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Abstract

Now that business innovation is based on external sources, the characterization of the knowledge spillovers firms benefit from is crucial both for their strategies and for public innovation policies. This article proposes to model their dynamics through a spatio-temporal knowledge production function of firms (MSTIF), built, validated and estimated for firms in the regions of France between 1998 and 2014. Based on data from the INPI database about patents filed in France, and on the R&D survey undertaken by the Ministry of Higher Education, Research and Innovation among firms in France, the MSTIF model makes it possible to identify knowledge spillovers essential for business innovation: first, those from the human resource in R&D of all firms in the region, then those from the public R&D expenditure in the region, and finally those from the weight of the region in the national scientific employment.

JEL codes: C5; L2; 031; R12

Key words: Knowledge production function, geography of innovation; business innovation, R&D, knowledge spillovers

1. Introduction

The issue of key resources for business innovation has been an acute one for several decades, in a context of increased competition between actors and between spaces, and of race for innovation. Although for much of the 20th century the innovation model was based on the intra-organisational resources and efforts made by firms, particularly in terms of expenditure on Research and Development (R&D), an evolution was confirmed from the 1980s onwards. Indeed, business innovation is increasingly following a model where the dynamics of openness to actors outside the firm play a significant role. New business innovation models are now those of open innovation (Chesbrough 2003), network innovation (Roussel, Saad, and Erickson 1991), collaborative projects (Hagedoorn 2002), and even knowledge communities (Amin and Roberts 2008). In other words, business innovation depends on positive externality effects, which can be referred to as knowledge spillovers. Two dimensions characterise this opening up of firms' innovation processes, and make it possible to understand the nature and vectors of knowledge spillovers: an inter-organisational dimension (the firm's innovative activity extends its organisational boundaries to other firms, suppliers, customers and consumers, public research centres, etc., forming knowledge networks), analysed by the economy of innovation and knowledge (Gibbons 1994; Ferrary and Pesqueux 2004; Nonaka and Toyama 2005); a geographical dimension (business innovation thrives in areas marked by the phenomena of agglomeration of actors: clusters, technology districts, *milieu innovateurs*, in which proximity relationships are established), which has fuelled many works in innovation geography (Aydalot 1986; Camagni and Maillat 2005; Torre 2010).

Knowledge spillovers were mainly approached from the angle of the circulation of knowledge: indeed, it is because knowledge moves between organizations of the same network, and/or between actors close to each other, that firms can benefit from it in their innovation process. This angle has been complemented by consideration of the co-production of knowledge by these actors, made possible by collaborations that can take place at large or short geographical distances, and that are based on sharing knowledge (Jacquier-Roux 2018).

The dual nature of knowledge spillovers, both organisational and geographical, has consequences for the distribution in space of the most innovative firms and actors. While new information and communication technologies make it possible to envisage the circulation and co-production of knowledge at a distance, work in geography of innovation underlines the enduring importance of territorial inequalities in innovation, at the regional level (Chalaye and

Massard 2012), as at the urban level (Krugman 1992; Veltz 1996). It is therefore not indifferent, for a firm, to be established in such a region or such a metropolitan area rather than another, in terms of knowledge spillovers that it could benefit from.

The aim of this article is to analyse the determinants of business innovation in a contemporary environment marked by the significant role of knowledge spillovers and by geographical inequalities in scientific activity. It is therefore a question of enriching an economy of innovation approach through the contributions of the geography of innovation. This approach leads us to a conceptual and empirical choice: to approach the innovation of firms through a Knowledge Production Function (KPF). This choice evokes a rich literature, as there are many works proposing KPF. We make it our basis for reflection. But we focus the analysis on both firms and the French territory, a target which had few works dedicated to. Therefore, our research question is: how to identify a firms' KPF in a given spatio-temporal context? From this, our empirical objective is to test the validity of this KPF on firms in the French regions at the turn of the 21st century.

Deeply, with this research, we want to contribute to the understanding of the determinants for business innovation in the French regions, while many questions arise today about the existence and nature of geographical knowledge spillovers, in a French scientific space marked both by the decentralization of scientific and technological policies and by the persistence of strong territorial inequalities in terms of innovation.

Our article proceeds according to the following plan: section 2 presents a state-of-the-art on the firms' KPF; in Section 3, we specify a new KPF for firms in France which bases the MSTIF model described in Section 4; we present in section 5 the mobilized data used to then identify the parameters of the model and validate it in section 6; we proceed to the interpretation of the results in section 7 before concluding.

2. State-of-the art on Knowledge Production Function of firms

At the beginning of the approaches in terms of KPF of firms, we find the founding works of Griliches (1979). Included in a broader analysis of the determinants of a firm's productivity, its KPF considers that the knowledge production of a firm in t, measured by the patents it has obtained, is explained by three main factors: the R&D expenditure of the firm on t, the R&D expenditure of the firm cumulated up to t, and external sources of knowledge within the sector and from other sectors[1], referred to as knowledge spillovers. The analysis by Griliches lays the foundations that can be found, a few years later, in developments in the innovation economy. Indeed, on the one hand, the fact that a firm produces knowledge not only through its R&D expenditure in t, but also through its past R&D expenditure is not content to avoid a problem of simultaneity between these expenditures and the knowledge created. It evokes what the evolutionary literature in innovation economy has established since the 1980s: the cumulative nature of knowledge, which creates organizational and cognitive routines (Nelson and Winter 1982) and dynamic adaptive capabilities (Teece, Pisano, and Shuen 1997). On the other hand, consideration of the knowledge spillovers that a firm can benefit from thanks to its environment was supported by Teece (1986), before finding in the work of Cohen and Levinthal (1989) a complementary analysis showing that a firm's "knowledge absorption capacity" is significantly enhanced by its own cumulative R&D effort. Griliches' KPF therefore has a significant potential for understanding the contemporary developments we have mentioned above, as regards the business innovation model, and the growing importance of knowledge spillovers.

The works which subsequently developed on the KPF of firms went in several directions. The first that can be mentioned returns to the link between a firm's R&D effort (present and past) and its knowledge production. This is proposed by the work of Crépon, Duguet, and Mairesse (1998, 2000), which applied this relationship to companies in France at the end of the 1980s. In particular, they examine the risk of selection bias in the Griliches KPF: on the one hand, counting patents as a marker of innovation ignores the fact that some firms innovate without filing patents – which leads them to propose another indicator of innovation, the share of less than five-year-old products in the firm's sales; on the other hand, some firms innovate without doing R&D, or very little – suggesting that sectoral and size determinants, among others, influence R&D spending.

The second direction followed by the KPF literature is the analysis of the nature of knowledge spillovers that the firm benefits from. In the Griliches KPF, they are intra- and inter-sectoral, with no spatial specification. An essential analytical step is then taken thanks to the work of Jaffe (1989), which proposes two structuring dimensions of the nature of spillovers: on the one hand, they occur in a given geographical space, on an intra and inter-sectoral basis; on the other hand, they go through the vector of *relations between firms and actors of public research*

[1] "The level of productivity achieved by one firm or industry depends not only on its own research efforts but also on the level of the pool of general knowledge accessible to it." (Griliches 1979).

(universities, public research institutions).

However, it should be noted that Jaffe's statement does not concern the KPF of firms, but that of a given geographical area (in this case, the American federated states), within which spillovers operate. The nuance is important because the considerable amount of work on KPF that followed (see Varga and Horváth [2015] for a review) largely takes this point of view of the spaces in which spillovers operate: what is analysed is KPF of geographical spaces[2], in a geography of innovation issue. As a result, this literature is moving away from our concern, which is that of spillovers which should be incorporated into a *firm's* KPF.

Despite this reservation, this literature contains a recurring question, which interests us for determining our KPF of firms: that of the spatial scale to capture geographic knowledge spillovers. Indeed, if the scale is too broad, the proximity relationships are diluted, even impossible to distinguish from systemic institutional effects. Then, as Jaffe (1989) must have done, econometric sophistication is essential, such as the calculation of a "geographic coincidence index" between private and public R&D actors. Symmetrically, if the scale is too narrow, then there are problems of overflow in the game of spillovers: there too, to take account of it, econometric models become more complex and must integrate inter-spatial spillovers. For example, the analysis conducted at the level of metropolitan areas in the United States (Anselin, Varga, and Acs 1997), or departments in France (Autant-Bernard 2001), requires the consideration of spillovers involving R&D carried out in the spaces bordering those examined. The question of the relevant spatial scale of analysis is therefore important, and several studies have chosen to examine whether the scale of the region (in the European sense of the term), insofar as proximity is physically and socially possible, and as, at the same time, knowledge dynamics are potentially autonomous (thanks to decentralized science and technology policies and the presence of public research institutions and universities) allows to neutralize inter-space spillovers. The results are not unanimous: if, for example, Bertinelli (2004) considers that the European regions are experiencing significant inter-regional spillovers, Bode (2004) considers them insignificant in the case of the West German regions.

Jaffe's contributions about the nature of spillovers, combined with Griliches' early work on the definition of a firm's KPF, have, from the 1990s onwards, led to a series of studies focusing on the full or partial applications of KPF to firms. Acs, Audretsch, and Feldman (1994) apply the

[2] The innovation measured in these cases is that of all the actors present in these spaces: firms, universities, public research centres, individual inventors.

KPF defined by Jaffe to firms in the various American states, using as an indicator of innovation, not the patents obtained, but the innovations counted. Their main result is to show that large firms benefit more from the influence of their R&D spending, while small firms benefit more from the influence of spillovers. Mansfield (1995) brings an original analysis, focused on spillovers that benefit to firms from public research, without a priori spatial concern. Its KPF considers as dependant variable the innovations of the firms the latter declare to be due to research work in the universities; the independent variables concern the universities mentioned: R&D expenditure, reputation, and integration of the university into a local sectoral network of enterprises. Added to this is the impact of federal research funding. The value of this approach is the illustration that it offers of the mechanisms underlying spillovers from public research for firms. Still in an approach focused on the nature of spillovers benefiting firms, Gallié and Legros (2007) examine the spatial dimension of inter-firm spillovers, for firms in France at the beginning of the 2000s, on an urban spatial scale, in a KPF where the explanatory variables are the R&D expenditure of: the firm, the firms of the same sector in the same city and in neighbouring cities, the firms of the other sectors in the same city and in neighbouring cities. The results show that the firm's R&D spending plays favorably, as well as its size; that intra-sector spillovers are negative in the same city and positive with neighbouring cities; that inter-sectoral spillovers are positive in all cases and grow with the consideration of neighbouring cities; and finally that inter-sectoral spillovers are stronger than intra-sectoral spillovers, which is consistent with the results of Audretsch and Feldman (1999) demonstrating the importance of a diversified scientific basis for occuring of local spillovers.

The literature on firms' KPF therefore exists, and the specifications of this KPF have covered both the indicators of enterprise innovation and the independent variables to be incorporated. However, there is still a blind spot in these analyses: the human capital dimension is generally absent from these firm's KPF. Labour, as a conventional factor of production, certainly plays a role in the Griliches' approach, but this role lies in the overall production function and is envisaged in terms of the impact on the productivity of the firm. Here, it is a question of considering that human capital, and more precisely the human resources dedicated to innovation constituted by research staff[3], plays a role in the production of knowledge of the firm. In other words, the proposal is to add to R&D expenditure and spillovers another explanatory variable in firms' KPF: research staff. This approach was retained previously, but rather in works on

[3] By "research staff" we mean all employees of R&D departments: researchers, engineers, support staff (technicians, administrative staff, workers).

KPF in specific spaces: for example, Charlot, Crescenzi, and Musolesi (2015) integrate human resources (without limiting them to research staff) into their KPF in European regions. Their research highlights one aspect that should not be overlooked, that of the additivity between R&D spending and human resources: 'Innovation theory suggests that R&D investments and HK are strongly complementary in their contribution to innovation.' (p.1243). They suggest econometric solutions to this problem. For our part, we propose to consider a pragmatic solution: to break down R&D expenditure into non-human capital expenditure (equipment and material capital, intangible capital, current expenditure, data supply, etc.) on the one hand, and wage expenditure for remuneration of R&D staff on the other hand, in order to retain only the former in firms' KPF for R&D expenditure. Thus, by diminishing the R&D expenditure of its part corresponding to human capital, and by considering apart the number of research staff, our objective is to measure the specific impact of the contribution of the research staff in the firms' KPF.

3. Specification of a new KPF for firms in France

The literature review we have carried out has enabled us to identify successive developments in the firms' KPF, and to identify the specifications that we consider essential in the perspective of an approach that integrates the contributions of both the innovation and knowledge economy and the geography of innovation.

Thus, the KPF for firms we propose has the following characteristics:

- The dependant variable is the innovation of firms in each French region: thus, the data to be considered are indeed data relating to firms. The choice we make about which indicator to measure business innovation is the classic choice of the number of patents filed by firms. The literature is abundant on the limits of such a choice. We have pointed out above the objections raised by Crépon, Duguet, and Mairesse (1998, 2000) as to the partial nature of such an indicator: indeed, all innovations are not equivalent, some innovations do not give rise to a patent, and some patent filings are motivated by considerations other than the strict publication-protection of an innovation. However, research conducted using other proxies for innovation does not, on the whole, give contradictory results with that of work based on patents: the indicator proposed by Crépon, Duguet, and Mairesse (1998, 2000), the share of less than five-year-old products in firm's sales, is considered to be more representative of company innovation by the authors, without invalidating the results obtained with patents[4]. Similarly, Acs, Audretsch, and Feldman (1992), in a strict application of Jaffe's KPF to the American federated states, but with a direct indicator of innovations carried out by firms, instead of patents, arrive at consistent results[5]. These factors in favour of maintaining an indicator of company innovation based on their patents are also in line with practical elements: patent data are available from solid sources (patent offices and intellectual property institutes), with continuity over long periods, and explicit methodologies.

- The explanatory variables for R&D are:
    - Corporate R&D spending is considered net of wages paid to R&D staff, in order to reduce the additivity problem between R&D spending and research staff. Indeed, by withdrawing wages, we give more weight in R&D spending to what does not depend on the number of research staff: buying patents, setting up experimental platforms, etc. in other words, fixed costs are given more weight. There remains, however, a selection bias, reported by Crépon, Duguet, and Mairesse (1998, 2000): not all innovative firms necessarily engage in R&D. Therefore, other variables will be introduced.
    - Corporate R&D staff are integrated to bring the role of work and human capital in knowledge production back to the centre of the analysis.
    - Spillovers to firms from public research are considered through public research R&D expenditure, as well as R&D staff in public research. It should be noted that the work of Autant-Bernard (2001) underlines a dependency between public research R&D spending and business R&D spending: it concludes that the former has an impact on the latter[6]. We do not include this dimension in our analysis.

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[4] 'Overall, these two measures provide a comparable explanation of the significant productivity gains resulting from research in manufacturing. However, the second approach makes it possible to take better account of the effects of variables such as the demand pull or the inherent dynamics of technology.' (Crépon, Duguet, and Mairesse 2000, 65)

[5] 'Substitution of the direct measure of innovative activity for the patent measure in the knowledge-production function generally strengthens Jaffe's (1989) arguments and reinforces his findings.' (Acs, Audretsch, and Feldman 1992, 366)

[6] 'There is strong evidence of the presence of public externalities. Private research is positively and significantly correlated to public research.' (1075)

- The spatial scale:

  The geographical and spatial character of spillovers, whether they come from the R&D of other firms, or from public R&D, is understood in a simplified way, by choosing a geographical scale for measuring explanatory variables: that of the region. This choice makes it possible to abstain from the two constraints often present, as we have seen, in the literature on geographical knowledge spillovers: having to calculate a geographical coincidence index when the spatial scale is too wide, and having to consider inter-space spillovers when the spatial scale is too narrow.

  - The scale of the region lends itself to such freedom, especially in the case of France, for several reasons. First, from an institutional point of view, an essential part of science, research and innovation policy is defined and implemented at this level, which translates into the allocation of regional research funding to firms and universities, and through a decentralized policy on Higher Education and Universities. Second, from a geographical point of view, given the small size of European countries, the choice of the region to capture knowledge spillovers is particularly relevant. On the one hand, research and its dynamics find a certain autonomy, which can neutralize the phenomena of inter-regional spillovers: indeed, inter-departmental and inter-urban spillovers, a configuration that can be found in works on the French case, are much more likely than spillovers from one region to another, because the regional scale is larger, the metropolitan areas are contained within the borders of the regions, their hinterlands also. At the same time, the scale is sufficiently narrow to assume a spatial coincidence close enough to generate spillovers, whether they occur between firms, or from public research (each French region has universities, and firms are close to these universities; similarly, such called *pôles de compétitivité* are present in all regions; finally, scientific diversity, which is a geographic spillovers factor (Audretsch and Feldman 1999; Gallié and Legros 2007; Brossard and Moussa 2012), is significant at this level). So, we do not need a Jaffe-style coincidence index.
  - In order to consider the specificities of each region, which may play a role in the effectiveness of regional spillovers, we therefore introduce a regional explanatory variable which measures the weight of each region in the total

national research staff. This makes it possible to control the impact of the strong contrasts between the French regions on this subject and its evolution[7], on the game of regional spillovers. This choice joins that of various works that integrate variables of characteristics of spaces: size, production, share of scientific activity in production, etc. (Autant-Bernard 2001; Gallié and Legros 2007; Gallié 2009; Brossard and Moussa 2012, 2016).

- The temporality of the impact of research effort (R&D spending and research staff) and spillovers, on innovation is considered thanks to a 3-year time lag. This time lag makes it possible to exceed the limits of analyses presenting a simultaneity between the interplay of innovation factors and the results obtained (for example, Gallié and Legros [2007], or Autant-Bernard and Lesage [2011]). Originally, Griliches' model had already pointed out this problem, and had proposed to solve it by considering the cumulative R&D expenditure of firms, which reflected the cumulative nature of knowledge, and the bonus to pioneers in the race to know. It complemented this approach by incorporating a deflator of R&D spending. The same option was taken by Crépon, Duguet, and Mairesse (1998, 2000). We choose another solution, justified by the evolution of business innovation models, which resulted in the advent, in the 1980s, of the standard of innovation by project (as evidenced by literature in economy of innovation and innovation management – Clark and Fujimoto [1991]; Clark and Wheelwright [1992]; Midler [1993]), to the detriment of the linear model of innovation based solely on the knowledge accumulated in research laboratories. Business innovation is based on a dynamic of projects, whose temporality is in the range of 18 months to two years. To this is added the time of patent filing. Thus, we arrive at a lag of about 3 years, as proposed by Autant-Bernard (2001) and Gallié (2009)[8]. We therefore prefer this proposal to that, which corresponds more to the linear logic, made by Hal, Hausman, and Griliches (1984), of a 1-year lag.

[7] For example, the Île de France region, which accounted for 42% of national scientific employment in 2000, rose to 38.2% in 2015, while at the same time the share of the Rhône-Alpes region increased from 11% to 13% (Source: MESRI (R&D survey) and our processing on the data of this survey).

[8] 'This assumes a lag structure between the moment when R&D takes place and the moment it leads to an invention. We can indeed consider that an investment in research needs time to materialize through the registration of a patent.' (Autant-Bernard 2001, 1072)

In the end we propose a renewal of the analysis of KPF of firms in France. Indeed, there is little work in terms of KPF applied to the French case. Table 1 shows a comparison[9] of these, both in terms of the variables included in the KPF and in terms of the data considered. It shows how the choices we have made distinguish our approach and provide the basis for a real spatio-temporal analysis of business innovation in France.

KPF	Analysis Level		Integration of Human Capital		Knowledge Spillovers				Temporal Analysis		Input-Output Lag				Regional Explanatory Variable
						Geographical									
Studies	Space	Firms	Indirectly	Directly in the KPF	Public R&D to private R&D	City	Departement	Region	Spot	M to LT period	Simultaneous	Cumulativeness	1 year	3 years	
Autant-Bernard 2001	√		√		√		√		√					√	√
Autant-Bernard & LeSage 2011	√				√		√			√	√				
Brossard & Moussa 2012, 2016	√									√			√		√
Crépon et al. 1998, 2000		√	√							√		√			
Gallié 2009	√								√					√	√
Gallié & Legros 2007		√				√			√		√				√
MSTIF		√		√	√			√		√				√	√

Table 1. Comparative table of work in terms of KPF applied to the French case

On these bases, we propose a new KPF for a spatio-temporal economic model, called MSTIF (Spatio-Temporal Model for the Analysis of Firm Innovation), making it possible to analyse the degree of innovation of firms in the regions of France and its evolution over time in periods of 5 years. In this MSTIF model, human capital is incorporated directly into the KPF as a factor of knowledge production, in addition to the explanatory variables concerning: public R&D, private R&D, the R&D weight of the business location region. Thus, the MSTIF model is characterized by a regional spatial dimension and a periodic temporal dimension with a 3-year lag between input and output, adapted to the pace of R&D and business innovation in France.

More formally, the MSTIF model can be presented by a KPF with five variables explaining business innovation at spatial (s) and temporal (t) scales.

[9] This comparison does not claim to be exhaustive.

4. The MSTIF Spatio-Temporal Model

The MSTIF model, which form is a Cobb Douglas function[10], is formulated by the following equation:

$$I_{s,t} = C \times (FE_{s,t})^{a1} \times (BE_{s,t})^{a2} \times (FA_{s,t})^{a3} \times (BA_{s,t})^{a4} \times (PR_{s,t})^{a5}$$

With:

s: regional spatial scale of the model

t: periodic time scale where innovation is measured at the end of the period and factors at the beginning of the period

Is,t: degree of innovation, *i.e.* the number of patents published at the moment (t) by firms located in the region (s)

FEs,t: human resource factor (in FTE workforce) of the R&D of firms performing R&D in the region (s) at the moment (t)

BEs,t: financial factor of the R&D of firms, *i.e.* the budget they devote to their R&D in the region (s) at the moment (t)

FAs,t: human resource factor of R&D of public administrations located in the region (s) at the moment (t)

BAs,t: financial factor of R&D of public administrations located in the region (s) at the moment (t)

PRs,t: R&D size factor of the regions, *i.e.* the share in percentage of the region (s) at the moment (t) in the total French R&D

C: a parameter including other explanatory factors (not explained in the model) and the not explained part

$a1$, $a2$, $a3$, $a4$, $a5$: coefficients related to the five input variables of the model

This function is defined for any region of the spatial territory (S) and for any period of the time

[10] Following with that choice Jaffe's choice, and many others' one after him.

horizon (T).

The MSTIF spatio-temporal model makes it possible to analyse the evolution of business innovation in the totality of French regions (S), over a time horizon (T) of a number of years ranging from a_0 to a_n. For each year, innovation is measured by the number of patents filed by firms in the INPI database, considering the year of publication of patents (for multi-applicant patents, there is one patent for each). The MSTIF model makes it possible to analyse this innovation over (P) periods of (d) successive years. The *spatial dimension* (s) of the model is the region where the companies' R&D is located in France. During each of the periods (p), for each year (t), the main R&D implementation region of the companies reported in the MESRI R&D survey is considered. In the MSTIF model, it is assumed for each period that the innovation territory of a research actor is invariable over time and that the region of implementation of its R&D is the same over the entire period. The scope of the MSTIF model is thus the totality of the R&D implementation regions over all the periods studied in the time horizon (T).

As regards the periodic *temporal dimension* of the model, a time lag between R&D time and the time of the innovation produced is considered in each period: R&D carried out at the beginning of the period will produce innovation at the end of the period. Business innovation over a period (p) is measured at the end of the period by the sum of patents filed over a number of years (y). The R&D activity of firms, carried out at the beginning of the period, is estimated in terms of the budget (excluding wages) devoted to R&D and the number of employees (FTEs) employed for R&D. These R&D variables are calculated by a smoothed average over a number of years (x) at the beginning of the period. The individual company data are then aggregated by region to determine regional innovation and R&D by the sum of the values of three variables (patents, workforce and R&D budget) of all firms located in the region. In addition to the R&D of firms in a region, the MSTIF model also considers, as explanatory variable of business innovation, the R&D of public administrations located in the same region. This public R&D is also estimated in terms of the number of R&D employees and R&D spending of public administrations according to the MESRI R&D survey. Unlike companies, the R&D budget of administrations is measured including the wages of R&D staff. These two amounts, aggregated by region, are calculated at the beginning of each innovation period by a smoothed average over the same number of years (x) as for firms.

The MSTIF model also considers the potential of regional research in France, which can vary considerably from one region to another. This potential, or R&D weight of a region, is appreciated by the region's share of total R&D in France. This indicator makes it possible to introduce into the model a measure of the size of a region that can change over time. It is estimated, by relating the R&D workforce of a region to the total R&D workforce in France (public and private combined). This indicator is calculated for each period, like all explanatory variables, by a smoothed average over the same number of years (x) at the beginning of the period.

The MSTIF spatio-temporal model thus makes it possible to measure the innovation of firms by periods (p) in the regions of a space (S) and over a time horizon (T) of a duration (h), more or less in the long term, from year a_0 to year a_n. It may be instantiated for any period p of a duration (d between 1 and h) which begins at the moment (t-1) by a subperiod of R&D of a duration (x<=d) and ends at the moment (t) by a subperiod of innovation of a duration (y<=d). The two sub-periods may overlap.

In this model, the time horizon, the period of innovation and the lag between R&D and innovation can be adapted. If d=h then we have a single period on the horizon T. If x=y=d, then it is a model without time lag between R&D and innovation.

The data we gathered for our study allow us to calibrate our model over a 20-year time horizon from 1997 to 2016, to test and validate the 5-year period adapted to business innovation (d=5), to test and choose the appropriate 3-year lag between R&D and business innovation (x=y=3 with one year of intersection). In addition, these data allow us to delimit our study space to the 21 regions of the metropolitan territory of France (Corsica is counted with the PACA region). We chose the regions as they existed over our time horizon: the former regions defined in France until 2015 and not those resulting from the territorial reform adopted in 2015.

5. The Data

We used three sources of data for this work:

- The database of the Institut National de la Propriété Industrielle (INPI), which provides detailed information every year on all patents filed in France, in particular that we need to measure business innovation: the number of the patent filed, the date of publication, the type of applicant (firm or other establishment), the identification of the applicant

(SIREN for firms). We pre-processed these data to obtain the number of patents filed by firm and year of publication. We obtained the population of innovative firms in France who filed patents with the INPI between 2000 and 2015.

- The R&D survey undertaken each year by the Ministry of Higher Education, Research and Innovation (MESRI) among firms in France. It provides for each survey year and for each firm surveyed carrying out R&D activities in France: the SIREN identification number, the main region where its R&D activity is located, the number of R&D employees for this R&D activity, the total R&D budget, specifying current wages expenditures. We used data from this annual survey between 1997 and 2016.
- Summarised regional data from the MESRI R&D survey on public administration R&D in France in terms of staff and spending[11].

Starting from the INPI patent database, we crossed it with the R&D database of MESRI to obtain, after processing, our data on R&D and business innovation in France. We then aggregated these data about firms at the R&D implementation region level. Finally, the joining of regional data on business R&D with those on R&D of public administrations allows us to constitute all the useful observations for the construction of our spatio-temporal model about business innovation in the French regions. We have that regional data from 1997 to 2016.

So, we consider all the firms that innovate according to the INPI and that do R&D according to the MESRI. We do not consider those of the INPI which are not surveyed by the MESRI, nor those which carry out R&D according to the MESRI survey but which do not appear in the INPI database.

Although our study covers all firms that file INPI patents, this does not prevent certain biases on the data used in the construction of the MSTIF model, particularly those related to the size and sector of the firm. In fact, not all innovative firms file patents: for example, large firms in a monopoly position thanks to a high-value patent have less interest than SMEs in patenting their subsequent inventions. Similarly, 5-year innovation period is not always suitable for certain sectors such as health, for example, where innovation may require a longer period of R&D.

[11] Both latest types of data for this article are covered by the statistical confidentiality of INSEE (Institut National de la Statistique et des Etudes Economiques) in France. In order to access and to process them, we obtained the lifting of statistical confidentiality from the Statistical Confidentiality Committee.

6. Parameter Identification and MSTIF Model Validation

6.1. Identifying Model Parameters

After the calibration of the spatial and temporal dimensions of the MSTIF model, we transformed the KPF into a logarithmic form with multiple linear regression:

$$ln(I_{s,t}) = a1 \times ln(FE_{s,t}) + a2 \times ln(BE_{s,t}) + a3 \times ln(FA_{s,t}) + a4 \times ln(BA_{s,t}) + a5 \times ln(PR_{s,t}) + ln(C)$$

To identify the parameters of the MSTIF model, we constructed a sample based on data on innovation and R&D of firms in France between 1998 and 2014. The sample covers a population of 5,248 firms that have filed at least one INPI patent for one year (t) between 2000 and 2014, while having an R&D activity (according to the MESRI survey between 1998 and 2012) at least one year during the three-year period (t-2, t-1 or t) preceding the filing of patents. Our sample, thus constructed, represents 68% of companies in the INPI database (2000-2014) doing R&D according to the MESRI survey (1998-2012)[12]. These firms generate a total of 8,770 individual observations leading to 105 regional observations. The 105 regional observations in our sample cover the 21 regions of the spatial territory studied, over 5 5-year periods, across the time horizon from 1998 to 2014.

On the basis of the constructed sample, we estimated the linear regression model using the Ordinary Least Squares (OLS) method, which is implemented in the data analysis utility of Excel. The results of these estimates are summarized in Table 2.

[12] The number of INPI companies (2000-2014) doing R&D according to the R&D survey (1998-2012) represents 46% of INPI companies and 26% of companies surveyed by MESRI during these periods.

Regression Statistics	
Multiple R	0.9412
R Square	0.8859
Adjusted R Square	0.8801
Standard Error	0.4228
Observations	105

ANOVA	*df*	*SS*	*MS*	*F*	*Significance F*
Regression	5	137.3652	27.4730	153.6649	0.0000
Residual	99	17.6998	0.1788		
Total	104	155.0650			

Regression Results	*Coefficients*	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	2.3136	1.8400	1.2574	0.2116	-1.3373	5.9645
FE	0.9591	0.1485	6.4569	0.0000	0.6644	1.2538
BE	0.0219	0.1180	0.1855	0.8532	-0.2123	0.2561
FA	-0.9614	0.4116	-2.3356	0.0215	-1.7782	-0.1446
BA	0.7352	0.3144	2.3388	0.0214	0.1115	1.3590
PR	0.0278	0.1811	0.1536	0.8782	-0.3315	0.3871

Table 2. Estimation Results for the OSL method Linear Regression applied to MSTIF model

Table 2 shows an overall significant regression, within a 95% confidence interval, with a coefficient of determination greater than 88%, and the majority of the coefficients of the variables estimated with less than 5% probability of error. We are therefore using this model for validation.

6.2. Model Validation

To validate our model, we can analyse the residue graphs from the linear regression estimation. Figure 1 presents eight residues graphs, respectively, by time, standardized residues, endogenous variable (I) and 5 exogenous variables: FE, BE, FA, BA and PR.

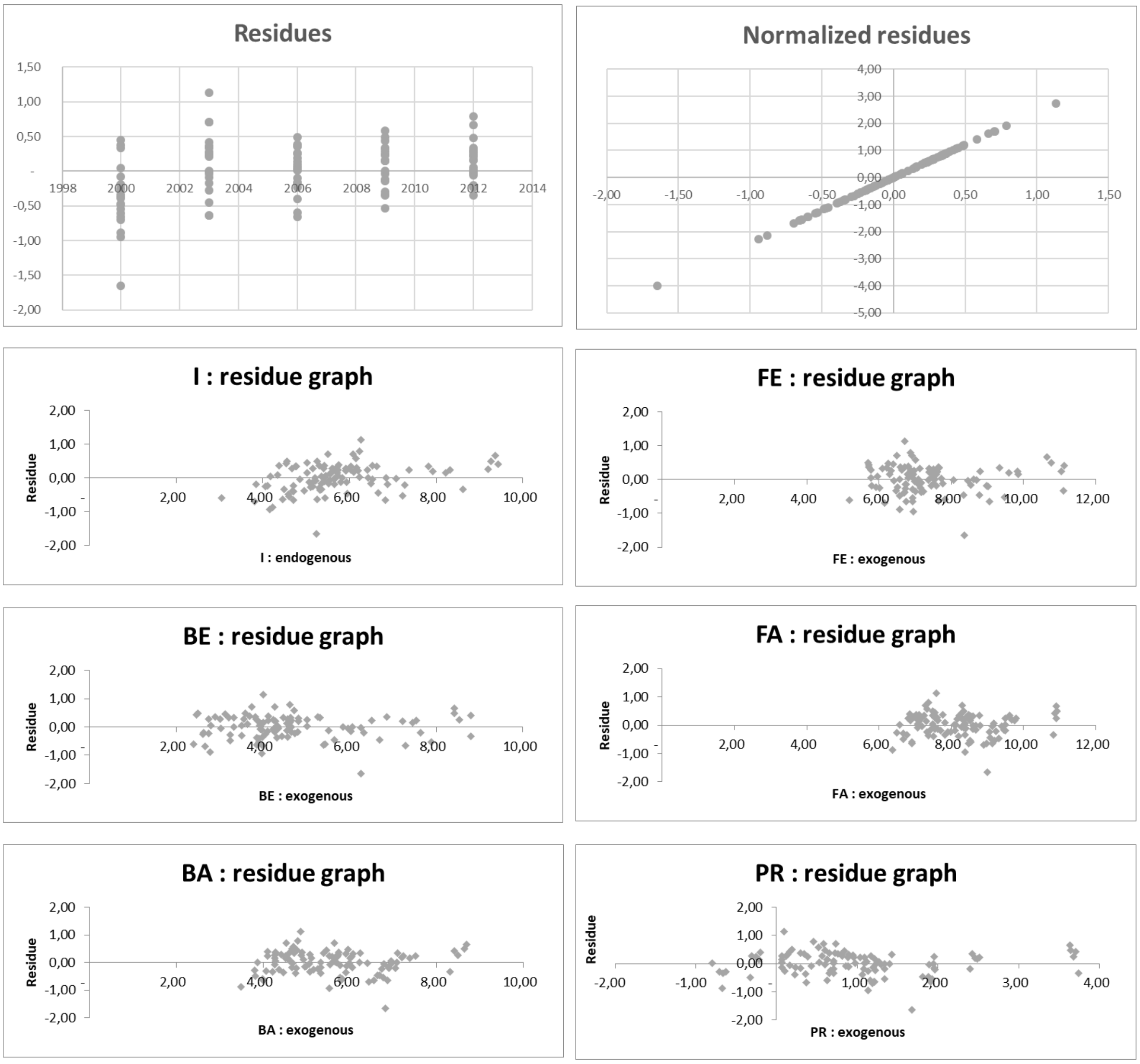

Figure 1. MSTIF Model Linear Regression Estimation Residue Graphs

On all of these residue graphs, we can visually verify that our estimates respect the main assumptions of a linear regression: normality and independence of errors, linearity, exogeneity, homoscedasticity. There are no pathological cases (non-linearity, asymmetry, or structural breakdowns) that can invalidate these assumptions.

- The time-dependent residue graph does not show alternating (+/-) sequences, indicating the lack of residue autocorrelation and thus confirming the independence of the sample observations, even if the manipulated data are temporal.
- The normalized residue graph (the normal probability plot) confirms the normality of the errors.

- On the six residues graphs concerning the endogenous variable or each of the five exogenous variables, we can observe: that the points are randomly distributed on both sides of the x-axis; the absence of atypical or influential points which deviate aberrant from the others; the absence of structural break-up in the dispersion of residues.
- The residue graph concerning the endogenous variable does not show any atypical or influential points that may be related to model specification problems. Nor does it reveal any asymmetry of residues that may result from overestimated or underestimated values of the endogenous variable. The lack of non-linear shape on this graph confirms a linear regression model. In addition, there is no structural breakdown on this graph, which indicates that there is only one regression for the entire population. This is also true for the residue graphs for exogenous variables.
- Residue graphs concerning exogenous variables do not show heteroscedasticity or dependence between residues and exogenous variables.

The MSTIF model, estimated and validated in its logarithmic form, can therefore be represented by the KPF:

$$I_{s,t} = 10.11 \times (FE_{s,t})^{0.96} \times (BE_{s,t})^{0.02} \times (FA_{s,t})^{-0.96} \times (BA_{s,t})^{0.74} \times (PR_{s,t})^{0.03}$$

To complete the validation of the MSTIF model, the graph in Figure 2 compares the innovation calculated with this KPF with the innovation observed, through 5-year periods, in all regions across the time horizon studied.

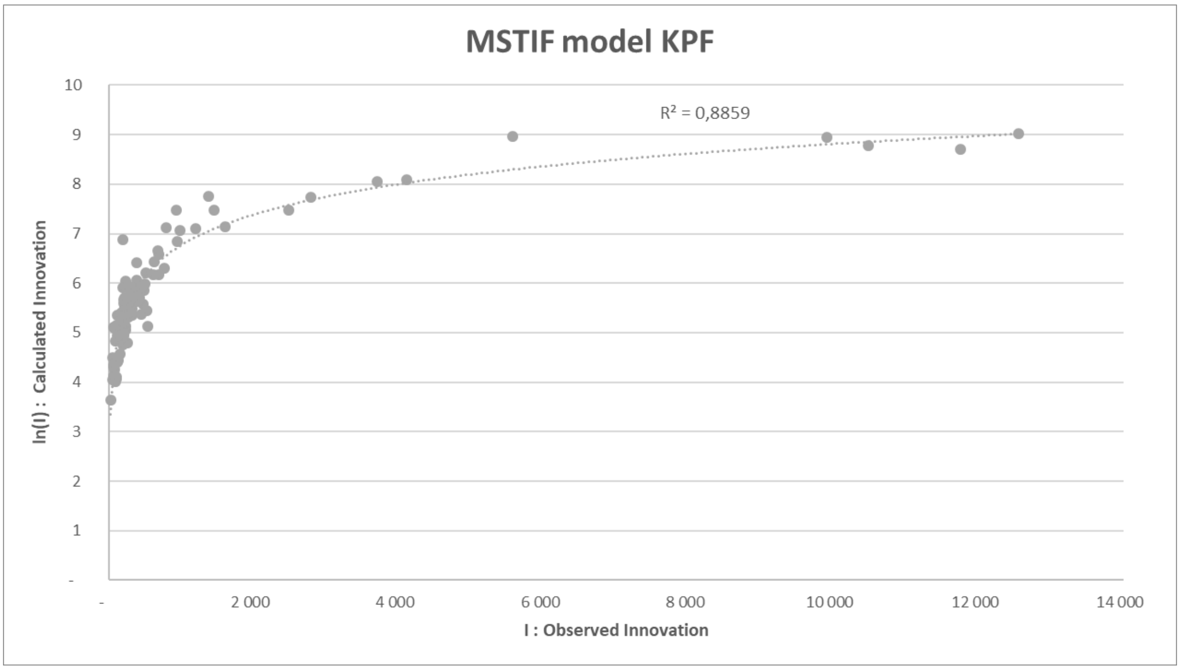

Figure 2. Observed innovation and estimated innovation by the MSTIF model KPF

This graph confirms that the KPF of the MSTIF model reproduces at 88 % the degree of innovation of 5,248 firms, observed in 21 regions of France between 1998 and 2014, through 5-year periods.

7. Interpretation of results: characterization of knowledge spillovers favouring business innovation in France

The KPF of the MSTIF model thus indicates globally that the knowledge produced by firms in a region increases thanks to the combination of knowledge-generating factors of several kinds: the labour factor (FE and FA), the capital factor in the broad sense (BE and BA), and a regional externality factor (PR).

Figure 3 brings together four graphs each representing the marginal contribution of knowledge-generating factors to innovation of all firms in the French regions[13].

[13] For the last graph in Figure 3, it presents public R&D by a composite factor, expressed in euro per researcher (FTE), combining these two factors: capital and labour.

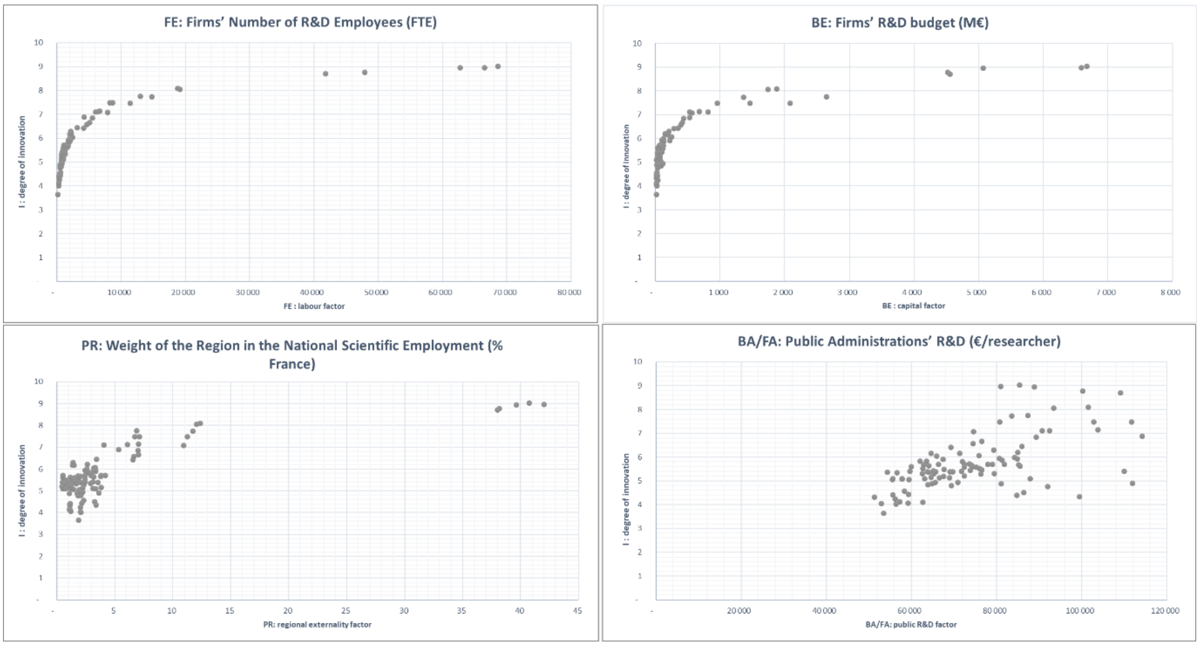

Figure 3. Contribution of R&D factors to the production of business innovations in France

The first three graphs show that the degree of innovation of firms in France increases with the increase of each explanatory variable, before stabilizing beyond a certain level of this variable. Thus, for small firms in terms of R&D effort, any increase in effort has a significant impact on innovation, unlike firms that have already achieved a significant R&D effort. Similarly, the regional impact will increase all the more as the firm is located in a region with a low weight in the national scientific employment; when this weight is already high, an increase in the latter little improves the results of the firms.

The latest graph also confirms the growth in the degree of innovation with the increase in R&D of public administrations, with a clear impact for an expenditure per researcher ranging from 50,000 to 80,000 euros. Beyond this threshold, innovation, which is very high, increases less rapidly, to varying degrees depending on the region.

Thus, we can characterize the knowledge spillovers that firms benefit from in the French regions as intervening in the following descending order of importance:

- Inter-firms spillovers in the region: our model highlights the important role of the FE variable, therefore of the work factor (research staff) in firms. It is therefore mechanisms related to human resources that must be considered here, before the impact of R&D spending: regional private intellectual activity driving effect, regional networks of researchers, regional market of the scientific workforce, mobility, collaborations, etc.

This result is similar to that of Charlot, Crescenzi, and Musolesi (2015), for which the scientific human resource (private and public) plays a significant role. However, their study considers that this factor does not overcome R&D spending, whereas we find a notable difference.

- Spillovers from public research in the region: our results about coefficients in the KPF show a significant impact of public R&D spending in the region (BA) on business innovation[14]. Firms here benefit from the support of basic research, which requires heavy funding and equipment, provided by public research centres. We thus confirm the results of the literature, from the work of Mansfield (1995) on the innovations of firms that have benefited from the results of public research, to those of Acs, Audretsch, and Feldman (1994) about the importance of spillovers from public research for small firms (which cannot afford the equipment needed for basic research). However, in terms of the marginal contribution of this factor, it can be seen that the effects of a high expenditure per researcher reach a maximum threshold.
- The regional spillovers related to the weight of the region in the national scientific employment: this factor ultimately plays moderately in the whole, according to the coefficients found for the variable PR. Thus, the geographical concentration of scientific employment seems relatively less decisive on the basis of these coefficients, even though the graph in Figure 3 shows that an increase in the weight of regions with little weight potentially has a significant impact on business innovation. A more detailed spatio-temporal analysis would therefore be desirable in future work.

Finally, these results are also broadly similar to those of Autant-Bernard (2001), for which the most significant explanatory variables are public R&D spending in the region and R&D spending by firms in the region. However, we provide elements of precision by detailing this R&D spending of firms, by the withdrawal of wages, and thus the possibility of distinguishing the impact of the labour factor and that of the capital factor.

[14] Since the two variables BA and FA have a complementary and additive effect between them, they can appear in the KPF equation with opposite sign coefficients. Moreover, the negative sign of the coefficient of the FA variable in our KPF does not necessarily mean a negative correlation between the number of R&D employees in public administrations and the degree of innovation of firms. This result can be explained by the specificity of public research in France and its public service mission, which results in researchers tending to value their innovation through scientific publications rather than protecting them by filing patents.

8. Conclusion and further investigations

This paper proposed the construction, validation and interpretation of a KPF for firms in the French regions over the period 1998-2014. By adopting a singular construction approach, and relying on robust data, it proposes a spatio-temporal KPF, and helps to confirm and characterize the knowledge spillovers that firms in the regions benefit from to innovate. In this respect, he contributes to the existing literature on the KPF of firms in France.

The results that can be highlighted are the following: firms in the French regions rely on different categories of knowledge spillovers: first all those coming from the human resource in R&D of all firms in the region, followed by those from public R&D spending in the region, and those from the region's weight in national scientific employment.

These lessons bring bases for defining public policies about business innovation. At the national level, business innovation in France, which performs poorly when compared internationally (OECD 2018), could be supported by rising spending on public research (whereas budgetary constraints sometimes lead governments to opt for cuts in the budget for research and higher education), but also by strengthening policies to reduce regional inequalities in scientific employment, in order to better equip the regions with the least weight in this field. At the regional level, scientific policies must integrate into their tools concerns beyond university research (their natural competence field), supporting the enrichment of firms' human resources in R&D. This raises issues in terms of the attractiveness of the regions for private researchers.

The MSTIF model has limitations that should be noted here, which are all possible avenues for improvement. The analysis of the impact of the expenditure in euro per researcher in public research would be more accurate if data on this area were distinguished: it is therefore necessary to define the method for removing the wages of researchers FA from the public R&D expenditure BA in the French regions. This would limit the complementarity and additivity between these explanatory variables in the KPF

In addition, the content of *C* remains to be explored, in particular to identify possible additional explanatory variables that allow for the more complete capture of knowledge spillovers that firms in the regions benefit from. Among other things, the nature of the inter-organisational relations in which firms are inserted could be introduced through an institutional (regional industrial and scientific history, presence of clusters, traditions of cooperation, etc.) and politic (facilitation led by regional science policies, *pôles de compétitivité*, openness to outside the region, etc.) analysis.

Beyond these improvements to the model, its teachings invite us to use it for further investigations. We already identify three of them.

The emphasis of the model's KPF on the major role played by the FE variable calls for analyses of the human resource aspects of knowledge spillovers and innovation performance. It would be interesting to understand how the dynamics of the scientific and technical human capital of firms operate at the regional level, to contribute to their innovation. For example, what role can researcher mobility play in the sharing of knowledge and the circulation of knowledge? What dimensions of this mobility are favourable to innovation: from a geographical point of view, but also from an organizational point of view (between firms, between firms and academic circles), and in what temporality (permanent, temporary mobility)? Similarly, how do the collaborations that researchers establish with external partners feed innovation in companies? Ultimately, it is about understanding the human resource dynamics of knowledge networks in business innovation today.

A second investigation would be to test the KPF of the model on a different time lag than the one we selected, concerning the time lag between the mobilization of resources for innovation, and the innovation achieved. For example, instead of the three years we've chosen, in accordance with much of the literature, we could see whether the impact exists significantly in the longer term. Our long-term data are suitable for such treatments. The effects of the accumulation of knowledge in research, both public and private, as well as the risks of loss of value of obsolete knowledge could be analysed. Similarly, it would be interesting to see whether regional inequalities in the weight of scientific employment create irreversibility, or whether efforts, even late, to increase the weight of weak regions, are fruitful.

A third investigation, finally, could be provided by a spatio-temporal analysis refined according to the categories of regions in France. The KPF of the MSTIF model would be applied to geographically and scientifically differentiated groups of regions in order to identify the types of knowledge spillovers most important for each group. Regions could be distinguished by groups according to the strength of the business innovation in these regions, to identify spillovers associated with excellence; according to the weight of regions in national scientific employment, to focus on regional dynamics of scientific human resources; or, depending on whether the regions contain metropolitan areas or not, to participate in the debates on geographical inequalities related to metropolisation.

Thus, by proposing the KPF of the MSTIF model, this article provides insights on the key resources of business innovation in France today. The results obtained, and the extensions envisaged, can feed the reflection of public decision-makers on science and innovation policy at national level and in the regions. They can also enable companies to identify sources of knowledge spillovers that will help them innovate, in order to make choices in resource allocation as well as localization.

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