremental/modular innovation activities across both firm and national boundaries requires a capability disadvantage greater than two kinds of transaction costs. The first type of transaction cost relates to utilizing market contracts, related to factors such as uncertainty, asset specifity, and transaction frequency (Williamson, 1975). Second, additional transaction costs may result when selecting a supplier across national boundaries that reflect cultural and institutional differences. Thus, we identify a further contingency that 'mists' the mirroring hypothesis. Design tasks are unlikely to migrate across firm boundaries, even when the product architecture is modular, unless there is a comparative disadvantage in design capability between the focal firm and suppliers. Furthermore, firms will prefer a home country supplier unless the gains from trade associated with an international supplier exceed the additional transaction costs associated with cultural and institutional differences.

While working with very small numbers, the majority of architectural or radical innovations occurred within the boundaries of a single firm, consistent with our second proposition. However, it was not universally the case. There were examples of intense collaboration between two or more independent firms. However, innovations that require the overturning of the existing product architecture, or parts of it, require considerable investment in building strong collaborative relationships that are enhanced through physical interaction and co-location, or at least in very close physical proximity. Thus, the cases of architectural/radical innovations we highlighted, such as the Lotus aero-frame, the Fallbrook continuous variable transmission drive and the Pulstar straight-pull spoke hub, are characterized by collaborating firms located in close physical proximity to each other, and therefore specialized firms may use co-location and bi/multi-lateral contracts in conjunction with extensive communication and information exchange as a substitute for vertical integration. Thus, while our case analysis provides support for the mirroring hypothesis in respect of architectural/radical innovations, the support is not unqualified, and misting occurs where firms utilize co-location and bi/multi-lateral contracts as a substitute for vertical integration.

While design collaboration across national boundaries is possible in the presence of a modular product architecture - at least in respect of incremental and modular innovations - the question can be asked as to why we do not see much greater levels of international collaboration? It has been suggested that locational advantages, such as lower cost structures or access to valuable resources, make the internationalization of an industry value chain a theoretically natural consequence of a modular product architecture (Elia et al., forthcoming). But this was not clearly evident in our case analysis concerning design tasks. Rather, it would seem that the various types of transaction costs of doing business across national boundaries may counter some of the potential locational advantages (Narula & Verbeke, 2015). Pertinent to design tasks, where outcomes are uncertain and non-predictable, it would appear that the challenges of operating across cultures and facing different institutional environments may well restrict firm efforts to internationalize their innovation processes. Transaction cost economics recognizes that high uncertainty, low frequency of transactions and the presence of specialized assets may create higher transaction costs (Williamson, 1975; Macher & Richman, 2008). But the very concept of a transaction cost works on the principle of being able to articulate the character of a transaction. Langlois (2006) identifies the mundane transaction costs of defining the outputs, establishing criteria for the output such that it can be counted and agreeing upon compensation, and these are invariably challenging when discussing collaboration as part of an R&D process. In essence, modular product architectures provide the basis for a low transaction cost environment, but in respect of R&D and innovation, the challenges of cultural difference and different institutional environments create a 'tax' that restricts the attractiveness of undertaking innovation activities across national boundaries, especially where differences in comparative design capabilities are weak. Overall, the uncertainty and complexity inherent in creating contracts for innovation tasks highlight that internationally dispersed innovation efforts are more likely to feature networks and hierarchies over the use of markets. Firms will look to external firms that may be able to provide specific capabilities not readily available internally or locally, but even in cases of modular product architectures, these will be limited to those cases where the perceived benefits of collaboration across national boundaries outweigh the costs and risks.

In respect of the theoretical contribution, work to date concerning the impact of modular product architectures on vertical structure has tended to consider the production function (eg Cabigiosu & Camuffo, 2012; Furlan, Cabigiosu & Camuffo, 2014; Schilling & Steensma, 2001). Where this work has extended to consider national boundaries (eg Elia et al., forthcoming) in light of potential location benefits, the focus has remained on production. Innovation related activities bring with them considerably different challenges. While modular product architectures enable embedded coordination and outsourcing, the move away from vertical integration is not nearly as obvious in respect of innovation as it is in respect of the production function. Firms that engage in incremental and modular innovation have the opportunity to pursue innovation activities beyond the boundaries of the firm and benefit from the capabilities of specialized firms – irrespective of where they are located in the world. But the option to do this, versus the likelihood of them doing so, is where our theoretically derived proposition deviates from what was observed. We suggest that the uncertainty and complexity associated with innovation activities, along with the ‘tax’ created by unfamiliar cultures and institutional environments, potentially negates the low transaction cost environment that would normally be associated with modular product architectures.

In respect of radical and architectural innovations, we expected that firms would remain vertically integrated and pursue such innovations within the boundaries of the firm. While this occurred in the majority of cases, it was also observed that firms did seek the specialized capabilities of other firms in the innovation process. However, co-location and strong bi/multi-lateral ties were required here to act as an effective substitute for vertical integration. As such, there were no cases of such innovations spanning both firm boundaries and country boundaries.

Managerial Implication

Managers have long recognized the potential benefits of undertaking some task activities with external firms in the industry value chain (or with firms in other industries) given the opportunities of lower cost structures or access to valuable capabilities, knowledge or resources. Innovation activities, however, have not internationalized to nearly the same degree. The product architecture provides one contextual determinant that may well determine the potential for managers to actively pursue an internationalization strategy around their innovation activities. Where products utilize a modular architecture, embedded coordination lowers transaction costs and provides opportunities for firms to benefit from engaging with other specialized firms that bring additional or complementary capabilities to the innovation process. However, internationalizing innovation is not simple or costless. The challenges of differing cultures and institutional environments creates something of a ‘tax’ relative to these low transaction costs and the inevitable uncertainty and complexity associated with innovation makes it difficult to outsource in the same manner as other activities in a value chain, such as production or operational management.

Where the product architecture is more integrated (or the innovation is designed to overturn an existing modular architecture) the potential benefits that come with embedded coordination are no longer present. It therefore makes sense to pursue such innovations within a vertically integrated structure. However, it is sometimes necessary to source specialist capabilities not held within the firm and in such cases, co-location allowing for extensive collaboration and cross-firm communication may act as a substitute for a vertically integrated structure.

Future Directions

Many industries feature a range of product architectures with some parts of the product being modular and other parts being relatively integrated (eg mobile phones and motor vehicles). In turn, the modular components may sometimes subscribe to international standards, whereas other components may simply utilize firm-defined interface standards. Such industries would provide a greater level of diversity in respect of how such products should be managed along a global value chain. In all industries (with the possible exception of those at the truly embryonic stage of development) there will always be considerably more incremental innovation relative to radical innovation, however, industries with a range of different product architectures would potentially help illuminate the nuances of how, why and when firms pursue innovation activities within firm boundaries versus when they engage with other firms both nationally and internationally.

A further key consideration is, like many other studies pertaining to the mirroring hypothesis, there is an absence of detail in respect of how all of these choices impact firm performance. The success (in terms of market uptake) of different innovations varied markedly. But why? Certainly some innovations are invariably ‘better’ than others, but does engaging with other specialized firms – especially international firms – provide opportunities for greater market uptake and diffusion through the industry? Thus the performance dimension still remains a missing piece in respect of the mirroring hypothesis.

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TABLE 1: Distribution of Bicycle Industry Innovations

Total number of innovations identified	186
Total number of innovations that were fully tracked	121
Total number of incremental/modular innovations	114
Total number of incremental/modular innovations involving international collaboration	11
Total number of architectural/radical innovations	7

TABLE 2: Distribution of Incremental and Modular Bicycle Industry Innovations

Total number of incremental/modular innovations	114
Number of incremental/modular innovations developed within firm boundaries	84
Number of incremental/modular innovations developed across firm boundaries, but within national boundaries	19
Number of incremental/modular innovations developed across firm boundaries and across national boundaries	11