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How does Internationalisation affect the productivity of R&D activities in large innovative firms? A conditional nonparametric investigation

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Abstract
This work explores the relationship between multinational R&D and innovation productivity among top corporate knowledge and R&D producers by adopting a twofold concept of internationalisation: (1) the firm's degree of R&D internationalisation, and (2) the firm's geographic diversification. We model the patent production process with an appropriate and robust conditional Data Envelopment Analysis (DEA) estimator, using a unique database of firms that matches financial indicators and patent information. Our results reinforce the fundamental role of internationalisation in the knowledge production process when the internationalisation process is properly and strategically managed. We interpret our empirical evidence through the theoretical lens of the learning theory of internationalisation, and we postulate that a high R&D intensity is a key driver to overcoming the challenges of internationalisation.

Keywords R&D productivity · Multinationality · Conditional efficiency · Patents · DEA modelling

JEL classification O32 · F23 · L25 · C44

1 Introduction

Firms in high-cost economies have increasingly globalised their activities and processes, including knowledge-intensive processes (Sidhu and Volberda, 2011). In this context, R&D activities of foreign affiliates was found as one of the most dynamic elements of the process of globalisation at the end of the 20th century (OECD, 2005; OECD, 2011; UNCTAD, 2005; Dachs et al., 2014; Dachs, 2017). R&D internationalisation aims at enhancing competence exploitation, competence creation among MNEs in advanced economy (Awate et al., 2015).

While emerging countries have received an increasing interest in the literature, the EU countries and the USA are still the main host destinations for relocalising internationally

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targeted R&D and the home regions of multinational firms. However, the R&D multinationality patterns are changing, and R&D internationalisation in lesser developed countries has become more widespread (Laurens, et al., 2015).

The multinational firms' R&D location decisions are complex and subject to several factors. Centrifugal and centripetal forces pulling R&D abroad compete. Multiplying R&D activities in different places and countries requires good technical absorbing capacity (Kafouros, 2020). Management capacities and organisational skills have to be fully optimised. As the firms need to align their R&D strategies with their overall strategy to succeed, we expect different models of multinational innovation to be effective. International R&D activities exhibit a high heterogeneity across countries, industries and firms.

The impact of R&D internationalisation on firm innovation capacities was usually estimated by measuring the change in R&D outputs, such as the change in the patents obtained, before and after internationalising firm R&D. Most studies found that internationalisation of R&D improved a firm's innovative activities (Ambos, 2005; Papanastassiou and Pearse, 2009; Wang et al., 2018; Belderbos et al., 2015; Hurtado-Torres et al., 2018) but some studies find negative effects (Belderbos, 2001). This lack of consensus drives the research question that we address with our empirical analysis.

Enhanced R&D productivity through internationalisation could be related to synergies and complementarities between home and host R&D units, as well as across foreign laboratories. When R&D productivity is the main objective of internationalisation across intensive R&D industries, multiplying geographically disperse R&D activities abroad can both enhance innovative capacity and increase R&D outputs (innovations). However, without an efficient managerial organisation of R&D, R&D redundancy across different units would decrease R&D productivity through inefficient use of resources.

Therefore, there exists a need for properly collected and analysed empirical evidence to assess the effect of the R&D multinationality on the relative productivity of a firm's inventive activities. Our contribution to the existing literature is focused on R&D productivity and differs from existing literature by conducting the analysis from a wider view of firm productivity. Our analysis is designed to quantify the R&D productivity benefits attributed to R&D relocation outside its home country. Our analysis utilizes firm level patent data to reflect the firm's innovative performance, and uses inventors' addresses to determine the R&D locations. We consider a relative valuation of patent costs across technologies by employing a technology-dependent weighted number of priority patents to proxy R&D outputs, and the R&D investments and workers as the inputs. Our analysis adopts a two-fold concept of internationalisation: the firm's degree of R&D internationalisation and the degree of its geographic diversification.

To empirically estimate the relationships described above, we follow the modeling approach of Badin et al. (2012) by applying a flexible and innovative nonparametric *conditional* Data Envelopment Analysis (DEA) method. This methodology does not require specifying a parametric assumption or an economic *a priori* relationship between the performance metrics and the variables of interest, in this case, the degree of R&D internationalisation. This approach avoids the conceptual pitfalls of previous empirical works, in particular, when determining in advance a (positive or negative) effect of internationalisation. Using a unique and comprehensive dataset, our analysis estimates the R&D efficiency as the distance of each firm's R&D productivity from the estimated best practice frontier.

The paper is organised as follows. Section 2 provides a literature review of existing works related to multinationality and a firm's performance, and lists our research questions. The modelling strategy is introduced in Sect. 3. Sections 4 and 5 each present, respectively, the data employed and the methodology applied to the data. The empirical results are reported in Sect. 6, where the patterns of the firm's R&D internationalisation are described. This section also presents our core results for the R&D efficiency-R&D multinationality relationship, as well as discusses the role of firm-related contextual elements used in analysing these results. Section 7 discusses the empirical results and Sect. 8 concludes.

2 Literature review and research questions

Over the last thirty years, local economies have become increasingly interconnected, and firms are now widely operating globally. As R&D Multinational Enterprises (MNEs) were taking advantage of their geographical diversification, the understanding of the firms' improved performance through internationalisation needs to be clarified (see Vrontis and Christofi, 2021, and Papanastassiou, et al., (2020).

2.1 Rationales and trade-offs in multinationality and firm's performance

Internationalisation of R&D efforts is not an unambiguous process, but the modelling approach of many previous studies has added to the degree of ambiguity surrounding the estimation of this relationship. The relationship between the multinationality of the firm (foreign market penetration or foreign production presence) and the firm's financial or operational performance has been modeled in many ways, including a strictly positive relationship, a U-shaped relationship, an inverted U-shaped relationship, or an S-shape relationship (Ruigrok and Wagner, 2003; Thomas and Eden, 2004). What is known is that R&D multinationality is mainly driven by the largest R&D investors. Indeed, 94% of the world's largest innovators now conduct R&D programs abroad in locations where their sales and manufacturing are growing fastest, and where they can access the optimal technical talent (Global Innovation 1000 study, 2015). Firms enhance their technological capabilities by gaining access to the spill overs of foreign localised knowledge (Kuemmerle, 1999). Adapting products to local foreign customers allows firms transfer internal knowledge assets to foreign markets to be exploited after adaptation (an "asset exploiting" or "home exploiting" strategy).

The effect of R&D multinationality on the firm's R&D innovation performance has been the subject of many empirical studies (Hsu et al., 2015; Singh, 2008; Lahiri, 2010; Chen et al., 2012; Rako, 2016). Most of them concluded that R&D multinationality was beneficial to firms, particularly from technology sourcing in the US (Griffith et al., 2006; Harhoff et al., 2014). Anon Higon and Manjon Antolin (2012) and Castellani et al. (2017) reach similar results but find that the relationship between internationalisation and performance is not always straightforward. For example, having a greater share of international subsidiaries was found to increase a firm's labour productivity, but spreading subsidiaries across many different countries it was found to decrease labour productivity. However, when examining whether R&D *intensity* enhances productivity, they found that the positive effect of multinationality on productivity was due to the complementary effect of both internationalisation

and geographical diversity on the firm's R&D intensity. Not all gains in firm R&D effectiveness were directly related to the degree of multinationality alone.

While technological knowledge can be a core asset, there are also incentives for the firms to keep a certain amount of R&D in the home country. This enables them to remain embedded in their national innovation system and prevents them from significant causing their own knowledge spill overs that might benefit multinational competitors. Moreover, coordinating a network of several R&D sites abroad can become expensive and problematic in the absence of the proper infrastructure (Belderbos et al., 2013).

The Global innovation study considers that large firms have improved in managing disseminated R&D. Being "simultaneously a knowledge seeker and arbitrageur of comparative advantages, skilled in contracting and managing alliances as well as in coordinating global supply chains and innovation networks", firms need to develop particular skills to offshore successfully (Contractor et al., 2010). The competencies rely on the capacities to optimise the degree of value chain disaggregation and to carefully select both the locations and the chronology. Optimising global R&D is thus quite challenging and requires a learning process to develop a "capability to outsource internationally" (Mol et al., 2004).

The learning process takes place when a firm starts to expand abroad or when a change of strategy occurs. Confronting liabilities of newness and foreignness, all firms need to learn how to operate optimally. As a result, an increase or a change in R&D multinationality can initially induce a productivity decline, followed by learning and adaptation that pushes the firms to enter into a phase of increasing productivity, at least up to a possible threshold (Chang and Wang, 2007; Steinberg, et al., 2017). Thus, the benefits of R&D multinationality also depend on the knowledge capability of the firm's home country. Belderbos et al. (2015) has shown that only when the knowledge the firms need is lacking in the home country, firms benefit from R&D carried out abroad. Otherwise, domestic R&D remains the primary source of productivity growth.

2.2 The role of geography in R&D internationalisation

The geographical patterns of multinationality play a key role. The dispersion of R&D units enables the firms to achieve proximal access to external knowledge pools in different countries, to access ideas from diverse contexts, and to facilitate knowledge recombination (Alonso-Martìnez, 2018). Beyond some point, however, the costs of utilising knowledge over geographically distributed R&D overrides the benefits of access to new knowledge sourced from different locations. Those firms distributing their R&D activity too widely tend to lower the quality of innovation (Athukorala and Kohpaiboon, 2010; Kafouros et al., 2008). Hurtado-Torres et al. (2018) show that the degree of R&D internationalisation and international geographic diversification increases the MNE's innovative output in the energy sector, but deteriorates the innovative performance at very high levels.

The performance effects of international expansion can differ depending upon the level of geographic diversification across foreign countries (Verbeke and Brugman, 2009). As specified by the extensive and in-depth review done by Papanastassiou (2020), what appears to be indeed new in more recent research, and which still needs further investigation, is the complementarity between internal and external networking. Thus, both the degree of internationalisation (internationalisation depth) and the geographic diversification (geodiversity or internationalisation breadth) should be analysed separately.

2.3 Relationship between R&D productivity and R&D internationalisation

The impact of R&D internationalisation on the firm innovative performance has been most often analysed in terms of innovation capacities for R&D outputs, such as the number of patents received by each firm (Awate and Mudambi, 2018; Cantwell and Noonan, 2002; Criscuolo et al., 2005; Dachs and Pyka, 2010; Picci, 2010; Huang and Li, 2019). Most studies have concluded that R&D internationalisation does improve innovation performance (Ambos, 2005; Papanastassiou and Pearse, 2009; Wang et al., 2018; Belderbos et al., 2015; Hurtado-Torres et al., 2018).

A subsection of this literature examines how the geographic dispersion of R&D units enable firms access to external knowledge and ideas in different countries, to capture any externalities in the areas of excellence and to facilitate knowledge recombination (Athukorala & Kohpaiboon, 2010; Cloodt et al., 2006). The degree of R&D internationalisation and the R&D geographic diversification increase the MNE's innovative output (measured by the number of patents for each billion of sales), but at the maximum level, the costs of utilising knowledge across increasingly distributed R&D may overrides the benefits and deteriorate innovative performance (Lahari, 2010; Hurtardos-Torres, 2018).

Yet, to our knowledge no study has ever evaluated the impact of R&D internationalisation on the degree of R&D productivity. Does the positive impact of R&D internationalisation on the innovative performance of a firm result from a gain of the R&D productivity? R&D productivity could be enhanced if R&D internationalisation induces a rationalisation of the R&D function production thanks to synergies, complementarities between home and host R&D units, access to more valuable internal or external knowledge. This could be expected when knowledge production is a key firm asset at the core of the R&D internationalisation in intensive R&D industries, particularly under home-based knowledge augmenting where technology exploiting strategies could produce incremental innovation at limited R&D cost.

However, multiplying delocated R&D activities without an efficient rationalisation can indeed enhance the innovative capacity while also decreasing the R&D productivity. This arises when a dilution of knowledge, R&D redundancy, lack of coordination or a low degree of managerial involvement or skills of the headquarters in R&D activities occurs (Mani et al., 2014; Beugelsdijk and Jindra, 2018). This could be the case when R&D activities are not an essential target in the R&D internationalisation under mergers and acquisitions occur in low tech industries.

Many other variables may moderate the relationship of the R&D internationalisation and R&D productivity. To succeed, companies must develop R&D strategies that are carefully aligned with overall strategy and are appropriate for the business environments in which they operate. Besides the high- and low-tech sectors, other characteristics like the firm R&D intensity, the size of the firm, and the characteristics of both home and host countries (market size, national innovation system) can also matter (Martinez-Roman, 2019).

Based on the above literature, we frame our work to analyse how the R&D productivity of the top actors of the R&D worldwide internationalisation (the North American firms and the European firms) with the largest R&D investments benefits from R&D relocation out of their home country[1]. We seek to pursue the following two research questions:

[1] Top R&D performers headquartered in Asian countries were discarded from this study because of the very low R&D internationalisation level of most of Asian firms. The overall R&D internationalisation level

Question 1 Does the pattern of the R&D internationalisation influence (either positively or negatively) the firm's R&D productivity?

Question 2 Can different trends among R&D actors be identified when analysing the relationship between R&D productivity and R&D multinationality?

3 Methodology

To answer our research questions, we implement a robust efficiency analysis using a nonparametric approach to estimate the impact of conditioning variables on the production process of firms. This analysis is based on a flexible nonparametric regression model suggested by Badin et al. (2012). The inventive activity of multinational firms is modeled within an Activity Analysis Framework, according to which a set of inputs, where $X \in \mathrm{R}_{+}^{\mathrm{p}}$ is used to produce a set of outputs $Y \in R_{+}^{q}$. $\mathrm{Z} \in \mathrm{R}^{d}$ represents the influencing variables that are neither inputs nor outputs, but may still affect the performance of the production process.

According to Cazals et al. (2002) and Daraio and Simar (2007), the set of technically feasible combinations of firms *(x, y)* (*unconditional production set)* is

$$\Psi = \left\{(x, y) \in R_{+}^{p+q} | xcanproducey\right\}$$

This can be characterised in a probabilistic way (Daraio and Simar, 2007). The unconditional (marginal) output-oriented Farrell–Debreu technical efficiency of a firm *(x, y)* is defined as:

$$\lambda\,(x, y) = sup\left\{\lambda\,|(x, \lambda y) \in \Psi\right\} = sup\{\lambda|\, S_{Y|X}\big(\,\lambda y\,|x) > 0\}$$

where $S_{Y|X}\,(y|\,x\,) Prob(\,Y \geq y|X \leq x)$ is the nonstandard conditional survival function of X given that $X \leq x$.

Daraio and Simar (2005) introduced the conditional output-oriented technical efficiency of a production plan$(x, y) \in \Psi^{z}$, where z is the conditioning factor and $\Psi^{Z} = \{(\mathrm{x}, \mathrm{y})\,, xcanproduceyfacingconditionz\}$ as:

$$\lambda\,(x, y|z) = \left\{sup\lambda\,|(x, \lambda y) \in \Psi^{z}\right\} = \sup\{\lambda|\, S_{Y|X,Z}\Big(\,\lambda y|x, z) > 0\}$$

where $S_{Y|X,Z}\,(y|\,\mathrm{x},\,\mathrm{z})$=Prob(Y $\geq$ y | X $\leq$ x, Z = z).

This is a measure of the performance that examines the maximum expansion of the outputs that is feasible for the firm, given the inputs it is using and the conditions it is facing.

Assuming that the truly attainable sets are convex, and firms can freely dispose of inputs and outputs, the DEA estimator of this conditional frontier can be written as (Daraio and Simar, 2007):

of Asian firms was 3.5% and it was below 1% for 60% of the Asian firms. Similar results were obtained in Laurens et al. 2015.

$$\Psi_{DEA}^{z} = \left\{ (x,y) \in R_{+}^{p} \times R_{+}^{q} | y \leq \sum_{j \in J(z)} \gamma_j y_j; x \geq \sum_{j \in J(z)} \gamma_j x_j; \gamma_j \geq 0 ? s.t. \sum_{j \in J(z)} \gamma_j = 1 \right\}$$

where $J(z) = (j = (i,v)| \, z - h_z < z_{i,v} < z + h_z)$; h_z are bandwidths of appropriate size selected by data-driven methods (see Badin et al. 2019).

The effect on the boundary can be detected, following Badin et al. (2012), by analysing the ratios between these conditional and unconditional efficiency measures, defined as follows:

$$R_O(x,y|z) = \frac{\lambda(x,y|z)}{\lambda(x,y)}$$

We herein refer to this ratio as the "DEA ratio". Our study aims to analyse the effects of the external factors (Z) on these ratios. We use nonparametric estimators of the efficiency scores and explore the effect of Z by looking at the behaviour of $R_O(x,y|z)$ as a function of Z (Fig. 1).

Examining the behaviour of the above ratios, we investigate if and how the environmental variables (in our case, z), the internationalisation level of inventive activities and the geodiversity of invention, all affect the inventive production process of the firm via its R&D efficiency production. According to Badin et al. (2012), if the ratios as a function of z show an increasing trend, this points to a *positive* effect of z on the production process. On the contrary, a decreasing trend of the ratios shows a *negative* effect of z on the production process. A *flat* trend displays no effect of z on the production process.

The flexible approach described above is meaningful and appropriate because we did not need to assume *a priori* a positive or negative effect of internationalisation on the R&D production process. Indeed, that is one of the main gaps of previous studies. Through this meth-

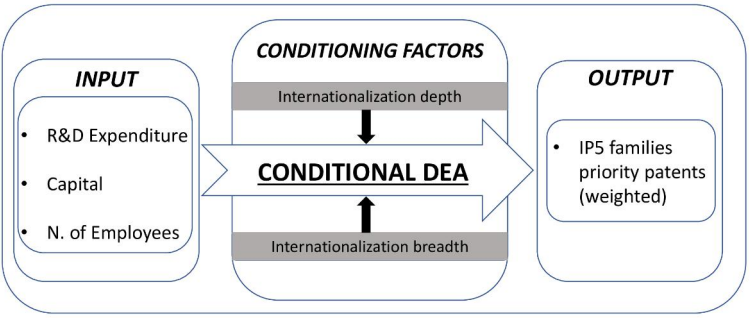

Fig. 1 An overview of the analysis carried out

odology, we can fill the gap in the literature by obtaining a global overview of the effect of our conditioning variables, the degree of internationalisation and geodiversity. The latter is among the most important variables for companies that carry out research and development.

4 Modeling strategy

Our model, displayed in Fig. 1, explores the inventive activity of large firms from North America and Europe. The model assesses, through an efficiency analysis[2], the effects of the level of internationalisation on the firm's R&D multinationality-productivity, studying the conditional and unconditional Data Envelopment Analysis scores.

This paper adopts an innovation production framework and considers the R&D knowledge generation activity in each multinational firm as a production process. This process includes observable measures as inputs (capital and labour), as well as an output (the results of the knowledge process). Following a well-established formulation, we define the conditional variables not as inputs or outputs, but something that can *condition* the innovation production process. Maintaining the input and output variables, as in the traditional production function models, we use the geographical diversity and the degree of internationalisation of patents as conditional variables (Table 1).

5 Data description

5.1 Analysed sample

The dataset consists of the technological activities and financial performance of 244 R&D-intensive firms. Of these firms, 126 are European firms, with 54% headquartered in large countries (Germany, France, United Kingdom, and Italy) and 46% located in small to medium size countries. The remaining 118 firms are in North America. All firms are listed in the European Industrial R&D Scoreboard (2008 edition). They all are also among the top R&D-intensive firms worldwide, represent a very wide selection of industries, and exhibit sustained inventive activities, i.e., they applied at least three transnational priority patents (patents applied in different countries) every year from 1997 to 2006. The firm patent appli-

Table 1 Model of the production of inventions

Variable	Measures
Inputs	R&D expenditures Capital Number of Employees
Output	Weighted number of IP5 family priority patents
Conditional factors	Geographical diversity Level of internationalisation of patents

[2] We measure the performance in terms of efficiency, i.e., a measure of the distance from the best practice-benchmarking frontier in terms of output/input usage. Productivity and efficiency are often used as a synonym. We will use both terms to qualify the same measure of performance.

cations were identified by matching names of firms and their subsidiaries with the name of patent applicants in the Patstat database[3].

The US and European firms show different sectoral distributions. North American firms are more oriented towards Telecommunications and Technologies and are more focused on Industrials (including "Industrial goods and services" and "Construction and materials") than their counterparts in Europe (Table 2).

5.2 Data description

Data and indicators are aggregated at the firm's perimeter level and include the parent company and its subsidiaries. The input variable Labour is represented by the number of workers, while R&D expenditure and Total Capital have been used as a proxy for the Capital variable. In line with existing literature (Penner-Hahn and Shaver, 2005; Hsu et al., 2015), we proxy the innovative output of the firms by counting priority patent applications (weighting their number according to the technologies they cover).

Of course, not all the R&D activities of the firm produce protected inventions, but patent rights are close to inventions and major inventions are often patented (Van Pottelsberghe et al., 2001). To give information on the inventive production of firms providing a patent quality threshold, we count the IP5 family priority patents, i.e., the priority patents extended at least in one foreign office and whose Inpadoc family contains one patent application in an IP5 office (EPO, USPTO, JPO, CNIPA, KINO). Similar indicators were used in many studies to proxy for the level of innovative activities (de Rassenfosse et al., 2013; Rako, 2016; Squicciarini et al., 2015).

However, the issue of the heterogeneity across industry sectors must be addressed, particularly concerning the costs of patents in firms covering different technologies. In this light, we assign a weight factor to patents. Recent studies have estimated the R&D investments per patent in different sectors and showed that the cost per patent varies greatly (Gkotsis and Vezanni, 2019; Neuhäusler et al., 2017). As the average costs in Gkotsis's study were calculated on a set of firms very similar to ours, we use them to calculate the output of our production process. We are aware that such a weighted count of patents by technology field remains a coarse measure. The *R&D output* of a firm is defined as a weighted volume of its patents applied during the period of time t per millions invested in R&D during the three

Table 2 The distribution of firms by industrial sectors

Industrial sector (ICB industry)	Europe	Northern America	Total
Basic Materials, Oil & Gas	22	18	40
Industrials	51	32	83
Consumer Goods & Services	27	21	48
Health Care	13	14	27
Technology and Telecommunications	13	33	46
Total	**126**	**118**	**244**

[3] See the details of the database construction in Laurens et al. (2015).

previous years. We rely on the average value of the R&D investments per patent calculated by Gkotsis et al. (2019) for the 35 technological fields (WIPO classification), and the R&D efficiency for firm j is:

$R\&D\ productivity_j = \sum_{i,j} (A_i \times N_i)_{\text{ in 2005–2006}} / R\&D\ expenditures_{\text{ in 2002–2004}}$.

where A_i is the average cost of a patent in the technological field i, and N_i is the fractional counting of the number of IP5 family priority patents of firm j in the technological field i.

The two *conditional* variables describing the multinationality of the firm's inventions are: (a) the *internationalisation degree*, which is calculated using fractional counting to determine the share of patents invented outside the firm's home country, and (b) the *geographical diversity index*, which is calculated using the inventors' country to proxy the

Table 3 The description of the variables used in the analysis

Variable	Definition	Source
R&D expenditure	R&D expenditure (only investments funded by, and performed for, the companies themselves) (2002–2004)	Industrial R&D Investment Scoreboard
Capital	The total amount of capital (2002–2004)	Orbis Database
Employees	The total number of employees (2002–2004)	Industrial R&D Investment Scoreboard
IP5 family priority patents	The total number of priority transnational patents applied for which the extended family includes a patent filed in one of the IP5 offices (2005–2006)	CIB Database
Internationalisation degree	The share of IP5 family patents with inventors, who are located outside of the firm's headquarters (fractional counting) (2005–2006)	CIB Database
Geographical diversity	Invention's geographical diversity at the country level (1-Herfindhal Index on inventors' countries) (2005–2006)	CIB Database

Table 4 Summary statistics

Variables	Mean	Std. Err.
Employees (avg)	51 263	4 595
R&D expenditures (avg) (M€)	556	67
Capital (avg) (M€)	16 354	37 100
The number of IP5 family patents (unweighted) (avg)	91	12
The number of IP5 family patents (weighted) (avg)	289	39
The level of internationalisation of inventions (avg)	0.27	0.0225
- Northern America:	0.38	0.0283
- Europe:		
The geodiversity of inventions (avg)	0.34	0.0182
- Northern America:	0.41	0.0219
- Europe:		

invention's location. We calculate the geodiversity as (1 - Herfindhal Index value of the inventors' country) to obtain an increasing measure of internationalisation in depth. Table 3 summarises the definition and the sources of the data.

These variables were standardised and log-transformed, and the summary statistics are presented in Table 4.

Generally, European and North American firms do not show statistically significant differences, but European firms are more multinational in their inventive activities than US firms (Table 4).

6 Results

In this section, we characterise both the European and the North American firms, contrasting the level of internationalisation and geodiversity of their inventions. Then, we present how the multinationality variables (internationalisation depth and breadth) influence the firms' R&D efficiency. The effects of the R&D multinationality on the R&D efficiency are not identical in all firms. Furthermore, a group of outperforming firms differs from the remainder of the sample, as they are not affected by internationalisation. We end by establishing the main characteristics, i.e., firms' internal factors, of this latter outperforming group.

6.1 The multinationality of the inventive activities

The R&D activities are more multinational in European companies than in the North American ones, both in terms of the internationalisation depth and the internationalisation breadth: the level of internationalisation of EU firms (mean: 38,4%) is 11 points higher than the level of internationalisation of the North American firms (mean: 27,4%), and the geodiversity of the former (0.41) exceeds the diversity of the latter (0.34).

The internationalisation of European firms highlights very different patterns. Half of the EU firms have a level of R&D internationalisation below 28% (10 points below the mean value), but one-third of the EU firms are very internationalised and carry out more than half of their inventions outside their home country. In North America, the median and mean values are closer (respectively 22% and 27%). There is also a small group of very internationalised companies: 13% of North American firms have an internationalisation level above 50% (with a few outliers whose internationalisation levels are above 80%[4]).

Europe is by far the first destination of the internationalisation: European firms internationalise 27.2% of their inventions in European countries and North American firms internationalise 25.2% of them in Europe[5]. The attraction of European countries as a foreign location for R&D activities has already been described as a major trend of the early 2000s (Laurens et al., 2015). The overall relationship between the level of internationalisation and the geodiversity of inventions for European and North American firms follows a global inverted U-shape[6] (Fig. 2).

[4] They are discarded from further analysis.

[5] By contrast, the European firms and the North American companies internationalise respectively 9% and 2.2% of their inventions in North America and 2.2% and 3.3% in Asia.

[6] R-squared=0.8823.

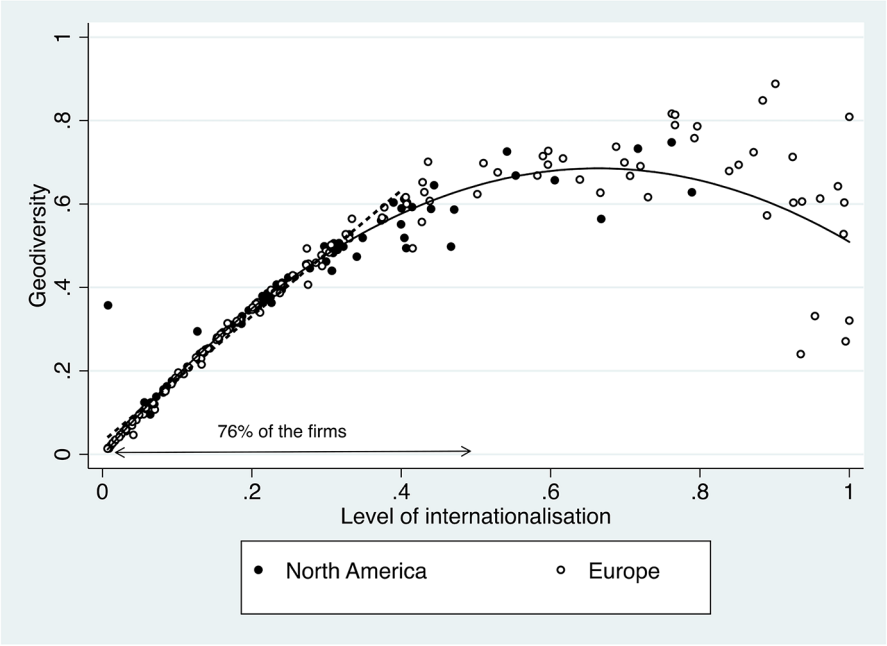

Fig. 2 The evolution of the geographical diversity of inventors' location with the degree of internationalisation

In a core set of firms, the majority, the level of internationalisation remains below 50%, and the internationalisation level and the geodiversity are linearly correlated. These firms rely first on national R&D facilities to develop new technological knowledge. When internationalising R&D activities, they simultaneously extend their internationalisation depth and breadth in order to access new competencies and/or new markets in a larger set of countries. This holds true for EU and US firms.

When the level of R&D carried out abroad dominates, a larger internationalisation depth is not always correlated with a wider internationalisation breadth. Most of the companies that carry out their R&D abroad, do it only where their markets are located, i.e., in a limited number of countries. Structural reasons and organisational modes can also explain this situation, such as the merging with foreign R&D entities, the acquisition of foreign R&D facilities, or the relocation of administrative units following financial incentives. Still, a few European firms do not comply with this mainstream mode of high level but low geodiversity R&D internationalisation. Their home countries (Northern European countries or Benelux) do not provide a large enough home market. Thus, they need to look beyond their domestic frontiers and become more globalised to generate growth.

Using the theory of organisational learning, we interpret the above results in terms of learning phases in the process of R&D internationalisation (Ruigrok and Wagner, 2003, Mani et al., 2014). According to such a scheme, a firm starts to internationalise R&D by increasing both the internationalisation depth and breadth. However, as internationalisation is costly and requires managerial skills to benefit from foreign R&D, a firm gaining in

maturity in its internationalisation development will optimise its R&D internationalisation. Different strategies could emerge depending upon the firms' own goals and strategies. This is why the mature firms could show diverging strategies and customised internationalisation scenarios.

6.2 The effects of the multinationality on the firm's R&D efficiency

From this empirical analysis, we can gain insight into the dynamics of internationalisation effect on the production process, via investigating the ratios of conditional and unconditional efficiency measures for full frontier. The full frontier ratios with respect to the geodiversity and the internationalisation depth are shown respectively in Figs. 3 and 4. The results show a heterogeneous behaviour of the analysed firms. The overall trend (dashed line) shows a slight and constant decreasing trend of the DEA ratios with respect to geodiversity (Fig. 3). This means that the R&D efficiency is weakly negatively affected by the geodiversity degree. This holds true on the whole range of internationalisation levels and applies to 87% of the North American firms and 80% of the European firms[7].

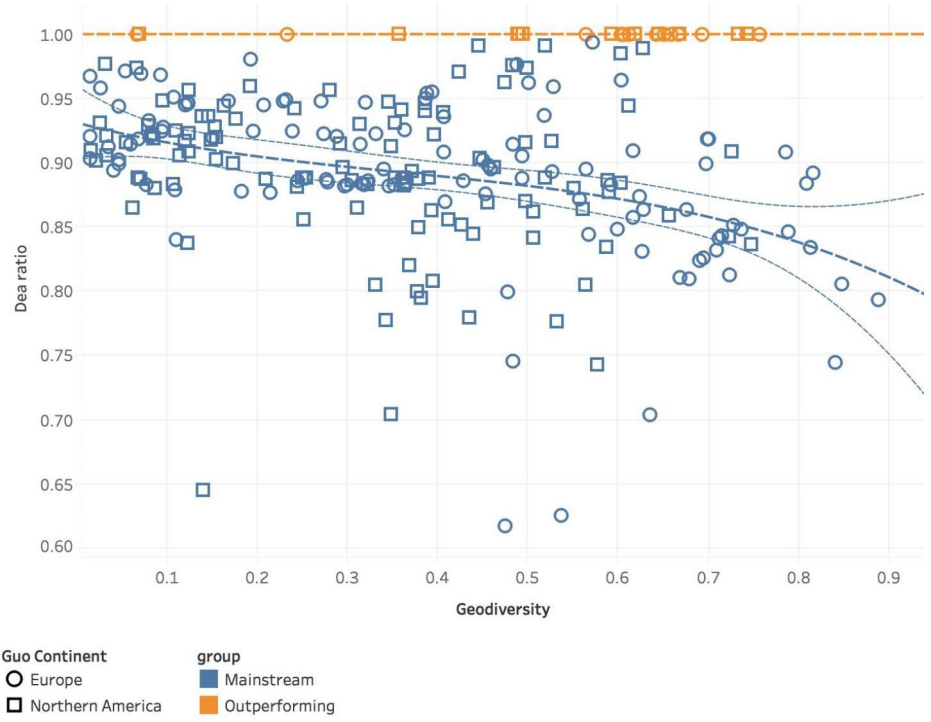

Fig. 3 The evolution of the DEA ratios with the geodiversity

[7] A few very iinternationalised European firms diverge from the main trend: increasing the level of R&D internationalisation increases their DEA ratios.

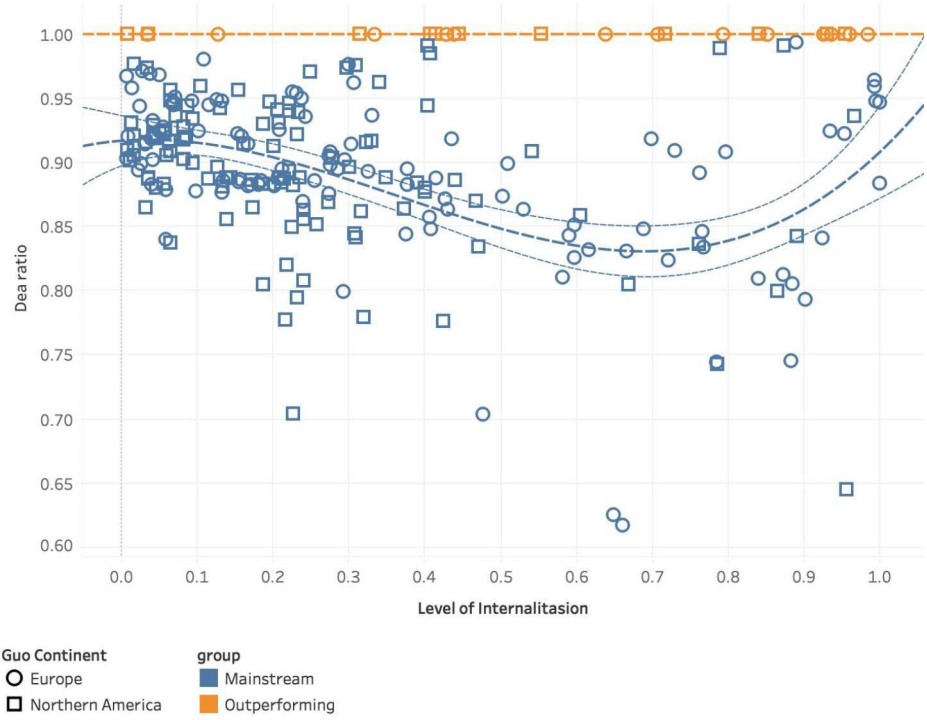

Fig. 4 The evolution of the DEA ratios with the level of internationalisation

Focusing now our attention on Fig. 4, we see a different situation. First, a nonlinear relationship is evident, implying that the nonparametric approach is appropriate for our analysis. Second, there is again a negative effect of the conditional variable (in this case, the internationalisation of patent) until the value of internationalisation level equals 0.6. A positive trend emerges after this point. In general, the graph displays a U-shaped relationship. Interestingly, the level of internationalisation at 0.6 is the same "changing point" as appears in Fig. 2. This implies that a threshold exists, beyond which the companies have specialised their internationalisation strategy. Before this turning point, however, the strategy is common across firms, where both indicators of internationalisation appear to grow constantly, as already mentioned.

The combined analysis of these three graphs (Figs. 2 and 3, and 4) reveals two clear implications: (1) the internationalisation follows a path of growth in both dimensions considered in the analysis (geodiversity and patent internationalisation), and (2) this effort is detrimental for R&D efficiency. Starting from the turning point around the level of internationalisation equal to 0.6 (and geodiversity also equal to 0.6), each company chooses its own mix between geodiversity and patent internationalisation. From this point, we can see a clearly positive effect of this last conditioning variable on R&D efficiency. These trends are similarly evidenced on both sides of the Atlantic in the shared range of internationalisation level (0 – 80%).

6.3 Characteristics of the two groups of outperforming and mainstream firms

Next to this strong trend, a small group of 28 outperforming firms (40% are Northern American firms, 37% originate from small or medium-sized European countries, and the other firms are from Germany or the United Kingdom) appear to behave differently. They exhibit a DEA ratio equal to unity. Neither the internationalisation depth nor the geodiversity affects their R&D efficiency.

In this subsection, we aim to characterise these two groups of firms to find empirical evidence that could help us to explain why a group of firms is not affected by R&D multinationality. We analyse whether the internal features of outperforming firms differ from those of the mainstream group. Singling out these outperforming firms from the mainstream firms on a level of internationalisation-geodiversity plot (Fig. 5) did not permit us to identify a range of levels of internationalisation or geodiversity where such high performing firms are clustered. However, the average internationalisation depth and breadth were significantly higher in this group of outperforming firms (respectively equal to 0.59 and 0.54 in the outperforming group and respectively equal to 0.34 and 0.29 in the mainstream group)[8].

From a geographical perspective, the continent of the firm's headquarters is not a variable that determines if a firm is mainstream or outperforming. The share of North American

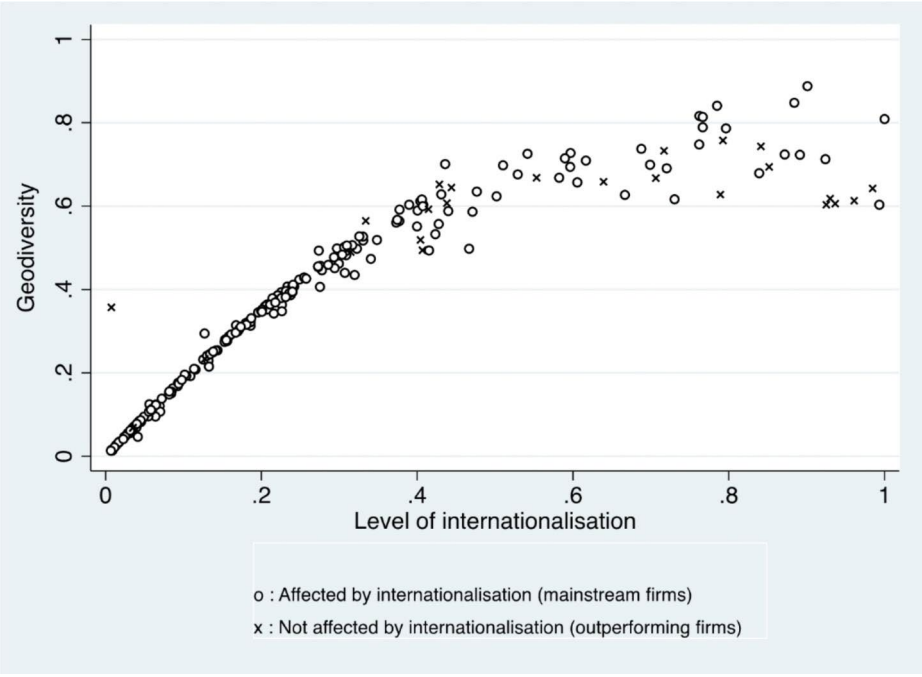

Fig. 5 The identification of outperforming and mainstream firms with respect to the R&D internationalisation depth and breadth

[8] P-values = 0.000 (Kolmogorov Smirnov test).

firms is not significantly different in the outperforming group compared to the mainstream group (42% versus 48%).

It seems that the firm's industrial sector and the size of the firm's home market are factors that discriminate between the two groups. The outperforming firms are more often active in the sector of 'Software and computer service.' In Europe, the outperforming firms are more often headquartered in small or medium-sized European countries, where the reduced dimension of the home market encourages these firms to extend their activities beyond national borders.

The R&D multinationality is, on average, higher in the outperforming group (both in internalisation depth and breadth as shown in Fig. 5), but the internationalisation depth is quite heterogeneous among the outperforming firms (mean = 0.59; standard error = 0.059). This shows that there is a variety of cases, where modulating the R&D multinationality to an overall business strategic scheme does not deteriorate the R&D productivity.

These results imply that the level of R&D intensity, calculated by the total amount of R&D expenditure on the number of employees devoted to R&D activities, is a key parameter to determine the behaviour of the firm in its internationalisation process. It is only when reaching a certain level of R&D intensity that firms can overcome the uncertainty inherent to R&D globalisation.

Due to innovation in products and production processes, the R&D intensity contributes to improving, first from an operational point of view, the firm's global performance. Indeed, R&D intensity positively affects the firm's labour productivity (Kotabe et al., 2002; Castellani et al., 2017). However, how the operational performance gains are distributed along the chain value is still under study. Our results support this theory: with such high investments dedicated to R&D activities (as seen in Table 5), the outperforming firms surpass the group of mainstream firms when dealing with variables related to the firm's R&D productivity (as measured by the weighted IP5 family patent/R&D ratio), allowing them overcome the uncertainty of internationalisation. Indeed, the latter does not affect the production process of the outperforming firms' group.

Our overall findings can now be summarised. By and large, in the mid-2000s, the large, western R&D corporate producers still relied to a large extent on national R&D skills, and their R&D efficiency did *not* benefit from R&D multinationality. This is true for a small to medium level of internationalisation. Starting from a medium-high level of internationalisation of patents (equal to 0.6), we see a positive effect of multinationality on R&D efficiency.

There are companies whose efficiency is not affected by internationalisation. In these outperforming firms, both the R&D intensity and the R&D production are above the sample average. These firms strongly rely on foreign R&D to produce inventions, and their R&D efficiency does not suffer from the costs of internationalisation. Often located in small countries, such firms had to expand their markets internationally. Being smaller than

Table 5 The characteristics of firms that differ in the mainstream group and the outperforming group

Variables	Mainstream firms	Outperforming firms	Kolmogorov Smirnov test (p value)
Weighted IP5 family patents/R&D	0.76	1.22	0.002
R&D intensity	12.3	20.5	0.000

the mainstream firms, these outperforming firms can be seen as more mobile and more agile, increasing their capacity to adapt to new international opportunities. These firms are characterised by a high level of R&D intensity, which seems to cushion the turbulence of internationalisation.

7 Discussion

We frame our work within the literature concerning broad Multinationality-Performance relationships. This literature has explored this well-known relationship with often conflicting and contradictory results, in great part mediated by R&D intensity. This means that the more important the R&D is for the future of the firm, the more important will be the role of the R&D internationalisation in its two critical dimensions: enlarged access to knowledge resources ('home expanding' strategies) and product adaptation to key markets ('home exploitation' strategies). R&D remains manpower-intensive and global value chains are becoming increasingly fragmented. The implication is that the performance of R&D production is becoming an increasingly important influence over the firm's strategic management efforts. This creates a growing interest in the productivity of R&D itself.

Our analysis confirms that most firms in both the US and European are engaged in R&D internationalisation. While EU firms are, on average, more internationalised (particularly when located in small EU countries and seeking expansion into external markets), they may well be currently engaged in a learning phase that negatively impacts their R&D performance. For the average firm, most R&D activities are conducted at home. The depth and breadth of the R&D internationalisation are strongly correlated, and both play a similarly part in the deterioration of R&D performance.

Such empirical results can be interpreted through the lens of prior, conceptual works revealing how the management of internationalised R&D bears both network and governance costs, requiring firms to undergo a learning process (Chen et al., 2015; Singh, 2008; Gammeltoft, 2006). This means that R&D productivity deteriorates until internationalisation becomes rooted within the firm. Both US and EU firms suffer from R&D internationalisation. Considering that European firms do massively internationalise R&D in Europe (the location for about ¾ of their internationalised inventions), it is not necessarily easier for European firms to internationalise R&D in nearby countries in Europe than it is for a US firm to internationalise overseas in Europe.

At higher levels of internationalisation, the R&D efficiency frontier sees diverging evolutions. Though the negative trend in the geodiversity degree within the inventors' country remains, we still witness European firms showing a reversal of this negative trend among firms with high levels of internationalisation. Looking at such highly internationalised European firms, we have anecdotal evidence that there is a connection between the relative size of their markets (Martìnez-Romàn et al. 2019) and the respective roles of the countries where their R&D internationalisation is carried out, with a combination of home expanding and home exploiting rationales (Laurens et al., 2015).

Lastly, the analysis has also shown that a subgroup of mature internationalised firms did not witness a change in their efficiency arising from R&D internationalisation. These 'outperforming' firms are not gathered in the expected quadrant of both high depth and high

breadth. On the contrary, they display a rather high level of geodiversity and cover a broad range of levels of internationalisation.

Overall, our results raise several questions for future developments in research efforts. First, we show that internationalisation of R&D activities satisfies strategic goals, whether a firm is looking for complementary knowledge resources or trying to adapt products to new geographical markets, and this remains true despite a loss of productivity of overall R&D activities. Is that observed deterioration in productivity a lasting feature, when compared to R&D centralised in the 'home' country of multinational firms? It does not seem so, as we observe that nearly one quarter of the firms in our robust sample have not witnessed such a movement. These firms bear two dominant characteristics: (1) they are more R&D intensive, and (2) they witness a large geographical spread of their R&D activities.

Moreover, the internationalisation of R&D activities is a long learning process towards achieving those institutional and organisational proximities (Boschma, 2005) that can counterbalance the deterioration of R&D performance. This raises two questions: 1) what speeds up this process (R&D intensity seems a potential core factor? and 2) what may define a maturity stage? The answer to this latter question is intriguing, when considering how geodiversity of R&D activities is compared to the markets of the firms seems to be a good candidate to explore further.

At last, there may be multiple stable situations of productive R&D internationalisation, as is witnessed by the few 'mature' cases in our sample. This remains an open interrogation that may find elements in a similar analysis made on firms one decade into the future, anticipating that the sample would include a far greater number of mature firms. But one may well also consider, in the achievement of a stable productive R&D situation, the role of fragmentation in value chains and the relative importance of R&D activities in the firm added value. These questions pave the way to future works on the one hand including a larger sample of firms with more recent data to facilitate an in-depth analysis of individual cases. Questions related to the R&D internationalisation and its influence on the R&D productivity during a global pandemic is also of interest. Very preliminary evaluations indicate that R&D investment drops were limited and the location of the industrial sites across countries remains stable among top R&D investors (Grassano et al., 2021).

Lastly, we have shown that US firms and European firms seems to behave quite similarly in their loss of R&D productivity when internationalising. Investigating this relationship in set of firms that do internationalise more slowly (Japanese firms for example) or more recently (firms from emerging countries) would also be a highly relevant.

8 Conclusions

Overall, we show that there is not a unique, best way for R&D internationalisation for 'mature' internationalised firms. Rather, a variety of situations exist for dealing both with the level of internationalisation and the geographical diversity of the countries where R&D is undertaken (von Zedtwitz et al., 2004; Vrontis and Christofi, 2019). Such variety is well illustrated the outperforming firms, which, by being very effective when internationalising R&D, tend to exhibit three key differentiating characteristics: on average, (1) they mobilise twice the R&D assets as the mainstream firms, (2) they are more R&D productive, and (3) they are more R&D intensive.

Other studies have shown how the R&D intensity weighs on the multinationality-performance relationship (Kirca et al., 2011; Castellani et al., 2017). Kotabe et al. (2002) have shown that companies tend to enjoy operational improvement (i.e., positional strengths) from foreign expansion *before* realizing financial improvement arising from increased R&D intensity. Similarly, our analysis implies that the R&D intensity also plays a role in the relationship between a firm's R&D efficiency and its R&D internationalisation. Below a certain level of R&D intensity, the R&D productivity is lowered by the internationalisation of R&D activities. However, that companies may enjoy R&D productivity improvements from foreign expansion as soon as their R&D intensity is high enough to overcome the challenges of R&D internationalisation. The level of R&D intensity that allows firms to reduce instability and economically benefit from internationalisation certainly depends on the firm's internal factors. Yet, the data constraints of our analytical approach prevented us from gaining further insights into this issue. Our sample was simply not large enough to test whether typical situations of productive R&D internationalisation exist to assess the role of the firm's external parameters (either across industries or across countries). This calls for further analyses, especially if considering the situation one decade later.

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