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Article

Knowledge transfer profiles of public research organisations: the role of fields of knowledge specialisation

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Abstract

While Public research organisations (PROs) are increasingly expected to transfer knowledge to businesses and other stakeholders, their engagement in knowledge transfer (KT) activities is still under-researched. Better understanding of PROs' KT engagement, including how it is shaped by PROs' organisational characteristics, could lead to better tailored policies in support to PROs' effort to transfer knowledge. We develop a conceptual framework linking PROs' specialisation in different fields of knowledge to their profiles of KT engagement and validate it empirically using a six-year panel data set of 33 PROs in the UK. We use multidimensional scaling and cluster analysis techniques to identify three distinct KT profiles, which are stable over time, and strongly associated with the PROs' knowledge field specialisation. We argue that these profiles may depend on the different market readiness and user specificity of knowledge outputs arising from different fields of knowledge and derive implications for theory, policy, and practice.

Key words: public research organisations (PROs); multidimensional scaling; knowledge transfer; knowledge bases; market readiness; user specificity.

1. Introduction

Public research and development (R&D) investment is an important driver of economic growth and socioeconomic development (e.g. Crow and Bozeman 1999) and a key policy target in many countries (e.g. Gouardères 2019). Over time, social expectations around the effectiveness and efficiency of public R&D investment have escalated, leading to increasing demands for public research systems to 'give back' to society by transferring knowledge to industry and other external stakeholders (e.g. Maxwell-Jackson 2011).

Most public research systems rely (to different extents) on two main types of institutions: universities and public research organisations (PROs), the latter being also called national laboratories or government research institutes. While there is a wide literature on universities' knowledge transfer (KT) activities (see Perkmann et al. 2013; Ankrah and Al Tabbaa 2015, for comprehensive literature reviews), the specificities of PROs' engagement in KT have not been investigated extensively, probably due to the paucity of extensive and reliable data.

When PROs are studied, they are often part of larger and heterogeneous samples that include universities as well (e.g. Dutrénit and Arza 2010; Dutrénit et al. 2010; Orozco and Ruiz 2010; Arza and López 2011) or combine both government research centres and private non-profit organisations engaged in R&D activities such as research foundations (Teirlinck and Spithoven 2012; Landry et al. 2013).

Findings from studies of universities and other types of research organisations might not be easily generalised to PROs, since the latter have different organisational characteristics. In particular, universities and PROs differ in relation to, among others, their activities (PROs focus on research with very limited, if at all present, teaching activities), their scope (many PROs specialise in one or a few closely-related scientific fields), and the nature of their research (usually midway between fundamental academic research and commercial industrial R&D). Hence, more research focused specifically on PRO's KT engagement with external stakeholders is needed (Gulbrandsen 2017; Hallonsten 2017; Rossi and Athreye 2021).

With the present study we investigate the extent to which PROs have different profiles of engagement in KT—intended as different combinations of resources and channels used to transfer knowledge to external stakeholders (de la Torre et al. 2019)—and what explains these different profiles. By integrating literature from KT management and the economics of knowledge, we propose a novel conceptual framework associating KT engagement profiles to field of knowledge specialisation, on the basis of the economic properties of the different knowledge bases. This framework is then validated empirically thanks to a unique, purposefully constructed six-year panel data set of PROs in the UK.

Through a combination of multidimensional scaling (MDS) and clustering techniques, we identify several profiles of KT engagement, and we analyse these profiles' associations with the PROs' specialisation in different fields of knowledge and other organisational characteristics.

Our findings contribute to theory, policy, and management. In terms of theoretical contribution, we provide empirical support for our argument that different knowledge bases, building on different fields of knowledge, are associated with different degrees of usability and market readiness of knowledge outputs, which in turn favour the use of different KT channels and lead to different overall KT profiles. While prior literature has discussed some associations between fields of knowledge specialisation and use of different KT channels, it has not, to our knowledge, proposed an overarching explanation for these associations based on the economic properties of the different knowledge bases. In terms of science policy implications, better understanding of the implications of field of knowledge specialisation for KT can help to design policies that are better tailored to the needs of PROs in different fields. Our findings can also help PRO managers to understand which KT profile is more suited to their organisation and why and plan the resources needed.

The UK PRO sector is very varied, comprising organisations of different types, in relation to, among others, governance, affiliation, and remit. Given this variety, and PROs' freedom to engage in many channels of KT, UK PROs are likely to have experimented over time with different KT approaches to find those that best suit their characteristics. Consequently, we are able to identify a variety of KT profiles and a particularly high degree of alignment between such profiles and some of the PROs' organisational characteristics, including their field of knowledge specialisation.

This paper is structured as follows: Section 2 discusses the variety of KT activities and explores the links between field of knowledge specialisation and KT and innovation activities. We then develop a conceptual framework associating fields of knowledge to KT profiles. Section 3 describes PROs in the UK and illustrates our data and methodology. Section 4 presents the results of the empirical analysis, validating and extending our initial framework. Section 5 concludes with implications for theory, policy, and management and avenues for further research.

2. Field of knowledge specialisation and KT engagement: a theoretical framework

2.1 Antecedents to PROs' KT engagement and the role of field of knowledge specialisation

PROs are facing increasing social demands to generate impact on their socio-economic environment in the form of creation of new markets, offsetting risk for businesses, and averting social losses by providing disaster prevention information, environmental monitoring, and so on (Matsumoto et al. 2010). They also face growing pressures to diversify their income streams in the context of shrinking public funding (Maxwell-Jackson 2011; Archibugi and Filippetti 2018). Consequently, PROs increasingly strive to transfer knowledge to external stakeholders, both to derive additional income and to demonstrate their economic and societal relevance (Lyall et al. 2004; Dutrénit and Arza 2010; Rossi and Athreye 2021).

Research suggests that PROs commercialise their research outcomes through a variety of KT channels, among others, research contracts, consultancy services, prototyping, testing, personnel secondment, sharing of physical facilities, public engagement, outreach activities, spinning off companies (Neresini and Bucchi 2011; Smith 2015; Hughes et al. 2016a; Hallonsten et al. 2020), and patent filing and licensing—the latter being the most extensively investigated KT channel in the case of PROs (Azagra-Caro 2011, 2014; Rossi and Athreye 2021).

Nonetheless, the combinations of KT resources and channels that PROs deploy, and how these relate to the PROs' organisational characteristics, have not yet been investigated. Studies of universities have shown that different types of universities develop different profiles of KT engagement, which correlate with their research and teaching intensity (e.g. Kitagawa et al. 2016), subject specialisation (Benneworth and Jongbloed 2010), institutional resources, and strategic prioritisation of specific stakeholders (de la Torre et al. 2019). Similarly, we might also expect that different types of PROs, with different organisational characteristics—which imply different resource endowments—could approach KT in alternative ways, engaging in different KT channels.

Field of knowledge specialisation could be a particularly important organisational characteristic in this respect, as in many R&D systems, including the UK, PROs tend to specialise in one or a few fields of knowledge. Different fields of knowledge build on knowledge bases with intrinsically different features, and these might influence how knowledge is produced (the resources available for KT) and how knowledge is transferred and to whom (the channels used for KT).

Previous studies have linked the field of knowledge specialisation of research organisations to their patterns of KT engagement. This is because different knowledge fields rely on different knowledge production processes and organisational patterns (Lepori et al. 2010). First, their knowledge bases have different features. In science, technology, engineering, and maths (STEM), knowledge is usually highly codified and embodied in outputs that can be protected and commercialised through industrial and intellectual property, while in the humanities and social sciences (HSS), knowledge is often tacit or difficult to protect, so commercialisation relies on the provision of services such as consulting and research contracts (Olmos-Peñuela et al. 2014). Second, different fields of knowledge involve different costs: since STEM usually require large investments and running costs in equipment and facilities, interactions with business often involve collaborative research projects with public investment; in HSS, instead, research and KT costs are lower and small-scale consultancies are more common (Olmos-Peñuela et al. 2014). Third, markets in HSS are usually small, not well developed and with strong public sector participation, so collaborations are often occasional and informal, while STEM enjoy large markets in which long-term commercial exchanges are established through formal collaborations with industry (Olmos-Peñuela et al. 2014). Evidence confirms that academics and departments in STEM and HSS adopt different models of KT engagement, both in terms of the channels they use (Abreu and Grinevich 2013) and of the stakeholders they engage with (Kitagawa et al. 2016; Blasi et al. 2018).

In this study, we argue that the characteristics of the different knowledge bases in different fields are associated with different degrees of user specificity and market readiness of knowledge outputs, which in turn favour the use of different KT channels. This approach extends the above literature in several ways. First, to our knowledge, none of the previous studies have proposed any theoretical explanations for the association between field of knowledge specialisation and KT engagement based on the economic properties of knowledge bases. Second, empirical studies so far have mainly focused on universities rather than PROs, leaving the door open for further investigations in this domain.

2.2 Economic properties of knowledge bases in different fields and their links to KT channels

Asheim and Coenen (2005) and Davids and Frenken (2018) distinguished between three types of knowledge bases needed for innovation: analytical, synthetic, and symbolic. Analytical knowledge is needed to understand and explain empirical phenomena: it is highly codified, although tacit knowledge remains a necessary complement to understand and validate it. Synthetic knowledge refers to know-how and it is more tacit in nature: it is typically used to design artefacts and solutions to practical problems. Finally, symbolic knowledge is used to produce cultural meaning often in the form of cultural artefacts (Davids and Frenken 2018). This framework can provide useful elements to characterise the economic properties of the knowledge outputs of different fields of knowledge and to link these to different types of KT engagement.

The natural sciences have an important component of analytic knowledge (Spencer and Vinodrai 2006), which is abstract and universal, characterised as 'know what' and 'know why' (Lundvall and Johnson 1994), based on a commonly accepted language that can be easily codified and transferred, with relatively constant meaning across context (Autio 1997; Johnson et al. 2002). Typically, KT occurs through the embodiment of analytical knowledge into standardised information-based products such as patents, blueprints, recipes, software codes, maps, models, or forecasting tools (Asheim and Gertler 2005). These products have a high degree of market readiness: they can be commercialised to potential users without the need for prolonged further development. Analytical knowledge tends to be generalisable to a wide range of domains, so its user specificity is low and its codified nature means that direct interactions with the knowledge producer is not crucial for KT to occur (Asheim et al. 2007). Therefore, we can expect PROs whose knowledge base lies mainly in the natural sciences, to provide fairly standardised services and products, which can often be transferred through commercial transactions that do not require a lengthy further involvement on the part of the knowledge producer. We expect to find a prevalence of KT channels based on the commercialisation of information-based products and services. This leads to our first hypothesis:

H1: There is a positive association between a PRO's specialisation in the natural sciences and its use of KT channels based on the commercialisation of information-based products and services.

The technical sciences—like engineering and biotechnology and to some extent clinical sciences like medicine—have an important component of synthetic knowledge (Coenen et al. 2006; Spencer and Vinodrai 2006) since they often involve the search for solutions to specific applied problems. Synthetic knowledge is only partly codified and, when applying the knowledge to the solution of a user-specific problem, tacit knowledge 'know-how' and 'know-who' (Lundvall and Johnson 1994; Lundvall 1996) are important. With high user specificity, the application of synthetic knowledge to problem-solving usually demands the direct involvement of the knowledge producer (Dougherty 2004; Gertler 2004). Often, synthetic knowledge is applied to problems whose solution requires some kind of technological implementation (Gabrielsson et al. 2016), which implies a long and resource-intensive process that can involve numerous stages (including prototyping, testing, trialling, and scaling up) until knowledge is ready for commercialisation. That is, the degree of market readiness of knowledge outputs is low.

In many countries, technological development activities are considered the remit of the private sector, and government intervention in knowledge production is limited to funding basic research and some applied research in areas of strategic interest (Nelson 1959; Crow and

Tucker 2001; Cozzi and Galli 2017). Hence, PROs in such countries are unlikely to possess the resources needed to undergo the whole development and implementation process internally. Therefore, we can expect PROs whose knowledge base lies mainly in the technical and clinical sciences to rely for the exploitation of their research on external companies that are able to focus on the development stage and collect funds from the market—for example through various forms of venture capital. Very often, these will be spinoff companies, since they allow for a close involvement of the knowledge producer and since many companies are reluctant to invest in early-stage technology. In fact, in the case of universities, spinoff companies very often emerge from engineering or biotechnology departments (Caldera and Debande 2010; Matricano et al. 2013). PROs specialised in the technical and clinical sciences might also license their knowledge to external companies, which will then engage in the development and implementation process themselves. This leads to our second hypothesis:

H2: There is a positive association between a PRO's specialisation in the technical and clinical sciences and its use of KT channels based on the exploitation of intellectual property on the part of third parties—such as spinning out of companies and licensing of intellectual property.

The social sciences are characterised by knowledge created and transmitted in the form of interpretative frameworks and abstracted models of social behaviour, which contain a mix of analytical and symbolic knowledge (Spencer and Vinodrai 2006). The research outputs are abstract and in principle codified and have a high degree of market readiness, since they do not require a large amount of further technological development. However, this knowledge needs to be contextualised for the specific user in order to be meaningful. For example, the models and frameworks produced by social scientists in the context of business consulting or policy advice for government need to be adapted and contextualised to the specific situation of the user (Jacobson et al. 2004; Olmos-Peñuela et al. 2014), which entails the use of a shared cultural framework based on 'conventions, common languages and rules for developing, communicating and interpreting knowledge' (Storper 1997: 206). Therefore, we can expect PROs whose knowledge base lies mainly in the social sciences to have a high degree of user specificity, and therefore to rely on KT channels that involve direct interactions with their knowledge users, for example consultancies and research contracts. This leads to our third hypothesis:

H3: There is a positive association between a PRO's specialisation in the social sciences and its use of KT channels based on direct interaction with users—such as consultancies and research contracts.

Table 1 presents our original conceptual framework linking different fields of knowledge to different types of KT channels. The knowledge base that is prevalent in each field (synthetic, analytic, or symbolic) is associated with different degrees of market readiness and different degrees of user specificity, which in turn favour different types of KT channels.

3. Methodology

3.1 Context: public research organisations in the UK

PROs are important actors in the UK's research system—estimates suggest that public investment in the PRO sector is currently about one-third of the public investment in the university sector (Rossi and Athreye 2021). The origins of the system of PROs in the UK, like in many other countries in Europe, date back to the mid-19th century, in response to the need to regulate and standardise traded goods. In the late 19th century, public research laboratories were established to support military research, focusing on physics (e.g. the UK's National Physical Laboratory was founded in 1900). Since the Second World War the institutional environment of PROs has become increasingly turbulent in many countries (see Bozeman and Crow 1990 for the US case or Boden et al. 2004 for the UK), with a complex mix of external forces shaping the development and reforms of PRO systems. In the case of the UK, the PRO system received further boost in the post-war era (Charles and Howells 1992) which saw large government investment in public research laboratories, to promote national competitiveness in areas of strategic interest such as energy and space, in line with similar trends occurring in the USA and in other European countries (Organisation for Economic Co-operation and Development, OECD 1989; Slaughter and Roades 1996; Lawton-Smith 1997).

Starting from the 1960s, the system of UK PROs has undergone a process of progressive opening up to engagement with the private sector. On the one hand, PROs have been encouraged to collaborate with commercial organisations and initiate research contracts. PROs have been allowed to received private funding (Science and Technology Act, 1965) and more recently some government funds were specifically earmarked to support PROs' KT activities (the Public Sector Research Exploitation Fund, implemented in 2001, 2004, and 2006; HM Treasury 2007). On the other hand, since the late 1980s, under the banner of increasing efficiency and effectiveness of government investment, the UK government has implemented a process of progressive rationalisation of PROs, through mergers, closures, and transfers to the private sector (Lawton-Smith 1997; Lawton-Smith and Swyngedouw 2000; Boden et al. 2004; BIS 2015). Following this process, the UK PRO sector is smaller than it used to be and has converged on what Cruz-Castro et al. (2020) define as 'government laboratories'[1]: public institutions mainly focused on applied research activities that contribute to solving public policy issues, with some involvement in basic research (Baker 1999). Most basic research in the UK is carried out in universities, different from countries such as Germany, France, and Spain, where some PROs carry out substantial basic research (Cruz-Castro et al. 2020; Rossi and Athreye 2021).

Bozeman and Crow (1990) classified US PROs on the basis of their level of government influence (public funding) and their market influence (type of research outputs), considering a broader range of laboratories (also including some private ones). PROs in the UK are affiliated either to a UK Research Council or Government department as a 'specific parent body', so we could state that UK PROs would be classified as high government influenced in Bozeman and Crow (1990)'s classification. While UK PROs are expected to fulfil the missions and provide research services required by their parent body, evidence suggests that PROs have also increased their efforts to engage in KT activities with other stakeholders in industry and the public sector, beyond the engagement with their parent body (BIS 2014), showing different degrees of market influence (as defined by Bozeman and Crow 1990).

3.2 Data and sources

This study exploits a unique, purposefully constructed six-year panel data set of PROs in the UK, built mainly from public administrative records (annual reports and financial returns) and integrated with information from the PROs' websites, the European Patent Office (patents), Scopus, and Web of Science (WoS) (publications). We created a comprehensive list of 103 currently active organisations by analysing eight recent studies of PROs in the UK (Lyall et al. 2004; Maxwell-Jackson 2011; Government Office for Science 2013; BIS 2007, 2011, 2014; Smith 2015;

Hughes et al. 2016b). We then excluded organisations that primarily engaged in cultural missions (such as museums and film and sports councils), institutions that no longer engage in research (an institute that has become purely a payment agency, and two organisations that provide KT services to PROs) as well as institutions that, while government-funded, are based within universities and rely on university staff and organisational structures (34 Medical Research Council units).

For the remaining PROs, we collected demographic information from their websites and information from their annual financial statements for 6 years (2011/12 to 2016/17). Since financial statements are only produced by organisations that report independently, the final sample for which complete information was available includes 33 organisations (see the Appendix A). Of these, 27 (81 per cent) are affiliated to government departments and 6 (18 per cent) are affiliated to research councils. Such proportions are close to those of the overall universe of 103 PROs.

3.3 Empirical strategy

Our empirical analysis is performed in two stages. First, we identify PROs' KT profiles based on the resources they rely on and the KT channels they adopt; second, we explore the organisational characteristics of the PROs in each profile, including their field of knowledge specialisation. Figure 1 summarises our empirical approach.

For the identification of the KT profiles of PROs, we first apply Ordinal MDS (Kruskal and Wish 1978) to a set of variables capturing their KT resources and channels, listed in Table 2. MDS is a distance-based multivariate statistical technique increasingly used in innovation and higher education research (e.g. Sagarra et al. 2015, 2017; de la Torre et al. 2016, 2018, 2019). It summarises the information hidden in the structure of the data and displays in a multidimensional map the similarities and differences among the PROs analysed: when two PROs have very similar (different) variable structures, they are placed next to each other (far apart) in the Euclidean space (Sagarra et al. 2018). Unlike Factorial or Principal Component Analysis, MDS can deal with strong heterogeneity in the data, it is robust to outliers and redundant information, and does not assume normality.

We follow common practice in the literature (Sagarra et al. 2015) and run a single MDS analysis for the 6 years together, so for each of the 33 PROs we obtain six sets of coordinates (each PRO is located six times on the MDS multidimensional space, one for each year). This way we can follow the PRO's location in the MDS map over time (in comparison to the other institutions). This practice is not affected by endogeneity or multicollinearity because MDS is a multivariate technique that describes the structure behind the data (does not show causality) and naturally shows whether the profile of an institution is stable.

Additionally, following common practice in the MDS literature, we use property fitting (ProFit) to interpret the results of the MDS analysis. The ProFit analysis consists of parallel regressions (one for each variable initially included in the MDS analysis) that allow for the inclusion in the MDS multidimensional map of vectors that indicate the direction in which each of the PROs characteristics grows.

To identify PROs' KT profiles, we perform two parallel cluster analyses (Ward 1963): one (Cluster Analysis A) on the coordinates that locate PROs on the MDS map, so we can identify which PROs are located close to each other in the multidimensional space—i.e. which PROs have a similar KT profile and in which years; and a second cluster analysis (Cluster Analysis B) on the coordinates of the vectors from the ProFit analysis, so we can identify which variables capturing the characteristics of PROs are more closely linked to each other.

The nine variables included in the MDS analysis portray a comprehensive characterisation of the main KT resources and channels of PROs in the UK. We avoid size-related effects by including the dimensions that are most size-dependent in the form of ratios.

Six of these variables capture the PROs' KT channels, as follows: two relate to the commercialisation of information-based products and services (in order to test H1)—the number of external (subsidiary and associate) companies the PRO relies on to provide services (*outsourced_ser*) and the number of patent applications (*patent*). Three variables relate to the third-party exploitation of intellectual property (to test H2): the number of external (subsidiary and associate) companies the PRO relies on for research commercialisation (*outsourced_res*), the number of spin-offs (subsidiary and associate companies that perform research exploitation activities), *spinoffs* and the presence of an incubator (since usually only one incubator per PRO is present, if at all, we use the binary variable *incubator* equal to one if the PRO can rely on the services of an incubator). One variable relates to direct interactions with users (to test H3): the share of income from private sources, *income_private* (capturing interactions with the private sector through income-generating activities like research contracts, consultancies, or service provision, including, among others, testing services and training courses).

Additionally, three variables capture the resources that the PRO can use as inputs for its KT activities: intellectual resources (publications per employee, *public_employee*) and public financial resources (shares of core income, *income_core*, i.e. income allocated to the PRO directly by the government department or research council it is affiliated to; and share of competitive public income, *income_competi*, i.e. income won by the PRO by applying for research grants from a variety of public funders).

Once the KT profiles have been defined, we describe the organisational characteristics of the PROs belonging to each profile. We place a special emphasis on the PROs' field of knowledge specialisation. We know that different fields of knowledge *within* these broader domains are themselves characterised by different types of production processes and organisational patterns (Lepori et al. 2010) and are grounded on different knowledge bases. Hence, research organisations specialised in different sub-fields may develop different KT profiles. Consequently, unlike previous studies on subject specialisation of research institutions, which compared very broad knowledge domains (e.g. STEM and HSS), we base our empirical analysis of the field of knowledge specialisation of the PROs on a more fine-grained approach.

In particular, we follow two parallel approaches. First, we analyse the economic sectors that each PRO reports to be the main 'users' of its knowledge. We use a classification of user sectors into 21 categories, identified through expert interviews (Smith 2015: 19)—for greater clarity we have aggregated these into eight main categories.[2] Second, to gain clearer insight about the actual knowledge bases of PROs, we consider the scientific publications of each PRO in each of the 254 fields of science reported in the WoS database, for the usual 6 years, (2011/12 to 2016/17) and we examine the association between PROs' KT profiles and their fields of knowledge specialisation. To allow for interpretability of these results, we resort to the classification of the WoS fields into 15 main categories suggested by Glänzel and Schubert (2003). This classification was produced by combining expert opinion with the scientometric analysis of scientific journals, and it considers recent developments in disciplinary fields—for example, this classification clearly separates biosciences as an emerging discipline. To further aid interpretation, we aggregate the 15 categories suggested by Glänzel and Schubert (2003) into Technical and Clinical Sciences, Natural Sciences, and Social Sciences and Humanities. Table 3 shows the classification of the 15 categories into the main fields of knowledge, as well as the shares of publications in the full sample for each category. The distribution of publication shares is much skewed, with Biology and Bioscience accounting for the majority of publications.

4. Results

Following common practice in the MDS literature, we look for the optimal number of dimensions for the MDS configuration: the one that balances its goodness of fit ($Stress_1$—see Kruskal and Wish 1978) and interpretability of results. Our final MDS construct summarises the nine variables in Table 1 in six dimensions, which return a value of $Stress_1$ of 0.037, considered to be 'excellent' in Kruskal's (1964) verbal classification. As it is evident from Table 4, which shows the results of the ProFit analysis, all the regressions on the six dimensions of the MDS are highly explanatory (Adjusted *R*-squared higher than 0.74). The vector of private income points towards the positive side of the first dimension, implying that the PROs located towards the positive side of the first dimension have a higher share of private income than those PROs located in the opposite side. The second dimension is associated with outsourced service provision, the third with publications per employee and competitive income, the fourth with share of private income, the fifth with outsourced research commercialisation, and finally the sixth dimension is highly associated with spinoffs, outsourced service provision, and publications per employee.

Having derived the MDS coordinates, first, we ran a cluster analysis (Cluster Analysis A) on the MDS coordinates for the 198 observations, obtaining three optimal clusters. The allocation of the 33 PROs to the three clusters in the six periods is shown in Fig. 3. To aid in the interpretation of these clusters, Table 5 reports, for each cluster, the average values of the nine variables used in the MDS analysis.

The PROs in Cluster 3 are research-intensive institutions with high number of publications per employee and a high share of non-competitive core income. They rely on external infrastructures for the exploitation of their knowledge outputs: spinoffs, incubators, and companies dedicated to research commercialisation. We call this the ‘External Exploitation’ (EE) profile because the process of developing marketable products based on the knowledge transferred from the PRO is carried out outside the PRO, by the spinoff companies or by the businesses that acquire the PRO’s intellectual property (in fact, PROs receive a relatively small share of income directly from private sources, suggesting that most of their KT activities are managed externally).

The PROs in Cluster 1 obtain a large share of their research funds competitively, and they rely on market commercialisation both for their research outcomes (through patenting) and for the provision of services (through specialised companies). They also receive a relatively high share of income from private sources. We call this the ‘Market Commercialization’ (MC) profile.

Finally, PROs in Cluster 2 may be characterised as having a ‘User Collaboration’ (UC) profile, which is developed through government-funded research and direct collaborations with users through research contracts, consultancies, and the provision of services, managed by the PRO without relying on external companies.

These results are consistent with those of Son et al. (2019) who (for the case of China), identify negative effects of PROs–industry collaboration on spin-off creation (and therefore these activities are likely to belong to different KT strategies).

Cluster Analysis B on the coordinates for vectors' direction of the nine variables further supports these findings. According to the dendrogram shown in Fig. 2, the variables can be grouped in three clusters that are strongly aligned to the three afore-mentioned KT profiles: the 'EE profile' cluster includes the variables capturing the share of core public income, the number of publications per employee, the number of companies to which research commercialisation is outsourced, the number of spin-offs, and the presence of an incubator. The 'MC profile' cluster includes the variables capturing the share of competitive public income, the number of patent applications, and the number companies to which service provision is outsourced. The 'UC profile' cluster includes the variable share of private income.

It must be noted that, as evident from Table 5, all PROs, irrespective of their KT profiles, tend to engage in *all* channels of KT to some extent. However, the relative importance of these channels will be different for PROs that adopt different profiles—some (EE profile) emphasise spin-offs and licensing, others (UC profile) emphasise direct collaborations with users, yet others (MC profile) emphasise the commercialisation of information-based products and services.

Considering the clusters' evolution over time (Fig. 3), we find remarkable stability. Only four PROs belong to different clusters in different periods, one switching between the MC and UC clusters, one switching between EE and UC, one between MC and EE, and one first switching from UC to EE and then to MC. Moreover, only six switches occur overall, out of a possible 198 time-observation points. The PROs' knowledge bases are also stable, since we find no significant differences in the mean shares of publications in each subject over the six periods, in the overall sample, and in each of the three clusters separately. This further aligns with our suggestions that KT profiles are associated with field of knowledge specialisation, as the stability of the former is associated with stability in the PROs' underpinning knowledge base.

We can use the results of the MDS mapping to show how each PRO moves over time in the space of the coordinates of the six dimensions. However, since the MDS configuration is a map in a six-dimensional space, we need to resort to projections on pairs of dimensions. We have explored different configuration projections, verifying that the different combinations among the first and most relevant dimensions show a clear distinction among the three clusters and their specific KT profiles. For instance, Fig. 4 shows the projection of the MDS configuration on Dimension 1 and Dimension 3 in Years 2012 and 2017. Interestingly, this figure shows that the MC and EE profiles seem to be more 'extreme' profiles, with the UC profile being somewhat intermediate between the two (the UC cluster is positioned at the centre of the figure while EE and MC clusters are positioned at opposite ends, EE towards the left and MC towards the right). Also, the MC profile PROs are getting closer to the UC profile PROs. A possible explanation could be that direct collaborations with PROs help firms to leverage patenting investments (Thursby et al. 2001; Son et al. 2019) so we see an increasing complementary use of these channels.

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Having identified three significant KT profiles, we then explore whether they are underpinned by different organisational characteristics.

We find significant differences among the three clusters in terms of PRO age and size, even though our MDS analysis specification aimed to avoid size-related effects. According to Table 6, PROs that adopt the EE profile have a high share of income from core government funding (almost 80 per cent) and a low share of public income from competitive grants (about 13 per cent) and about 9 per cent of their income comes from private sources. They are in between the other two clusters in terms of size (employees and overall income), and they are on average younger. PROs that adopt the UC profile derive about 71 per cent of their income from core public funding and about 14 per cent of their public income from competitive public funding; they have an intermediate share of private funding (13 per cent). They are larger in terms of employees and overall income. Finally, PROs that adopt the MC profile have low share of income from core government funding (only about 22 per cent), high share of public income from competitive research grants (almost 60 per cent), and they get a high share of income from private sources (about 40 per cent). They are older and smaller in terms of employees and overall income.

Focusing on the specialisation of PROs by 'user sectors' (Table 7) and fields of knowledge according to their scientific publications (Table 8), KT profiles seem to be related to research specialisation in specific fields of knowledge, aligned with the hypotheses arising from our conceptual framework (Table 1). Also, as a robustness check, we have performed the same analysis according to the knowledge classification provided by the OECD (2007) together with the concordance with WoS field, for which similar results hold.[3]

The EE cluster comprises PROs with an above-average share of publications in Engineering and Medicine (Table 8), and whose knowledge is particularly used in the Health and Pharmaceutical, Biology, Security, and Spatial Planning sectors (Table 7). Health and Pharmaceutical sectors are typical users of clinical knowledge while the Security and Spatial Planning sectors are users of technical knowledge. Many of these PROs develop technologies emerging from biotechnology or defence-related research. The technical and clinical sciences are characterised by knowledge that is often translated into product innovations that require very long development time to become market-ready. Hence, the main mode of KT is based on spinoff companies, which allow for further development before commercialisation, or on the licensing of intellectual property to companies willing to engage in their own further development. This is consistent with our hypothesis H2.

The MC cluster comprises mainly PROs with an above-average share of publications in the natural sciences, particularly the study of the physical environment (Geosciences and Space science, Maths, Physics, and Chemistry—Table 8), whose knowledge is mainly used in Agriculture and Food, Computational Modelling, and Policy Advice (Table 7). The natural sciences are characterised by analytical knowledge that can be transferred in codified form and does not require very long development time to become market-ready. Among these, the study of the physical environment leads to findings that are generalisable and not very user-specific, hence they can be commercialised through the provision of outsourced services. In particular, many of these PROs transfer knowledge in the form of software codes, maps, models, or forecasting tools that can be used by various clients with minimal adaptation. This is partly consistent with our hypothesis H1, since we find a positive association between this mode of KT and specialisation in the sub-field of natural sciences that focuses on the study of the physical environment (but not on biological systems). These findings are aligned with the evidence from Nilsen and Anelli (2016) who, in a case study of CERN, show that software commercialisation is one of the main commercialisation channels for this organisation with a significant knowledge base in the sciences of the physical environment.

The UC cluster comprises PROs with an above-average share of publications in social sciences and in biological sciences (Table 8) whose knowledge is particularly used in providing Business and Policy Advice and in Environmental management (Table 7). Social sciences knowledge does not require very long development times to become market ready, but the findings are often user-specific, and they require direct interactions with users to be transmitted adequately. Hence, the main mode of KT is based on interactions with users via consultancies and research contracts. Many of these PROs transfer knowledge in the form of policy and compliance advice and training, which require specific interactions with users. This is consistent with our hypothesis H3, since we find a positive association between this mode of KT and specialisation in the social sciences. Interestingly, this group also includes some PROs specialised in the natural sciences, specifically in biology, agriculture, and environment. Like all natural sciences, biological sciences have a content of analytical knowledge, so a high degree of market readiness, but they are perhaps more user-specific than the sciences of the physical environment, and therefore they require direct interactions with users to be effectively transferred. This finding confirms the limitations of those studies on the subject specialisation of research institutions that focused their analysis on very broad knowledge domains (e.g. STEM and HSS). As we noted before, different fields of knowledge *within* these broader domains present diverse characteristics and behaviours.

Our conceptual framework also provides us with an interpretation for the finding that the MC and EE profiles are more ‘extreme’ profiles, with the UC profile being intermediate between the two (Fig. 4). Indeed, according to our framework, the UC profile is associated with knowledge with high degree of market readiness, like the MC profile, and high degree of user specificity, like the EE profile; thus, the UC profile is underpinned by a knowledge base whose economic properties are intermediate between those of the knowledge bases underpinning the other two profiles.

Bringing together our initial theoretical framework with our empirical findings, Fig. 5 proposes a model to explain PROs' KT profiles on the basis of the two main dimensions: the degree of market readiness of the knowledge produced (high or low additional resources required for further development) and the need for customisation for the user (high or low user specificity).

5. Conclusions

Unlike in other countries (e.g. the USA, Spain, or France), the public organisations or laboratories dedicated to research in the UK are rather homogeneous in the sense that they all are government dependent and all are considered to be 'government laboratories' (as defined by Cruz-Castro et al. 2020), focusing mainly on applied research activities. However, they display a broad range of objectives and activities, suggesting strong heterogeneity at the micro level. This study represents a first step to make sense of complex KT profiles of PROs, which so far have been under-researched. We propose a theoretical explanation for the links between field of knowledge specialisation and KT engagement, based on the economic properties of the different knowledge bases. Then, we empirically test it using evidence from PROs in the UK.

The three KT profiles of PROs may be termed 'External Exploitation' (EE), 'User Collaboration' (UC), and 'Market Commercialization' (MC). Each profile is related to specific organisational characteristics: size, income streams, and field of knowledge specialisation, which shows a strong knowledge-based differentiation. Consistent with our theoretical framework and hypotheses, as PROs are highly specialised in specific fields of knowledge, they rely on different resources, and resort to different balances of KT channels, because the nature of the knowledge they produce entails different degrees of market readiness and user specificity.

These findings allow to acknowledge new sources of UK PROs diversity, suggesting several implications for theory, policy, and PRO management.

Theoretically, we propose the argument that different knowledge bases (building on different fields of knowledge) are associated with different degrees of usability and market readiness of knowledge outputs—which in turn favour the use of specific KT channels and lead to different overall KT profiles of PROs. Our empirical evidence is consistent with the hypotheses that we developed building on this argument, although causal mechanisms cannot be directly proven. This framework could be used to further test and refine hypotheses on the evolution of PROs populations, being helpful to explain emerging patterns of KT engagement also in other settings, in relation to organisations whose research activities emerge from knowledge bases in specific fields and in relation to different national contexts. In relation to this last point, our findings are somewhat aligned with the analysis by Bozeman and Crow (1990) in the USA, in particular in relation to the subset of US laboratories highly dependent on government. Although Bozeman and Crow (1990) classified US public and private R&D laboratories on the basis of different factors (public versus market influence) compared to our study (where we classify UK PROs according to their knowledge transfer profiles), we find interesting parallels between both studies. As we argued earlier, the UK PROs we analyse are, in Bozeman and Crow's terminology, highly government dependent but showing different degrees of market influence. Accordingly, our MC profile shows similar features to Bozeman and Crow's 'public technology laboratories', which display 'high market influence' (low share of core public funding and high shares of competitive public funding and of private income). Our UC profile seems similar to Bozeman's 'public science and technology laboratories', which show a moderate market influence (moderate shares of competitive public funding and of private income and high share of core public funding). And finally, our EE profile shows similarities with Bozeman's 'public science laboratories', which rely mainly on core public funding to perform basic and long range applied research and have low market influence. Parallel to Fig. 4, EE and MC profiles are also the extreme clusters in Bozeman's classification (high and low market influence) with the UC profile in the middle (moderate market influence). Bozeman and Crow did not analyse research laboratories according to their fields of knowledge specialisation, but a look at their classification shows that the 'high market influence' (MC) group includes some PROs that specialise in sciences of the physical environment (e.g. geology), the 'moderate market influence' group includes some PROs that specialise in agriculture, and the 'low market influence' group includes some PROs that specialise in engineering and clinical sciences. This suggests that our conceptual framework could apply to the case of PROs in other national contexts, although this would have to be tested with appropriate data.

In terms of policy implications, in order to ensure efficiency and effectiveness in public expenditure, public science and innovation policies must consider the specificities of different PROs to properly support and assess their impact on their socio-economic environment. For example, the impact of the research carried out by PROs adopting the EE profile may be more difficult to track because it will need further development, which will take place outside the PRO, whereas PROs that adopt the UC and MC profile may be able to track the impact of their KT engagement more directly. Therefore, the metrics to evaluate PROs' success in KT should be different according to the KT profile they have developed.

Another example is the type of support that the different types of PROs need. Our findings are relevant to the design of fine-grained PRO public policies that take into account PRO specificities and institutional heterogeneity, considering their relation to system-level effects in large-scale policies. For example, if policymakers pursue accelerating innovation in particular sectors, they should take into account the knowledge bases of the PROs involved. Policies could support innovation in sectors relying on the knowledge produced by the EE profile PROs, by providing these PROs with access to seed funds and public venture capital to build and grow spin-off companies, and by providing facilities like incubators and accelerators. MC profile PROs could be provided with access to funding and expertise to set up companies to commercialise their services. UC profile PROs could be supported in setting up consultancy services and in networking with businesses. Consequently, based on the strategic priorities of governments on the short/long term, support policies should consider different design features.

Also, our results could help to find complementarities among PROs, being useful in future reforms of the PRO sector. Of course, there are many other factors not covered in this research that should be considered in PRO policy design (e.g. environmental patterns and organisational structure) in order to systematically plan the consequent changes in knowledge flow and direction (Bozeman and Crow 1990), taking into account the organic scientific change in policy-driven changes (Boden et al. 2004). This could help to better consider the needs, performance, and role of those PROs located in the boundaries of our profiles.

Regarding management, PROs that adopt the EE model must plan their resources to ensure that they have the competences to manage their relationship with external commercialisation companies as well as the ability to set up spinoff companies and seek financing for them. PROs that adopt the MC model need to ensure that they have the management competences to set up appropriate contracts with external service companies and to regulate their relationship in a mutually beneficial way. Finally, PROs that rely on a UC model need to ensure that they have the appropriate internal resources and competences to manage the relationships with clients (de Silva and Rossi 2018), and they need to organise their internal resources so as to maximise the synergies between research and KT. This is an exploratory study building on a small data set that has been carefully constructed by integrating different sources, the main one of which is PROs' financial reports. It would be valuable to develop similar analyses for a larger set of PROs, if more information could be collected for example through interviews or surveys. The knowledge base of the PROs has been assessed using information about publications in Scopus and WoS, but this has some limitations, including the fact that not all PROs publish and these databases are skewed towards specific fields of knowledge. Therefore, other ways to analyse the PROs' knowledge base could be attempted. More detailed information about the PROs' use of different KT channels would also be valuable. Also, this study focuses on the UK and the findings might be specific to this context; similar analyses could be carried out for PROs in other countries in order to understand whether the patterns identified here are robust in other contexts. Another complementary area that so far has received limited attention is the type of competences that PROs need to develop to perform their KT processes more efficiently and effectively.

Decades ago, Hannan and Freeman (1977) wondered about why there are so many different kinds of organisations. Some researchers suggested that environmental factors foster the emergence of alternative paths for institutional evolution (e.g. Campbell 1965; or Bozeman and Crow 1990 for the case of research laboratories). Our findings, in line with previous research (e.g. Lepori et al. 2010) show that the specific internal characteristics of research institutions (the knowledge bases underpinning their research) also shape the organisational features and the role of PROs within their innovation system.

Conflict of interest statement. None declared.

Notes

1. Cruz-Castro et al. (2020) categorise PROs from eight European countries (not including the UK) depending on their mission, legal status, orientation of their R&D activity, their membership to research and technology organisations' associations. They identify four typologies or PROs: Research councils, Technology and innovation centres, Government laboratories (UK PROs belong to this category), and Hybrids.

2. The eight sectors are Health and Pharmaceuticals (includes Human Health and Wellbeing, Disease Control, Laboratory Services, and Pharmaceuticals); Agriculture and Food (includes Agriculture, Animal Health, Food, Biological Sciences, Plants, Marine Environment, and Aquatic Life); Environmental management (includes Climate Change, Environmental Science, Sustainability, and Space and Earth Observation), Spatial Planning (includes Land Use and Built Environment); Policy Advice; Business; (National) Security; and Computational Modelling (includes Mathematical Modelling and Physical Sciences).

3. These results are available in a Technical Annex upon request from the corresponding author. The concordance table is available from http://help.prod-incites.com/inCites2Live/filterValuesGroup/researchAreaSchema/oecdCategoryScheme.html (accessed March 2021).

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Appendix A List of PROs included in the sample.

N	Full name	Acronym
1	The Met Office	met
2	National Physical Laboratory	phys
3	UK Atomic Energy Authority	atom
4	National Measurement and Regulation Office	measure
5	Ordnance Survey	ordn

N	Full name	Acronym
6	UK Space Agency	space
7	Animal and Plant Health Agency	animal
8	Centre for Environment, Fisheries and Aquaculture Science (Cefas)	aqua
9	Environment Agency	environ
10	Royal Botanic Gardens Kew	botanic
11	Veterinary Medicines Directorate (VMD)	vet
12	Natural England	natural
13	Public Health England (PHE)	health
14	Forest Research	forest
15	Health and Safety Executive	safety
16	Atomic Weapons Establishment	weapons
17	Defence Science and Technology Laboratory (DSTL)	dstl
18	Hydrographics Office	hydro
19	Royal Botanic Garden Edinburgh	botedin

N	Full name	Acronym
20	Scottish Natural Heritage	scottnat
21	Moredun Research Institute	moredun
22	James Hutton Institute	hutton
23	Biomathematics and Statistics Scotland	biomaths
24	Agri-Food and Biosciences Institute of Northern Ireland	agrifood
25	Forest Service (Northern Ireland)	forestnorth
26	National Nuclear Laboratory	nuclear
27	Earlham Institute	earlham
28	Babraham Institute	babra
29	Quadram Institute	quadr
30	John Innes Centre	innes
31	Rothamsted Research	roth
32	Pirbright Institute	pirbright
33	Armagh Observatory	armagh

Table 1. Fields of knowledge and KT activities.

Field of knowledge	**Natural sciences**	**Social sciences**	**Technical and clinical sciences**
Type of knowledge base	Analytical knowledge	Symbolic and analytical knowledge	Synthetic knowledge
Degree of user specificity	Low	High	High
Degree of market readiness	High	High	Low
Expected prevalent KT channel	H1: Commercialisation of information-based products and services	H3: Direct interactions with users (e.g. consultancies and research contracts)	H2: Exploitation of intellectual property on the part of third parties (e.g. spinning off companies and IP licensing to business)

Table 2. Variables used to identify PROs' KT profiles.

Dimension	N	Variable ID	Variable description	No. of obs.	Min	Max	Mean	St. Dev.	Skewness	Kurtosis
KT channels	1	outsourced_res	Outsourced research commercialisation	198	0	3	0.41	0.89	2.10	6.03
	2	patent	No. of patent applications[a]	198	0	6	0.43	1.01	3.01	14.04
	3	outsourced_ser	Outsourced service provision	198	0	10	0.87	1.76	3.20	14.90
	4	spinoffs	No. of spin-offs	198	0	7	0.47	1.27	3.45	14.73
	5	incubator	Presence of at least one incubator (binary)	198	0	1	0.17	0.37	1.79	4.2
	6	income_private	Share of private income	198	0	0.95	0.19	0.25	1.91	5.77
KT resources	7	public_employee	No. of publications per employee[b]	198	0	570	35.38	66.34	5.29	38.00
	8	income_competi	Share of competitive public income	198	0	1	0.25	0.30	1.36	3.70

Dimension	*N*	Variable ID	Variable description	No. of obs.	Min	Max	Mean	St. Dev.	Skewness	Kurtosis
	9	income_core	Share of core income	198	0	1	0.59	0.32	−0.55	2.02

[a]Source: European Patent Office’s database.

[b]Source: Scopus database.

Note: The remaining variables were drawn from the PROs’ financial statements.

Table 3. Aggregation into main fields of knowledge and main statistics on the shares of publications.

Group	Field	Category (Glänzel and Schubert 2003)	Share of publications in sample
Technical and Clinical Sciences	***Engineering***	Bioscience	0.26
		Engineering	0.22
		Biomedical research	0.05
	Medicine	Clinical Medicine Internal	0.14

		Clinical Medicine External	*0.02*
		Neuroscience and Behaviour	*0.01*
Natural Sciences	***Biological systems***	Biology	0.39
		Agriculture and Environment	0.17
	Physical environment	Geosciences and Space science	0.15
		Maths	0.05
		Chemistry	0.07
		Physics	0.06
Social Sciences and Humanities	***Social/human systems***	Social Sciences—economic and political issues	0.07
		Social Sciences—general, regional, and community issues	*0.01*
		Arts and Humanities	*0.00*

Note: shares do not sum to 100, since each publication can be attributed to more than one category in the WoS database. The fields listed in italics in the table are those that count for less than 5 per cent of the publications of PROs, on average and in the sample. There are 174 observations because not all PROs were published in WoS every year.

For consistency with our framework, we have made two small changes in the application of the Glänzel and Schubert classification: (1) we have included Computer Science in the Maths category and (2) we have included Chemical Engineering in the Engineering category.

Table 4. Results of the ProFit analysis.

Dimension	Variable ID	Dim1	Dim2	Dim3	Dim4	Dim5	Dim6	Adj. R^2
KT channels	outsourced_ser	0.01	**0.60**	−0.03	0.45	−0.28	**0.60**	0.74
	patent	−0.12	0.45	0.45	0.08	**−0.63**	−0.43	0.89
	outsourced_res	−0.46	0.44	0.08	−0.03	**0.75**	0.19	0.86
	spinoffs	−0.33	0.27	−0.44	−0.20	−0.32	**0.70**	0.78
	incubator	−0.16	0.24	−0.35	−0.29	0.24	**−0.81**	0.95
	income_private	**0.60**	0.26	−0.39	**0.61**	0.21	−0.06	0.90
KT resources	public_employee	−0.20	−0.13	**0.52**	0.47	0.15	**0.65**	0.83
	income_competi	0.25	0.35	**0.50**	**−0.70**	0.22	0.15	0.92
	income_core	**−0.74**	**−0.53**	−0.11	0.10	−0.38	−0.09	0.93

Table 5. Variables used in MDS analysis by cluster. Average by cluster.

Dimension	**Variable ID**	**Cluster number and acronym**			***F*-test**	**Prob > *F***
		1—MC	**2—UC**	**3—EE**		
Number	—	52	116	30	—	—
KT channels	outsourced_ser*	**1.83**	0.22	1.73	23.77	0.00***
	patent**	**0.98**	0.16	0.57	13.94	0.00***
	outsourced_res*	0.31	0.07	**1.90**	104.52	0.00***
	spinoffs*	0.23	0.21	**1.90**	29.03	0.00***
	incubator*	0.10	0.00	**0.93**	322.37	0.00***
	income_private*	**0.40**	**0.13**	0.09	31.61	0.00***
KT resources	public_employee*	21.81	37.15	**52.05**	2.1	0.13
	income_competi*	**0.58**	0.14	0.13	68.95	0.00***
	income_core*	0.22	**0.71**	**0.79**	98.43	0.00***

Note: statistical significance of the mean difference between clusters, *>90 per cent.

**>95 per cent.

***>99 per cent.

Table 6. Characteristics of PROs by cluster. Average by cluster.

Cluster acronym	**N**	**Age**	**Size**		**Funding model**		
			No. of employees	**Total income (million)**	**% private income**	**% core income**	**% competitive public income**
MC	52	121.29	656.33	77.00	0.40	0.22	0.58
UC	116	79.55	1,690.23	332.00	0.13	0.71	0.14
EE	30	59.97	905.50	146.00	0.09	0.79	0.13
Sample average		87.55	1,299.80	237.00	0.19	0.59	0.25
F-test		5.83	5.59	3.62	31.61	98.43	68.95
Prob > *F*		0.003***	0.004***	0.029**	0.000***	0.000***	0.000***

Note: statistical significance of the mean difference between clusters, ~~*>90 per cent.~~

**>95 per cent.

***>99 per cent.

Table 7. Distribution of PROs by user sectors.

Cluster acronym	**Health and pharmaceuticals**	**Security**	**Spatial planning**	**Environmental management**	**Business**	**Policy advice**	**Computational modelling**	**Agriculture and Food**
MC	0.31	0.12	0.00	0.23	0.12	**0.37**	**0.46**	**0.65**
UC	0.38	0.05	0.10	**0.36**	**0.16**	**0.35**	0.26	0.37
EE	**0.80**	**0.20**	**0.20**	0.20	0.00	0.00	0.00	0.63
Sample average	0.42	0.09	0.09	0.30	0.12	0.30	0.27	0.48
F-test	11.69	3.50	5.04	2.37	2.74	8.22	11.39	7.79
Prob > *F*	0.000***	0.03**	0.01**	0.096*	0.07*	0.000***	0.000***	0.001***

Note: statistical significance of the mean difference between clusters, *>90 per cent.

**>95 per cent.

***>99 per cent.

Table 8. Average shares of publications by field of knowledge and KT profile.

Cluster acronym	**Natural sciences**		**Social sciences**	**Technical and clinical sciences**	
	Physical environment	**Biological systems**	**Social/human systems**	**Engineering**	**Medicine**
MC	**0.48**	0.50	0.03	0.43	0.22
UC	0.42	**0.64**	**0.10**	0.38	0.13
EE	0.22	0.36	0.01	**0.79**	**0.27**
Sample average	0.40	0.56	0.07	0.46	0.17
F-test	3.13	3.77	2.63	17.63	6.20
Prob > *F*	0.05***	0.02**	0.08*	0.000***	0.003***

Note: statistical significance of the mean difference between clusters, *>89 per cent.

**>95 per cent.

***>99 per cent.

For robustness check, we ran the same analysis but excluding those few fields with less than 5 per cent of the publications in the sample, getting similar results.

Figure 1. Empirical strategy.

Figure 2. Dendrogram for the cluster analysis on the variables' vectors (ProFit analysis).

Figure 3. Clustering of PROs based on MDS coordinates over time.

Figure 4. PROs' location on the MDS configuration for Years 2012 and 2017. Dimensions 1 and 3.

Figure 5. Market readiness, user specificity, and fields of knowledge.