Multinational Firms and Global Innovation*

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Abstract

Multinational companies play a key role in the increasing fragmentation of production and innovation across firms and countries. This paper examines how MNCs organize their global production and innovation. We establish novel stylized facts using rich data on the network of production affiliates and patent activity of German multinationals. We rationalize these facts with a heterogeneous-firm model, in which companies jointly determine the location and scale of manufacturing, basic innovation and applied innovation, under asymmetric complementarities across these three activities. Empirical evidence consistent with the model indicates that bigger MNCs innovate more intensively in terms of patent frequency and quality, and offshore innovation to more countries, including both countries with and without production affiliates. Moreover, MNCs' innovation map follows countries' comparative advantage across technology classes, with applied innovation more likely to be co-located with production than basic innovation.

JEL codes: F20, F23, F63, L23, L24, O31, O32.
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1 Introduction

Multinational companies (MNCs) are at the heart of two key globalization trends: the fragmentation of production chains and the internationalization of technological progress. MNCs are focal in global value chains (GVCs), in that they manage complex production networks across multiple countries and offshore manufacturing stages to both foreign affiliates and independent parties. At the same time, MNCs are also responsible for the vast majority of frontier R&D and cross-border technology transfer. These phenomena have first-order implications for the optimal design of trade and innovation policy in developed and developing countries. They also shape the impact of technological leaps such as automation on the global distribution of production, innovation and adoption, and thereby on economic growth across countries.

While a large literature examines the global organization of MNC production, relatively little is known about the global organization of MNC innovation. Traditional priors might suggest that MNCs headquartered in rich countries retain skill-intensive activities at home and offshore low-skill intensive manufacturing to poorer countries. Yet anecdotal evidence points to increasing offshoring of innovation, to both advanced and emerging economies. For example, while leading German car producer BMW has for a long time sourced auto components from China, in 2018 it also unveiled a large research and development center in Shanghai to specialize in digital services, autonomous driving, and automotive design. In 2017, Mercedez-Benz opened its sixth R&D lab in Seattle, primed as a digital hub for cloud computing.

This paper provides one of the first analyses of MNCs' global production and innovation activities. We establish novel stylized facts using uniquely rich data on the network of production affiliates and patent activity of German multinationals.[1] We rationalize these facts with a heterogeneous-firm model, in which companies jointly determine the location and scale of manufacturing, basic innovation and applied innovation, under asymmetric complementarities across these three activities. Empirical evidence consistent with the model indicates that bigger MNCs innovate more intensively in terms of patent frequency and quality. Such companies also offshore a greater share of their innovation to more countries, including both countries with and without production affiliates. Moreover, MNCs pursue innovation across countries and technology classes following countries' comparative advantage, with applied innovation more likely to be co-located with production than basic innovation.

Our first contribution is to uncover new facts about the global innovation activity of multinational companies. We obtain firm-level data on German MNCs and their worldwide network of production affiliates from the Microdatabase Direct Investment (MiDi) of Deutsche Bundesbank, and match it to patent-level data from the European Patent Office Database (PATSTAT). For each parent company, we use the country locations of its subsidiaries and patent inventors to identify innovation conducted at the headquarter country, offshored to a country with an affiliate, or outsourced to a third country. We further classify patents into basic and applied, based on distance to fundamental

[1] We use "patenting" and "innovation" interchangeably throughout the paper for expositional convenience.

science as proxied by backward citations to scientific articles. We also quantify patent quality with the number of forward citations by subsequent patent applications.

We establish three stylized facts. First, MNCs innovate actively and frequently abroad. Second, MNCs innovate in multiple locations, and offshore innovation both to locations with and without affiliates. Third, MNCs that innovate more intensively have higher innovation quality.

Our second contribution is to develop a partial-equilibrium three-country model of MNCs' global production and innovation strategy, motivated by the new stylized facts. In the model, heterogeneous firms jointly choose the location and scale of their output production, basic innovation, and applied innovation to maximize global profits. Firms optimally operate a single manufacturing facility due to economies of scale in production. Innovation of each type may or may not be offshored, to the same or multiple countries, with or without a production affiliate in the same location. Innovation costs are separable across locations, rise with innovation intensity, are higher for offshored innovation, and depend on local innovator wages. Importantly, there are cost synergies between production and applied innovation, but not with respect to basic innovation. The returns to innovation are additive across locations within an innovation type and multiplicative across innovation types, with basic innovation increasing future expected profits, while applied innovation increases profits immediately by lowering marginal production costs. This generates complementarities in innovation across types and locations.

This model delivers several key predictions. First, more productive multinationals are more likely to innovate and to innovate more intensively. Second, more productive MNCs are more likely to offshore innovation and to innovate in more countries. Given the geographic concentration of production, this also implies that more productive MNCs have a greater propensity to simultaneously pursue innovation both in locations with and without a manufacturing subsidiary. Third, MNCs are more likely to innovate and to innovate more intensively in countries with lower innovator wages. When innovator wages vary across countries and technological classes, MNCs thus locate innovation activity according to countries' comparative advantage. Finally, MNCs are more likely to co-locate applied innovation in countries where they operate a production affiliate compared to basic innovation.

Our third contribution is to provide systematic empirical evidence for the operations of German multinationals that is consistent with the model's predictions. In the absence of direct productivity measures and innovation data, we use global firm sales and observed patent outcomes as model-consistent proxies.

We first confirm that bigger MNCs are more likely to hold patents. Conditional on any patent activity, bigger MNCs generate more patents, record more total patent citations, and receive more citations per patent on average. These patterns furthermore hold separately for each of basic and applied innovation.

We then establish that larger firms are more likely to offshore innovation, i.e. to own patents whose inventors are located abroad. Along the extensive margin, bigger MNCs have a greater probability of innovating at least once in at least one foreign country. Along the intensive margin,

bigger MNCs develop a greater share of their patents abroad. Larger firms also innovate in more countries on average, and are more likely to pursue R&D both in locations with and without a production affiliate. All of these findings hold both with respect to total innovation activity and separately within each innovation type.

We next document that individual MNCs respond to cross-country differences in comparative advantage in innovation activity across technological classes. We construct indicators of revealed comparative advantage based on the total number of patents invented in each country and patent technology area, by any patent owner from any origin country who has filed a patent with the 5 leading national patent agencies (US, EU, China, Korea, and Japa). We observe that even within an MNC-technology area, the pattern of patent location across countries strongly follows comparative advantage.

Lastly, we demonstrate that multinationals are more likely to develop applied patents in locations where they also operate a production affiliate, compared to basic patents that are closer to fundamental science.

Our paper contributes to several strands of literature. At a broad level, we add to a large body of work on the drivers of multinational activity. There is extensive theoretical and empirical evidence that firm productivity, cross-country differences in production wages, and economies of scale in production at both the firm and establishment level are key determinants of the pattern of global multinational production (***). Our analysis incorporates these ingredients in a generalized model of the joint production and innovation decisions of global MNCs.

We also extend an emerging literature on the innovation activity of multinational firms. Closely related is recent work on the effect of production offshoring on MNCs' innovation at home. For example, Branstetter et al. (2021) study a policy change in Taiwan, and find that increased possibilities for relocating production to China affect both the level and the nature of domestic innovation by Taiwanese IT firms. Fort et al. (2020) examine the innovation behavior of US firms over the long run, and link the increasing importance of former manufacturing firms for US innovation to the fragmentation of production. Griffith et al. (2006) document that production offshoring can lead to knowledge spillovers from foreign to domestic operations, as MNCs benefit from inventors at foreign facilities tapping into local knowledge. Related, Bilir and Morales (2020) document that MNC parents earn a substantial share of the returns on their domestic innovation investments abroad. Bircan et al. (2021) further uncover an important role for time-zone differences in the creation and diffusion of knowledge within multinational firms. We contribute novel evidence and insights to this line of research by merging for the first time MNC production and patent data, and doing so for a major source country of both FDI and innovation such as Germany. Our study highlights that MNCs offshore innovation not only to countries where they also maintain affiliates, but also to countries without foreign operations, and explores the economics behind this phenomenon.[2]

To shed light on the determinants of innovation offshoring, we leverage ideas from a separate liter-

[2]Arkolakis et al. (2018) and Fan (2021) quantify the welfare effects of MNC operations in models that allow for innovation by the parent and the parent and affiliate, respectively. Our evidence helps assess the plausibility of the assumptions underlying their models.

ature on innovation and more generally the links between innovation, gtowth and entrepreneurship. This literature has explored various determinants of innovation activity inside the firm, typically focusing on domestic innovation and its links to firm performance, firm dynamism, and aggregate growth (***). An active area of research focuses specifically on patent activity, the patent review process, and the impact of patent grants on subsequent firm performance (***). It has in particular emphasized the importance of foundational science for private-sector innovation (Ahmadpoor and Jones 2017, Watzinger et al. 2019), and generally sought to distinguish between basic (i.e. science-based) and applied innovation. Our paper adds a new angle to this literature by exploring global innovation and innovation offshoring.

The paper is organized as follows. Section 2 introduces the data and novel stylized facts about the global production and innovation activity of German multinationals. Section 3 develops a stylized theoretical model of MNC operations that rationalizes these facts and delivers a series of additional testable predictions. Section 4 provides systematic empirical evidence consistent with the model. The last section concludes.

2 Data and Stylized Facts

We first establish novel stylized facts about the global production and innovation activity of multinational firms using uniquely rich new data for Germany. This presents an ideal economic environment in which to study multinational activity, as Germany is the third biggest exporter in the world, hosts many globally engaged firms, and is a global innovation leader.

2.1 MNC Production and Innovation Data

We combine administrative firm-level data on German multinational firms from the Microdatabase Direct Investment (MiDi) of Deutsche Bundesbank (German Central Bank) with rich patent-level data from the European Patent Office Database (PATSTAT). Due to limited MiDi data access and delays in result disclosure during the COVID pandemic, we have also generated a comparable dataset that links Bureau van Dijk's ORBIS dataset to PATSTAT. The descriptives and stylized facts in this Section 2 have not yet been disclosed and are currently based on this alternative data source. All other results in the paper are qualitatively consistent across the two datasets.

MNC production: MiDi covers approximately 15,000 German parents and their global network of affiliates in around 200 host countries during 1999-2016.[3] Since German parent firms are legally obliged to report their foreign investments, MiDi provides high-quality information from the accounting statements of each parent and each subsidiary (e.g. sales, employment, balance sheet total, industry affiliation).[4] The alternative ORBIS data comprises approximately 4,400 German

[3]MiDi also comprises private and public households. We exclude those in our analysis

[4]See Drees, Schild and Walter (2018) for a comprehensive description of the dataset. German parent firms are required to report to the Bundesbank if they directly own at least 10% of the shares or voting rights in a foreign company with a balance sheet total above EUR 3 mil. German parent firms must also report indirect investment relationships and relationships that mix direct and indirect ownership if they hold at least 50% controlling share in a

manufacturing MNCs with information on ownership structure, financials and sector of activity.

Panel A of Table 1 summarizes the substantial variation in multinational production activity across firms and over time. The average German parent has 7 affiliates in 3 countries, with standard deviations of 59.4 and 6.3 around these means. The typical multinational generates EUR 906mil worth of sales revenue at its headquarters and EUR 233 mil across its foreign subsidiaries, with standard deviations of 6,891 and 3,129 respectively. The largest German multinational enterprises have extensive global reach, with companies at the 90th percentile maintaining 7 facilities in 5 countries.

MNC innovation: PATSTAT contains detailed patent-level data on over 100 million patent documents filed around the world. We build a comprehensive dataset on the global production and innovation operations of German multinationals by merging MiDi and PATSTAT based on unique firm identifiers.[5] The baseline matched sample includes about 2,500 German MNCs with at least one patent and roughly 441,000 patent families generated by these firms over the 1999-2016 period.[6] Out of these, roughly 172,000 patent families contain an application filed with the European patent office, which we refer to as EP patents below. We focus on these EP patents in the rest of the analysis as we observe additional information about their nature as described below. Note that a patent as a unit of observation refers to a DOCDB patent family, i.e. the collection of patent documents pertaining to a single invention. We use information on the location of the patent inventor to identify where the underlying innovation activity took place.

Panel B of Table 1 presents summary statistics for German MNC innovators, where we have retained all years that an MNC is active in MiDi as long as it appears at least once in PATSTAT. We discuss key patterns in the next subsection.

Figure 1 plots the number of German MNC-owned patents against inventor country GDP per capita. Innovation activity is highly concentrated, with the top 5 innovation hubs generating roughly 95% of all patents: Germany (89%), USA (2.7%), Austria (1.5%), France (1%), Switzerland (0.7%). At the same time, numerous other countries across the income distribution maintain non-trivial innovation activity.

By combining information on the location of MNCs' production affiliates and patent inventors, we can distinguish between three innovation modes: (i) conducted in the headquarter country, (ii) offshored to a country with an affiliate, or (iii) outsourced to independent innovators in a third country. Within this data structure, we will for convenience refer to (i) and (ii) as co-located innovation and to (iii) as offshore not co-located innovation. [7]

foreign company with a balance sheet total above EUR 3mil. MiDi carefully tracks changes in affiliate ownership over time. We do not focus on ownership turnover as this is a rare event in our baseline sample.

[5]We link MiDi to PATSTAT via the Bureau van Dijk's ORBIS database. The Deutsche Bundesbank Research and Data Center has developed a mapping from MiDi parent firms to ORBIS firm identifiers (BvDID), using supervised machine learning. The Bureau van Dijk's ORBIS dataset in turn provides a crosswalk from ORBIS to PATSTAT.

[6]The alternative sample based on the matched ORBIS-PATSTAT data on German MNCs contains 2,533 firms and roughly 439,000 patent families. Out of these, around 187,000 patent families contain an EP application.

[7]For a given MNC, (i) and (ii) could in principle be performed by independent parties in locations with MNC presence, while (iii) is unlikely to be performed within firm boundaries as any foreign subsidiary should be visible with a balance sheet in MiDi. Our assignment of innovation ownership may therefore either be subject to classical

Patent characteristics: PATSTAT contains detailed verbal descriptions of the patented innovation, preceding patents and articles it cites (i.e. backward citations), and subsequent patents and articles that cite it (forward citations). Drawing on techniques from the innovation literature, we exploit this information to categorize the type of innovation activity underlying each EP patent and to evaluate its quality.

We use information on backward citations to classify patents into basic innovation and applied innovation, following Ahmadpoor and Jones (2017). In particular, we measure a patent's distance to science based on the frequency of backward citations to fundamental science, as proxied by publications in leading scientific journals. We link patents to scientific articles using the Marx and Fuegi (2019) open-access dataset of patent front-page citations to scientific articles. This produces a score of $\{1, 2, 3, ...\}$, with lower scores signifying more proximate relation to foundational science. We label patents receiving a score of $\{1, 2\}$ as basic, and patents receiving a score of at least 3 as applied.[8]

For each patent, we also quantify innovation quality with the number of forward patent citations within 5 years of a patent grant. This methodology follows common practice in the literature (e.g. Hall, Jaffe and Trajtenberg 2005), and rests on the premise that innovation of higher quality acts as a stepping stone for more subsequent innovation activity.

Panel C of Table 1 reports summary statistics at the firm level in the dataset. Since innovation can be time-consuming but patenting sporadic, we collapse the time dimension and consider patenting activity at each firm across all years it is active in the panel. [9] The average patenting German multinational generates 66 EP patents over the 1999-2011 period, and the distribution of innovation activity is extremely skewed with a standard deviation of 588. There is also significant variation in patent quality across firms, such that the mean number of citations stands at 141, while its standard deviation reaches 1,258. The share of basic patents is likewise dispersed, averaging 19% with a standard deviation of 27.

Panel D of Table 1 provides summary statistics at the patent level. 27% of all EP patents are classified as basic. The average patent attracts 2.1 citations, but there is a large standard deviation of 4.6 around this mean.

2.2 Stylized Facts

The database is unique in painting a comprehensive picture of the global innovation activity of multinational firms. We begin by establishing three novel stylized facts that emerge from this data.

Fact 1: *MNCs innovate actively and frequently abroad.*

The data reveal that 59% of all German multinational companies own one or more patents. Of

measurement error or underestimate (but not overestimate) the extent of offshore not co-located innovation.

[8] One can also differentiate between product and process innovation by relying on textual analysis of patent abstracts as in Danzer, Feuerbaum and Gaessler (2020). We document systematic patterns in the data based on the basic-applied distinction, and find little variation of interest by further distinguishing between product and process innovation.

[9] Panel C spans patents granted in the truncated panel of 1999-2011 since citation counts are based on 5-year forward citations.

those, 44% apply for at least one patent with a foreign inventor. At the patent level, this translates into approximately 14% of all patents having a foreign inventor.[10]

Fact 2: *MNCs innovate in multiple locations and offshore innovation to locations both with and without affiliates.*

The Venn diagram in **Figure 2** summarizes the global organization of MNC innovation activity at the firm level. About 56% of all innovating multinationals hold only patents that have been developed at home. Some 7% conduct patent-generating innovation both at home and in another country where they maintain a production affiliate, while 21% do so both at home and in a third country with no subsidiary. Fully 14% of all firms undertake patented research in all three possible locations. Only a negligible 2% of patenting MNCs conduct research only abroad.

Table 2 complements **Figure 2** by summarizing the global geography of innovation at the level of the individual patent. 82.5% of all German MNC patents result from innovation activity within Germany. Of the patents generated abroad, 12.6% are invented in countries where the MNC runs a production affiliate, with the remaining 4.9% not co-located with production. Distinguishing between basic and applied patents reveals that basic innovation is disproportionately more likely to be offshored and to be offshored to locations without a production affiliate: 23.6% of all basic patents are generated abroad, of which $16.5/23.6 = 70\%$ in locations with a subsidiary. In comparison, only 15.2% of applied patents originate abroad, of which $11.2/15.2 = 74\%$ in countries with a subsidiary.

Fact 3: *MNCs that innovate more intensively have higher innovation quality.*

The binscatter in **Figure 3** indicates a strong positive relationship between innovation intensity and innovation quality across firms. We assign firms into 10 bins based on the total number of patents they generate in the 1999-2011 panel, and plot the average number of citations per patent against the average log number of patents per bin.[11] MNCs that own more patents hold patents of systematically higher quality.

3 Theoretical Framework

Motivated by the novel empirical facts established in Section 2.2, we develop a theoretical model of multinational activity that characterizes the global organization of firms' production and innovation. We adopt a stylized, partial-equilibrium setting in order to transparently illustrate the key economic mechanisms that govern firm decisions, while retaining analytical tractability. We relegate all proofs to the appendix, and provide below the intuition for the main results of interest.

[10] A subset of patents report multiple inventors, some of which may be located in Germany and some abroad. We consider such patents as foreign-invented and note that the vast majority of an inventor team is typically located in one location, which we consider the main innovation location.

[11] The panel captures 1999-2016 and we bin firms based on patent activity in 1999-2011 since the patent quality measure is based on 5-year forward citations.

3.1 Set-up

Consider a world comprised of three countries: West, East and South. In each country, a continuum of heterogeneous firms produce horizontally differentiated goods which they sell at home and potentially also abroad. Consumers exhibit love of variety, such that the representative consumer in country $j = \{W, E, S\}$ has CES utility $U_j = \left[\int_{i\in\Omega_j} (x_{ji})^{\alpha}\, di\right]^{\frac{1}{\alpha}}$, where x_{ji} is the quantity consumed of variety i, and Ω_j is the set of goods available to j. The elasticity of substitution across products is $\sigma \equiv 1/(1-\alpha) > 1$, with $0 < \alpha < 1$. If total expenditure in country j is R_j, j's demand for variety i is $x_{ji} = R_j P_j^{\sigma-1} p_{ji}^{-\sigma}$, where $P_j = \left[\int_{i\in\Omega_j} (p_{ji})^{1-\sigma}\, di\right]^{\frac{1}{1-\sigma}}$ is the ideal price index, and p_{ji} is the price of good i in market j.

In each country, two types of labor engage respectively in manufacturing consumption goods and in innovation. From the perspective of individual firms, the wages of production and innovation workers, w_j and r_j, are exogenously determined in the labor market. This assumption can be microfounded, for example, with the presence of two freely tradeable homogeneous goods, each produced by a different type of labor under constant returns to scale and fixed aggregate labor endowments.

We are interested in understanding the production and innovation decisions of multinational companies. We therefore examine the operations of firms headquartered in West, and interpret the exogenous variation in w_j and r_j as cross-country differences in comparative advantage in production vs. innovation. To focus on meaningful trade-offs in Western firms' profit maximization, we assume that $w_S < w_E < w_W$ and $r_E \leqslant r_S < r_W$, such that South has absolute and comparative advantage in production, while East has comparative (and potentially absolute) advantage in innovation.

3.2 Production Technology

Western entrepreneurs incur sunk entry costs associated with setting up headquarters. They face ex-ante uncertainty about their production efficiency, and draw productivity $\varphi \in (0, \infty)$ from distribution $G(\varphi)$ upon entry. Firm operations entail fixed costs of headquarter services f^H that must be performed at home. However, production can be offshored, such that the marginal cost of manufacturing in country j is w_j/φ.

Upon observing their productivity draw, firms either exit immediately or commence production and potentially become multinational and/or innovate. Western firms face a trade-off when deciding whether to locate production at home or abroad: Setting up a foreign affiliate implies additional fixed costs f^{FDI} associated with plant equipment, local management, and remote monitoring by headquarters, but it may reduce variable costs if host-country production wages are lower or if there are profitable complementarities with innovation activities.

3.3 Innovation Technology

Western firms can choose whether, where, and how much to invest in two types of innovation: basic and applied. Each innovation activity can be performed by headquarters at home, in-house by a

foreign production affiliate, and/or at arm's length by a foreign unaffiliated party. Firms can choose to innovate in multiple locations at the same time, with innovation costs additively separable and innovation returns as specified below.[12]

Applied innovation increases profits today and forever. Applied innovation of quality $q_j^A \geqslant 0$ improves production efficiency and lowers marginal production costs to $w_j / \left(1 + q_j^A\right) \varphi$. This is qualitatively isomorphic to applied innovation enhancing product appeal and hence demand, for example by improving product quality, marketing competence, or packaging and delivery.

Basic innovation raises the probability of higher future profits. Given an exogenous death rate δ, the present discounted value of the future stream of profits for a firm with current profits $\pi(\varphi)$ is $\pi(\varphi)/\delta$. We conceptualize basic innovation as higher per-period profits or lower death rate, such that basic innovation of quality $q_j^B \geqslant 0$ boosts the present value of expected profits to $\left(1 + q_j^B\right) \pi(\varphi)/\delta$. This is a reduced-form way of introducing dynamic returns to basic innovation, for instance because basic innovation is a prerequisite for subsequent successful applied innovation.

These two types of innovation can be illustrated with an intuitive example: If a pharmaceutical company discovers a new chemical reaction today (basic innovation), this could improve its future chances of developing a more effective drug formulation or a more efficient production process (applied innovation).

Innovation costs increase with innovation quality, and depend on the location and organization of innovation activity. The cost of innovation of quality q in country j is $\mathbf{1}(q_j^{RD} > 0) r_j \left(f_{j,ORG}^{RD} + \frac{\left(q_j^{RD}\right)^\beta}{\beta} \right)$, where r_j is the innovator wage in j, $RD = \{B, A\}$ indicates the type of innovation (B =basic, A =applied), $ORG = \{I, O\}$ denotes whether innovation occurs within firm boundaries (I =in-house, O =outsource), and $\beta > 1$.[13]

We make three assumptions on the cost structure of innovation to build conceptual understanding. First, a Western multinational cannot perform in-house innovation abroad without having first set up a production affiliate. Formally, a firm must incur the fixed subsidiary costs f^{FDI} before that subsidiary can undertake any innovation, and when f^{FDI} is sufficiently high, it would never be optimal to establish pure innovation subsidiaries.

Second, the fixed cost of basic innovation is higher when it is conducted abroad, but is otherwise independent of the Western firm's organizational structure, $f_{W,I}^B = f_{W,O}^B < f_{E,I}^B = f_{E,O}^B = f_{S,I}^B = f_{S,O}^B$. This captures the idea that communication, monitoring and incentive provision requires more financial and managerial resources when headquarterts need to supervise basic innovation at a distance and outside the firm's home jurisdiction.

Finally, a Western firm likewise faces higher fixed costs of applied innovation when it is offshored, but lower fixed costs in any location when it is performed in-house and therefore co-located with

[12] In a richer framework, we have considered multi-product firms that draw firm-wide productivity and firm-product specific expertise. Multi-product firms can pursue applied process innovation to lower marginal production costs across all products and applied product innovation to lower product-specific fixed production costs. Our main theoretical results continue to hold, with more productive firms innovating more intensively and more frequently abroad across all innovation types.

[13] For tractability, we consider a static model that is qualitatively isomorphic to a dynamic model in which sunk innovation costs are captured by constant per-period amortized fixed costs.

production, $f^A_{W,I} < f^A_{E,I} = f^A_{S,I} < f^A_{W,O} < f^A_{E,O} = f^A_{S,O}$. This reflects the scope for synergies between owned-operated production and applied research that can arise from frequent interactions among production and sales managers with practical know-how, scientists with innovation talent, and technicians as two-way design and implementation liaisons.

To fix ideas, take the pharmaceutical example above. The assumptions on the innovation cost function mean that a stand-alone laboratory would be equally, if not better equipped to engineer new chemical reactions than a production unit, be it owned-operated or independent. By contrast, the R&D team at an owned-operated manufacturing facility would be best positioned to improve production methods (e.g. reduce gas dissipation) or product design (e.g. combo-vitamin pack), because it can benefit from the knowledge of site managers and easier implementation of test runs.

3.4 Firm Problem

Western firms face a multi-dimensional problem: they must choose the optimal location and scale of production, basic and applied innovation to maximize global profits. Optimal decisions are uniquely determined by productivity as the single dimension of firm heterogeneity. However, the model can in principle accommodate various patterns of MNC activity in different segments of the parameter space that govern countries' absolute and comparative advantage in production and innovation. Motivated by the stylized facts above, we make two simplifying assumptions in order to focus on the empirically relevant case and the novel mechanisms of interest. These assumptions yield considerable transparency and tractability with little loss of generality.

First, we abstract away from trade costs, such that all consumers have access to all varieties produced in the world. This implies that firms face the same global demand regardless of where they manufacture, captured by world aggregate expenditure R and a worldwide price index P.

Second, we posit that economies of scale in production are sufficiently strong (i.e. fixed FDI costs f^{FDI} are sufficiently high), such that firms find it optimal to concentrate manufacturing in one location and use it as a platform from which to serve all three markets. Moreover, production wages are sufficiently lower in South than in East to ensure that a Western multinational company would always be incentivized to establish its single foreign subsidiary in South. Given this organizational structure, the relevant consideration set of country-specific fixed innovation costs for a multinational headquartered in West would be $f^B_{W,O} < f^B_{E,O} = f^B_{S,I}$ for basic R&D and $f^A_{S,I} < f^A_{W,O} < f^A_{E,O}$ for applied R&D.

In this environment, a Western firm may choose to remain domestic and produce in-house at home. Such a firm may decide to innovate only in-house at home in W, only at arm's length abroad (in S and/or in E), or both. Alternatively, a Western firm may choose to become multinational and offshore production to an affiliate in S. This multinational may furthermore innovate only at home in W, only abroad (in-house at S and/or at arm's length in E), or both. In other words, firms' innovation strategy can span multiple locations and mix in-house and arm's length R&D. Of note, interdependencies between production and innovation can in principle make it profitable to offshore both, even if offshoring each activity alone might not be desirable.

Upon entry, a Western firm will determine its optimal production and innovation strategy in case it remained domestic and in case it established a foreign affiliate, and go multinational if the latter option is more profitable. With fixed FDI costs, firms above a certain productivity threshold would endogenously sort into multinational activity, consistent with the prior theoretical and empirical literature.

Given our interest in global MNC operations, we henceforth consider the profit maximization problem of a multinational company headquartered in West with a production affiliate in South and no subsidiary in East:

$$\begin{aligned}\max_{\mathbf{G}\equiv\left\{p,x,\left\{q_j^B,q_j^A\right\}\right\}} \pi(\varphi) &= \underbrace{\left(1+\sum_j q_j^B(\varphi)\right)\left(p(\varphi)\,x(\varphi)-\frac{x(\varphi)\,w_S}{\left(1+\sum_j q_j^A(\varphi)\right)\varphi}\right)}_{\widetilde{\pi}(\varphi)}- \\ &\quad \underbrace{-f^H-f^{FDI}-\sum_{RD}\sum_j \mathbf{1}\left[q_j^{RD}(\varphi)>0\right] r_j\left(f_{j,ORG}^{RD}+\frac{\left(q_j^{RD}(\varphi)\right)^\beta}{\beta}\right)}_{F(\varphi)} \\ \text{s.t.}\quad x(\varphi) &= RP^{\sigma-1}p(\varphi)^{-\sigma}.\end{aligned} \tag{1}$$

The MNC global strategy is characterized by the location of production (South in this context), output quantity x and price p, and the incidence and quality q_j^{RD} of each innovation activity RD in each location j. We denote this strategy as $\mathbf{G}\equiv\left\{p,x,\left\{q_j^B,q_j^A\right\}\right\}$. Note that innovation costs are additively separable across locations and innovation types. Innovation returns by contrast are not, because applied innovation additively reduces marginal production costs, while basic innovation additively increases variable profits $\widetilde{\pi}(\varphi)$.

3.4.1 Optimal Production Conditional on Innovation Strategy

The MNC problem (1) can be reduced to first determining the optimal production level and pricing conditional on an innovation strategy and then identifying the optimal innovation strategy. In particular, given $\left\{q_j^B,q_j^A\right\}$, the maximization problem is isomorphic to that of a firm with exogenously set overhead costs, marginal production costs, and actuarial profit factor. Under monopolistic competition and CES consumption preferences, firms therefore optimally charge a constant mark-up $1/\alpha$ above marginal cost and generate the following output quantity and sales revenues:

$$p\left(\varphi,\left\{q_j^B,q_j^A\right\}\right)=\frac{w_S}{\alpha\left(1+\sum_j q_j^A(\varphi)\right)\varphi}, \tag{2a}$$

$$x\left(\varphi,\left\{q_j^B,q_j^A\right\}\right)=RP^{\sigma-1}\alpha^{\sigma}w_S^{-\sigma}\left(1+\sum_j q_j^A(\varphi)\right)^{\sigma}\varphi^{\sigma}, \tag{2b}$$

$$r\left(\varphi,\left\{q_j^B,q_j^A\right\}\right)=R\left(P\alpha/w_S\right)^{\sigma-1}\left(1+\sum_j q_j^A(\varphi)\right)^{\sigma-1}\varphi^{\sigma-1}. \tag{2c}$$

Note that greater applied innovation directly enables firms to set lower prices and thereby earn higher sales and variable profits. By contrast, basic innovation does not directly affect production choices, but it may do so indirectly through the joint decision that the firm makes over both types of innovation. Note also that conditional on an innovation strategy, more productive firms as usual set lower prices and earn higher sales and profits. We will see below that this advantage gets amplified by the higher innovation intensity they endogenously choose.

3.4.2 Optimal Innovation Strategy

The global production and innovation strategy that maximizes MNC profits can be determined by incorporating the optimal production strategy conditional on innovation activity from equations (2a) and (2b) into equation (1) and solving for the optimal innovation strategy in the reduced firm problem:

$$\begin{aligned}\max_{\left\{q_j^B,q_j^A\right\}}\pi(\varphi) \;=\; & \underbrace{R\left(P\alpha/w_S\right)^{\sigma-1}\left(1+\sum_j q_j^B(\varphi)\right)\left(1+\sum_j q_j^A(\varphi)\right)^{\sigma-1}\varphi^{\sigma-1}/\sigma}_{\widetilde{\pi}(\varphi)}- \\ & \underbrace{-f^H-f^{FDI}-\sum_{RD}\sum_j \mathbf{1}\left[q_j^{RD}(\varphi)>0\right]r_j\left(f_j^{RD}+\frac{\left(q_j^{RD}(\varphi)\right)^{\beta}}{\beta}\right)}_{F(\varphi)}.\end{aligned} \tag{3}$$

The firm faces a complex choice set with respect to the global organization of its innovation activity. It can in principle choose to conduct each of basic and applied R&D in any subset of the three possible country locations and at varying intensity levels. The global innovation strategy can thus be characterized by a vector of 6 non-negative innovation quality levels, $\left\{q_W^B,q_E^B,q_S^B,q_W^A,q_E^A,q_S^A\right\}$, which are jointly determined by the following set of first-order conditions:

$$\partial\pi\left(\varphi\right)/\partial q_j^B = 0 \Longleftrightarrow R\left(P\alpha/w_S\right)^{\sigma-1}\left(1+\sum_j q_j^A(\varphi)\right)^{\sigma-1}\varphi^{\sigma-1}/\sigma = r_j\left(q_j^B(\varphi)\right)^{\beta-1},\ q_j^B(\varphi)\geqslant 0, \tag{4a}$$

$$\partial\pi\left(\varphi\right)/\partial q_j^A = 0 \Longleftrightarrow R\left(P\alpha/w_S\right)^{\sigma-1}\left(1+\sum_j q_j^B(\varphi)\right)\left(1+\sum_j q_j^A(\varphi)\right)^{\sigma-2}\varphi^{\sigma-1}\left(\sigma-1\right)/\sigma = r_j\left(q_j^A(\varphi)\right)^{\beta-1},$$
$$q_j^A(\varphi)\geqslant 0. \tag{4b}$$

Although there is no closed-form solution to equations (4a)-(4b), the optimal innovation strategy exhibits properties that inform the underlying economic mechanisms and allow us to derive comparative statics of interest.

A key feature of the firm problem is that innovation decisions will be interdependent across countries. Consider first applied innovation. From equation (4b), the optimal amount of applied innovation in any given location will depend on the global level of applied innovation. This arises because the returns to applied innovation accrue at the firm level, and manifest in lower marginal production costs regardless of where production takes place. Applied innovation will be complementary across locations if $\sigma > 2$ and $\partial^2\pi\left(\varphi\right)/\partial q_j^A\partial q_{j\prime}^A > 0$, substitutable across locations if $1 < \sigma < 2$ and $\partial^2\pi\left(\varphi\right)/\partial q_j^A\partial q_{j\prime}^A < 0$, and independent across locations in the knife-edge case of $\sigma = 2$ and $\partial^2\pi\left(\varphi\right)/\partial q_j^A\partial q_{j\prime}^A = 0$.

Equation (4b) also implies that applied innovation in any given location - and therefore also globally - will be complementary with the total and regional levels of basic innovation, $\partial^2\pi\left(\varphi\right)/\partial q_j^A\partial q_{j\prime}^B > 0$. This results from basic innovation amplifying variable profits, which rise whenever applied innovation lowers marginal production costs. This means, for example, that any shock that encourages a firm to undertake more basic innovation will induce it to also conduct more applied innovation, and vice versa.

Consider next basic innovation. From equation (4a), optimal basic innovation in any one location does not directly depend on basic innovation elsewhere. This occurs because expected profits increase linearly with firm-level global basic innovation. However, optimal local basic innovation rises with total applied innovation and its components, $\partial^2\pi\left(\varphi\right)/\partial q_j^B\partial q_{j\prime}^A > 0$, which are implicit functions of global basic innovation. This implies there will be complementarity in basic innovation intensity across locations, $\partial^2\pi\left(\varphi\right)/\partial q_j^B\partial q_{j\prime}^B > 0$.

Finally, how much basic and applied innovation a firm performs in a given country depends on local conditions and global levels of basic and of applied innovation, but not on the geographic and implicitly organizational (in-house vs. arm's length) composition of these global levels. In particular, while basic and applied innovation are complementary in raising production profits, they incur additively separable costs across locations and innovation types, i.e. $\partial^2 F\left(\varphi\right)/\partial q_j^A\partial q_{j\prime}^A = \partial^2 F\left(\varphi\right)/\partial q_j^B\partial q_{j\prime}^B = \partial^2 F\left(\varphi\right)/\partial q_j^A\partial q_{j\prime}^B = 0$. Since innovation costs depend on innovation wages r_j

and organizational structure, the optimal q_j^{RD} will therefore be a function of its type and location and of the total levels of applied and basic innovation, but not directly on the latter's location.

3.5 Theoretical Predictions

The integrated model of global production and innovation activity delivers rich predictions for the pattern of MNC operations. We focus here on the novel results for the optimal innovation strategy of multinational firms. These stem from the combination of firm heterogeneity in productivity and a rich structure of innovation costs and returns that depend on innovation location, integration and quality.

We consider first the incidence and intensity of innovation activity across firms:

Proposition 1 *More productive MNCs are more likely to innovate and innovate more intensively.*

More productive multinational companies will be incetivized to innovate more actively for two reasons. Along the intensive margin, firm profits are supermodular in productivity and innovation quality of either basic or applied type, $\partial^2 \pi(\varphi) / \partial \varphi \partial q_j^B > 0$ and $\partial^2 \pi(\varphi) / \partial \varphi \partial q_j^A > 0$. Intuitively, applied innovation directly amplifies the advantage of more productive firms via multiplicatively lower marginal production costs, while basic innovation multiplicatively augments variable profits. Along the extensive margin, innovation entails fixed costs that more productive firms can more easily amortize because they earn higher revenues and profits. These extensive and intensive margin patterns are true for each type of innovation activity, basic and applied. They hold for any given location and, aggregating across locations, also for innovation activity at the firm level.

We turn next to firms' optimal location and management of research and development:

Proposition 2 *More productive MNCs are more likely to offshore innovation and to innovate in more countries.*

More productive firms will be more likely to innovate abroad because of economies of scale in both production and innovation. Recall that profits are supermodular in productivity and innovation intensity, while innovation in any given location entails fixed costs. *Ceteris paribus*, there will thus be a minimum productivity cut-off $\varphi_{j,RD}^*$ above which innovation of type RD in country j becomes profitable. Since fixed costs abroad are higher than at home ($f_{W,O}^B < f_{E,O}^B = f_{S,I}^B$ for basic R&D and $f_{S,I}^A < f_{W,O}^A < f_{E,O}^A$ for applied R&D), this productivity threshold will tend to be higher for offshore innovation (except potentially for applied innovation at home in West vs. at the affiliate in South).

By the same logic, more productive MNCs will also be more likely to offshore innovation to more countries. Productivity cut-offs $\varphi_{j,RD}^*$ will generally vary across countries depending on local fixed innovation costs, local innovator wages, and model parameters that govern consumer demand and production and innovation technologies. More productive multinationals will clear the minimum threshold for more innovation locations, for at least one of the two types of R&D.

Recall that we consider the innovation strategy of multinationals headquartered in West that operate a subsidiary in South. If such a multinational opts to innovate in both East and South, it

would be conducting both in-house and arm's length innovation abroad. Proposition 2 thus implies the following corollary:

Corollary 1 *More productive MNCs are more likely to innovate both in locations with and in locations without a production affiliate.*

The model also speaks to the variation in MNC innovation activity across countries based on their comparative advantage in innovation:

Proposition 3 *An MNC is more likely to innovate and to innovate more intensively in countries with lower innovator wages.*

When deciding where to undertake innovation, firms find it advantageous to choose locations with lower innovator costs. Along the extensive margin, there is a maximum innovator wage r_j above which innovating is not profitable because of the fixed innovation costs. Along the intensive margin, firms optimally pursue higher-quality R&D in countries with lower r_j. This can be readily observed from the first order conditions (4a) and (4b). Consider equation (4a) for basic innovation. The left-hand side contains only variables at the firm level, including total basic innovation, while the right-hand side increases with both r_j and $q_j^B(\varphi)$. Hence $\partial q_j^B(\varphi)/\partial r_j < 0$. The analogous result for applied innovation, $\partial q_j^A(\varphi)/\partial r_j < 0$, follows from equation (4b).

Assuming that $r_E \leqslant r_S < r_W$, such that East has comparative (and potentially absolute) advantage in innovation, Proposition 3 suggests that innovation quality will be higher abroad than at home within a Western firm-innovation type. Moreover, Propositions 2 and 3 together imply that aggregating across firms within an innovation type, average innovation quality would be higher for foreign R&D than for domestic R&D.

While our baseline model considers an economy with a single manufacturing sector and a single innovation sector, the analysis can be extended to a world with multiple manufacturing sectors that map to multiple innovation sectors based on their relevant technological area. If innovator wages vary both across countries and sectors, Proposition 3 would imply that innovation activity responds to countries' comparative advantage in innovation across sectors:

Corollary 2 *An MNC is more likely to innovate and to innovate more intensively in a given sector in countries with lower innovator wages in that sector.*

Finally, the model has implications for the co-location of production and innovation activities, and thereby for the internalization of innovation activity abroad.

Proposition 4 *Applied innovation is more likely to be co-located with production than basic innovation.*

Innovation technology is such that there are synergies between applied innovation and production when performed in the same facility. In particular, the fixed costs of applied innovation are strictly

lower when it is co-located with production. All else constant, this implies that a multinational will be more likely to find it profitable to pursue applied R&D in countries where it also operates a manufacturing affiliate.[14]

4 Empirical Evidence

The theoretical framework above can rationalize the stylized facts documented in Section 2.2 for the global organization of MNC innovation activity. Through the lens of the model, MNCs have an incentive to perform R&D both at home and abroad, in order to increase current and/or future profits (*Fact 1*). Moreover, the variation in innovation activity across firms can be attributed to more productive MNCs choosing to innovate at greater intensity, which manifests in the data as both more patents and higher average patent quality as measured by patent citations (*Fact 3*).

The model further suggests that MNCs may offshore innovation to benefit from cross-country differences in innovator wages. They can furthermore choose whether or not to co-locate each type of foreign innovation with foreign production depending on the associated innovation costs and returns. The observed distribution of offshoring and co-location of innovation activity across multinationals can thus be attributed to heterogeneous firm productivity, combined with variation across innovation types within firms (*Fact 2*). For example, the least productive MNCs may opt to innovate only at home, while the most productive MNCs may undertake applied innovation in locations with an affiliate (where production wages are low and there are synergies with production) and basic innovation in locations without an affiliate (where innovator wages are low and synergies with production are irrelevant).

In this section, we show that the model's predictions find strong empirical support in the global operations of German multinationals that go beyond rationalizing *Facts 1-3*.

4.1 Estimation approach

We evaluate Propositions 1-4 and Corollaries 1-2 in the data by estimating variants of three empirical specifications at different levels of aggregation:

$$I_{ft} = \alpha + \beta\varphi_{ft} + \delta_s + \delta_t + \varepsilon_{ft}, \tag{5}$$

$$I_{fact} = \alpha + \beta\varphi_{ft} + \gamma_{RCA}RCA_{act} + \delta_a + \delta_c + \delta_t(+\delta_{fat}) + \varepsilon_{fact}, \tag{6}$$

$$I_{fpt} = \alpha + \beta\varphi_{ft} + \gamma_{RD}D_{RD=A} + \delta_a + \delta_t + \varepsilon_{fpt}. \tag{7}$$

In regression (5), the outcome variable I_{ft} reflects various aspects of innovation activity at the firm-year level ft, such as an indicator variable for any patent application, the (log) number of

[14] The cost synergies between applied innovation and production may also manifest in lower variable innovation costs, such that total applied innovation costs are $f^A_{j,ORG} + \mu^A_{j,ORG}\frac{\left(q_j^{RD}\right)^\beta}{\beta}$, where $f^A_{S,I} < f^A_{W,O} < f^A_{E,O}$ as in the baseline and $\mu^A_{S,I} < \mu^A_{W,O} = \mu^A_{E,O} = 1$. If so, both the incidence and the quality of applied innovation would be higher when co-located with production.

patents , or the (log) average number of citations across patents. The main variable of interest on the right-hand side, φ_{ft}, is a proxy for parent firm productivity. We condition on year fixed effects, δ_t, to absorb fluctuations in aggregate supply and demand conditions. For instance, δ_t would capture any changes in Germany in production and innovation wages, tax regime, or trade and investment promotion policies. We further account for observed and unobserved sector characteristics that may govern innovative activity with a full set of 23 sector fixed effects, δ_s, based on the primary industry of activity of each parent company in the 2-digit NACE 2.0 classification. These subsume, for example, cross-sector differences in factor intensities, technological scope for fragmenting or offshoring manufacturing, synergies between production and applied innovation, and the costs and returns to innovation more broadly. We conservatively cluster errors ε_{ft} by firm, to allow for correlated shocks within firms over time.

We follow common practice in the literature, and use (log) global firm sales as our baseline proxy for a multinational firm's productivity φ_{ft}. As in standard heterogeneous-firm models of international trade and investment, in our framework too global firm sales are monotonic in firm productivity. The main advantage of using this proxy is that it poses minimal data requirements and is not subject to potential estimation biases in constructing productivity from accounting statements. In the case of German MNC data from MiDi in particular, we do not have sufficient information to build TFP estimates.

Strictly speaking, innovation activity and total revenues are joint outcomes of the firm's profit maximization problem. We therefore interpret coefficient β as a conditional correlation consistent with the model's predictions, rather than the causal effect of productivity underlying it. We nevertheless demonstrate that the baseline results are robust to using alternative measures of firm productivity such as log sales per worker, which lends more credibility to the causal mechanisms in the model.

In regression (6), we unpack firm-level patent activity, and analyze instead outcomes I_{fact} that characterize firm f's innovation within technological area a in country c in time t. These include the (log) number of patents and (log) average number of patent citations generated. Given the sparsity in firm patent activity in the data, we consider 3 non-overlapping periods t (1999-2003, 2004-2008, 2009-2014), where the outcome variable aggregates up patent activity within the period of interest.We map each patent to one of 34 technology classes following Schmoch (2008), in order to assess the heterogeneity in comparable innovation activity across firms and countries within technology areas. In addition to parent firm productivity, φ_{ft}, we now also consider countries' revealed comparative advantage by technology class and year, RCA_{act}, as constructed below. Country fixed effects, δ_c, condition on the overall institutional and economic environment in a given country, to isolate the role specifically of differences in innovation conditions across technology classes within countries. Year and technology area fixed effects, δ_t and δ_a, in turn account for supply and demand factors analogously to year and sector fixed effects in regression (5). In more stringent versions of this estimating equation, we condition additionally on firm-technology area two-way fixed effects, which subsume firm productivity and δ_a. We continue to cluster errors ε_{fact} by firm.

To examine the model's predictions with respect to the variation in inventor wages across countries and technology classes, we construct a novel measure of countries' revealed comparative advantage, RCA_{act}, in terms of their capacity to enable patent-generating innovation. Specifically, we take the full set of DOCDB patent families in PATSTAT that contain at least one European, American or Asian (Chinese, Korean or Japenese) patent application; these constitute the 5 leading national patent authorities in the world in terms of patent numbers and citations. We assign each patent family to its inventor country and main technology area, and we define RCA_{act} as the number of patents generated in technology area a in country c in time t, as a percent share of all patents produced in that country and period. Scaling by the total number of patents ensures that RCA_{act} does not capture country size effects and also subsumes cross-country differences in absolute advantage in innovation. Given this definition of RCA_{act} and the inclusion of country and technology area fixed effects, specification (6) thus identifies how the innovation strategy of multinational firms responds to a country's comparative advantage in innovation in a given technology class, relative to other countries and technology classes.

Finally, in regression (7), we examine innovation outcomes I_{fpt} at the most granular level of individual patents, indexed by the firm-patent-year triplet fpt. These include the number of forward citations and indicators for innovation co-location with production.In addition to parent firm productivity, φ_{ft}, the main right-hand side variable of interest is a dummy for applied patents, $D_{RD=A}$, with basic patents the excluded category. Year and technology area fixed effects, δ_t and δ_a, control for exogenous variation in innovation conditions across time and technology areas. We once again cluster errors ε_{fpt} by firm, this time to accommodate correlated shocks to research and development operations across time and space within firms.

4.2 Innovation intensity

We first provide evidence that innovation activity varies systematically with total firm sales, in a way consistent with the prediction of Proposition 1 that more productive firms are more likely to innovate and to innovate more intensively. To examine the extensive margin, we estimate specification (5) in the full panel of German multinationals,where we set the outcome variable to an indicator for any patenting activity by firm f in year t. To evaluate the intensive margin, we then consider the log number of patents, the log number of total citations across all patents, and the average log number of citations across patents by firm-year.Conceptually, these two variables can be seen as proxying the quantity and quality of innovation, respectively, which are isomorphic and captured by q in the model.

We show in **Panel A of Table 3** that bigger MNCs pursue systematically more innovative activities. Column 1 first indicates that they have a significantly higher probability of holding any patents. We report results from a linear probability model, but the patterns are robust to using a probit specification instead. In Columns 2-4, we further observe that bigger MNCs own more patents that are cited more frequently on average and generate more total citations. All coefficient

estimates are highly statistically significant at the 1%.[15] The economic magnitudes are also sizeable: The estimates imply that doubling firm size is associated with 8% greater probability of patent-generating innovation, and, conditional on patenting, approximately 50% more patents and 2.4% more citations per patent, compared to baseline averages of ***%, *** and ***, respectively.

Panels B and C of Table 3 confirm that larger multinationals have superior innovative performance within each innovation type. In particular, we repeat the regression analysis in **Panel A** separately for basic and applied patent activity. Since not every innovating company owns patents of both types, the number of observations varies across specifications. We find that the probability of holding any patent is an order of magnitude more sensitive to firm size for basic than applied innovation. Conditional on some innovative activity, by contrast, both the frequency and the quality of patenting is equally elastic with respect to firm size across the two innovation types.

4.3 Innovation offshoring

We next establish that larger multinationals are more like to innovate abroad, to undertake innovation in more foreign countries, and to offshore a greater share of their total innovation activity, in line with Proposition 2. We first analyze whether a firm performs any patenting activity abroad, by estimating specification (5) in the full panel with an indicator variable for at least one patent with a foreign inventor as the outcome of interest. We present the results in **Panel A of Table 4**. Column 1 establishes that bigger MNCs are disproportionately more likely to hold patents developed abroad. Columns 2 and 3 provide consistent evidence for each type of innovation activity by redefining the outcome variable to be an indicator respectively for any basic or any applied foreign-invented patents. All estimates are highly statistically significant and comparable in magnitude across innovation types. A doubling of global sales is associated with approximately 20% greater probability of offshoring innovation of either type.

We then consider the intensive margin of offshored innovation. In **Panel B of Table 4**, we study the percent share of patents with a foreign inventor in the subsample of innovating multinationals, where we restrict the latter further to multinationals with basic or applied innovation abroad in the respective regressions by innovation type. Larger companies generate a bigger share of their patents in foreign locations. The average firm would relocate an additional 3.6% of its total patents abroad were its size to double, with an almost identical rise in the shares of basic and applied patents. Note that this result is not simply a reflection of larger multinationals innovating more both at home and abroad. Instead, it suggests that the geographic composition of innovation activity varies systematically with firm size.

Panel C of Table 4 confirms that larger MNCs offshore R&D to more foreign locations, by setting the outcome variable in equation (5) to the number of foreign inventor countries in a firm's patent portfolio. Odd columns in this table establish this result first for all patents and then sep-

[15] While our baseline sample includes only PATSTAT patents filed with the European patent office in order to have information on the applied vs. basic type of each patent, we have confirmed that similar results hold in the sample of all PATSTAT patents filed with any patent authority.

arately for basic and applied patents. A doubling of firm size corresponds to 1.6-1.8 more offshore innovation locations, relative to a sample average of ***.Even columns in this table expand the specification to include both global sales and the number of countries with production affiliates on the right-hand side. The coefficient on firm size falls by approximately 40% for basic ainnovation and approximately 50% for applied innovation, but remains highly significant. In other words, bigger multinationals pursue patent-generating R&D in more countries even controlling for their number of production locations. Moreover, multinationals that produce in more locations are also more likely to innovate in more locations, with a somewhat larger and statistically more significant elasticity for applied patents relative to basic patents. Through the lens of the model, these patterns are consistent with the presence of fixed innovation costs at the country level, along with synergies between innovation and production, especially for applied innovation.

Finally, we evaluate the implication of Corollary 1 that more productive multinationals are more likely to innovate in locations both with and without a production affiliate. **Panel A in Table 5** provides summary statistics for the variation in MNC firm size across 4 mutually exclusive categories of German multinationals. Consistent with **Table 4**, we observe that average firm size is lowest for MNCs with only domestic innovation. Average firm size rises monotonically as we move to MNCs that innovate both at home and in countries without a subsidiary, to MNCs that innovate both at home and in countries with a subsidiary, to MNCs that innovate at home and in foreign countries both with and without subsidiaries. Very similar patterns emerge in **Panels B and C of Table 5** where we replicate the analysis separately for basic and applied innovation.

4.4 Innovation comparative advantage

We next demonstrate that MNC innovation activity responds to cross-country differences in comparative advantage across technology classes, as per Proposition 3 and Corollary 2. In particular, within a given technology area, firms develop systematically more patents and generate more patent citations as a marker of innovation quality in countries with a strong revealed comparative advantage for innovation in that technology area.

We document this pattern in **Panel A of Table 6**, where we estimate specification (6) at the firm-technology area-country-year level, using the log number of patents as the outcome of interest. We find robust evidence that economies with stronger RCA_{act} in a given patent class attract significantly more innovation activity by foreign multinationals. Column 1 establishes this baseline result conditioning on a full set of country, technology area, and year fixed effects, such that the main coefficient of interest is identified from the variation in comparative advantage within a country across technology classes and within a class across countries.

Given earlier results that innovation incidence increases with firm size and may synergize with the presence of a production affiliate, we add in Columns 2-4 progressively more controls for firm size, the presence of an MNC affiliate in the same country, or firm-technology area two-way fixed effects. The latter estimation is particularly informative, as it identifies the role of revealed comparative advantage purely from the variation across countries, even accounting for potential heterogeneity

in innovation costs and returns across firms or across technologies within firms that is outside our theoretical framework. The estimated impact of RCA_{act} remains highly robust, and its magnitude is highest under the most stringent firm-technology area fixed effects. The other coefficient estimates are consistent with earlier findings.

We also consider the log total number of citations generated by all patents produced by a firm in a given technology class and location, as a more comprehensive measure of the quality-weighted extent of innovation activity. Columns 5-8 replicate the analysis for this metric. We consistently observe that revealed comparative advantage is a strong driver of the location of multinational firms' research and development. The estimates suggest that a doubling of RCA_{act} in a given location would attract 2% more of a firm's patents in a given technology area.

Finally, we distinguish between basic and applied patents in **Panel B of Table 6.** Repeating the analysis for citation weighted patent counts separately by innovation type produces similarly strong results for revealed comparative advantage for each activity. Of note, the coefficient estimate on the dummy for the presence of a production affiliate is higher for applied than for basic innovation. This is consistent with the presence of stronger synergies in co-locating applied innovation in close proximity to production activity and anticipates the next set of results.

4.5 Innovation co-location

We conclude by assessing multinationals' strategy with respect to co-locating foreign production and innovation activities in line with Proposition 4. We document that conditional on offshoring innovation, firms are systematically more likely to co-locate applied innovation with production than basic innovation. This is consistent with promixity to manufacturing experience being more synergistic with applied innovation, for example because it enables cheaper or more effective applied research.

We analyze co-location strategies at the patent level in **Table 7**. For each patent, we construct a binary variable equal to 1 if the patent belongs to a parent company with an active production affiliate in the country of invention. We use this indicator as the outcome of interest in estimating equation (7). In **Column 1**, we confirm that bigger multinationals are more likely to develop foreign patents in locations with a subsidiary, compared to smaller multinationals. This result is related to, but goes beyond the predictions of Proposition 2 and Corollary 1 that more productive firms are more likely to innovate in multiple locations, including countries with and without production affiliates. **Column 2** in turn demonstrates that applied patents are systematically more likely to be developed in countries with production affiliates, even conditioning on firm size.

5 Conclusion

Multinational companies play a central role in global value chains and frontier R&D. We provide one of the first integrated analyses of MNCs' global production and innovation strategy. We establish novel stylized facts using uniquely rich data on the network of production affiliates and patents

of German multinationals. We rationalize these facts with a heterogeneous-firm model in which companies jointly choose the location, scale and integration of manufacturing, basic innovation and applied innovation. Empirical evidence consistent with the model indicates that more productive MNCs innovate more intensively in terms of the number and quality of patents. Such companies also offshore more innovation to more countries, spanning both countries with and without a production affiliate. Finally, MNCs pursue innovation across countries and technology classes following countries' comparative advantage, with applied innovation more likely to be co-located with production than basic innovation.

Our findings open the door to various avenues for future research. Richer data on the inputs and outputs of innovation activities, such as data on both R&D investment and successful patenting, can provide a more holistic understanding of the factors governing MNC operations. Also of interest is the role of intellectual property rights protection and general contract enforcement for the location and integration of MNC production and innovation.

In turn, it is important to understand the implications of MNCs' globalized production and innovation for the design of trade and innovation policy. These implications will inform the scope for multilateral agreements, especially as developed and developing countries occupy different segments of global value chains and engage differently in technological innovation and adoption. For example, our work points to complementarity rather than substitutability in innovation activity across countries, which may alleviate concerns about the impact of offshoring innovation on sending economies. Likewise, MNC operations shape the impact of technological leaps such as automation on the global distribution of production, innovation and adoption, and thereby on economic growth across countries. Our work

6 References

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Table 1: Summary Statistics

Panel A. MNC production		
Sample: All German MNC		
	Firm-year level	
Variable	Mean	St. dev.
Number of affiliates	7	59.4
Number of foreign countries	3	6.3
Parent sales, mil. €	906	6,891.8
Affiliate sales, mil. €	233	3,128.7
Panel B. MNC production		
Sample: Innovating German MNC		
	Firm-year level	
Variable	Mean	St. dev.
Number of affiliates	10	76.8
Number of foreign countries	4	7.7
Parent sales, mil. €	1,215	8,260.4
Affiliate sales, mil. €	347	3,894.7
Panel C. MNC Innovation		
	Firm level	
Variable	Mean	St. dev.
Number of patents	66	588
Number of citations	141	1,258
Share basic	0.19	0.27
Share applied	0.81	0.27
Panel D. Patent quality and type		
Sample: EP Patents		
	Patent level	
Variable	Mean	St. dev.
Number citations, 5yrs. EP	2.1	4.6
	Percentage	
Basic	27 %	
Applied	73 %	

Notes: Summary statistics of German MNCs and their innovation activities. Data based on the link between ORBIS and PATSTAT. We cover approx. 4,400 German manufacturing companies, our of which roughly 2500 file at least one patent between 1999-2016.

Table 2: Geography of MNC Global Innovation

	All EP Patents			EP applied			EP basic		
Innovation location	N	Percentage	Share within offshore patents	N	Percentage	Share within offshore patents	N	Percentage	Share within offshore patents
Germany	154,007	82.50		115,204	84.80		38,802	76.36	
Offshore co-located	23,595	12.64	72.24	15,222	11.20	73.70	8,373	16.48	69.72
Offshore not co-located	9,069	4.86	27.76	5,432	4.00	26.30	3,537	7.16	30.28

Notes: This table presents the distribution of inventor locations of individual patents considered. We include all EP patents of the German MNCs and summarize their inventor locations across three dimensions: (1) patents with inventors located in Germany, (2) patents with inventors located in countries where affiliates are present and (3) patents with inventors located in countries where there are no production sites. Data source: ORBIS and Patstat.

Table 3: Innovation Intensity

Dependent variable	(1) any innovation (0/1)	(2) log # patents	(3) log # citation weighted patents	(4) avg log # citations
Panel A: EP patents				
Log global sales	0.039***	0.495***	0.490***	0.024***
	(0.002)	(0.027)	(0.033)	(0.004)
# MNC-years	68,999	9,545	6,180	9,545
Panel B: Basic patents				
Log global sales	0.101***	0.407***	0.404***	0.017*
	(0.006)	(0.037)	(0.047)	(0.007)
# MNC-years	9,007	3,986	2,543	3,986
Panel C: Applied patents				
Log global sales	0.019***	0.483***	0.475***	0.023***
	(0.003)	(0.028)	(0.034)	(0.004)
# MNC-years	9,007	8,217	5,227	8,217
Sector FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes

Notes: This table reports empirical results evaluating Proposition 1 (*More productive firms are more likely to innovate and to innovate more intensively*). Column 1 examines the extensive margin in the full panel of German multinational firms. The outcome variable is an indicator for any patenting activity within each firm - year combination. Columns 2-4 evaluate the intensive margin in the panel of patenting multinational firms. Outcome variables are the log number of patents, log number of citation weighted patents and the average log number of citations across patents by firm-year, respectively. Standard errors are clustered at firm level. Panels B and C present regression results repeating the same analysis by each innovation type. Stars denote * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 4: Innovation Offshoring

	EP patents		Basic patents		Applied patents	
	(1)	(2)	(3)	(4)	(5)	(6)
Panel A						
Dependent variable: Any offshore patent (0/1)						
Log global sales	0.115***		0.090***		0.106***	
	(0.005)		(0.009)		(0.006)	
# MNC-years	9,545		3,986		8,217	
Panel B						
Dependent variable: % offshore patents						
Log global sales	0.018***		0.017**		0.017***	
	(0.004)		(0.005)		(0.004)	
# MNC-years	9,545		3,986		8,217	
Panel C						
Dependent variable: # foreign inventor countries						
Log global sales	0.953***	0.522***	0.869***	0.510***	0.824***	0.401***
	(0.208)	(0.122)	(0.212)	(0.130)	(0.216)	(0.103)
# affiliate countries		0.094*		0.069+		0.088**
		(0.040)		(0.037)		(0.032)
# MNC-years	2,920	2,920	1,327	1,327	2,309	2,309
Sector FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes

Notes: Table 4 provides empirical results in line with Proposition 2 (*More productive MNCs are more likely to offshore innovation and to innovate in more countries*). Panel A examines the extensive margin in the sample of patenting MNCs: we analyze whether a firm generates any patents with at least one foreign inventor, either overall or separately within each innovation type. For brevity, we refer to patents with at least one foreign inventor as *offshore patents*. Panel B examines the intensive margin by studying the percent share of patents with a foreign inventor in the sample of patenting MNCs, conditioning on MNCs having at least one basic or applied patent in columns 3 and 5, respectively. Lastly, Panel C studies the number of foreign inventor countries in the panel of patenting MNCs, conditioning on MNCs having basic or applied patents in columns 3-4 and 5-6, respectively. At the firm x year level, we count the number of distinct foreign inventor countries related to all patents, basic patents and applied patents for each corresponding column. In columns 2, 4 and 6, we additionally control for the number of affiliate countries the MNCs are present in. Standard errors clustered at the firm level are presented in parentheses. Stars denote * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 5A: Multiple Innovation Locations

Log global sales	N	Mean	p10	p50	p90
Domestic only	4,599	18.7	17.3	18.6	20.6
Domestic & offshore not co-located	763	19.6	18.0	19.5	21.5
Domestic & offshore co-located	787	21.1	18.7	20.9	24.5
All locations	413	21.6	19.4	21.5	24.6

Table 5B: Multiple Innovation Locations - Basic Innovation

Log global sales	N	Mean	p10	p50	p90
Domestic only	767	19.3	17.4	19.1	21.5
Domestic & offshore not co-located	104	20.1	18.5	20.1	22.0
Domestic & offshore co-located	155	21.3	18.9	21.2	25.0
All locations	92	21.6	19.7	21.8	23.2

Table 5C: Multiple Innovation Locations - Applied Innovation

Log global sales	N	Mean	p10	p50	p90
Domestic only	2,612	18.8	17.4	18.6	20.5
Domestic & offshore not co-located	180	19.3	17.9	19.4	20.8
Domestic & offshore co-located	140	20.1	18.7	20.0	21.6
All locations	19	19.9	18.7	19.9	21.8

Notes: Summary statistics for the variation in firm size as measured by log global sales across MNCs. We consider four mutually exclusive categories for the MNCs: (1) those that invent only domestically,(2) those that invent domestically and in locations where production does not take place, (3) those that invest both domestically and in locations where production also takes place and (4) those that invent in all mentioned locations. Average firm size rises monotonically as we move across the different categories. Means are statistically significant from each other. Unit of observation: firm x year. All patents are included. Panels B and C replicate the analysis considering separately basic innovation and applied innovation, respectively. Data source: Orbis and Patstat.

Table 6: Innovation Comparative Advantage

Panel A: EP patents

Dependent variable	log # patents				log # citation weighted patents			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
RCA	0.015***	0.021***	0.017***	0.021***	0.020***	0.028***	0.020***	0.025**
	(0.004)	(0.005)	(0.004)	(0.006)	(0.005)	(0.007)	(0.005)	(0.008)
Log global sales		0.097***				0.130***		
		(0.021)				(0.020)		
Affiliate country = 1			0.393***	0.189***			0.404***	0.174*
			(0.069)	(0.047)			(0.088)	(0.070)
Observations	8,970	5,972	7,978	6,606	5,643	3,702	5,042	4,106

Panel B: Basic and applied patents

Dependent variable: log # citation weighted patents

	Basic patents				Applied patents			
RCA	0.017*	0.019*	0.017*	0.021*	0.018*	0.029**	0.018*	0.021*
	(0.007)	(0.009)	(0.008)	(0.010)	(0.007)	(0.010)	(0.007)	(0.009)
Log global sales		0.123***				0.111***		
		(0.020)				(0.020)		
Affiliate country = 1			0.288**	0.149+			0.353***	0.171*
			(0.099)	(0.086)			(0.088)	(0.084)
Observations	2,833	1,907	2,598	2,121	3,499	2,337	3,172	2,460
Tech area FE	Yes	Yes	Yes	No	Yes	Yes	Yes	No
Period FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Firm x tech area FE	No	No	No	Yes	No	No	No	Yes

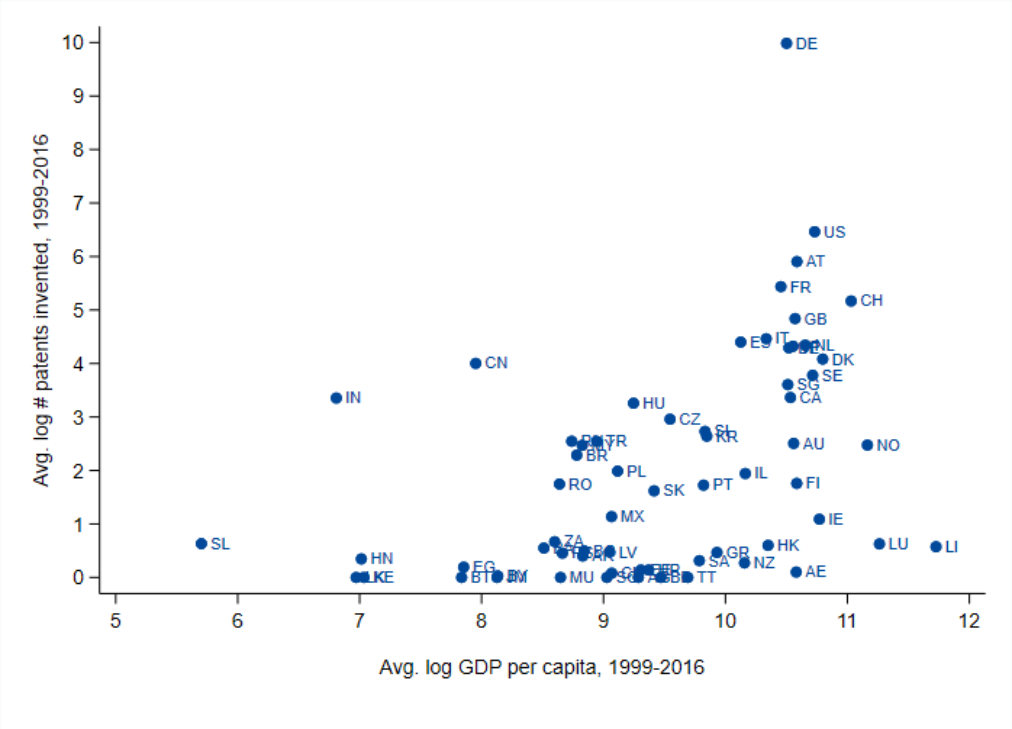
Notes: Unit of observation: firm x period x tech area x inventor country. For the current analysis, we aggregate the data into 3 time period of 5, 5 and 6 years respectively. We study how firms' patenting decisions respond to inventor countries' revealed comparative advantage in given technology areas. Panel A examines firm behavior with respect to the total number of EP patents it generates (col. 1-4), while also taking into account the quality dimension in col. 5-8 where patent counts are weighted by citations. Panel B presents results of the same analysis by innovation type. For brevity, we report the results using citation weighted patent counts as dependent variable. Standard errors are clustered at firm level. Stars denote * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 7: Innovation Co-location

	co-located offshore patent (0/1)	
	(1)	(2)
Log global sales	0.113***	0.113***
	(0.008)	(0.008)
Applied patent (0/1)		0.039**
		(0.015)
Tech. area FE	Yes	Yes
Year FE	Yes	Yes
# patents	22,172	21,997
# MNC	819	761

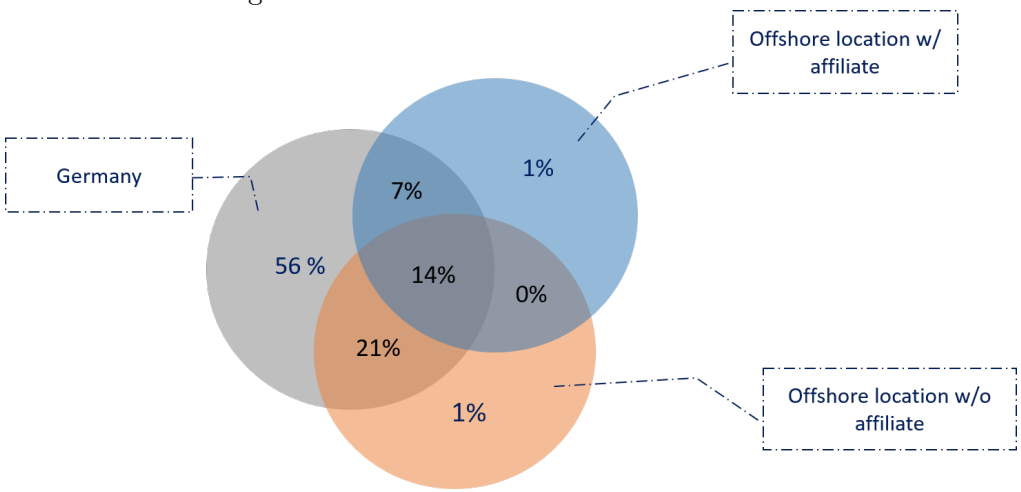
Notes: Table 7 assesses MNC's strategy regarding the integration of innovation activities they locate abroad. Firms choose between co-locating innovation activities with foreign production and offshoring innovation to locations where there are no production sites. We report results from evaluating Proposition 4 (*Applied innovation is more likely to be co-located with production than basic innovation*). In both columns, we study the integration strategies at patent level, considering only patents that have at least one foreign inventor. The outcome variable is a binary variable that takes value 1 for patents that were invented in countries where production also takes place. Column 1 indicates that larger multinationals are more likely to co-locate innovation with production relative to smaller multinationals. Column 2 provides evidence for Proposition 4, adding a 0/1 indicator for applied patents. Standard errors are clustered at the firm level and reported in parentheses. Symbols denote $^{+}$ $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Figure 1: Patenting and GDP per Capita Across MNC Invention Locations



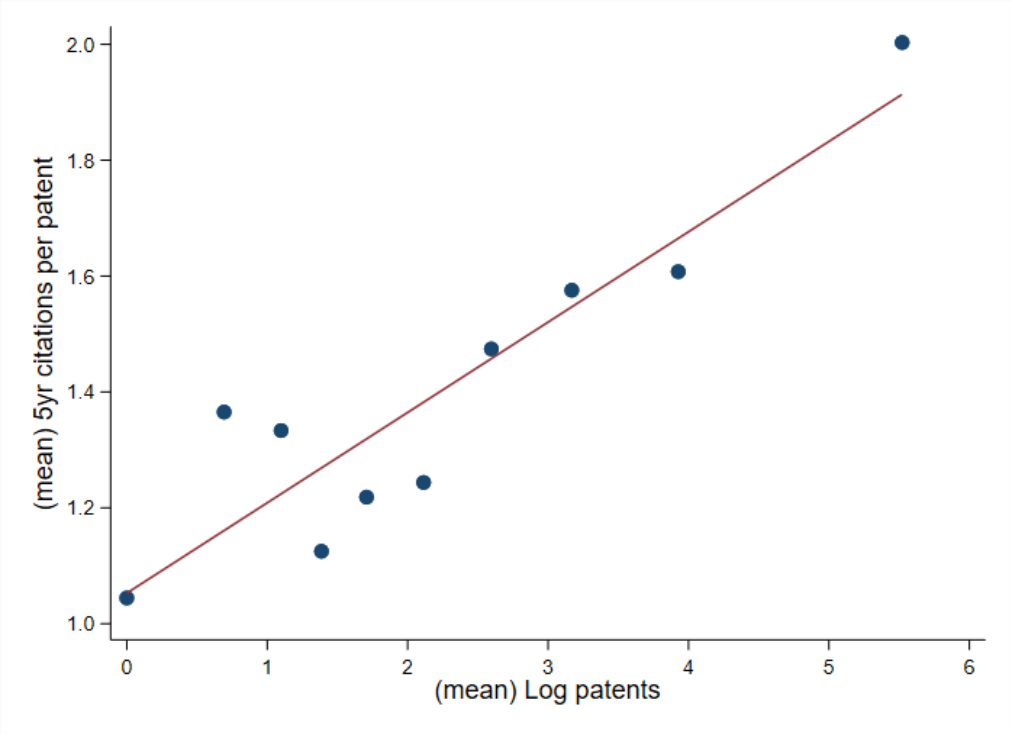
Notes: This figure plots the annual log number of German MNC-owned patents against inventor country GDP per capita, both averaged across 1999-2016. The sample comprises *** countries with at least 1 patent invented per year on average.

Figure 2: Location of Global MNC Innovation



Notes: This Venn diagram summarizes the global organization of German MNC patent activity in 1999-2016. Each segment indicates the share of firms that hold patents invented a given combination of locations: (1) at home in Germany, (2) offshore in a country with an MNC affiliate, and (3) offshore in a country with no MNC affiliate.

Figure 3: Innovation Intensity and Quality Across MNCs



Notes: This figure plots average patent quality against innovation intensity across German MNCs in 1999-2011. Firms are grouped into 10 bins along the horizontal axis based on their log number of patents. The vertical axis gives the average number of 5-year forward citations across all patents held by firms in a given bin.