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Cross-Border Innovation for Global Value Chain Orchestration[1]

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Abstract

This study investigates how multinational enterprises (MNEs) leverage cross-border innovation to enhance their capacity for orchestrating global value chains (GVCs). Grounded in systems integration theory, and using the context of the aircraft engine industry of the aerospace sector, we propose that architectural knowledge is imperative for MNEs to orchestrate their GVCs. This leads us to hypothesize that orchestrating MNEs possess a broader technological scope and a wider range of cross-border innovations compared to other firms. Moreover, we demonstrate the rising complexity and interdependency of the sector's technological system and conjecture that this increases the scope advantage that orchestrating MNEs need over other firms. To test these hypotheses, we analyze a unique longitudinal dataset on formal inter-firm linkages from 2002 to 2014. Our findings provide empirical support for our theoretical predictions.

Keywords: systems integration, architectural knowledge, orchestration, knowledge connectedness, global value chain, technological scope, patent, international co-invention, aircraft engine

[1] First and second author lead the paper with an equal contribution.

1. Introduction

The practice of cross-border innovation, which involves local inventors collaborating with foreign peers to create patentable innovations, has emerged as a fundamental component of the innovation strategies of multinational enterprises (MNEs) (Branstetter, Li & Veloso, 2014; Crescenzi et al., 2019). In academic circles, its prevalence has sparked extensive discussions regarding the circumstances under which MNEs can leverage international technological partnerships to access knowledge assets abroad that are unavailable locally (Ambos et al., 2021; Cano-Kollmann et al., 2016; Papanastassiou et al., 2020). Empirical research has established a strong link between cross-border innovation and the ex-post technological performance of MNEs in both developed and developing countries (e.g., Hill & Mudambi, 2010; Giuliani, Martinelli & Rabellotti, 2016; Ebersberger, Feit & Mengis, 2023; Ervits, 2023; Scalera, Perri & Hannigan, 2018).

International business scholars have primarily viewed cross-border innovation through the lens of global knowledge sourcing (Ambos et al., 2021; Papanastassiou et al, 2020; Scalera et al., 2018). This perspective suggests that MNEs innovate by recombining and integrating existing knowledge components (Galunic & Rodan, 1998; Xiao, Makhija & Karim, 2022). It portrays cross-border innovation as a key mechanism for MNEs to access knowledge components that are unavailable locally, thereby creating international knowledge connectedness that enhances the learning processes associated with new knowledge combinations (Cantwell, 1989; Cantwell & Janne, 1999; Cantwell & Santangelo, 1999). This global knowledge sourcing view lies at the heart of a vibrant scholarship that has, among other things, studied the asset-acquiring or knowledge-seeking motive for foreign direct investment (e.g., Kogut & Chang 1991; Chung & Alcácer 2002;

Berry 2006), the internationalization of R&D to capture 'home-base augmenting' or locally 'competence-creating' benefits (e.g., Papanastassiou & Pearce 1997; Cantwell & Mudambi 2005), and the importance of global knowledge connectedness for innovation performance (Cano-Kollmann et al., 2016; Scalera et al., 2018; Turkina & Van Assche, 2018).

In this study, we posit that the ongoing scholarly debate on the motivations for MNEs to engage in cross-border innovation needs further refinement, and especially in the context where MNEs act as lead firms that orchestrate complex global value chains (GVCs). We do not contest the main premise of the global knowledge-sourcing view that MNEs primarily use cross-border innovation as a knowledge-augmenting strategy to leverage different expertise and technology specializations that is available across various countries (Papanastassiou et al., 2020). Rather, we argue that extant scholarship has largely overlooked an additional motive for some MNEs to seek knowledge abroad, beyond expanding their own innovation capabilities, which is to bolster their ability to effectively orchestrate and integrate the distributed capabilities and learning processes that are generated in the full GVC system that they lead. *The aim of this paper is to theorize and empirically validate the notion that orchestrating MNEs, which lead complex GVCs, engage in a wider scope of international co-invention, develop a broader technological scope, and draw more on basic science and technology than other firms to orchestrate these value chains more effectively.*

Our paper draws inspiration from recent academic work that has identified a unique role that many MNEs play as orchestrators within GVCs (Buckley, 2009; Kano, 2018; Lunnan & McGaughey, 2019; Pitelis & Teece, 2018). According to this literature, MNEs that orchestrate complex GVCs generally bear the extra responsibility for enhancing and securing the overall efficiency and effectiveness of the entire value chain (Pitelis & Teece, 2018). To fulfill this role, it is argued, they must among other things put into place processes to facilitate knowledge sharing among its GVC partners, economize on partners' bounded rationality and reliability, and identify and address bottlenecks that could potentially disrupt the smooth functioning of the value chain (Kano, 2018; Lunnan & McGaughey, 2019). To date, however, this literature has not made a link between a MNE's role of "joint value orchestrator/GVC community leader" (Kano, 2018) and the innovation strategy that it adopts to enhance its ability to orchestrate and integrate dispersed GVC activities. The purpose of this paper is to develop this link and illustrate how MNEs that orchestrate GVCs can leverage cross-border innovation to develop GVC orchestration capabilities.

To establish the connection between GVC orchestration and cross-border innovation, we build on insights from systems integration research (Brusoni, Prencipe & Pavitt, 2001; Prencipe, Davies & Hobday, 2003; Hobday, Davies & Prencipe, 2005; Davies, Brady, Prencipe & Hobday, 2011). This body of literature studies the intricate challenges that orchestrating firms face when they manage complex inter-organizational projects where multiple interdependent subsystems need to be integrated for them to function seamlessly as a unified system. A central insight from these studies is the importance for orchestrating firms to develop architectural knowledge, which is the technical understanding of how different components are linked together in a coherent organizational system (Henderson & Clark, 1990; Baldwin & Clark, 2000). In our theory development, we will argue that the systems integration problem is a key part of a MNE's GVC orchestration challenge and that it thus needs to develop architectural knowledge to effectively manage its GVCs (see also Kotha & Srikanth (2013) and Larsen & Pedersen (2014)). Furthermore, we will theorize that cross-border innovation is a key mechanism that orchestrating MNEs leverage to develop architectural knowledge, thus boosting their ability to orchestrate GVCs. Building on these foundational principles, we will hypothesize that orchestrating MNEs have both a broader technological scope and a broader scope of international co-invention than other firms. Furthermore, we will hypothesize that an orchestrating MNE's advantage over other firms in terms of technological and international co-invention scope increases when the complexity of a technological system rises.

To empirically validate our research hypotheses, we rely on a unique network dataset that we have developed on formal inter-firm linkages within the aircraft engine industry for the period 2002–2014. The dataset covers the industry's five orchestrating MNEs (Pratt & Whitney, GE Aviation, Rolls Royce, Safran Aircraft Engines, and CFM International[2]), as well as their direct value chain partners and linkages among them. We have linked the network dataset with firm-specific patent and performance indicators, including information on each firm's international co-inventions. In common with many other studies of cross-border innovation, we find that the innovation system of the aircraft engine industry is growing more complex over time. However, a particularly striking finding of our study is the stark demonstration that the orchestrating MNEs' innovation networks went from being relatively disconnected at the beginning of our study period to being densely interconnected (and interdependent) at the end (Figure 2).

[2] We treat CFM International as an orchestrating MNE even if it is a 50% -50% joint venture between Safran and GE. This is because the company produces and commercializes its own LEAP engine family that has its own supply chain structure (https://www.cfmaeroengines.com/about/).

In our empirical analysis, we find evidence that the orchestrating MNEs indeed have a wider technological scope and a wider scope of international co-invention than other firms in the sample and that this advantage has increased as aircraft engines have become technologically more complex over time. These results confirm that orchestrating MNEs develop different cross-border innovation patterns compared to other firms, providing support to our theory that they do so to enhance their GVC orchestration capabilities.

We have organized this study as follows. The next two sections develop the conceptual background and present the research hypotheses. Section four describes the data and methods. Section five discusses the empirical findings. Section six concludes the study and offers research and managerial implications.

2. Conceptual background

This section introduces and defines several foundational terms in our theoretical analysis such as "systems integration" and "architectural knowledge". We offer a concise overview of existing contributions that delve into these concepts and discuss outstanding questions.

Systems integration, which is the technical ability to combine multiple technological subsystems that are supplied by a network of loosely coupled firms into a unified whole, is recognized as a critical characteristic of orchestrating firms in technologically advanced industries (Brusoni et al., 2001; Prencipe et al., 2003; Hobday et al., 2005; Davies et al., 2011). Systems integration scholars have proposed two structural strategies that orchestrating firms can adopt to improve systems integration: architectural design enhancement and the development of integration practices (Gholz, James & Speller, 2018; Tee, Davies & Whyte, 2019). In terms of product architecture design, it is argued that orchestrating firms can enhance systems integration by shaping the architecture of a complex product system in a way that minimizes technical interdependencies among subsystems and components (Ulrich, 1995; Baldwin, 2008). For example, Sanchez and Mahoney (1996) and Baldwin and Clark (2000) suggest that orchestrating firms can design modular architectures, where technical interdependencies are concentrated within subsystems rather than across them, to facilitate the coordination of production among a network of loosely coupled firms. In many industries, however, the degree to which a product architecture can be modularized is limited (Zirpoli & Becker, 2011). Consequently, it is suggested that orchestrating firms need to complement modular architecture design with effective integration practices to manage the technical interdependencies among firms within complex systems (Brusoni et al., 2001; Hobday et al., 2005; Gholz et al., 2018). In this paper, our focus is on the integration practices that orchestrating firms need to develop to attain systems integration.

Scholars emphasize the significance of *architectural knowledge* in developing effective integration practices (Granstrand, Patel & Pavitt, 1997; Patel & Pavitt, 1997, 2000; Brusoni et al., 2001). Architectural knowledge describes an orchestrating firm's understanding how the various components that make up a complex product system are integrated and linked together to form a coherent whole (Baldwin & Clark, 2000). It encompasses two types of knowledge: knowhow about the role of the different components underlying the system; and knowledge about the technical interdependencies or interfaces between these components (Henderson & Clark, 1990). When orchestrating firms lack organizational knowledge, it has been shown that it can lead to significant challenges such as time delays, quality deterioration and scalability problems (Zirpoli & Becker, 2011).

A series of studies have deepened this argument by highlighting a key feature that distinguishes orchestrating firms from other companies involved in complex product systems. The imperative for orchestrating firms to cultivate architectural knowledge implies that they need to develop extra knowhow outside the scope of their own productive activities to be able to coordinate loosely coupled networks of supply (Patel & Pavitt, 1997). In other words, orchestrating firms need to "know more than they make" (Brusoni et al., 2001). Evidence provided by Patel and Pavitt (1997) and Brusoni et al. (2001) back up this suggestion by demonstrating that large and diversified firms develop patents in technological areas that range beyond what they need for their in-house design and production activities. In our hypothesis development, we build on these arguments to relate an orchestrating MNE's imperative to develop architectural knowledge with the technological scope of its patents.

Some studies hint that the need to cultivate architectural knowledge motivates orchestrating firms to disproportionately draw on basic science and technology, although this argument has never been fully developed. The National Science Foundation (NSF) defines basic research as the "systematic study directed toward fuller knowledge or understanding of the fundamental aspects of phenomena and of observable facts without specific applications towards processes or products in mind" (NSF 2010: 9). While basic science and technology research is generally a lengthy process with less obvious market returns (Mowery & Rosenberg, 1991), it has been suggested that it helps mitigate systemic bottlenecks in complex production systems where components are tightly coupled

(Fleming & Sorenson, 2004; Perri, Scalera & Mudambi, 2017). In our hypothesis formulation, we leverage this discussion to establish a connection between an orchestrating MNE's necessity to cultivate architectural knowledge and its development of patents that draws on basic science and technology.

A key question that systems integration scholars have started to address is: which innovation strategies can orchestrating firms adopt to develop their architectural knowledge? Dibiaggio (2007) provides an important insight in this respect by pointing out that orchestrating firms need to not only invest in their in-house technological capabilities to cultivate their architectural knowledge but also develop collaborative knowledge integration efforts with their partners to create shared contextual knowledge. The latter can take on various forms. Orchestrating firms may share proprietary information such as blueprints and designs with their partners to better define complementarities between modules and favor the co-development of design solutions (Dibiaggio, 2007). They may also send engineers to work in the facilities of their partners for extended periods and vice versa to share and acquire valuable knowledge about the interfaces with their partners (Dyer, 1996; Dyer & Nobeoka, 2000). In this paper, we add the additional contention that technological collaboration on patentable innovations is yet another important vehicle that orchestration firms can use to develop architectural knowledge, suggesting a link between an orchestrating firm's quest for architectural knowledge and the scope of its co-inventions.

3. Hypothesis Development

This section relates GVC orchestration to systems integration. Specifically, we argue that orchestrating MNEs encounter a critical challenge when orchestrating complex GVCs:

how to effectively address the systems integration problem. We use the discussion from the previous section to formulate the key hypotheses of this study.

Our aim is not to provide a full review of the vast literature on GVC governance, which includes many seminal works such as Gereffi, Humphrey & Sturgeon (2005) Hernández and Pedersen (2017), Dallas, Ponte & Sturgeon (2019), Pananond, Gereffi, and Pedersen (2020) and Pla-Barber, Villar, and Narula (2021). Rather, we limit our discussion of the GVC literature to demonstrate important touching points with the systems integration literature.

The first building block of our argument is that GVCs in many ways resemble an integrated system. Kano, Tsang and Yeung (2020) define a GVC to be "a governance arrangement that utilizes, within a single structure, multiple governance modes for distinct, geographically dispersed and finely sliced parts of the value chain. In other words, a [GVC] is the nexus of interconnected functions and operations through which goods and services are produced, distributed, and consumed on a global basis." This definition encompasses both the loosely coupled network structure and the need for the technological and organizational integration of separate parts that are at the heart of integrated systems.

The second building block of our argument posits that GVC orchestrators – often large MNEs – assume a role akin to that of orchestrating firms in complex product systems. Kano (2018) proposes that the orchestrating MNE acts as a residual claimant of the GVC's final value proposition, thus making it interested in, and responsible for, the efficiency and effectiveness of the entire GVC. Vahlne and Johanson (2021) argue that multinational business enterprises effectively collaborate and exchange knowledge with a network of value chain parties and have developed governance means to cope with system complexity.

Pitelis and Teece (2018) and Lunnan and McGaughey (2019) point towards the role of the orchestrating MNE to enhance knowledge exchange and processing across the GVC, including for problem solving purposes.

We can thus infer from these arguments that an orchestrating MNE, which leads a GVC system, faces the imperative to develop architectural knowledge that allows them to seamlessly integrate the diverse subsystems and components supplied by a network of loosely coupled and globally distributed firms (see also Kotha & Srikanth, 2013; Larsen & Pedersen, 2014). From our previous discussion, we can infer that the quest for architectural knowledge requires orchestrating MNEs to both broaden its scope of technological knowledge (so they know more than they make) and to draw on basic science and technology. This leads to our first two hypotheses:

Hypothesis 1: An orchestrating MNE has a broader technological scope than other firms.

Hypothesis 2: An orchestrating MNE draws more heavily on basic science and technology than other firms.

We can also infer from our discussion in the previous section that the imperative for architectural knowledge requires orchestrating MNEs to develop technological collaborations with its value partners, often across borders. This leads to this paper's central contention, which is that orchestrating MNEs use cross-border innovation to strengthen their ability to strengthen the integration of the technological system underlying their GVCs. We state this as our third hypothesis:

Hypothesis 3: An orchestrating MNE has a broader scope of international co-inventions than other firms.

It is crucial to recognize that systems integration challenges in GVCs vary across industries and time. In our previous discussion, we have reviewed that orchestrating firms generally require a lower degree of architectural knowledge when they coordinate a system with a modular product architecture where the technological interdependencies between subsystems and components are limited. Hobday et al. (2005) goes a step further by arguing that the degree of architectural knowledge that an orchestrating firm needs to develop increases with both the technological complexity of the system (complexity of the hierarchy and number of interconnections between modules) and the technological novelty. We derive from these insights that an orchestrating MNE's efforts to develop architectural knowledge are more extensive when the technology underlying a GVC is more complex. These arguments lead to our final hypotheses:

Hypothesis 4: An orchestrating MNE's advantage over other firms in terms of technological scope increases when the complexity of a technological system rises.

Hypothesis 5: An orchestrating MNE's advantage over other firms in terms of international co-invention scope increases when the complexity of a technological system rises.

4. Data and Methods

Our empirical analysis focuses on the aircraft engine industry, which is dominated by a handful of lead MNEs that orchestrate vast and complex GVCs and face substantial systems integration challenges. In this section, we present a brief overview of these orchestrating MNEs and their GVCs, followed by a discussion of the data collection that we have conducted and the methods that we have used for the analysis.

The aircraft engine industry

The aircraft engine industry is prone to production problems. Within the larger aerospace sectors that has itself grappled with persistent delivery delays, aircraft engines have emerged as a frequent source of trouble (Boyden, 2019). In 2019, Boeing had to publicly postpone its 777X's first flight due to issues with GE Aviation's GE9X engine.[3] Pratt & Whitney has lately had its own share of difficulties delivering new engines for the Airbus A320neo and Bombardier C-Series (now Airbus A220) on time. And Rolls Royce has not long ago had to replace faulty turbine blades in engines for Boeing's 787 program.

Industry experts have attributed a substantial part of the problem to systems integration challenges in aircraft engine production (The Economist, 2018). Aircraft engines are highly complex products that are nowadays developed in global networks of loosely coupled firms. The GE9X, for example, is the result of a global partnership between GE Aviation (US), Safran Aircraft Engines (France), IHI Corporation (Japan), and MTU Aero Engines (Germany), not to mention the hundreds of suppliers around the globe that are involved in the production process. Prominent aircraft engine manufacturers deem this necessary due to the rapid pace of technology advancement in the industry, coupled with the high costs of development, which make it unfeasible for a single firm to handle all the necessary development in-house (Brusoni & Prencipe, 2011; Todd & Eriksson, 2015).

Aircraft manufacturers like Boeing and Airbus typically do not produce their own engines, but rather depend on specialist engine manufacturers to produce them. Developing aircraft engines is highly expensive, often amounting to about US$2 billion for the

[3] https://www.flightglobal.com/news/articles/ge-recalls-777x-turbofans-to-address-compressor-issu-460379/

development of a prototype (Todd & Eriksson, 2015). Due to the forbiddingly high entry barriers, the global aircraft engine industry is dominated by a select number of leading companies – orchestrating MNEs – which vigorously compete but at the same collaborate with a set of suppliers to mitigate risk (Todd & Humble, 1987, 46-48).

[Figure 1 about here]

At the top of the tier structure, the aircraft engine industry is dominated by five orchestrating MNEs: the two American companies Pratt & Whitney and GE Aviation, the two European companies Rolls Royce and Safran Aircraft Engines, and CFM International which is a joint venture between GE Aviation and Safran. A distinct feature of these orchestrating MNEs is their ability to master the complexities of design and integration of big turbofans (Todd & Eriksson, 2015).

Rolls-Royce, headquartered in Manchester, United Kingdom, is one of the world's leading producers of aircraft engines for large civil and military aircraft. The company powers more than 35 types of commercial aircraft and has over 13,000 engines in service worldwide.[4] Rolls-Royce is also involved in power systems, marine, and nuclear businesses. The company operates in more than 50 countries and has customers in over 150 countries.[5]

Pratt & Whitney – a United Technologies Corporation, is headquartered in Hartford, Connecticut, United States. The company manufactures large commercial engines and military engines and has a worldwide network of maintenance, repair, and

[4] https://www.rollsroycefirstnetwork.com/other-rr-engines
[5] https://www.rolls-royce.com/about/where-we-operate.aspx

overhaul services. Pratt & Whitney's large commercial engines power more than 25 percent of the world's mainline passenger fleet and provide military engines to 31 armed forces around the world.[6] Pratt & Whitney Canada has produced more than 80,000 engines, of which there are currently 50,000 engines in service with more than 10,000 operators in 200 countries.[7]

Safran, headquartered in Paris, France, supplies engines and equipment to all main producers of civil and military airplanes and helicopters. Safran Aircraft Engines – one of Safran subsidiaries, designs, develops, produces, and sells engines for commercial and military aircraft, launch vehicles, and satellites.[8]

GE Aviation – a subsidiary of General Electric is headquartered in Ohio, United States. The company is a world-leading provider of commercial, military, business, general aviation jet, turboprop engines, and components as well as avionics, electric power, and mechanical systems for aircraft.[9] About 25,000 jet engines from GE and its partners are in airline service.[10]

CFM International – headquartered in Ohio, United States – was established in 1974 as a 50-50 joint venture between GE Aviation and Safran. The company produces the widely used CFM56 and LEAP engine families that often power popular narrow-body jets like the Boeing 737 and Airbus A320 series.

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[6] https://www.pw.utc.com/products-and-services/products
[7] https://www.pwc.ca/en/company/news-and-events/news-details/pratt-whitney-canada-produces-100000th-engine?id=123035
[8] https://www.safran-group.com/aviation/aircraft-engines-and-nacelles/aircraft-engines
[9] https://www.ge.com/news/company-information/ge-aviation
[10] https://www.ge.com/news/company-information/ge-aviation

The five orchestrating MNEs lead highly hierarchical GVCs. They each deal with a set of first-tier suppliers that specialize in the design and development of engine subsystems (modules). These include large MNEs such as Honeywell and Williams International from the United States, MTU Aero Engines from Germany, ITP Aero from Spain, and the Japanese firm Ishikawajima-Harima.

The second tier of firms consists of engine component suppliers such as Japan’s Kawasaki and Mitsubishi and Korea’s Samsung. The third tier of firms consists of raw material suppliers such as Alcoa, Hexcel, Doncasters, and many others.

Data collection

In order to test our hypotheses, we collected a longitudinal network dataset on formal linkages between companies – orchestrating and non-orchestrating – in the aircraft engine industry through the analysis of company annual reports, approved supplier lists, and other publicly available information. We started the data collection exercise by mapping the ego networks of the five orchestrating MNEs (GE Aviation, Pratt & Whitney, Rolls Royce, Safran and CFM International) for each of the following three time-periods: 2002-2005, 2006-2009 and 2010-2014. Following Turkina et al. (2016) and Turkina and Van Assche (2018), we for each period identified the subsidiaries, buyers, suppliers, and partners of each orchestrating MNE and recorded the type of linkage that was developed (subsidiary relationship, lateral partnership, or vertical buyer-supplier linkage). In the first period, we have 15 partnership observations, 52 buyer-supplier observations, and 94 subsidiary observations; in the second period, we have 36 partnership observations, 58 buyer-supplier observations and 118 subsidiary observations; in the third period, we have 135 partnership observations, 159 buyer-supplier observations, and 162 subsidiary observations. In total, our dataset captures 829 linkages.

Next, for each firm in each period, we used Bureau van Dijk's Orbis database to collect firm attributes. Additionally, we collected information on a firm's principal area of specialization: *engine, assembly, component, distribution, materials, MRO, R&D, support, technology.*

We next accessed the USPTO's database on patent registrations for each firm to collect information about the portfolio of patents they developed between 2002 and 2014. This database includes information about the team of inventors involved in the development of a patent, their addresses, and the forward and backward citations of each patent. Overall, the firms in our sample registered 280,093 patents between 2002 and 2014.

Finally, to gain an understanding of new developments in the aircraft engine industry, we sought expert opinions from ten senior specialists located in the Montréal, Seattle and Toulouse aerospace clusters. Three specialists were from the engineering and R&D background, two from the production unit, two from the strategy department, one from the marketing department, one from the parts hub, and one from procurement. We conducted semi-structured interviews with these experts to better explain new trends in the aerospace industry.

Methods

The goal of our empirical analysis is to determine if orchestrating MNEs develop a broader scope of international co-invention, develop a broader technological scope, and draw relatively more on basic science and technology than other firms. Furthermore, we aim to analyze if the complexification of the industry over time has influenced these findings. For this purpose, we first map the evolution of the engine sector network over time to analyze the changing structure of orchestrating MNEs' GVCs. Next, we conduct a series of tests and regression analyses to determine differences in innovation strategies between orchestrating MNEs and their value chain partners.

In terms of tests, we first conduct a *t*-test with unequal variance to establish if there is a significant difference in means for technological scope and international co-invention scope between orchestrating MNEs and their suppliers. Next, we conduct a longitudinal analysis to capture trends over time. For this, we use a longitudinal mixed-effect model that accounts for the fact that firms are measured repeatedly over time and includes both fixed and random effects (Laird & Ware, 1982; Stiratelli, Laird, & Ware, 1984). This allows us to evaluate a mean trajectory for the entire sample, as well as subject-specific deviations from the mean for each firm in the data. The mean trajectory parameters for the whole sample are commonly called "fixed effects" (McNeish & Matta, 2018). Random effects capture how much the estimates for a particular firm differ from the fixed-effect estimate, which allows the growth trajectory to differ for each firm (McNeish & Matta, 2018). We generally estimate the following equation for firm *i* in period *t*:

$$Y_{it} = \beta_{0i} + \beta_1 OMNE_i + \beta_p \mathbf{P_{it}} + \beta_n \mathbf{N_{it}} + \gamma + U_i + r_{it}$$

where Y_{it} depicts the two dependent variables that we will use in our analysis: technological scope and international co-invention scope; $OMNE_i$ is a dummy variable that equals 1 if a firm is an orchestrating MNE, $\mathbf{P_{it}}$ is a set of firm-specific performance variables, $\mathbf{N_{it}}$ is a set of firm-specific network variables, γ are fixed-effect parameters, U_i is a vector of random effects, and r_{it} is the residual for the $_i$th firm at a given period of time.

Dependent variables

Our first dependent variable, *technological scope*, measures the total number of technological classes to which a firm's portfolio of patents is assigned in a period, normalized by the total number of technology classes for all firms in that period. Our selection of this dependent variable builds on a vast scholarship that has relied on technology classes to measure a firm's technological scope (e.g., Lerner, 1994; Nekar & Shane, 2003; Scalera et al., 2018).

Our second dependent variable, *international co-invention scope,* measures the total number of patent co-authors that a firm has in period which are from countries other than that of the main (i.e., first) inventor, normalized by the total number of foreign co-authors of patents by sample firms in that period. Our choice to use patent co-authorship to measure international co-invention scope builds on previous scholarship by, among others, Branstetter et al. (2014), van der Wouden (2020) and Basche (2022). In the field of IB, this measure is regularly used to capture international knowledge connectivity (e.g., Scalera et al., 2018).

Independent variable

Our independent variable of interest is *Orchestrating MNE*, which is a dummy variable that equals 1 if a firm is one of the five orchestrating MNEs that were presented in the data collection section, and 0 otherwise.

Control variables

Our regression analysis includes several performance-based controls that prior studies have identified as important drivers for a firm's knowledge scope, that is, firm size, profit margin, ROE (before tax), export revenues, and R&D expenses (Phene & Almeida, 2008; Scalera et al, 2018). We used Bureau van Dijk's Orbis database to collect these firm attributes per year, and then took the average per period.

Our analysis also includes the network variables eigenvector centrality and tie diversity as control variables. We include these controls recognizing that orchestrating MNEs play a central role as lead firms in GVCs, requiring them to manage a higher number of connections than their partners, thus affecting both centrality and tie diversity.

As far as network centrality is concerned, many studies of inter-firm networks found centrality to be an important variable that shapes the innovation strategy and performance of actors: more central actors have better access to network resources and knowledge flows (Riccaboni et al, 2021; Koka and Prescott, 2008). Social network scholars have developed several centrality measures to identify an actor's structural embeddedness in a network: degree, closeness, betweenness, and eigenvector centralities (Hanneman & Riddle, 2005). We have chosen to focus on *eigenvector centrality* since it is a richer measure that considers that an actor's network resources not only depend on the knowledge and resources that can be accessed through the actor's direct ties, but also on its partners' ability to obtain resources from elsewhere in the network (Ahuja, 2000; Turkina & Van Assche, 2018). Eigenvector centrality takes this into account by considering the configuration of the entire network and giving a higher weight to ties to partners which are more central in the network (Bonacich, 1987). In this respect, an actor that is more eigenvector central is considered to have higher network resources since it can more easily access key knowledge and resources from elsewhere in the network through both its direct and indirect ties (Podolny, 2001; Soh, Mahmood & Mitchell, 2004). In contrast, if an actor has a low eigenvector centrality, it can only tap into limited knowledge and resources from the network.

As far as *tie diversity* is concerned, in the study of biotech networks, Powell et al (2005) found that partier tie diversity had an important influence in the network formation of biotech firms. Therefore, we include it as a control variable, which is a binary index that takes the value of 0 if over 70% of a firm's linkages are of a specific type (e.g., buyer-supplier linkage), and the value of 1 otherwise.

5. **Analysis**

Mapping the network evolution

In our empirical design, we follow scholars who analyzed how firms leverage inter-firm collaboration structures (Guan and Liu, 2016; Turkina, Van Assche & Kali, 2016; Chuluun et al, 2017): scholars first model network structures and demonstrate their features and, next, they conduct regression analyses that include network measures from the modelled network structures. We also follow (Belso-Martínez et al, 2020) and use opinions from ten industry experts to nuance our description of the engine industry's collaboration networks.

To visualize the networks of firm linkages in the aircraft engine industry, we use a graphical approach similar to Powell et al. (2005) and Aharonson and Schilling (2016), although their networks are more decentralized and more complex as they consist of a higher number of nodes. Figure 2 presents the network structure for each time period. Black ties denote subsidiary linkages, blue ties depict buyer-supplier linkages, and red ties denote partnership linkages. Node colors depict different locations.

[Figure 2 about here]

In 2002-2005, the orchestrating MNEs in the aircraft engine industry mostly worked with their own set of suppliers. As it is shown in figure 2, the five orchestrating MNEs shared few common suppliers, rendering the network fragmented with multiple isolated islands of activity. The few exceptions where predominantly firms that supplied multiple orchestrating MNEs from the same region. The French company Dedienne Aerospace, for example, was a tooling supplier for several European lead firms, explaining one of the rare supply chain linkages (in blue) of CFM International and Safran Aircraft Engines with a common node. The U.S. military aircraft manufacturer Northrop Grumman was the sole company that purchased engines from the American lead firms Pratt & Whitney and GE Aviation, explaining the blue supply chain linkages between these firms and a common node. The sole notable exception of a linkage between the production networks of European and US lead firms was a direct partnership link (in red) between CFM International, Safran and GE Aviation since the former was a 50-50 joint venture between the two latter companies.

In the period 2006-2009, the system of relationships in the aircraft engine sector became more interconnected (figure 2). As explained by the industry experts, first, there was growing collaboration between orchestrating MNEs. Rolls Royce and Safran, for example, developed a new partnership (R&D on aerodynamic, thermal, and aero-elastic performance and noise-reduction), while GE Aviation and Safran formed a joint venture – Nexcelle in 2008 to develop engine nacelles for next-generation integrated propulsion systems. Second, several orchestrating MNEs started using more common suppliers. In 2005, for example, Boeing's spinoff Spirit AeroSystems started providing nacelle packages for the trio of engine suppliers Rolls Royce, GE Aviation, and Pratt & Whitney. BAE Systems also started providing aircraft engine controls to both Rolls Royce and GE Aviation during this period. One of the experts we interviewed gave another example of Hanwha Aerospace, a South Korean firm. It started as a supplier of engine cases for GE solely. Nevertheless, over time, it started expanded its customs base by supplying engine cases and parts to Pratt & Whitney and Rolls-Royce as well. It received both a supplier Gold certification from Pratt & Whitney and also it became the first company in the world to receive Rolls-Royce's Product Part Approval Process (PPAP) quality certification. This certification was important, as it granted Hanwha Aerospace the authority to verify the quality of newly developed aircraft engine components and approve them for mass production. Therefore, overtime, Hanwha Aerospace became a major supplier to three orchestrating MNEs.

The integration trend intensified substantially in the third period 2010-2014 (figure 2). The network diagram indicates that several firms managed to occupy the core of the network by becoming both suppliers and partners to several orchestrating MNEs. While in the first time-period the network is fragmented and consists of the isolated islands of activity, the network in the last time-period is fully integrated and moreover, has strong pairwise stability and is robust to failures. We interpret this as a growing complexity of aircraft engine GVCs over time. All the industry experts we interviewed, considered this trend to be the result of an intentional strategy by the orchestrating MNEs to utilise common suppliers and partners. The experts generally agreed that the complexity of aircraft engines has risen substantially over the past few decades, which made the integration of dispersed knowledge more complicated. According to a specialist from Pratt and Whitney, the use of common suppliers and partners helped to optimise cost structure and production strategy, improved stability and reliability of the whole system, and allowed for a unified effort to produce radical innovations, such as the development of a more sustainable plane. Interestingly, a common view among the experts was that both the growing technological complexity of aircraft engines and the move towards using common suppliers and partners instigated more technological collaboration between orchestrating MNEs and their value chain partners. One of the experts stated that "lead firms need to guide suppliers and co-develop and co-create with them". In our subsequent analysis, we further investigate this assertion.

In figure 3, we demonstrate that the growing interconnection in the network over time is primarily due to an increase in partnership linkages. The figure demonstrates the striking growth in partnership linkages, which were not typical in the global system of relationships in the first time period but became prevalent in the second and third periods. Moreover, the R&D focus of partnership linkages has dramatically increased over time. Another striking feature of figure 3 is how R&D was done internally in the first time period and how it became increasingly done in partnership in the latest time period. Therefore, we clearly see the growth of co-inventions in the engine industry.

[Figure 3 about here]

Figure 4 shows that this growing collaborative tendency is also present when we analyze the scope of international co-inventions. That is, the average number of authors from other countries per patent has grown over time for firms in the aircraft engine industry.

[Figure 4 about here]

Figure 5 finally shows that the technological scope of patents has also increased over time in the aircraft engine industry.

[Figure 5 about here]

Econometric Results

Table 1 presents the correlation matrix for all the variables. It shows that the correlations among hypothesized independent variables are low to moderate, suggesting that multicollinearity is not a concern.

[Table 1 about here]

To test our first and third hypotheses regarding orchestrating MNEs having a broader technological scope and international co-invention scope than its value chain partners, we conduct a *t*-test with unequal variances. Table 2 presents the results of the analysis, which indicates significant differences in means for both and high probabilities that the orchestrating MNE’s mean is higher than that of other firms. These results provide support for our first and third hypothesis.

[Table 2 about here]

Next, to evaluate if, over time, an orchestrating MNE’s advantage in terms of technological scope and international co-invention scope has grown relative to its GVC partners, we conduct a longitudinal mixed-effect regression on a panel data (evaluating change in our dependent variables over three time periods corresponding to the network diagrams). As discussed in the methods section, the model uses both fixed and random effects.

[Table 3 about here]

The empirical results from our estimation of equation (1) are presented in Table 3. Column 1 provides the results with technological scope as the dependent variable, while column 2 uses international co-invention scope as the dependent variable.

Columns 1 and 2 provide supporting evidence for hypotheses 4 and 5. As the technology underlying the GVCs in the aircraft engine industry has become more complex over time, both the technological scope advantage and the international co-invention scope advantage of orchestrating MNEs relative to other firms has increased as well.

The results of the performance-based control variables generally take on the expected signs, apart from ROE before tax in the first regression, which is negatively related to technological scope. One of the explanations may be that in cases when firms (or more specifically, firm management teams) are handling the shareholders’ money with high efficiency, they try to avoid risks by innovating in areas that are well known to them filing patents in the same technological categories. Otherwise, we find that both *size* and *R&D expenses* are positively related to a firm's technological diversity. We also find that technological scope is positively related to the network measures *eigenvector centrality* and *tie diversity*. In column 2, we find that international co-invention scope is positively related to the network measures *eigenvector centrality* and *tie diversity*. *R&D expenses* is positively related to international co-invention scope, but other performance-based measures are insignificant.

We also conduct a robustness check where we include Airbus, Boeing, Embraer, and Bombardier as orchestrating MNEs. In our previous analysis, we had treated them as GVC partners since they perform the role of buyers of output by aircraft engine MNEs. Table 4 presents the results of the analysis.

[Table 4 about here]

The results in Table 4 are very similar to our initial analysis, in fact with the coefficient on the orchestrating MNE variable gaining even more significance and higher impact in the case of technological scope.

Finally, to test our hypothesis 2 regarding orchestrating MNEs specializing more in basic science and technology than their value chain partners, we have selected a random subsample from our list of firms, which included two orchestrating MNEs and eighteen non-lead firms. We analyzed their patents for the three time periods and counted the number of times their patents cited fundamental science (academic research publications). We next conducted a test of difference to see if the patents produced by the orchestrating firms refer more to basic science than those of non-orchestrating firms. The statistical test (t statistic 3.103; p-value 0.000) indicates that orchestrating MNEs' patents are more prone to focus on basic science than those of non-orchestrating firms. These results thus support our hypothesis.

6. Discussion and conclusion

Our thesis in this paper is that (1) GVCs operate like integrated systems, that (2) orchestrating MNEs act like lead firms in integrated systems, and that (3) orchestrating MNEs therefore face the imperative of developing architectural knowledge to effectively integrate the various subsystems and components so that the GVC functions harmoniously. Our theoretical analysis has allowed us to hypothesize three ways how the quest for architectural knowledge shapes the innovation strategies of orchestrating MNEs: they need to develop a broader technological scope than other firms; they need to draw relatively more on basic science and technology than other firms; and they need to engage in a broader scope of international co-invention than other firms. We believe that the identification of these distinct innovation strategies addresses the call for more research that opens up the black box of the orchestration of GVCs (Lunnan & McGaughey, 2019) and makes significant contributions to the literature that studies MNEs and their orchestration capacity in GVCs (Kano, 2018; Pitelis & Teece, 2018; Vahlne and Johanson, 2021; Pananond, Gereffi and Pedersen, 2020).

We have tested our theoretical predictions by studying patenting trends in the global aircraft engine industry between 2002 and 2014. Our data analysis has shown that this knowledge-intensive industry is particularly interesting since it has gone through a substantial transformation during the sample period, which also coincides with a significant increase in technological complexity of aircraft engines. This changing configuration of GVCs and their underlying technological systems provided a unique opportunity to study the extent to which the orchestrating MNEs adapted their innovation strategies.

At the beginning of our study period, the five orchestrating MNEs operated more-or-less as “innovation islands”, each with their individual networks of supplier firms. By the end of our study period, all five orchestrating MNEs’ innovation networks were densely interconnected and interdependent (Figure 1). This shows the identification and reliance on the same set of world-leading suppliers by all orchestrating MNEs.

Our econometric analysis has confirmed our theoretical predictions. In the aircraft engine industry, orchestrating MNEs have a disproportionately large technological scope and international co-invention scope than their value chain partners. Adding to this, their scope advantages over value chain partners in terms of technological breadth and cross-border innovation have grown over time. And the orchestrating MNEs have higher expertise in fundamental science compared to their value chain partners who focus more on applied science.

At the same time, our results provide interesting insights for all firms in the aircraft engine industry: the results point to the strong relation between network eigenvector centrality and both technological and international co-invention scope, which means that those firms that increase their centrality in the aircraft engine network by developing linkages with multiple firms, develop more technologically diverse patents and increase their cross-border technological collaboration in patent development. This may be a suggestion that non-lead firms which disproportionately collaborate with multiple orchestrating MNEs also need to strengthen their architectural knowledge for integration purposes. Another important finding is related to tie diversity, which has a significant relation with both technological scope and international co-invention scope. This indicates that not only the magnitude of linkages is important, but also their content and firms that have a combination of different types of linkages (partnership arrangements, supplier arrangements) tend to produce more technologically diverse innovations and their invention teams tend to be more collaborative internationally. These results contribute to the recent literature that analyzes opportunities for upgrading in global values chains (Ryan et al, 2020).

Our findings contribute to the cross-border innovation literature by illustrating a new motive for some firms – orchestrating MNEs – to develop international co-inventions. Complementary to the global knowledge sourcing perspective (Kogut and Chang 1991; Chung and Alcácer 2002; Berry 2006; Scalera et al., 2018), we show that orchestrating MNEs disproportionately develop international co-inventions relative to other firms due to their need to develop architectural knowledge that can resolve systems integration problems. For managers of orchestrating MNEs, this signals the need to consider architectural knowledge development as they develop their cross-border innovation strategy.

Our study bears some limitations. The fact that an orchestrating MNE has a broader knowledge base than its GVC partners might be true in the specific case under investigation, which is the aerospace engine industry, but may be different in other knowledge-intensive or labor-intensive industries. Therefore, further research could analyze whether similar patterns can be observed in other industries and whether these trends have an impact on different types of innovation (e.g., product versus process innovations; radical vs. incremental innovations). Future studies could also analyze if collaborative tendencies transcend individual industries and how complex multi-level production systems emerge across multiple industries and countries.

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Table 1: Pearson's correlations

	International co-invention scope	Technological scope	Orchestrating MNE	R&D expenses	Tie diversity	Export revenues	Firm size	Profit margin	ROE before tax	Eigenvector centrality
International co-invention scope	1									
Technological scope	0.568***	1								
Orchestrating MNE	0.4146***	0.4196***	1							
R&D expenses	0.2255***	0.3109***	0.2183***	1						
Tie diversity	0.2899***	0.4308***	0.3447***	0.1592**	1					
Export revenues	0.1556**	0.1884**	0.4729***	0.0972*	0.2317**	1				
Firm size	0.1688**	0.2863***	0.1693**	0.2405***	0.1692*	0.1248**	1			
Profit margin	0.0564	0.0276	0.017	0.1268**	0.0228	0.0114	0.0972*	1		
ROE before tax	0.0447	-0.0685	0.1182**	0.1228**	0.0935	0.0827	0.0454	0.4818***	1	
Eigenvector centrality	0.4211***	0.4751***	0.6108***	0.1065*	0.4402***	0.2741***	0.2582***	0.0141	0.1406**	1

Notes: ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively.

Table 2: Analysis of difference

	Test 1	Test 2
Orchestrating MNE mean	0.0216667	0.0175
Other firm mean	0.0019655	0.0027241
T	-1.19867	-3.7583
Pr (T > t) diff >0	0.9638	0.9985

Table 3: Longitudinal regression results

Variables	Technological scope	International co-invention scope
Orchestrating MNE	0.005** (0.002)	0.01*** (0.003)
R&D expenses	0.0006*** (0.0001)	0.0005** (0.0002)
Tie diversity	0.004*** (0.0008)	0.002* (0.001)
Export revenues	-0.000008 (0.00002)	-0.00002 (0.00003)
Firm size	0.007** (0.003)	0.002 (0.005)
Profit margin	0.00005* (0.00003)	0.00005 (0.00005)
ROE before tax	-0.00005*** (0.00001)	-0.00002 (0.00002)
Eigenvector centrality	0.017*** (0.004)	0.02*** (0.006)
N	302	302
Chi2	198.97***	101.66***
Log likelihood	1151.67	1028.55

Notes: Results of a longitudinal mixed-effect regression model that includes both fixed and random effects. ***, **, and * denote significance at the 1% , 5%, and 10% levels, respectively.

Table 4: robustness check: longitudinal regressions with OEMs as orchestrating firms

Variables	Technological scope	International co-invention scope
Orchestrating MNE	0.009*** (0.002)	0.01*** (0.002)
R&D expenses	0.0006*** (0.0001)	0.0005** (0.0002)
Tie diversity	0.004*** (0.0008)	0.002** (0.001)
Export revenues	-0.00002 (0.00002)	-0.00003 (0.00002)
Firm size	0.006** (0.003)	0.002 (0.004)
Profit margin	0.00005 (0.00003)	0.00005 (0.00005)
ROE before tax	-0.00005*** (0.00001)	-0.00002 (0.00002)
Eigenvector centrality	0.01** (0.004)	0.01** (0.005)
N	302	302
Chi2	243.67***	135.17***
Log likelihood	1164.57	1040.60

Notes: Results of a longitudinal mixed-effect regression model that includes both fixed and random effects. ***, **, and * denote significance at the 1% , 5%, and 10% levels, respectively.

Figure 1: Tier structure of the aircraft engine sector

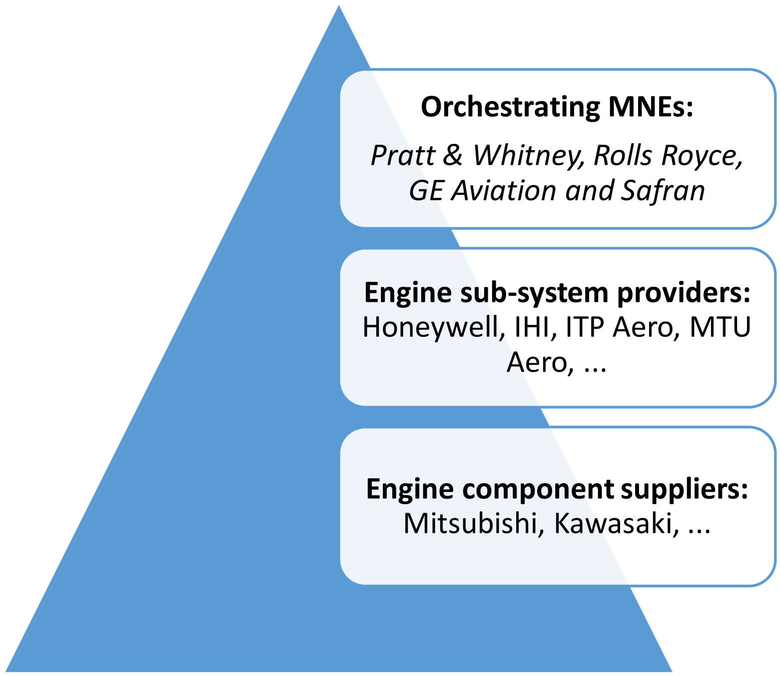


Figure 2: Aircraft engine networks, per time period

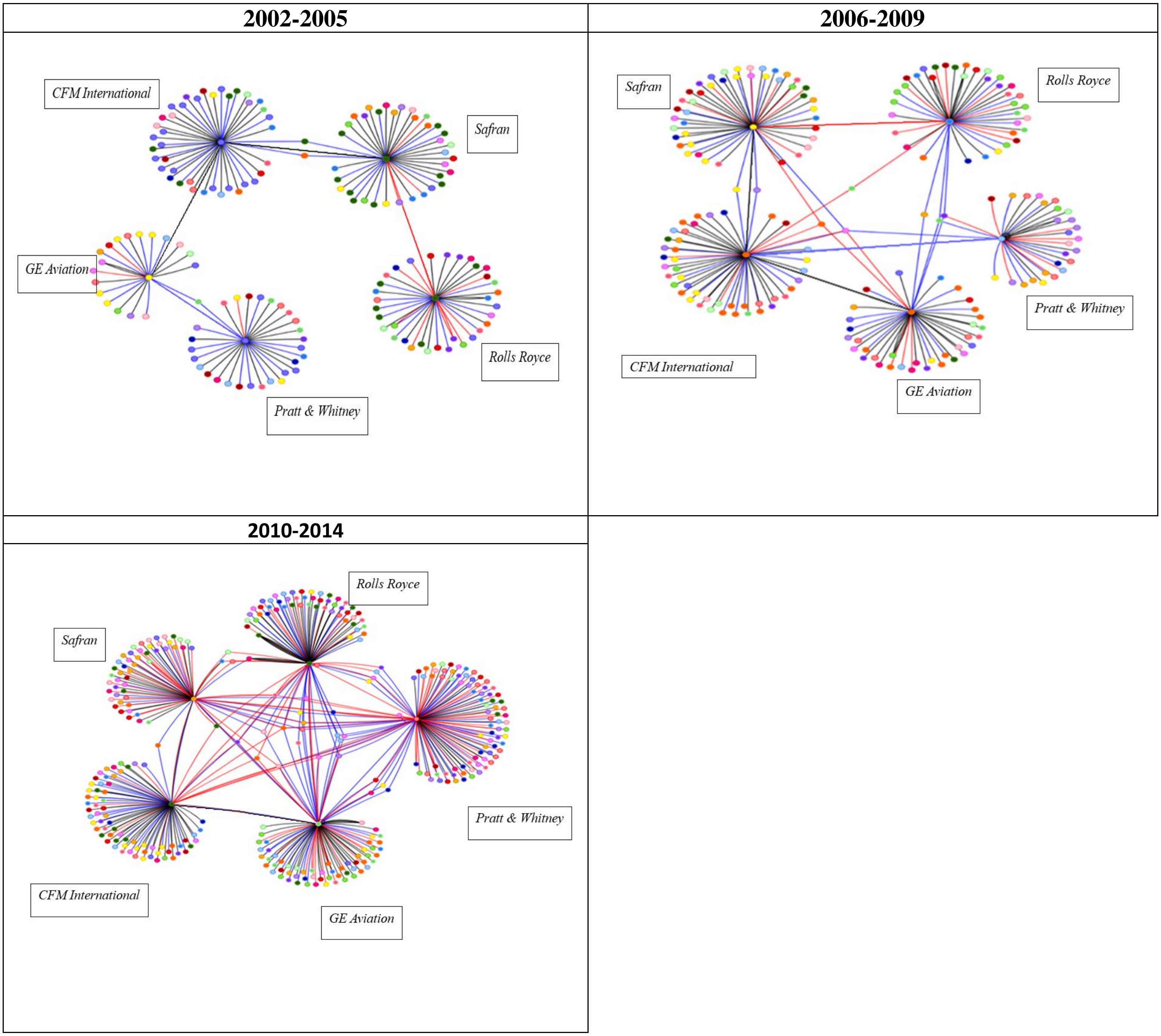
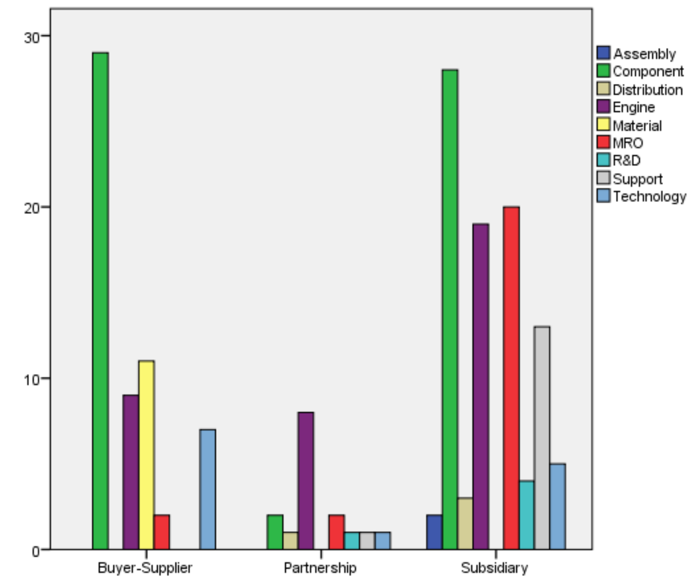
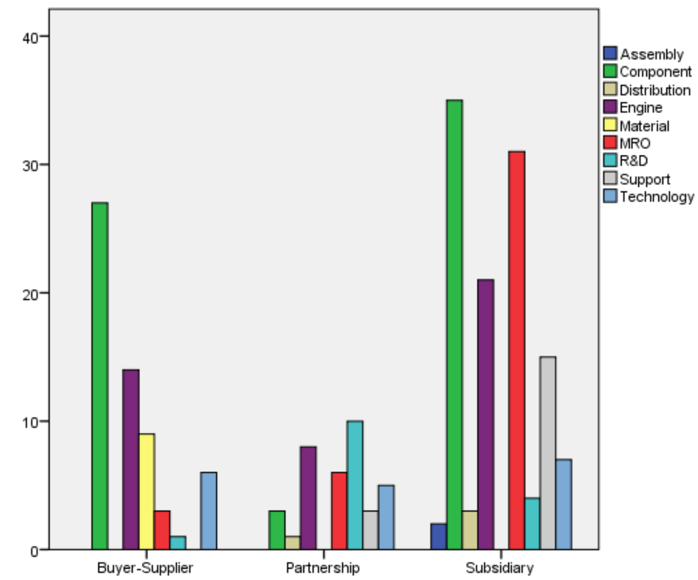


Figure 3: types of inter-organizational linkages, per time period

2002-2005



2006-2009



2010-2014

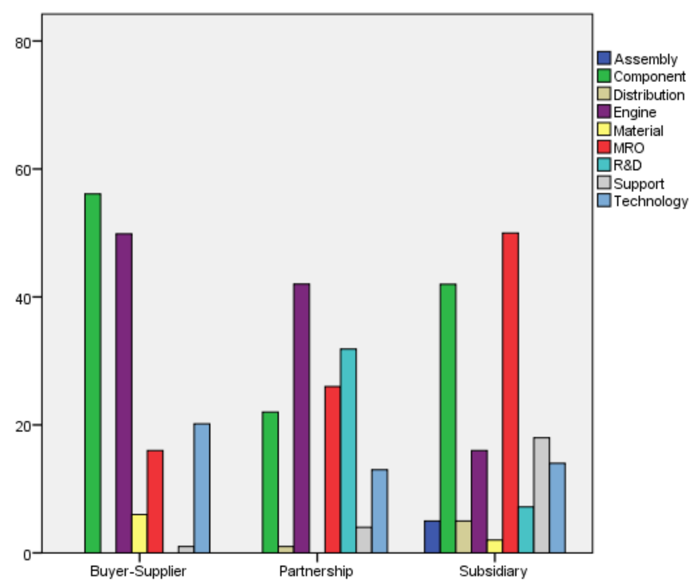


Figure 4: Average number of international co-authors per patent, different time periods

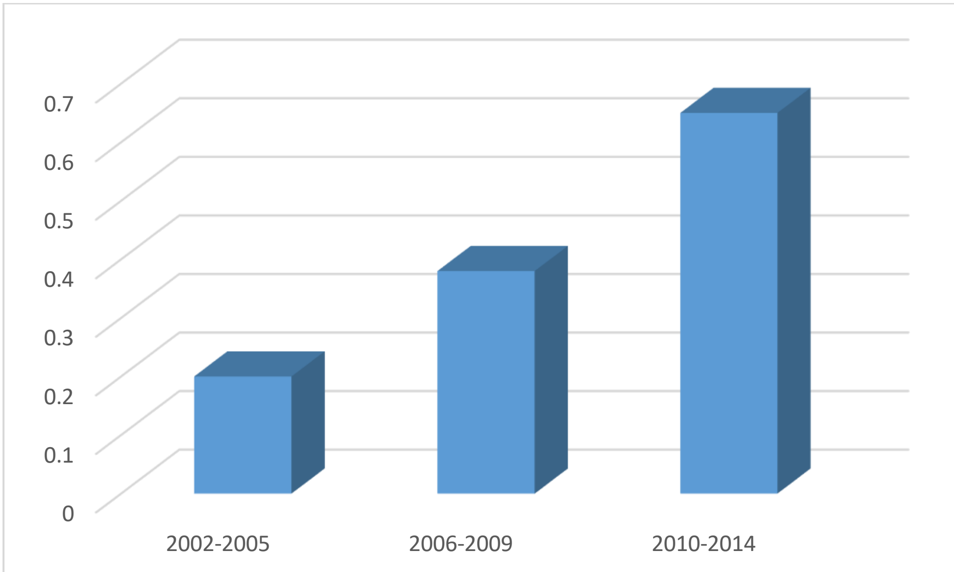


Figure 5: Average number of technological classes per patent, different time periods