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RESEARCH ARTICLE

Cross-Border Dynamics of IP Modularity: International Patenting in LEDs and Lithium-Ion Secondary Battery Technology

Peter M. Bican[1] · **Dirk Caspary**[2] · **Carsten C. Guderian**[1,2]

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Abstract

To profit from their inventions, multinational enterprises rely on various appropriation and internationalization strategies. Intellectual property modularity serves as a reliable option to master the tradeoff between owning the "right" (i.e., valuable) patents in a technology and sharing other "less valuable" patents to spur innovation and foster technology dissemination. Through an inductive, multi-case approach looking at light-emitting diodes and lithium-ion secondary battery technology, we expand prior intellectual property modularity to incorporate internationalization effects across borders. Relying on patent classifications, we trace the development of these two technologies and key multinational enterprises in various countries longitudinally from 1990 to 2018. We introduce the Dynamic IP Modularity Application Matrix and demonstrate that integrating the firm and country levels yields insights into dynamic internationalization developments, particularly when considering the drawbacks to intellectual property modularity. Herein, decision-makers need to secure not only currently valuable but also potentially valuable intellectual property to successfully apply an international intellectual property modularity value capture strategy.

Keywords Cross-border development · Intellectual property modularity · Internationalization · Multinational entities · Patents · Technology dissemination

✉ Peter M. Bican
peter.bican@fau.de

1 Chair of Technology Management, Friedrich-Alexander-University Erlangen-Nuremberg, Dr.-Mack-Straße 81, 90762 Fürth, Germany

2 PatentSight GmbH, Joseph-Schumpeter-Allee 33, 53227 Bonn, Germany

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1 Introduction

Globalization and intellectual property (IP) rights affect not only international trade but also dispersed knowledge generation and international knowledge flows (Branstetter et al., 2015; Ernst et al., 2022; Jaffe & Trajtenberg, 1999; Maskus & Penubarti, 1995; Rafiquzzaman, 2002). Modern innovation systems are characterized by cross-border research and development (R&D) organization and by increasing internationalization (De Rassenfosse & Thomson, 2019; Papanastassiou & Pearce, 2009; Zhao, 2006). This internationalization fosters access to additional knowledge and new partners, as well as the realization of cost reductions and productivity gains (Eaton & Kortum, 1996a, 1996b; Harhoff et al., 2014). Multinational enterprises (MNEs), in particular, profit from these developments (Cantwell & Mudambi, 2000; Dasgupta, 2012; Luo, 2005).

Decentralized, international R&D functions place a strong emphasis on IP to protect and appropriate their knowledge (Granstrand & Holgersson, 2014; Jacobides et al., 2006; Reitzig & Puranam, 2009). Herein, various options for value appropriation exist, and IP modularity is a valuable approach when technology ownership is partitioned among various stakeholders (Baldwin & Henkel, 2015; Henkel et al., 2013). IP modularity builds on the general concept of modularity as developed by Baldwin and Clark (2000), which describes the division of systems into individual parts (or modules), allowing all or most other modules to remain unchanged as changes occur in a focal module.

IP modularity is primarily used to assess how MNEs can collaborate and capture value, particularly in business environments with complex technologies in which various inventions come together and are owned by various industry players (Baldwin & Clark, 2000; Gomes & Joglekar, 2008; Langlois, 2003; Sanchez & Mahoney, 1996; Simon, 1962; Von Hippel, 1990). Creating a modular value appropriation strategy allows the MNE to master the tradeoff between owning too much IP in a technology, hampering innovation, or owning too little or the “wrong” invaluable IP and being leapfrogged by competitive businesses (Baldwin & Henkel, 2012, 2015; Henkel & Baldwin, 2009; Henkel et al., 2013; Waltl et al., 2012).

However, the strategic application of IP modularity has drawbacks, as MNEs still lose control of parts of their IP (Shaw & Stock, 2011). As part of their internationalization strategies, MNEs decide where to patent their inventions and, hence, benefit from temporary exclusivity (Conley et al., 2013; Putnam, 1996). Herein, they generate patent families with multiple member documents from various countries[1] (European Patent Office, 2017b). Still, research on IP modularity has primarily focused on firm-level decisions, neglecting value appropriation concerns for MNEs with internationally dispersed inventive activities (Almeida et al., 2002; Dechezleprêtre et al., 2015; Morescalchi et al., 2015). This is occurring despite the extant literature’s awareness of IP’s legal frameworks and countries’ limitations. For example, Baldwin and Henkel (2015)

[1] While we refer to countries for simplicity (versus “geographical areas” or similar descriptions), we acknowledge that patents may correspond to multiple countries: for example, patents filed in regional offices or via the Patent Cooperation Treaty.

acknowledged worldwide patents, paving the way for further recognition of these territorial rights' implications and drawbacks for IP modularity value appropriation strategies. The problem of cross-border legal limitations addresses one of the key constituents of IP modularity in enabling value capture "in situations where knowledge and value creation are distributed across many actors" (Henkel & Baldwin, 2009). Thus, our research question becomes: How do MNEs' cross-border inventive activities affect the successful application of IP modularity?

We approach this research question by relying on an inductive, multiple case study design and incorporating two levels of analysis – the firm and the country level – to focus on the different geographical origins of patent filings (Paavilainen-Mäntymäki & Hassett, 2015; Stake, 1995, 2013). Herein, we evaluate two distinct, self-compiled samples of 42,806 patent families in the light-emitting diode (LED) industry that are owned by 7760 MNEs and of 50,746 patent families in the lithium-ion secondary battery technology industry that are owned by 7733 MNEs. These patent families come from various key markets, including China, Germany, Japan, South Korea, Taiwan, and the United States of America.

Examining multiple analyses over three decades, we trace the development of inventive activities at the firm and country levels via patent filings in these two focal technologies through the lenses of IP modularity. Herein, we observe shifts from countries like Japan toward China, detect differences in technology focus based on International Patent Classification classes, and detect where MNEs' inventive activity occurs. Thus, we observe a geographical shift in value creation and, subsequently, value capture.

Importantly, we address issues related to internationalization strategy, industry evolution, and IP modularity dynamics. We make four key contributions: First, we integrate internationalization and IP strategies by expanding the current view on IP modularity with cross-border IP modularity, in that it becomes relevant to making decisions on where and when to protect the modules. Second, we contribute the concept of dynamic packaging of IP modules, expanding the focus on defining modules and decisions related to keeping or sharing certain modules in order to enable appropriation while spurring innovation as a dynamic decision. This addresses not only modules that are currently valuable but also modules that will become valuable if kept providently. Third, we contribute a multi-level analysis on the firm and country levels, showing various options for MNEs and policymakers on how to successfully apply an international IP modularity strategy for sustainable value appropriation. Fourth, we incorporate time-variant dynamics across multiple time periods to simultaneously assess the current and future importance of certain IP modules, introducing the Dynamic IP Modularity Application Matrix to guide researchers and practitioners alike.

2 Literature

2.1 Internationalization, R&D Organization, and Intellectual Property

Cross-border R&D organization and growing internationalization characterize modern innovation systems (Branstetter et al., 2018a; Papanastassiou & Pearce, 2009; Zhao, 2006). The globalization of R&D is driving productivity growth, enabling cost reductions, and is providing access to new knowledge and networks (De Rassenfosse & Thomson, 2019; Eaton & Kortum, 1996a; Harhoff et al., 2014). This development is driven by two major factors, residing inside and outside of MNEs: (1) firm-specific advantages and (2) country-specific advantages.

International business theory differentiates between firm- and country-specific advantages that contribute to MNEs' value-added services (Matysiak et al., 2018; Rugman et al., 2011). Among others, firm-specific advantages comprise proprietary technologies and intangible assets and refer to "the firm dimension of international business" (Hymer, 1960; Matysiak et al., 2018; Rugman & Verbeke, 2003). Country-specific advantages comprise natural resources and other endowment factors and refer to "the country dimension of international business" (Matysiak et al., 2018; Rugman, 1981). For MNEs that are operating across multiple countries, home and host country-specific advantages shape how firm-specific advantages are managed in each country (Rugman et al., 2011). This management comprises decisions on how R&D activities are organized, including which technologies to foster and where to subsequently protect proprietary corporate knowledge – for example, via IP.

As described by the World Intellectual Property Organization (2015), IP "refers to creations of the mind, such as inventions; literary and artistic works; designs; and symbols, names and images used in commerce." Proprietary knowledge, new inventions, and other intellectual assets are protected by different IP regimes, such as patents, copyrights, trademarks, and trade secrets (Bican et al., 2017). Approximately 80 percent of all technological content is only found in patents, meaning they constitute one of the most comprehensive, and valuable, windows into R&D activities globally (Asche, 2017).

Patents protect inventions' functions and yield temporary exclusivity for up to 20 years, allowing their owners to exclude others from commercially profiting from their inventions (Conley et al., 2013; Somaya, 2012). They are based on exclusion rather than use facilitation (Smith, 2006). Patents are territorial rights, wherein country-specific governing bodies each define patents' breadth and enforceability (Dreyfuss et al., 2008). Managing these patents over their lifetimes, which includes regular maintenance decisions to uphold patents' enforceability, is a dynamic capability that involves strategic considerations (Al-Aali & Teece, 2013; Conley, 2017; Conley et al., 2013; Eisenhardt & Martin, 2000; Somaya, 2012; Teece et al., 1997).

Publicly available patents reveal information on corporate strategies: for example, on MNEs' technological focus, the development of new technologies, industrial evolution, and tracing of technological change (Basberg, 1987; Guderian, 2019; Pavitt, 1985). Patent data on application, citation, or grant counts have been used to estimate the development stage within technologies' life cycles (Gao et al., 2013; Su, 2018). In the same vein, patent data are also used to trace countries' developments and cross-border interdependencies (Choi & Park, 2009; Griliches, 1990; Tong & Frame, 1994; Wieandt, 1994). This research traces international co-invention and knowledge flows (Branstetter & Maskus, 2022; Branstetter et al., 2015; Ernst et al., 2022; Jaffe & Trajtenberg, 1999), and patents are also often analyzed to measure MNEs' aforementioned R&D and internationalization decisions (Branstetter et al., 2018b). For example, Furman et al. (2002) relied on patent stocks as measures of countries' relative advantages, while Szulanski (1996) and Branstetter et al. (2018b) focused on knowledge transfer via patents. Other scholars have interpreted patent stocks as local, country-level knowledge stocks (Chung & Yeaple, 2008; Kerr & Kerr, 2018). In the same vein, Singh (2008) showed that patent stocks reflect more essential determinants of national innovative capacities. Instead of patent stocks, patent citations are also relied upon to capture knowledge flows and innovation activities, with citations measured between citing and cited countries, industries, or firms (Ernst et al., 2022; Jaffe & Trajtenberg, 1999; Maurseth & Verspagen, 2002; Peri, 2005).

However, while the aforementioned patent-based research traces the cross-border development of technologies and industries, these analyses omit the managerial perspective on corporate decision-making. It remains opaque how MNEs use their dynamic capabilities to sustainably benefit from their inventions, particularly in modern business environments with internationally dispersed or shared technological ownership (Alexy et al., 2009, 2013; Henkel & Baldwin, 2009). Consequentially, corporate decision-makers turn to patent tactics (Holgersson & Van Santen, 2018). These include decisions such as on what to patent or how to build their patent portfolio (Barros, 2015; Holgersson, 2013; Holgersson & Van Santen, 2018; Kumar & Turnbull, 2008; Pitkethly, 2001; Sternitzke, 2013), as well as on where to patent (Dolfsma, 2011; Guderian, 2019; Inkmann et al., 1998; Schmidt, 2013) and how to appropriate value (Belderbos et al., 2014; Conley et al., 2013; Reitzig & Puranam, 2009). Various options exist to profit or capture value from IP, with the use of IP modularity suggested particularly for open innovation environments or business contexts in which knowledge and IP are dispersed (Baldwin & Henkel, 2015; Henkel & Baldwin, 2009; Henkel et al., 2013; Waltl et al., 2012).

2.2 Intellectual Property Modularity

Key to the concept of IP modularity is the objective of value appropriation (Baldwin & Henkel, 2012; Waltl et al., 2012). IP modularity "brings together the theory of modularity from the engineering and management literatures with the modern economic theory of property rights and relational contracts to address the question of value appropriation" (Baldwin & Henkel, 2012), and it builds on the general concept of modularity as developed by Baldwin and Clark (2000).

According to the concept of modularity, tasks are partitionable, which allows MNEs to share the labor in R&D processes (Baldwin & Clark, 2000; Gomes & Joglekar, 2008; Henkel et al., 2013; Langlois, 2003; Sanchez & Mahoney, 1996;

Simon, 1962; Von Hippel, 1990). With independent modules, innovations or changes in one part of the system do not change, alter, or affect other parts of the system (Simon, 1962). This setup is not limited to the original inventor, as innovations can be contributed by other parties, like startups, users, MNEs, or other firms within modular systems (Baldwin & Clark, 2006; Franke & Von Hippel, 2003; Jeppesen, 2004; Von Hippel, 2001; Von Hippel & Finkelstein, 1979). Linking modularity with IP rights to analyze MNEs' value capture abilities paved the way to establish IP modularity as a form of modularity (Jacobides et al., 2006; Quan and Quan and Chesbrough, 2010; Henkel et al., 2013; Baldwin & Henkel, 2015).

IP modularity reconciles the tension between value creation and value capture, and it provides a framework to design value capture strategies for modular systems (Henkel et al., 2013). Within one innovative offering, there are distinct IP systems that can be split into independent modules. This is usually applied in the context of open innovation collaborations with distributed innovation and outsourcing settings within large systems (Henkel & Baldwin, 2009; Henkel et al., 2013); in these large systems, complexity is one of the main issues to cope with (Smith, 2006). Firms like MNEs must decide on designs, modular structures, technical boundaries, and whether to deploy IP in house or externally for each module (Henkel et al., 2013). Modularity enables firms to cope with this complexity by "eliminat[ing] incompatibilities between IP rights in a given module, while permitting incompatibilities within the overall system" (Henkel et al., 2013). According to Waltl et al. (2012), "[a] system is called 'IP modular' if its module boundaries are drawn in such a way as to separate parts of the system that the architect desires to, or needs to, treat differently with respect to intellectual property (IP)." One current characteristic of IP modularity is that its success and failure are determined by the existence or absence of IP modules, with prior research on IP modularity being largely based on theoretical or anecdotal evidence (Henkel & Baldwin, 2009). Further, the value creation described by Waltl et al. (2012) often conflicts with value appropriation. If too much IP is controlled internally, innovation might be deterred. Conversely, the control of too little IP – or of IP on irrelevant modules – could deter value capture opportunities and, depending on the portfolio size, be a significant cost factor.

This modularity could also influence how products are developed: for example, when external IP is needed for the product to develop its full potential. The external IP-protected parts might be sourced in, and the internal, new IP – built as a module – may be used in addition (Henkel et al., 2013). Hence, IP modularity is important for firms like MNEs to operate beyond their internal boundaries, such as when entering IP licensing or sharing agreements with various stakeholders, like employees, suppliers, or alliance partners (Baldwin & Henkel, 2015; Henkel et al., 2013). As Holgersson and Van Santen (2018) write, "[i]n complex technologies building upon several related inventions, firms can benefit from technical modularity combined with different levels of IP modularity."

However, IP modularity does come with drawbacks. For example, the dangers of defecting employees or limited scope of protection linger (Shaw & Stock, 2011). Stronger IP rights lower such threats to IP, including unauthorized use, substitution, theft, and/or imitation (Baldwin & Henkel, 2012). Distributing IP into discrete modules, making IP freely available to access otherwise restricted external sources, and combining weak internal with strong external IP rights have been rationales for successful IP modularity applications (Alexy et al., 2013; Baldwin & Woodard, 2009; Gawer & Cusumano, 2002; Harhoff et al., 2003; MacCormack & Iansiti, 2009; Peters et al., 2013; Tiwana, 2008a, 2008b; Waltl et al., 2012).

2.3 Cross-Border Intellectual Property Modularity

Henkel et al. (2013) note, "IP modularity is an important concept for MNEs that must manage IP across firm boundaries," and recognizing boundary conditions is central to this understanding of IP modularity. Without boundary conditions, systems lack decomposability – and, hence, a modularity application (Smith, 2006). However, boundary conditions exist on different levels. Within firms, Henkel et al. (2013) identified technical boundaries or "boundaries of parts with different IP status." Firm-specific advantages determine how these boundaries are strategically defined for MNEs (see also Rugman et al., 2011).

Looking beyond firms, country-specific advantages influence the external boundary conditions of IP modularity. This is analogous to the patent family concept: Patent families differ in size and application and, hence, potentially lack compatibility (Guderian et al., 2021). A patent family, like a module in a system architecture, spans a diverse set of countries, but at its core relates to the single invention that is claimed throughout all patent documents comprising the patent family (European Patent Office, 2017b). Consequently, incompatibilities between patents from different countries that form a patent family are determined by country-specific advantages.

In the modern business environment with decentralized corporate structures and internationally dispersed R&D operations, such open systems do not stop at national borders (Almeida et al., 2002; Dechezleprêtre et al., 2015; Morescalchi et al., 2015). IP modularity of the underlying products or processes enables internationally dispersed innovation activities (Baldwin & Henkel, 2012). However, when looking through the lens of the modularity concept, it becomes problematic to neglect other country-specific advantages, like legal frameworks and legal limitations (Carrier, 2007). IP is only valid in the countries in which it is sought (Dreyfuss et al., 2008).

With the internationalization of inventive activities and the need for IP modular system architectures, MNEs intensify knowledge generation beyond national borders by creating R&D centers in multiple countries, with knowledge flowing across borders (Criscuolo et al., 2005; D'Agostino & Santangelo, 2012; Maskus et al., 2019). Without accounting for legal frameworks and cross-border issues, IP modularity is prone to failure in protecting innovation sustainably by allowing value capture from IP. Thereby, the problem of cross-border issues addresses one of the key constituents of IP modularity in enabling value capture "in situations where knowledge and value creation are distributed across many actors" (Henkel & Baldwin, 2009): many actors, internationally dispersed innovation activities, dispersed knowledge transfers, and varying jurisdictions. In line with Pero et al. (2015), we argue that IP modularity is clearly defined between product modularity and legal modularity (Danese & Filippini, 2013). However, this neglects a critical aspect of IP: cross-border IP modularity. Baldwin and Henkel (2015) refer to worldwide patents without further addressing internationalization considerations and country-specific advantages that result from this boundary condition. This induces our research question: How do MNEs' cross-border inventive activities affect the successful application of IP modularity?

3 Methods

To address our research question, we have applied a longitudinal, cross-border, multiple inductive case study research design (Paavilainen-Mäntymäki & Hassett, 2015; Stake, 1995, 2013). The case studies span the international development of (1) light-emitting diodes – also commonly known as light-emitting devices or LEDs – and (2) lithium-ion secondary battery technology. The search results comprise data from 1990 to 2018. Despite patent information's availability for the recent filing years 2019 to 2021, these data are incomplete due to the publication lag at patent offices and were deliberately not considered. We chose these two technologies for several reasons: Both originated in Japan and have existed for a longer time period (i.e., patents had been filed throughout the past 30 years). Moreover, both technologies have recently surged in market penetration, as LEDs enable the reduction of greenhouse gas emissions and political changes have led to the replacement of traditional lightbulbs (Ershadi et al., 2018; Martin, 2018). In the same vein, changes in the information and communication sector – as well as the creation of portable devices such as smartphones, tablets, laptops, battery-run cars, vacuum cleaners, and electric scooters – have increased the demand for lithium-ion secondary battery technology. Hence, both industries are subject to a certain level of comparability (ScienceDirect, 2021; Zubi et al., 2018).

Our analysis is explorative, and we obtained data from PatentSight GmbH (2020). The PatentSight database comprises international patent data sourced from the European Patent Office's INPADOC and DOCDB databases, which are subsequently harmonized to account for, among others, corporate ownership structures and legal status information (Guderian, 2019; Guderian et al., 2021). The harmonization procedures allow for precise longitudinal analyses without hindsight bias by accounting for only active and pending patents per year that were owned by each MNE, which also includes subsidiaries and subsidiaries' subsidiaries (Guderian et al., 2021; LexisNexis Intellectual Property Solutions, 2021). The database interface permits querying the database for patent families based on filter and measure selection options (Guderian, 2019), with patent families constituting "a set of either patent applications or publications taken in multiple countries to protect a single invention by a common inventor(s) and then patented in more than one country" (European Patent Office, 2017b; see also Guderian, 2019). Hence, all information used for this manuscript was obtained from patent documents as publicly available sources; we did not rely on any internal firm information (see also Buehler et al., 2017; Guderian et al., 2021).

In addressing IP modularity success and failure, prior research has largely been based on theoretical and anecdotal evidence and focused on this evidence's mere existence or absence (Henkel & Baldwin, 2009). More precisely, its existence is considered success and its absence is regarded as failure. Our approach is to rely on five-digit International Patent Classification (IPC) classes (first sub-class level of the IPC classification scheme) to which patents are classified by experienced and independent examiners at the patent offices during the patent grant process. This has enabled us to capture technological modules, identify where these modules have been developed, and assess if the national focus on certain technological modules has shifted over time (European Patent Office, 2017a; World Intellectual Property Organization, 2020). Hence, we have based our analyses on objective, third-party-generated data, not on self-reported assessments, and detected modules based on patented technologies within each respective national technological focus.

For this purpose, we queried the PatentSight database for patent information related to the LED and lithium-ion secondary battery technology fields. For both technology fields, we used a combination of (1) keywords in the patent title, abstract, and claims; (2) IPC and CPC classification symbols; and (3) stop terms and stop patent classifications (European Patent Office, 2017a; World Intellectual Property Organization, 2020). More precisely, the LED technology field comprises the LED chip (die) features and the LED chip package features; this field does not include organic light-emitting diodes (OLEDs), as OLED constitutes an inherently different technology. The LED patent search yielded 42,806 active and inactive patent families, with 19,310 active patent families. The lithium-ion secondary battery technology field comprises the battery cell features anode, cathode, electrolyte, and separator, and the patent search yielded 50,746 active and inactive patent families, with 38,354 active patent families. The reporting date for all searches in the database was March 18, 2021.

The LED patent families are owned by 7760 firms. The top 20 firms each own approximately 0.9–3.7% of the patent families, meaning patent ownership is diverse and no origin country for the inventions is dominated by a single or small number of patent owners. The lithium-ion secondary battery technology patent families are owned by 7733 firms. The top 20 firms each own approximately 0.5–6.0% of the patent families, also meaning patent ownership is diverse and no origin country for the inventions is dominated by a single or small number of patent owners.

For the case studies, we relied on the following patent measures: (1) filing year; (2) portfolio size; and (3) inventor origins. The (1) filing year of a patent refers to the year in the date accorded to an application for which all application criteria are met and the application is submitted to the corresponding patent office (European Patent Office, 2020). As we relied on patent families, the filing year of the patent family refers to the year of filing of the first document in the patent family (PatentSight GmbH, 2020). The (2) portfolio size refers to the number of active patent families in a portfolio or owned by an entity (Guderian, 2019; Guderian et al., 2021). For our analyses, this refers to "the number of patent families selected in the filter queries," as in Guderian et al. (2021): i.e., all patents that are part of the LED or lithium-ion secondary battery technology. For (3) invention origins, the country where an invention is made is determined based on inventors' addresses, and we focused on the major countries where the LED and lithium-ion secondary battery inventions originate. For the LED inventions, these countries are China (CN), Germany (DE), Japan (JP), South Korea (KR), Taiwan (TW), and the United States of America (US); for the lithium-ion secondary battery technology inventions, the major countries are China (CN), Germany (DE), Japan (JP), South Korea (KR), and the United States of America (US). Following the queries, the database's interface was used to graphically conduct and extract the data analyses.

4 Results

4.1 Case Study: Light-Emitting Diodes

Figure 1 displays the LED patent filing trends by country from 1990 to 2018. The mosaic plot comprises one column per filing year, with the column width adjusted to the number of patent filings in the respective filing year relative to the total number of LED patent filings. Each filing year's column is divided by the countries where the invention originates, and the height of each column is adjusted to the number of inventions stemming from this country relative to the total number of inventions made in the respective filing year. The total area for a country for all filing years is

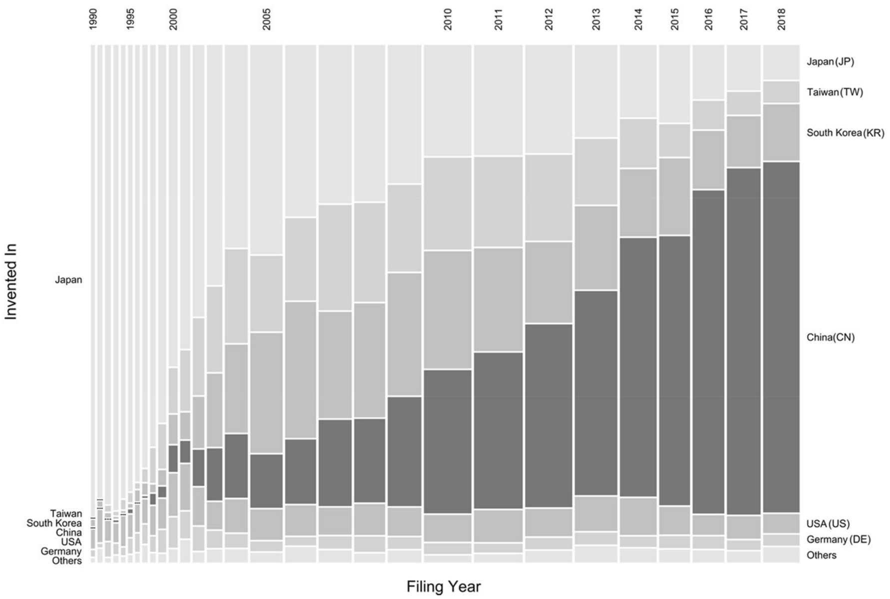

Fig. 1 LED inventive activity by countries: Mosaic plot. Source: Own illustration

proportional to the total number of inventions made in that country relative to all inventions.

The columns in Fig. 1 can be divided into three decades: (1) The number of patent filings per year appears relatively low in the filing years 1990 to 1999; (2) Between the filing years 2000 and 2009, the number of filings increases significantly; and (3) The patent filings reach their peak in the early 2010s. As the figure shows, in the earliest years, the share of inventions made in Japan dominates the patent filings and other countries add up to less than a 10% share. In 2000, the share of inventions made in Japan scales back, whereas the shares of inventions made in Taiwan and South Korea increase. In 2010, the share of inventions made in China increases significantly, while the shares made in Japan, Taiwan, and South Korea plummet. By contrast, the share of inventions made in the United States, Germany, and all other countries is relatively constant at low (double-digit) figures.

Figure 2 shows the trend for the LED inventive activity market share by originating country in a semi-logarithmic line chart, with the United States and Germany added to the "others" category for comparison purposes. This figure makes the LED patent filing trends across decades even more apparent: (1) Between 1990 and 1999, Japan's share dramatically declines, while China, South Korea, and Taiwan show slow growth rates at low levels; (2) Between 2000 and 2010, Japan's share further declines, whereas China, South Korea, and Taiwan show strong growth; and

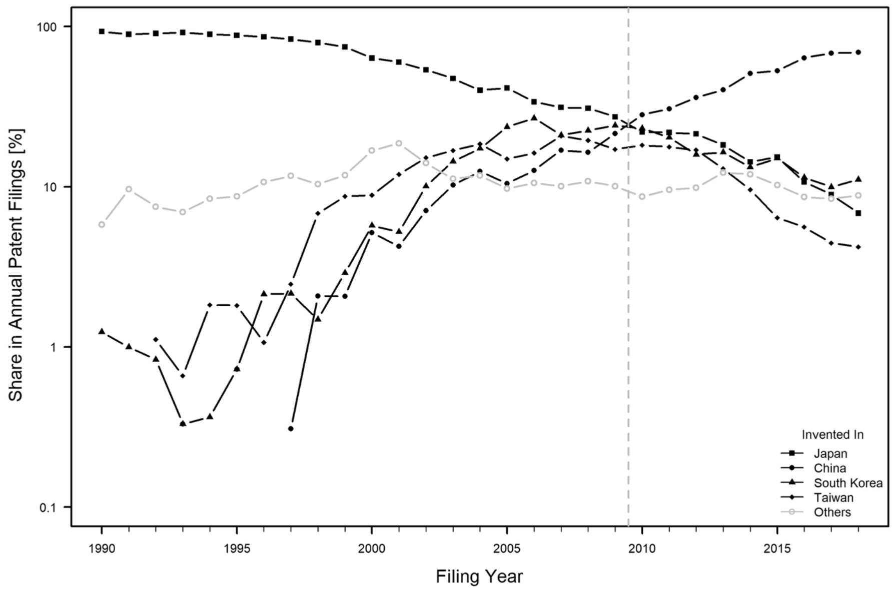

Fig. 2 LED inventive activity by countries: Semi-logarithmic line chart. Source: Own illustration

	H01L 21/02	H01L 33/00	H01L 33/02	H01L 33/36	H01L 33/48
China	3 %	39 %	25 %	8 %	11 %
Germany	5 %	14 %	15 %	3 %	12 %
Japan	5 %	4 %	20 %	9 %	18 %
South Korea	2 %	42 %	22 %	8 %	8 %
Taiwan	2 %	45 %	24 %	9 %	9 %
USA	4 %	17 %	16 %	7 %	10 %

Fig. 3 LED invention classification by technology focus: 1990 to 1999. Source: Own illustration

(3) 2010 marks a turning point, after which only China outperforms its prior activity, whereas South Korea and Taiwan decline alongside Japan. The other countries remain constant during the entire time period analyzed.

To analyze if different countries' inventions differ by technical subject matter, we relied on IPC classifications to determine the subject matter of the inventions. To group the technical subject matter into broader technical scopes, we used the first sub-class level focus on the overall top five IPC classifications: (1) H01L 21/02 – Manufacturing or treatment of semiconductor devices; (2) H01L 33/00[2] – Semiconductor devices with barriers specially adapted for light emission; (3), H01L 33/02 – LED chips (dies); (4) H01L 33/36 – Electrodes; and (5) H01L 33/48 – LED chip (die) packages. The analysis was separated into three time periods: (1) 1990–1999; (2) 2000–2009; and (3) 2010–2018. To compare the countries, we aggregated the classifications for the three decades; for each country, we calculated the relative share of classifications. For example, as shown in Fig. 3, 20% of the inventions made in Japan are related to LED chips (dies) and were classified with H01L 33/02 and its respective sub-classes.

Figures 3, 4, and 5 show the resulting technology classification heat maps for the three decades. From 1990 to 1999, inventions from Japan focus on the LED chip (H01L 33/02) and the packaging of the LED die (H01L 33/48). Inventions from China, South Korea, and Taiwan also focus on LED chips, but the share of LED chip packaging inventions is lower, and a larger share of inventions relates to more generic LEDs (H01L 33/00). During the filing years 2000 to 2009, the share of LED

[2] Please note that classification H01L 33/00 is an IPC group-level classification. This classification is less detailed than a first sub-class level classification and, therefore, cannot be simplified.

	H01L 21/02	H01L 33/00	H01L 33/02	H01L 33/36	H01L 33/48
China	6 %	29 %	6 %	4 %	16 %
Germany	4 %	15 %	6 %	3 %	13 %
Japan	4 %	11 %	13 %	4 %	21 %
South Korea	3 %	18 %	15 %	6 %	28 %
Taiwan	4 %	32 %	6 %	4 %	14 %
USA	4 %	14 %	8 %	3 %	11 %

Fig. 4 LED invention classification by technology focus: 2000 to 2009. Source: Own illustration

	H01L 21/02	H01L 33/00	H01L 33/02	H01L 33/36	H01L 33/48
China	1 %	19 %	14 %	4 %	28 %
Germany	4 %	8 %	6 %	3 %	15 %
Japan	3 %	10 %	5 %	2 %	21 %
South Korea	2 %	10 %	15 %	11 %	29 %
Taiwan	3 %	12 %	11 %	7 %	27 %
USA	3 %	10 %	9 %	4 %	13 %

Fig. 5 LED invention classification by technology focus: 2010 to 2018. Source: Own illustration

chip (H01L 33/02) and electrode (H01L 33/36) inventions from Japan drops. China and South Korea reduce their shares of unspecific inventions (H01L 33/02) and increase their share of LED chip packaging (H01L 33/48) inventions. Further, the share of LED chip inventions (H01L 33/02) from China and from Taiwan drops. In the decade beginning in 2010, the largest share of inventions across all technologies is related to LED chip packaging (H01L 33/48).

Table 1 Inventive activity in top 10 innovative firms across countries for LEDs

Owner	Origin	China			Germany			Japan			South Korea		
		1990–1999	2000–2009	2010–2018	1990–1999	2000–2009	2010–2018	1990–1999	2000–2009	2010–2018	1990–1999	2000–2009	2010–2018
ams AG	DE	0.0	1.1	3.1	92.9	79.9	68.1	0.0	2.5	1.6	0.0	0.0	0.3
Epistar	TW	8.6	28.1	14.5	0.0	1.1	0.0	2.9	4.1	6.5	0.0	0.4	0.0
Foxconn	CN	0.0	17.2	33.1	0.0	0.0	0.0	98.7	57.5	40.0	0.0	0.0	0.0
HC Sem-iTek	CN	0.0	88.9	99.1	0.0	0.0	0.0	0.0	0.0	0.2	100.0	11.1	0.7
LG Innotek	KR	0.0	0.6	0.0	0.0	0.0	0.0	0.0	0.3	5.3	0.0	97.8	94.3
Panasonic	JP	0.0	0.0	0.0	0.0	0.0	0.4	99.6	99.7	99.2	0.0	0.0	0.0
Samsung	KR	0.0	0.0	0.3	0.0	0.0	0.0	12.5	7.4	7.8	87.5	86.0	90.1
Seoul Semi-conductor	KR	0.0	0.0	1.4	0.0	1.8	1.8	25.0	2.9	4.3	0.0	91.7	86.3
Seoul Viosys	KR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.7	0.0	92.8	91.0
Toshiba	JP	0.0	0.0	3.2	0.0	0.0	0.0	99.1	98.4	83.3	0.0	0.0	0.0

Owner	Origin	Taiwan			USA			Others		
		1990–1999	2000–2009	2010–2018	1990–1999	2000–2009	2010–2018	1990–1999	2000–2009	2010–2018
ams AG	DE	0.0	0.0	0.0	3.6	6.7	16.9	3.6	9.9	10.1
Epistar	TW	85.7	63.1	75.2	2.9	1.1	3.8	0.0	2.3	0.0
Foxconn	CN	0.7	22.8	25.3	0.7	2.4	1.6	0.0	0.0	0.0
HC SemiTek	CN	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LG Innotek	KR	0.0	0.0	0.0	0.0	1.3	0.4	0.0	0.0	0.0
Panasonic	JP	0.0	0.1	0.4	0.4	0.1	0.0	0.0	0.0	0.0
Samsung	KR	0.0	0.0	0.3	0.0	2.9	1.1	0.0	3.7	0.5
Seoul Semiconductor	KR	0.0	0.0	0.4	75.0	0.7	5.8	0.0	2.9	0.0
Seoul Viosys	KR	0.0	0.0	0.0	0.0	4.5	4.9	0.0	2.7	1.5
Toshiba	JP	0.0	0.0	0.0	0.9	1.6	11.1	0.0	0.0	2.4

Source: Own illustration

Table 1 provides a comparison of the top 10 innovating firms in the LED market worldwide, as measured by their patent portfolio sizes. Firms are listed based on their inventive activity in the respective LED IPC classifications as previously described, and the firms are compared by their inventive activities in the most relevant LED markets over the three predefined decades based on the share of inventive activity within each of these countries (as a percentage): China, Germany, Japan, South Korea, Taiwan, and the USA. The comparison over the three decades – (1) 1990–2000; (2) 2001–2009; and (3) 2010–2018 – reveals two trends: Independent of their origin, MNEs like AMS (DE), Foxconn (CN), Seoul Semiconductor (KR), and HC SemiTek seem to shift their primary inventive activities to different countries. Some, like AMS (DE), reduce their dependence on their home country in this way, whereas other MNEs, particularly Asian ones like Foxconn (CN) and Seoul Semiconductors (KR), move their inventive activity in the opposite direction: to their home countries, reflecting the dominance of Asia – and particularly China – in the overall LED market (see Fig. 1). Other MNEs like Panasonic (JP), and Samsung (KR) can maintain most of their inventive activity in their home countries over all decades.

4.2 Case Study: Lithium-Ion Secondary Battery Technology

Figure 6 displays the lithium-ion secondary battery patent filing trend from 1990 to 2018. A key difference with LEDs (Fig. 1) is that Taiwan does not constitute a major country for lithium-ion secondary battery inventions and is, hence, included

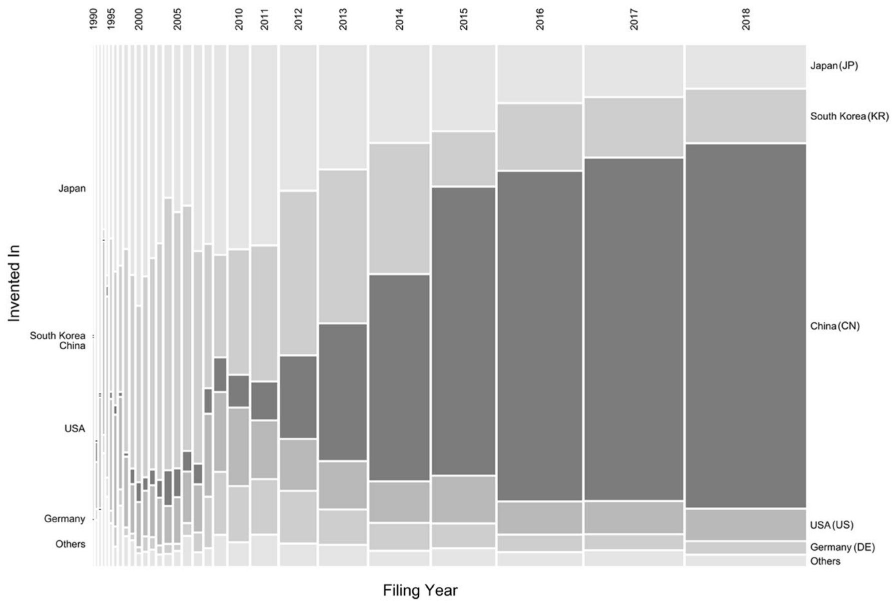

Fig. 6 Lithium-ion secondary battery technology inventive activity by countries: Mosaic plot. Source: Own illustration

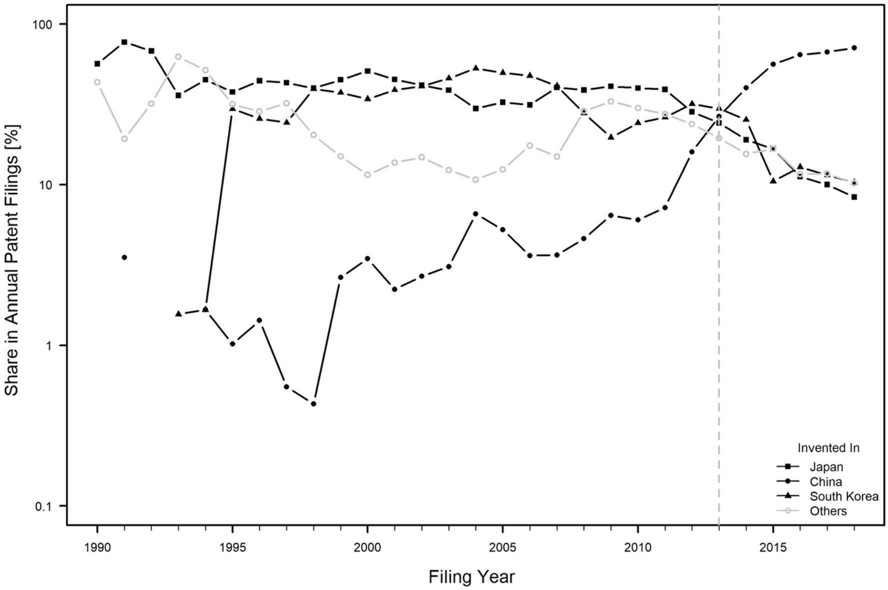

Fig. 7 Lithium-ion secondary battery technology inventive activity by countries: Semi-logarithmic line chart. Source: Own illustration

in the "others" group. As in Fig. 1, the column width is adjusted to the number of patent filings in the respective filing year relative to the total number of lithium-ion secondary battery patent filings. Further, each filing year's column is divided by inventions' country of origin. The height of each column is adjusted to the number of inventions stemming from this country relative to the total number of inventions made in the respective filing year, and the total area for a country for all filing years is proportionate to the total number of inventions made in that country relative to all inventions.

Like Figs. 1 and 6 columns can be divided into three decades: (1) The number of patent filings hardly increases between 1990 and 1999; (2) Between 2000 and 2009, the number of filings increase modestly; and (3) The patent filings increase significantly and steadily between 2010 and 2018. The share of inventions from Japan decreases over time, as with LED technology. Conversely, the share of inventions from South Korea increases even in the early stages of the analyzed period. Additionally, the share of inventions from China increases at a slower rate during the first and second decades but increases rapidly in the last decade.

Figure 7 depicts trends related to market shares where the inventions originate in a semi-logarithmic line chart, and as with LED technology, trends across the three aforementioned decades are even more apparent and a turning point occurs after which only Chinese patent filings in the technology increase, while the corresponding patent filings for all other countries decline.

To again analyze if different countries' inventions differ by technical subject matter, we relied on IPC classifications to determine the subject matter of the inventions, as in the LED technology. To group the technical subject matter into broader technical scopes, we used the first sub-class level focus on the overall top five IPC classifications: (1) H01M 2/02 – Cases, jackets, or wrappings; (2) H01M 2/14 – Separators; membranes; diaphragms; spacing elements; (3) H01M 4/02 – Electrodes composed of, or comprising, active material (anodes/cathodes); (4) H01M 10/05 – Accumulators with non-aqueous electrolyte (e.g., polymer electrolytes); and (5) H01M 10/42 – Methods or arrangements for servicing or maintenance of secondary cells or secondary half-cells. Based on the identified decades as described above, the analysis was separated by time period: (1) 1990–1999; (2) 2000–2009; and (3) 2010–2018. To compare the countries, we aggregated the classifications for the three decades; for each country, we calculated the relative share of classifications. For example, as shown in Fig. 8, 23% of the inventions made in Japan are related to accumulators with non-aqueous electrolyte and were classified with H01M 10/05 and its respective sub-classes.

Figures 8, 9, and 10 show the resulting technology classification heat maps for the three decades. The two dominant classifications relate to lithium-ion secondary battery technology with non-aqueous electrolytes like polymer electrolytes (H01M 10/05) and controlling the status of the battery cell (H01M 10/42). Therein, the focus for inventions from Japan and South Korea does not change by more than five percentage points in all three decades. Conversely, the focus for inventions from China changes from electrodes (H01M 4/02) in the first decade to lithium-ion secondary battery technology with non-aqueous electrolytes (H01M 10/05).

Table 2 compares the top 10 innovating firms in the lithium-ion secondary battery technology market worldwide, as measured by their patent portfolio sizes. The

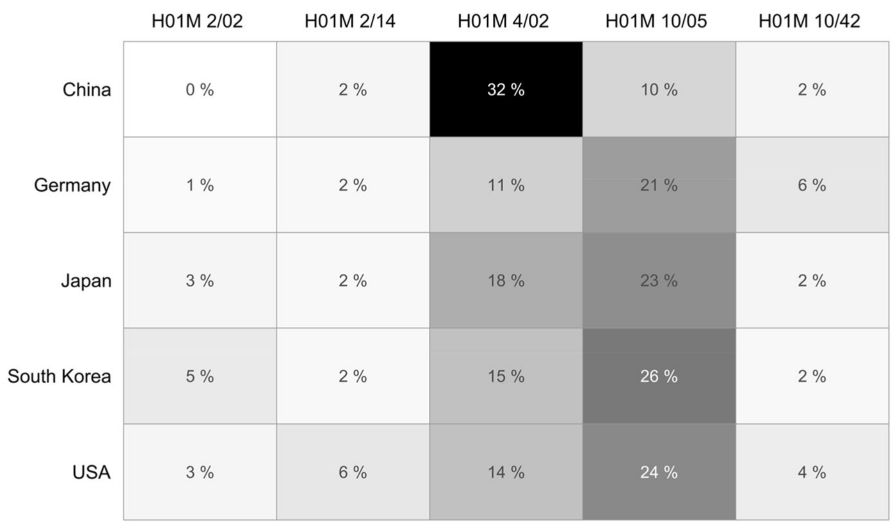

Fig. 8 Lithium-ion secondary battery technology invention classification by technology focus: 1990 to 1999. Source: Own illustration

	H01M 2/02	H01M 2/14	H01M 4/02	H01M 10/05	H01M 10/42
China	3 %	2 %	17 %	15 %	3 %
Germany	4 %	3 %	7 %	13 %	7 %
Japan	3 %	3 %	17 %	18 %	3 %
South Korea	4 %	4 %	18 %	25 %	2 %
USA	3 %	3 %	10 %	12 %	5 %

Fig. 9 Lithium-ion secondary battery technology invention classification by technology focus: 2000 to 2009. Source: Own illustration

firms listed are based on their inventive activity in the previously described lithium-ion secondary battery technology IPC classifications. They are compared by their inventive activities in the most relevant lithium-ion secondary battery technology markets over the three pre-defined decades based on the share of inventive activity within each of these countries (as a percentage). These countries are China, Germany, Japan, South Korea, and the USA. The comparison over the three decades – (1) 1990–1999; (2) 2000–2009; and (3) 2010–2018 – reveals the same trends as for LEDs, albeit more diffused: In line with Fig. 6, the dominance of Asia, and particularly China, grew. However, as the only non-Asian MNE in the top 10, Bosch (DE) reversed this trend, following a home country proximity trend in the last decade by concentrating even more inventive activity in Germany at the expense of its formerly two largest operations abroad (US and KR). Guoxuan High-Tech (CN) moved in the opposite direction, with an exodus of inventive activity from Germany and the USA toward concentrating its inventive activity almost exclusively in China. Conversely, resembling the trend for LEDs, Murata Manufacturing (JP) and Panasonic (JP) stayed loyal to their home countries in terms of inventive activity. However, not all Japanese firms remained this loyal; Shifting most of its inventive activity from the USA and Japan to China, TDK (JP) did not sustain the spike of shifting the inventive activity to its home country, as displayed in the second decade.

5 Discussion and Concluding Remarks

Our results bridge the gap between internationalization and IP modularity research. As (Baldwin & Henkel, 2012) note, "[m]odularity is not a single strategy: it is rather a large set of strategic options and related tactics that can be deployed in different

	H01M 2/02	H01M 2/14	H01M 4/02	H01M 10/05	H01M 10/42
China	1 %	3 %	29 %	39 %	3 %
Germany	4 %	4 %	12 %	19 %	6 %
Japan	2 %	3 %	19 %	22 %	4 %
South Korea	3 %	5 %	21 %	29 %	3 %
USA	1 %	4 %	15 %	19 %	4 %

Fig. 10 Lithium-ion secondary battery technology invention classification by technology focus: 2010 to 2018. Source: Own illustration

ways in different places." We complement prior research on IP modularity, which is primarily concerned with firm-level analyses and firm-specific advantages, by expanding beyond MNEs' boundaries to address country-specific advantages, cross-border IP modularity, dynamic developments, and a multi-level view (Matysiak et al., 2018; Rugman, 1981). By assessing five-digit IPC classifications of patents to detect IP modules as objective and fine-grained data, we describe the development of LEDs and lithium-ion battery technology to capture technological modules, identify where they are developed, and determine if the national focus shifts over time. To summarize our contributions, we have developed what we term the Dynamic IP Modularity Application Matrix to support decision-makers in managing their IP modules in terms of dynamics and importance.

5.1 Theoretical Contributions

Our results yield four specific contributions. First, through inventive activity as measured by patent filings per country (Figs. 1, 2, 6, and 7), we can observe how technologies develop over time and see dynamic development across countries' borders, independent of initial status, actors, or technologies. It becomes evident that firm-specific advantages alone render it challenging, even impossible, to control or dominate this development. New actors and involved countries continuously surface: competitors and partners alike change, which is typical for both IP modularity and R&D and for internationalization settings (Henkel & Baldwin, 2009; Hsu et al., 2015). In these environments, R&D and IP modularity challenges are not constrained by borders. Hence, to spur innovation and technology dissemination, it

Table 2 Inventive Activity in Top 10 Innovative Firms across Countries for the Lithium-Ion Secondary Battery Technology

Owner	Origin	China			Germany			Japan			South Korea			USA			Others		
		1990–1999	2000–2009	2010–2018	1990–1999	2000–2009	2010–2018	1990–1999	2000–2009	2010–2018	1990–1999	2000–2009	2010–2018	1990–1999	2000–2009	2010–2018	1990–1999	2000–2009	2010–2018
Bosch	DE	0.0	5.8	5.9	0.0	63.8	79.5	0.0	0.0	1.4	0.0	7.2	1.4	0.0	23.2	11.9	0.0	0.0	0.0
Central South University	CN	0.0	0.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Chinese Academy of Sciences	CN	100.0	100.0	99.2	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.0	0.0	0.0
Guoxuan High-Tech	CN	0.0	0.0	95.1	0.0	50.0	3.4	0.0	0.0	0.7	0.0	0.0	0.0	0.0	50.0	0.9	0.0	0.0	0.0
LG Chem	KR	0.0	0.0	0.3	0.0	1.7	0.1	10.5	2.6	0.4	89.5	95.4	98.4	0.0	0.3	0.9	0.0	0.0	0.0
Murata Manufacturing	JP	0.0	1.5	0.3	0.0	0.0	0.3	100.0	98.5	98.8	0.0	0.0	0.0	0.0	0.0	0.6	0.0	0.0	0.0
Panasonic	JP	0.0	0.0	0.3	0.0	0.2	0.2	100.0	98.6	99.0	0.0	0.0	0.0	0.0	1.2	0.5	0.0	0.0	0.0
Samsung SDI	KR	0.0	1.8	1.3	0.0	0.6	14.3	3.5	7.1	7.1	96.5	89.6	76.7	0.0	0.8	0.6	0.0	0.0	0.0
TDK	JP	0.0	19.2	77.5	0.0	1.9	0.0	41.7	75.0	22.2	0.0	0.0	0.0	58.3	3.8	0.3	0.0	0.0	0.0
Toyota Motor	JP	0.0	0.0	0.9	0.0	0.8	0.2	100.0	93.3	93.4	0.0	0.0	0.0	0.0	5.9	5.5	0.0	0.0	0.0

Source: Own illustration

becomes relevant to decide how to package or define IP modules and also which IP modules should be kept and which should be shared or released. The relevance of IP modularity needs to be expanded beyond firm-specific advantages in what defines (1) a module and (2) a valuable module to country-specific advantages; (3) where modules are relevant; and (4) during which time period they are relevant. This expansion only becomes visible when the view on firm boundaries is expanded to fully embrace IP, legal frameworks, and legal limitations (Carrier, 2007). Herein, we contribute the cross-border view of IP modularity, expanding the extant view on firm boundary conditions, and link it to prior R&D and internationalization research.

Second, as described in knowledge flow and technology life cycle research, technologies are subject to changing focus as they develop over time (Branstetter & Maskus, 2022; Branstetter et al., 2015; Jaffe & Trajtenberg, 1999). Such shifts can also be observed for LEDs and lithium-ion secondary battery technology, as shown in the top IPC classifications for the key countries across three decades (Figs. 3, 4, 5, 8, 9, and 10). We observed broad trends within technologies that link to this prior research: certain aspects become more or less relevant, as indicated by the changing patent filing figures. These general trends are difficult to counteract via firm-specific advantages alone. However, we observed that some countries' authorities and MNEs were able to secure larger shares of the technological shifts and that a modular structure supported these concentration efforts if the dynamic technological developments were considered when deciding on which technologies to package into modules. This relates to all forms of technological module packaging: packaging technologies in modules that are (1) valuable and, hence, relevant today; (2) valuable and, hence, relevant in the future; (3) always valuable and, hence, relevant; or (4) never valuable and, hence, irrelevant. Herein, we contribute the concept of dynamic packaging of IP modules to the current IP modularity debate.

Third, the inventive activity of the top 10 innovative firms across countries for both technologies (Tables 1 and 2) demonstrates that multiple IP modularity success strategies are viable. The results show dispersed inventive activity. For MNEs to successfully sustain inventive activity in these countries, one option is to maintain this activity domestically, while the other option is to shift it to other countries and/or technologies in accordance with firm- and country-specific advantages. This not only depends on the technology leadership status in certain countries but also on where MNEs' inventive activity is located. For example, we observed Japanese firms that dominated their technologies with inventive activity in their home country but subsequently shifted these activities to China. Conversely, Germany-based Bosch is an example of how shifts to home countries may be driven by initiatives to transfer value creation and value capture in future key technologies back to home countries. Multi-level analyses combining different countries and firms can determine the best individual strategies to apply. Herein, we contribute the value multi-level analysis on the firm and country levels to the IP modularity, R&D, and internationalization debates.

Fourth, we synthesize the first three contributions into a matrix, which we term the Dynamic IP Modularity Application Matrix (Fig. 11). The matrix allows us to incorporate time-variant dynamics across multiple time periods and countries and simultaneously assess the current and future importance of certain IP modules.

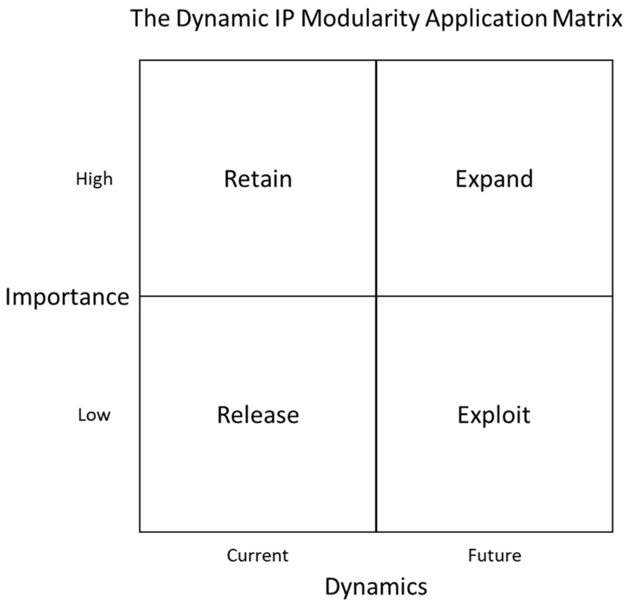

Fig. 11 The dynamic IP modularity application matrix. Source: Own illustration

Decisions related to IP modularity partitioning strategies, in which IPs are to be kept secured within certain MNEs and countries to secure strong and sustainable technology positions, must consider current as well as future relevance. As shown in the matrix's lower-left quadrant, IP modules with relatively low strategic importance today can be released to incentivize inventive activity by third parties, particularly when these are unlikely to gain relevance in the future. As shown in the lower-right quadrant, those IP modules that will be of low importance in the future should be exploited – that is, windfall gains can be realized. As dynamic developments turn the future into the present, there may be a future decision to also release these IP modules, as they are of lower importance, to spur innovation in the focal technology. This requires predictive analytics or technological foresight based on IP rights and may entail multi-sequential, agile approaches to actually assess the (future) potential relevance (Altuntas et al., 2015; Daim et al., 2006; Endres et al., 2022).

Conversely, as illustrated on the upper-left quadrant, IP modules that are of relatively high strategic importance today should be retained to realize returns on prior inventive activity, including through enforcement actions against third parties if necessary. Depending on their future relevance (which may be either high or low), these IP modules should be expanded, as shown in the upper-right quadrant. For example, these modules could be enhanced with additional appropriation and shielding strategies to secure their enforceability. In some cases, MNEs' currently relevant modules could become less important and released to spur innovation – hence, technology development and dissemination – while maintaining potentially relevant modules to profit from their proprietary knowledge. If corporate and technological intelligence render these currently highly relevant IP modules less relevant in the future, windfall gains may again be realized. Hence, when charting individual IP modules on the matrix, these modules may shift positions and quadrants over time. All these considerations need to be made in each country where MNEs are or may become active, as IP modules may be more relevant in certain locations and less so in others.

5.2 Managerial and Policy Implications

IP modularity can be used to mitigate threats to IP, as described by Baldwin and Henkel (2012): "These conditions imply three generic threats to the value of knowledge: (1) unauthorized use of knowledge by the firm's own agents; (2) imitation or substitution by third parties; and (3) withdrawal of the right to use complementary knowledge owned by others." As part of general tactics that include decisions around value creation, value capture, and value appropriation – i.e., which inventions will be patented and where corresponding patents will be filed, enforced, and maintained – corporate management must decide not only how they create modules but also which modules to keep or release (Baldwin & Henkel, 2015; Henkel et al., 2013; Holgersson & Van Santen, 2018). By considering firm- and country-specific advantages through cross-border IP modularity, corporate decision-makers need to decide which technologies to package into IP modules and where and when to protect them (Baldwin & Henkel, 2015; Henkel et al., 2013; Holgersson & Van Santen, 2018). Firms like MNEs need to decide not only which IP modules to keep but also where they keep them and for what time period. A viable option may be to share less valuable modules for less important countries to incentivize the continued development and dissemination of the technology, increasing the unshared modules' value.

As shown in prior research on knowledge flows and technology life cycles, dynamic developments need to be considered when addressing modularity. Such dynamic developments become evident in our two cases over the three decades, where in addition to general shifts in focus within the technological developments, certain countries' authorities managed the transition to core technological aspects such as LED packaging better than others did. Therefore, as part of the general IP modularity trade-off decision on what to retain and what to release, MNEs not only need to assess certain technology modules' relevance today but also predict future importance and future firm- and country-specific advantages.

Moreover, cross-border IP modularity is important for policymakers. As Matysiak et al. (2018) note, [c]ountry-specific capabilities "can be intentionally created by policymakers or firms via, e.g., market cocreation, filling institutional voids and creating related spill-overs, or lobbying with regulators." As evident in our cases, neglecting IP modularity considerations may result in MNEs and other types of firms – as well as entire countries – losing their competitive edge on specific technologies. Both LEDs and lithium-ion battery technology were largely developed in Japan, but the relative importance of Japanese patent filings decreased over the analyzed decades. Focusing exclusively on market champions can downplay real threats, as worldwide developments may impact incumbents' performance or cloud competing new entrants. Those actors, pioneer or follower, that dynamically adapt their value appropriation strategies in cross-border modular structures could prevail (Dreiling & Bican 2022). The dynamic, longitudinal view on developments becomes crucial. Policymakers may incentivize and support the consideration of cross-border IP modularity to strengthen their country-specific advantages. For example, policymakers may set up educational programs to upskill IP knowledge among decision-makers, particularly from less well-equipped MNEs or those under constraints or crises (Guderian et al., 2021). Such investments into human capital and capacity building with respect to IP are considered particularly relevant, as decision processes will be sourced toward artificial intelligence-based systems (Branstetter & Maskus, 2022).

Other policy measures may comprise awareness building on service providers, commercial and public resources, and data solutions to support decision-making progress in detecting relevant IP modules. Strengthening IP appropriation regimes to incentivize relying on IP, for example, by working toward reduced time and resource requirements, serves as another policy option. Additionally, subsidy programs could be initiated to incentivize the development and ownership of IP modules that could become relevant in the future. This could involve R&D tax policies that serve as fiscal incentives to spur inventive activity, allowing for the declaration of relevant modules (Cantwell & Mudambi, 2000; De Rassenfosse & Thomson, 2019). Creating markets for IP module exchange and incorporating current and future relevance assessments may also enhance the use of IP modularity strategies (Rugman et al., 2011). However, these policy measures will initially incur costs: “IP modularity is likely to increase the cost of design and may imply a loss of performance” (Henkel et al., 2013). The benefits of IP modularity considerations in cross-border designs for value appropriation will likely outweigh these costs, also constituting a viable avenue for future research.

5.3 Limitations and Future Research Implications

Our inductive, multi-case study approach is subject to some limitations, yielding ample opportunities for future research. First, we relied on two high-technology cases: LEDs and lithium-ion secondary battery technology. Future research could verify our findings by focusing on different technologies, such as in the pharmaceutical or chemical industries. Second, analyzing cross-border IP modularity with other methodologies beyond case studies – for example, quantitative empirical approaches or relying on multi-level models to capture cross-level effects – are viable options for future research (Raudenbush & Bryk, 2002; Tabachnick & Fidell, 2018). Such analysis might include benchmarking MNEs that successfully pursue a cross-border IP modularity strategy versus MNEs that do not to the same extent.

Third, researchers could develop finer-grained measures of IP modularity success, particularly to develop definitions related to which IP modules will be relevant in the future and need to remain proprietary. Our approach (relying on patents’ five-digit IPC classifications to capture technological modules, their origin, and the national shifts in focus for certain technologies) and our matrix are the first steps to assessing what determines IP modularity success and failure. Herein, future research could integrate different invention and IP quality measures into the considerations to account for fundamental differences in IP, and particularly patent, values (Gambardella et al., 2008; Webster & Jensen, 2011). Integrating smart patent indicators allows for the identification of valuable patents and changing patent portfolio value propositions, as well as cross-border knowledge flows (Buehler et al., 2017; Ernst et al., 2022; Jaffe & Trajtenberg, 1999).

Fourth, future research may also consider cases where an owner acquires IP which was invented in countries different to the owner's home country, i.e., foreign IP, and subsequently develops IP based on the acquired IP. Fifth, analyzing cross-border IP modularity with longitudinal data beyond IP, such as market or firm performance data, could focus on capturing dynamic performance effects. Sixth, as we focused our analyses on patents, future research could focus on integrated IP strategies (Fisher III and Oberholzer-Gee, 2013; Peters et al., 2013). Finally, future research could build on our Dynamic IP Modularity Application Matrix to develop the means to define, manage, and allocate IP modules in terms of dynamics and importance to support decision-makers in developing and enforcing their overall IP strategies and IP modularity strategies.

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Declarations

Conflict of Interest None.

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