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A quantitative measure to compare the disciplinary profiles of research systems and their evolution over time

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ABSTRACT

By modeling research systems as complex systems we generalize similarity measures used in the literature during the last two decades. We propose to use the mathematical tools developed within the spin-glasses literature to evaluate similarity *within* systems and *between* systems in a unified manner. Our measure is based on the 'overlap' of disciplinary profiles of a set of research systems and can readily be integrated in the framework of traditional bibliometric profile analysis. The investigation of the distribution of the overlaps provides useful insights on the dynamics of the general system, that is whether it converges toward a unique disciplinary structure or to a differentiated pattern.

We illustrate the usefulness of the approach by investigating the dynamics of disciplinary profiles of European countries from 1996 to 2011. We analyze several bibliometric indicators (including publications and citations) of European countries in the 27 Scopus subject categories. We compare the disciplinary profiles of European countries (i) among them; (ii) with respect to the European standard; and (iii) to the World reference.

We find that there is a convergence toward a unique European disciplinary profile of the scientific production even if large differences in the scientific profiles still remain. The investigation of the dynamics by year shows that developing countries are converging toward the European model while some developed countries are departing from it.

1. Introduction

The disciplinary structure of the scientific production of countries has been much studied in the literature (see e.g. Almeida, Pais, & Formosinho, 2009; Glänzel, Debackere, & Meyer, 2008; Tian, Wen, & Hong, 2008). Several studies have analyzed national publication profiles. National publication profiles indeed show interesting features about a country's research system and its national scientific policy. A commonly used approach is based on the study of publication profiles by discipline. Within this framework, the world's scientific output is divided into major scientific fields, and the relative contribution of each country with respect to each field is illustrated on a radar chart (see e.g. Glänzel, 2000; King, 2004). The publication profile of a national research system is then measured by the Relative Specialization Index which indicates whether a country has a relatively lower or higher share in world publications in a given discipline than in its overall share of world total publications.

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Several measures of similarities or diversities (dissimilarities) over given categories have been proposed.[1] Undoubtedly, the investigation on diversity has attracted the interest of many and various disciplines. Diversity has been studied in ecology, information science, in social sciences and also in Science and Technology (S&T) studies. In 2007 Stirling systematized the concept of diversity in three main pillars[2] and proposed a quantitative non-parametric diversity heuristic (named Δ hereafter) (see Stirling, 2007).

More recently, Zhou et al. proposed to study the diversity *within* systems and *between* systems together (see Zhou, Rousseau, Yang, Yue, & Yang, 2012). They proposed to use as a measure of diversity *within* systems the classical Gini index (named G hereafter) or the Simpson concentration index (S hereafter), which is known also in industrial economics as the Herfindahl–Hirschman index. On the contrary, to measure similarities *between* systems they proposed the popular Salton's cosine measure (named φ hereafter). In addition they introduced a structure of weights (d_{ij}, hereafter) to take disparity into account.

However, to the best of our knowledge, none of the existing studies have investigated the quantitative evaluation of disciplinary profiles of a set of S&T systems (i.e. countries, regions, Public Research Organizations (PROs), universities and so on) and their evolution over time in a general framework in which the scientific production is modeled as a complex system. This is exactly our aim.

In this paper we propose a more general measure of similarity of disciplinary profiles *between* systems, which includes as a special case the evaluation of similarity *within* systems. This measure is borrowed from the physics of complex systems, in particular from spin-glasses systems, which are the prototype of a complex system (that are increasingly applied in a wide range of empirical contexts in other fields, such as biology, computer science, economics of financial markets and so on) where it is named *overlap*. The specific case of similarity *within* a system is called *self-overlap* and coincides with Rao's quadratic diversity index. Therefore, by modeling research activities as complex systems we generalize similarity measures used in the literature during the last two decades and propose an approach that can readily be integrated in the framework of traditional bibliometric profile analysis.[3]

Furthermore, our approach offers the opportunity to investigate the *dynamics* of the system over time, that is whether the system converges toward a unique disciplinary profile or it diverges to a differentiated configuration. We illustrate the usefulness of our approach by investigating the dynamics of disciplinary profiles of European countries over the time span 1996–2011.

The remainder of the paper is organized as follows. In Section 2, we briefly introduce our framework. In Section 3, we describe our methodology. In Sections 4 and 5, we present the data and the main results, respectively. In Section 6, we conclude and outline further developments.

2. Setting the framework

In this paper we model research systems as complex systems. Conceived as physical systems, they are characterized by interacting subunits, the behavior of which can be described by more general laws like the physical laws (see van Raan, 2004). Research systems indeed are social systems which tend to produce complexity (see Liu & Rousseau, 2014; Scharnhorst, Borner, & van den Besselaar, 2012).[4] They are made up of single components or agents, nonlinear interactions among components, absence of central control, emergent behavior (see Holland, 1992). The relationships between scholars and the institutions they are affiliated with constitute the social characteristics of science. Scientific knowledge requires social infrastructures, such as funding, management, collaboration and less formal modes of communication. Social and cognitive aspects of science are interconnected and appear at different level of aggregation. Scholars use formal and informal channels of communication, but at the same time are embedded in organizations such as university departments and research centers. These institutions, with regional, national and transnational institutions, government agencies and industries shape the behavior of scholars. Different interactions in which scientists engage can result in different aggregates, such as 'invisible colleges',[5] specialties and disciplines. At the same time, these scholars are embedded through both training and employment, in larger units, such as fields or disciplines or university departments, regional and national research systems.

In this framework, we are interested in studying a set of N research systems (our 'units' of analysis, i.e. countries, regions, public research organizations, universities, etc.) labeled by the running index a (= 1, . . ., N). Each unit a has a specific pattern of 'research activities', $P_a(i)$. This quantity represents the share of a given kind of research results (papers, overall citations, etc.) produced in a subject category i (= 1, . . ., D) over the sum of the results in a given time span for unit a.

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[1] For an introduction, see Egghe and Rousseau (1990).

[2] Pillars are: *variety* is the number of categories of a given object, the different types of the considered element, in our case, the disciplines; *balance* represents the weight of each type of category on the mix of the unit; *disparity* refers to a kind of distance or proximity among the categories of an object; in our case the closeness among disciplines.

[3] We thank an anonymous reviewer for suggesting us this strength of our approach.

[4] There is a wide awareness about the complex nature of scientific activities also in the policy arena; see for instance Potocnik (2011).

[5] They are defined as sets of interacting scholars who share similar research interests concerning a subject specialty, who often produce publications relevant to this subject and work toward important goals in the subject, even though they may belong to geographically distant research affiliates (see Zuccala, 2006).

It is interesting to point out that alternatively we could consider patterns of 'technological activities' and investigate the disciplinary profiles of technological systems if data on patents, for instance, were available. Our approach in fact applies to both Science and Technology (S&T) systems. However, in the following we illustrate it on the activities of research systems due to unavailability of data on technological activities.

Basically, the pattern $P_a(i)$ is different for different units, but because of the 'interactions' that take place among different units one can expect that the patterns themselves evolve over time, giving rise to different phenomena, such as, for example, a *convergence* toward a common $P(i)$ for different a's or, on the contrary, a *differentiated* configuration of patterns. The interactions cited above can be of different origin, of different strength and of different resulting effect.

As an example, a large student and young researcher exchange among units will most likely push toward a *converging* pattern, the same is expected to happen to units that belong to a common geographic-economic area, where research grants are allocated by a common (e.g. governmental or federal) supra-unit decision maker. On the contrary, the competition for a limited amount of research grants in a limited environment could probably push toward 'specialization', i.e. different patterns; the same can also happen as a consequence of different cultural backgrounds.

Overall, we can sum up the complex social interactions among units by means of the 'Hamiltonian' model of spin glasses illustrated in details in Appendix A.

Our goal is to show that once the 'Hamiltonian' model has been supposed to hold, we are able to recover and generalize the empirical measures of similarity currently used in bibliometrics. Moreover, one can take advantage from the theoretical tools widely used in the physics of complex systems to derive some general features of the whole system, without having to know in details the behavior of its interacting sub-units. We can therefore compare these features with the empirical observation. The overall system may have different *regimes*, which can be:

- *convergent* or aligned pattern ('ferromagnetic' pattern in the spin glasses context) in which all the units have the same shares of research activities or *disciplinary profile*,
- *divergent* pattern ('paramagnetic' pattern in the spin glasses context), in which there is not visible influence among different units and then different disciplinary profiles emerge,
- *more complex configuration* (induced by multiple, competing interactions, like *frustration* in the spin glasses context that is the situation of a unit blocked between two opposing profiles, which is not able to choose the profile to follow) which leads to patterns in-between the two cases reported above.

Herein we propose the theory and the mathematical tools developed in the spin-glass literature as a suitable framework for empirically studying the actual pattern of the disciplinary structure, at a given time, of a given number of research systems, whose performance is measured by the number of papers published in a given subject category, citations, number of internationally co-authored papers and so on.

3. Method

3.1. A quantitative measure to evaluate similarity within and between S&T systems

As described in the previous section, once the theory of spin glasses is assumed to hold, we can recover and generalize some commonly used measures of similarity and empirically apply all the tools developed within the spin-glass context.

In this paper, to compare the disciplinary patterns of research systems, we compute the 'overlaps', quantities that are used in the spin glasses literature to determine the actual state (ferromagnetic, paramagnetic, etc.) of the system as a whole, that is whether the system converges toward the same disciplinary profile (*ferromagnetic pattern*) or to a differentiated pattern based on different disciplinary profiles (*paramagnetic pattern*).

The main variables analyzed here are the $P_a(i)$, i.e. the shares of articles published (or citations received, or number of internationally co-authored papers and so on) in a subject category i for a given country a over the sum of publications (or citations received, or number of internationally co-authored papers, and so on) in 1996–2011. Our *generalized overlap* between the pattern of disciplinary profiles of two research systems a and b, $P_a(i)$ and $P_b(i)$, respectively, that is the measure of similarity *between* systems, is defined as

$$Q_{ab} = \sum_{i=1}^{D} P_a(i) \; P_b(i). \tag{1}$$

To take *disparity among disciplines* into account, we can easily include weights in Eq. (1), multiplying each scalar product in the summation by d_{ij}, with $0 < d_{ij} \leq 1$.[6]

[6] However, given that we do not have an agreed set of weights, in the continuation of this paper we will illustrate our method, which can account for disparity among disciplines, in the case of $d_{ij} = 1$, for $i, j = 1, \ldots, D$.

Our similarity *within* systems is measured by the *self-overlap* that is defined as follows:

$$Q_{aa} = \sum_{i=1}^{D} P_a(i)^2 \doteq S. \tag{2}$$

It is interesting to note that Q_{aa} is Rao's quadratic diversity index, which coincides with the Simpson concentration index and is strictly linked to the Gini index defined in the following equation:

$$G \doteq 1 - \sum_{i=1}^{D} P_a(i)^2 = 1 - Q_{aa}. \tag{3}$$

Building on previous works, Stirling proposed the following *within* systems diversity heuristic (see Stirling, 2007):

$$\Delta \doteq \sum_{i,j(i \neq j)} d_{ij}^{\alpha} [P_a(i) P_a(j)]^{\beta}, \tag{4}$$

where the summation is across the half matrix of $(D^2 - D)/2$ nonidentical pairs of D elements ($i \neq j$).

According to Stirling (2007), Δ with $\alpha = 0$ and $\beta = 1$ is equal to $G/2$ [7]

$$\Delta = \sum_{i,j(i \neq j)} P_a(i)\ P_a(j) = \frac{1 - \sum_{i=1}^{D} P_a(i)^2}{2}, \tag{5}$$

from which:

$$Q_{aa} = 1 - 2\Delta. \tag{6}$$

Zhou et al. proposed to complete Stirling's approach by adding a similarity measure *between* systems a and b based on the popular Salton's Cosine measure given by (see Zhou et al., 2012):

$$\varphi_{ab} = \frac{\sum_{i=1}^{D} P_a(i)\ P_b(i)}{\sqrt{(\sum_{i=1}^{D} P_a(i)^2)(\sum_{i=1}^{D} P_b(i)^2)}}. \tag{7}$$

Considering Eq. (1), we can rewrite Eq. (7) as

$$\varphi_{ab} = \frac{\sum_{i=1}^{D} P_a(i)\ P_b(i)}{\sqrt{(\sum_{i=1}^{D} P_a(i)^2)(\sum_{i=1}^{D} P_b(i)^2)}} = \frac{Q_{ab}}{\sqrt{Q_{aa} Q_{bb}}}, \tag{8}$$

from which we can express our generalized overlap in terms of Salton's Cosine as follows:

$$Q_{ab} = \varphi_{ab} \sqrt{Q_{aa} Q_{bb}}. \tag{9}$$

To apply the spin-glass approach, we need to make our variables behave as in a spin system. To this purpose, we standardize their values as follows:

$$\sigma_a(i) = \frac{P_a(i) - \langle P_a(i) \rangle}{\sqrt{\langle P_a(i)^2 \rangle - \langle P_a(i) \rangle^2}}, \tag{10}$$

where $\langle \circ \rangle$ stands for the average of $\circ$.

These $\sigma_a(i)$ have the following properties:

$$\langle \sigma_a \rangle = 0 \quad \textit{and} \quad \langle (\sigma_a)^2 \rangle = 1. \tag{11}$$

This normalization permits us to scale the magnitude of disparities among disciplines. Then, our normalized measure of similarity between the profiles of two research systems, a and b, named as *overlap* and indicated as q_{ab} hereafter, can be calculated as follows:

$$q_{ab} = \frac{1}{D} \sum_{i=1}^{D} \sigma_a(i) \sigma_b(i), \tag{12}$$

where i denotes the subject category and D is the total number of subject categories, 27 in our case.

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[7] Given that $\sum_{i=1}^{D} P_a(i) = 1$ we have: $[\sum_{i=1}^{D} P_a(i)]^2 = 1 = \sum_{i=1}^{D} P_a(i)^2 + 2\sum_{i,j(i \neq j)} P_a(i)\ P_a(j)$, hence $1 - \sum_{i=1}^{D} P_a(i)^2 = 2\sum_{i,j(i \neq j)} P_a(i)\ P_a(j)$ from which $\Delta = G/2$.

Table 1
Presentation of the indicators analyzed in the paper.

Indicator	Description
PUB	Number of articles (integer count)
PUBf	Number of articles (fractional counts based on authors affiliations)
C	Total citations (4 years window, i.e. for articles in 2006 citations from 2006 to 2009)
CPP	Total citations per paper (4 years window, i.e. for articles in 2006 citations from 2006 to 2009)
HCPUB	Number of articles in top 10% of most highly cited articles in a discipline
PUBINT	Number of internationally co-authored papers
PUBNAT	Number of nationally (but not internationally) co-authored papers
PUBINST	Number of among institute co-authored papers
PUBSA	Number of non-collaborative (single address) papers

It is interesting to note that if $\langle P_a(i)\rangle$=0, $\forall a = 1, \ldots, N$, our q_{ab} coincides – but a constant D – to φ_{ab}. Remarkably, in this particular case ($\langle P_a(i)\rangle$=0), q_{ab} corresponds to Salton's cosine measure of similarity *between* systems amplified by the variety of the scientific production (D), which is itself a measure of diversity *within* systems.

Our overlap measure of similarity of profiles q_{ab} ranges from -1, meaning precisely the opposite profile, to 1, meaning precisely the same profile, with 0 representing independence and intermediate values indicating in-between levels of similarity or dissimilarity. Moreover, the overlap can be calculated with respect to another country or with respect to an average or standard value or with respect to a given distribution. This opportunity opens the way to *multilevel comparisons* of disciplinary profiles, combining macro, meso and micro S&T systems analyses.

3.2. Investigating the dynamics of research systems

The main property of the *overlaps* of a spin-glasses system that we empirically exploit in this paper is related to their distribution. The overlaps are the *order parameter* (see Parisi, 1983)[8] of the system.[9] Being the 'order' parameter, they describe the long-range order of the system. This means that by analyzing the distribution of the overlaps, we can derive useful insights on the 'slow' dynamics of the system.

Therefore, the distribution of the overlaps of a system of research units modeled as a spin-glasses system allows us to investigate the 'slow' dynamics of the system, that is whether the system converges toward a unique disciplinary structure (showing a pick on one) or to a differentiated pattern (showing two picks). Even more complex configurations could emerge (when broad overlap distributions appear).

Generally, complex systems as spin glasses are described by differential equations difficult to solve exactly. Nevertheless we can investigate both their *fast* and *slow* dynamics. Fast dynamics refer to how shocks of low entities affect the $P_a(i)$ of the analyzed research systems (represented by the Hamiltonian model described in Appendix A to which the reader is referred to), keeping fixed the complex social interactions among units (these complex social interactions are indicated as J in Appendix A). On the contrary, the slow dynamics in complex disordered systems as spin glasses refers to how the $P_a(i)$ change (or vary) over time when the complex social interactions among units (J) change, but without knowing the J. This latter is exactly the dynamics we investigate in our approach, the *slow* dynamics of the overall system: that is, as recalled above, whether the system converges toward the same disciplinary profile or diverges to different disciplinary patterns. Summing up, we analyze how the $P_a(i)$ evolve and adapt to the changes of J, but without having to know the J.[10] We show in the empirical illustration that follows how we can study the slow dynamics by analyzing the distribution of the overlaps that are the *order parameter* of spin glasses systems. For more technical details the reader is referred to Appendix A.

4. Data

Data come from the Scopus database and refer to the scientific production of 27 European countries and 27 Scopus subject categories (disciplines) listed and coded in Appendix B (Tables B.6 and B.7, respectively) from 1996 to 2011, including the total world scientific production by discipline as a reference. The available indicators are reported in Table 1.

In this section we provide a few descriptive analyses of the data. Exclusively for illustrative purpose and to save space in this section, we grouped countries with similar disciplinary profiles (see Table 2) and disciplines according to their scientific proximity (see Table 3).[11] Countries showing similar disciplinary profiles can be grouped according to their total publication

[8] See also Mezard, Parisi, Sourlas, Toulouse, & Virasoro, 1984a.
[9] See Appendix A for more technical details.
[10] More technically, we analyze how the $P_a(i)$ adapt to *adiabatically* follow the change of J, without knowing the J. An adiabatic change implies an infinitely slow change in the Hamiltonian model. For more details on the model, see Appendix A.
[11] In Section 5, instead, we report the results of the analysis carried out on all the 27 European countries and all the 27 Scopus subject categories.

Table 2
The groups are built according to a country's total volume of publications and are numbered from the smallest to the largest countries.

Group	Countries
G1	CYP–EST–LVA–MLT
G2	BGR–LTU–LUX–SVN
G3	CZE–HUN–ROU–SVK
G4	FIN–GRC–IRL–PRT
G5	AUT–BEL–DNK–POL
G6	ESP–ITA–NLD–SWE
G7	DEU–FRA–GBR

Table 3
Groups of Scopus subject categories in four main areas: medicine, sciences, social sciences, engineering

Groups of disciplines	Scopus subject categories included
Med	BIOC–IMMU–MEDI–NEUR–NURS–PHAR–VETE–DENT–HEAL
Sci	AGRI–CHEM–EART–ENVI–MATE–MATH–PHYS
SocSci	ARTS–BUSI–DECI–ECON–PSYC–SOCI
Eng	CENG-COMP-ENER-ENGI

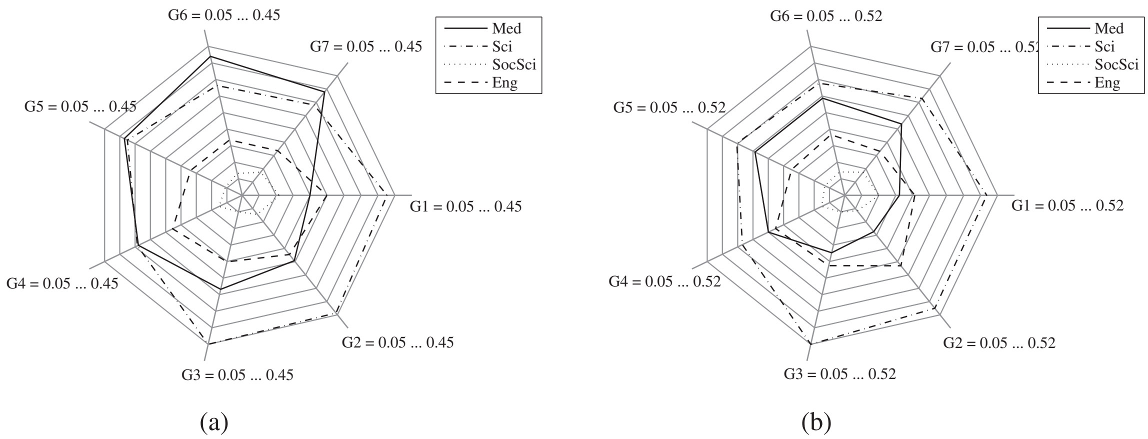

Fig. 1. Contribution of groups of countries in each group of disciplines for PUBf (a) and HCPUB (b). Stock of scientific production (1996–2011).

volume, so that the first group is composed of countries with the lowest number of publications and the last by countries with the highest number of publications. We observe that this grouping corresponds to that based on the gross domestic product (GDP).

We processed the available data in order to obtain the percentage of articles published in each country (or groups of countries) in a given subject category (or a group of them), summed over the time period 1996–2011.[12] Then, we put our data on radar charts (e.g. Glänzel, 2000) showing the share of each group of disciplines in each group of countries.

Examples of these charts are shown in Figs. 1 and 2 that clearly illustrate how European leading and 'developing' countries differ in terms of their scientific orientation. Fig. 2 in particular shows the contribution of each group of countries in each group of disciplines compared to both the European and World standard. What emerges is an expected result: countries with lower volume of publications (as well as lower GDP) contribute more in (the subject categories grouped within) Engineering compared to the world standard, whilst more productive (as well as richer) countries are more focused on life science disciplines.

[12] We summed over the period 1996–2011 for all indicators of Table 1 with the exception of CPP (total citations per paper), for which we used the average over the considered time span.

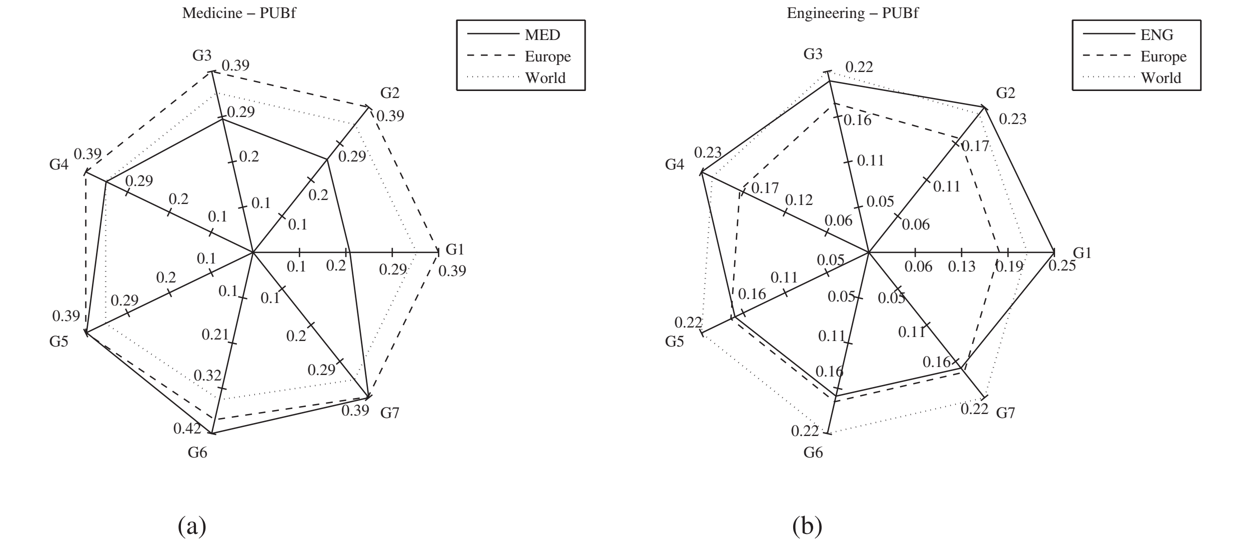

Fig. 2. Contribution of groups of countries in Medicine (a) and Engineering (b) macro categories, compared to the European and World standard for the PUBf indicator. Stock of scientific production (1996–2011).

Table 4
Overlap values among each country and the European and World standard – where possible – for PUBf, HCPUB, PUBINT and PUBSA indicators. At the bottom of the table some descriptive statistics are reported.

Country	PUBf		HCPUB		PUBINT	PUBSA	
	Europe	World	Europe	World	Europe	Europe	World
AUT	0.993	0.961	0.986	0.940	0.988	0.958	0.913
BEL	0.995	0.969	0.987	0.973	0.980	0.958	0.917
BGR	0.867	0.850	0.677	0.662	0.849	0.807	0.741
CYP	0.613	0.705	0.641	0.709	0.769	0.694	0.733
CZE	0.953	0.931	0.878	0.856	0.928	0.887	0.830
DEU	0.988	0.965	0.974	0.924	0.986	0.948	0.927
DNK	0.952	0.897	0.959	0.910	0.927	0.965	0.929
ESP	0.981	0.944	0.963	0.953	0.979	0.936	0.880
EST	0.762	0.786	0.838	0.794	0.954	0.678	0.686
FIN	0.972	0.969	0.972	0.948	0.974	0.878	0.897
FRA	0.992	0.973	0.977	0.947	0.981	0.961	0.891
GBR	0.968	0.950	0.964	0.948	0.967	0.917	0.915
GRC	0.967	0.968	0.932	0.970	0.964	0.867	0.870
HUN	0.936	0.899	0.961	0.914	0.960	0.881	0.836
IRL	0.978	0.976	0.987	0.984	0.971	0.897	0.881
ITA	0.992	0.957	0.988	0.965	0.991	0.907	0.843
LTU	0.671	0.747	0.775	0.843	0.906	0.627	0.610
LUX	0.815	0.830	0.878	0.904	0.827	0.904	0.864
LVA	0.590	0.686	0.881	0.907	0.830	0.500	0.548
MLT	0.845	0.872	0.890	0.885	0.741	0.809	0.802
NLD	0.967	0.931	0.958	0.925	0.943	0.971	0.969
POL	0.931	0.917	0.846	0.827	0.876	0.686	0.670
PRT	0.849	0.886	0.828	0.871	0.941	0.865	0.830
ROU	0.625	0.710	0.651	0.714	0.753	0.593	0.600
SVK	0.882	0.864	0.829	0.821	0.910	0.772	0.733
SVN	0.826	0.898	0.789	0.827	0.921	0.856	0.890
SWE	0.985	0.953	0.912	0.906	0.956	0.963	0.952
Min	0.590	0.686	0.641	0.662	0.741	0.500	0.548
Max	0.995	0.976	0.988	0.984	0.991	0.971	0.969
Mean	0.885	0.889	0.886	0.8982	0.917	0.840	0.821
Std. dev.	0.128	0.090	0.105	0.085	0.075	0.129	0.116

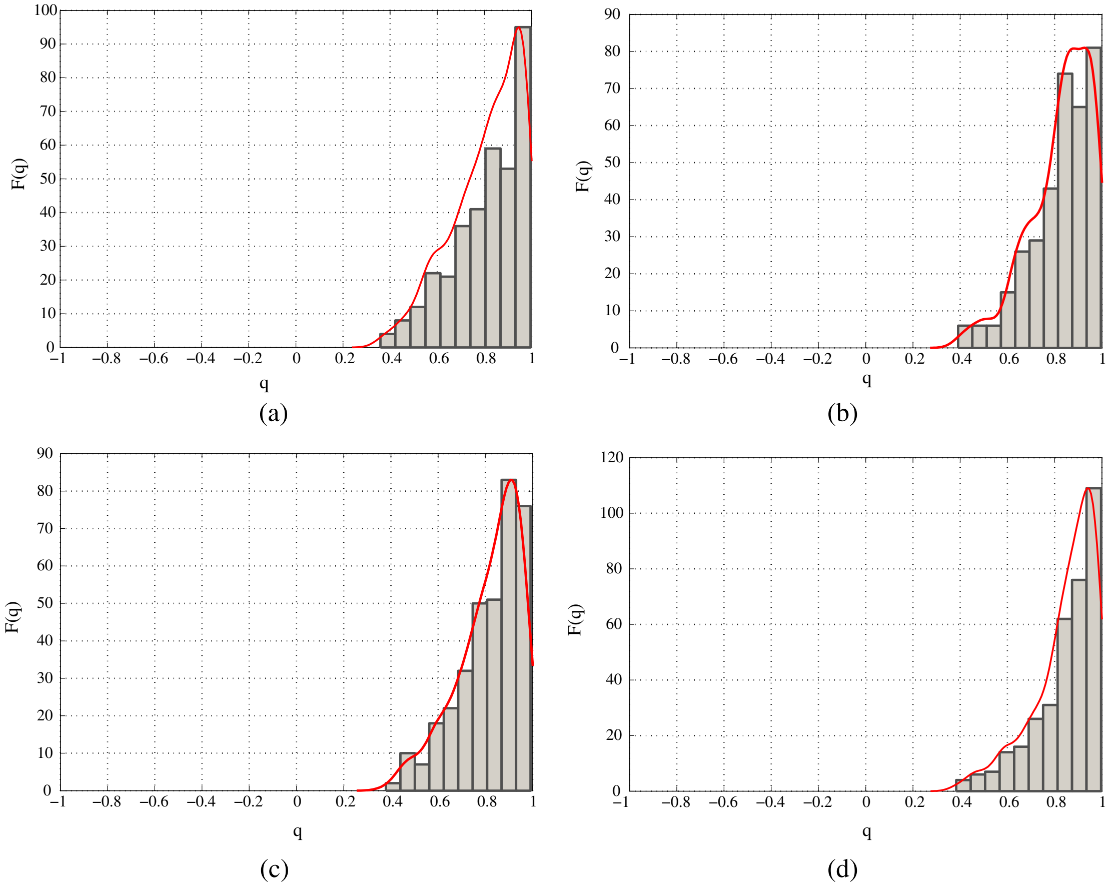

Fig. 3. Nonparametric kernel distribution of the overlaps among European countries for PUBf (a), PUB (b), HCPUB (c) and C (d) indicators. Stock of scientific production (1996–2011).

5. Results

To illustrate our method we carried out a *global* analysis on the scientific production of European countries on the whole period (1996–2011). We will refer to this analysis as an analysis on the *stock* of scientific production, and we then analyzed the dynamics of the scientific production by year. For the global investigation on the *stock* of scientific production, for each indicator of Table 1 we analyzed the cumulative sum of their values over 1996–2011, with the exception of CPP for which the yearly average over 1996–2011 was considered.

By applying the methodology described in Section 3, we compared the disciplinary profiles of European countries (1) between them, (2) with respect to the European standard and (3) with respect to the World reference. We considered the $P^a(i)$, i.e. the shares of articles (and the other indicators reported in Table 1) published in a subject category i for a given country a.

5.1. Stock of scientific production

In Table 4 the detailed values of the overlap between each country and the European and World standard are reported for PUB, PUBf, HCPUB and PUBINT indicators, respectively (only for the PUBINT indicator, the calculation of overlap between countries and the World standard was not possible due to lack of data).

Figs. 3 and 4 show the distributions of the overlaps among European countries calculated on various indicators. We observe that all distributions present a well-defined peak near 1, meaning that European countries tend to converge to the same disciplinary profile. This finding empirically confirms that there is a process of *globalization* of science in Europe. However, the distributions of the overlaps are wide, witnessing that differences among countries still remain.

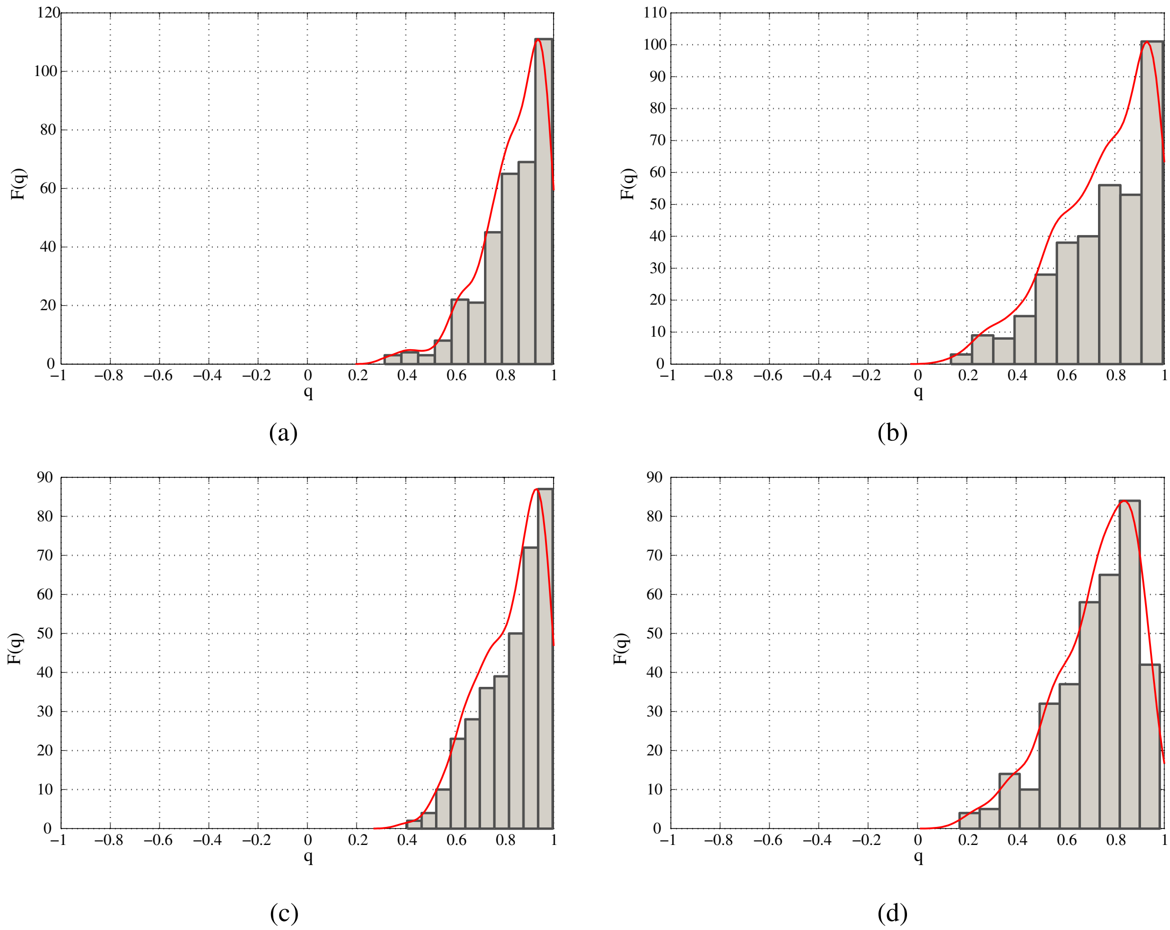

Fig. 4. Nonparametric kernel distribution of the overlaps among European countries for PUBINT (a), PUBNAT (b), PUBINST (c) and PUBSA (d) indicators. Stock of scientific production (1996–2011).

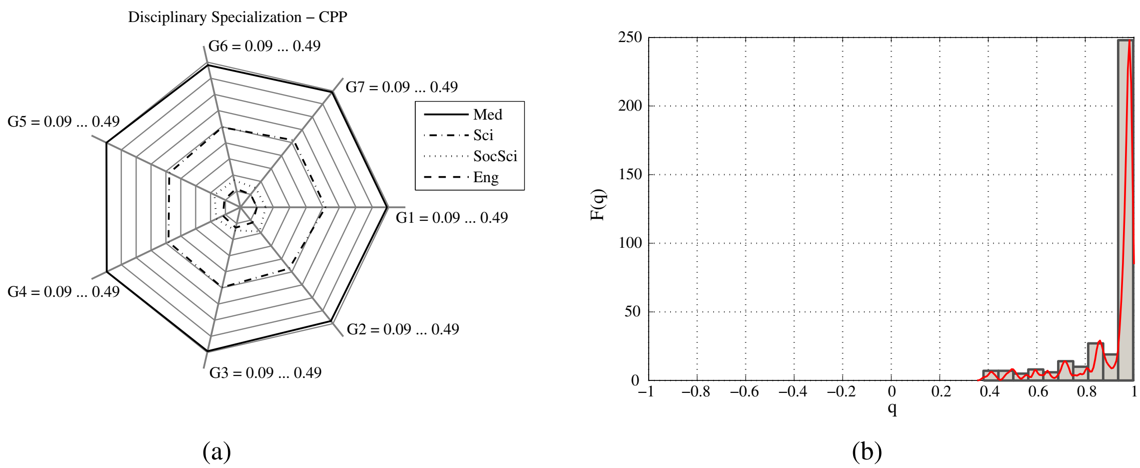

Fig. 5. Radar plot of CPP per groups of countries and disciplines (a) and nonparametric kernel distribution of the overlaps among European countries for the CPP indicator (b). Stock of scientific production (1996–2011).

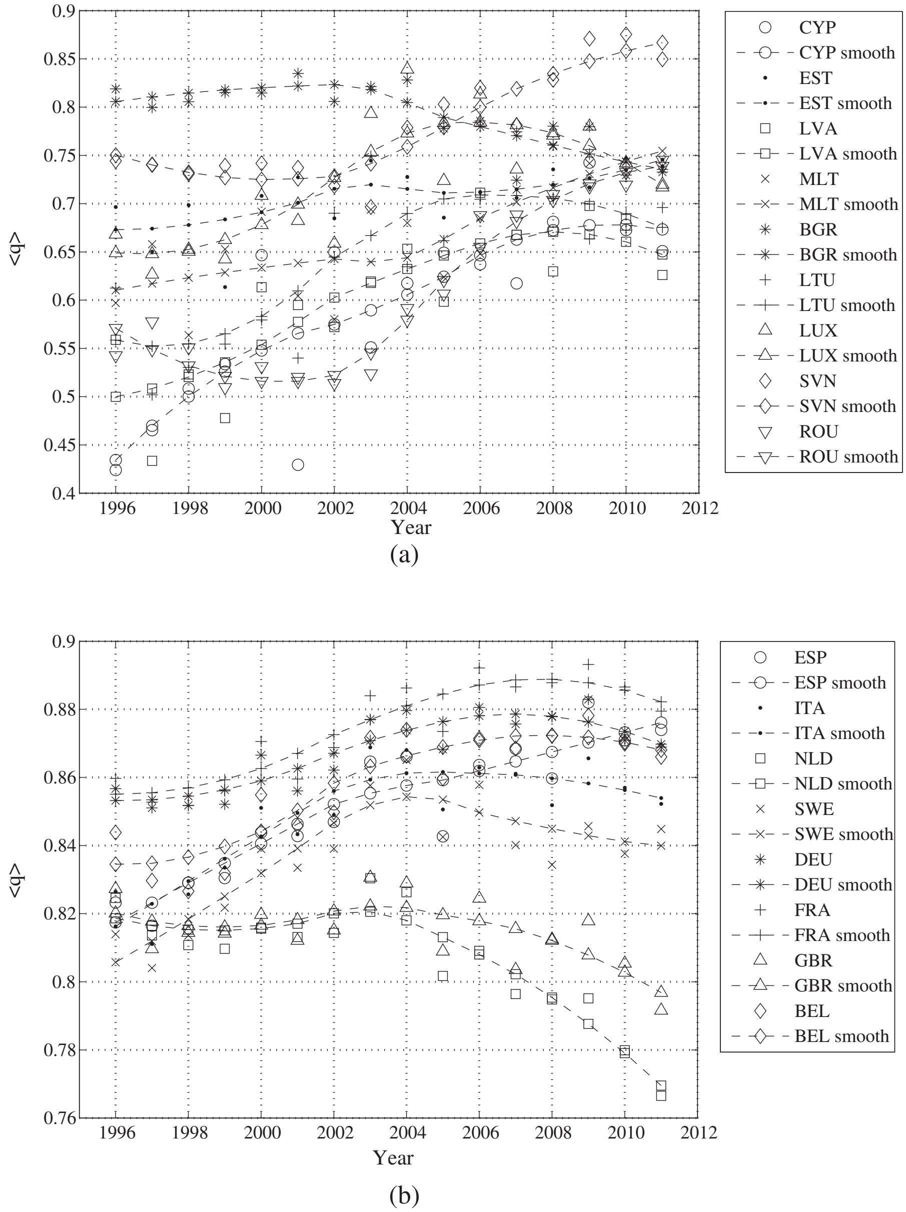

Fig. 6. Dynamics of overlaps for the PUBf indicator. Selected catching up countries (a) and selected leading countries (b).

Fig. 5(a) shows that the indicator CPP is uniform across groups of countries. This is confirmed by the sharp peak on one shown in the overlap distribution reported in Fig. 5(b).

5.2. *Evolution of scientific production over time*

Figs. 6–8 show the evolution of the overlaps over the temporal range 1996–2011 for selected developing countries, illustrated in panel (a), and leading countries reported in panel (b). In these figures each curve represents a country and each point represents the geometric mean of the overlaps calculated between that country and all the others for a particular year. Each curve represents a smoothed trend estimated by a local nonparametric regression with a quadratic fit (loess), using 70% of the points.

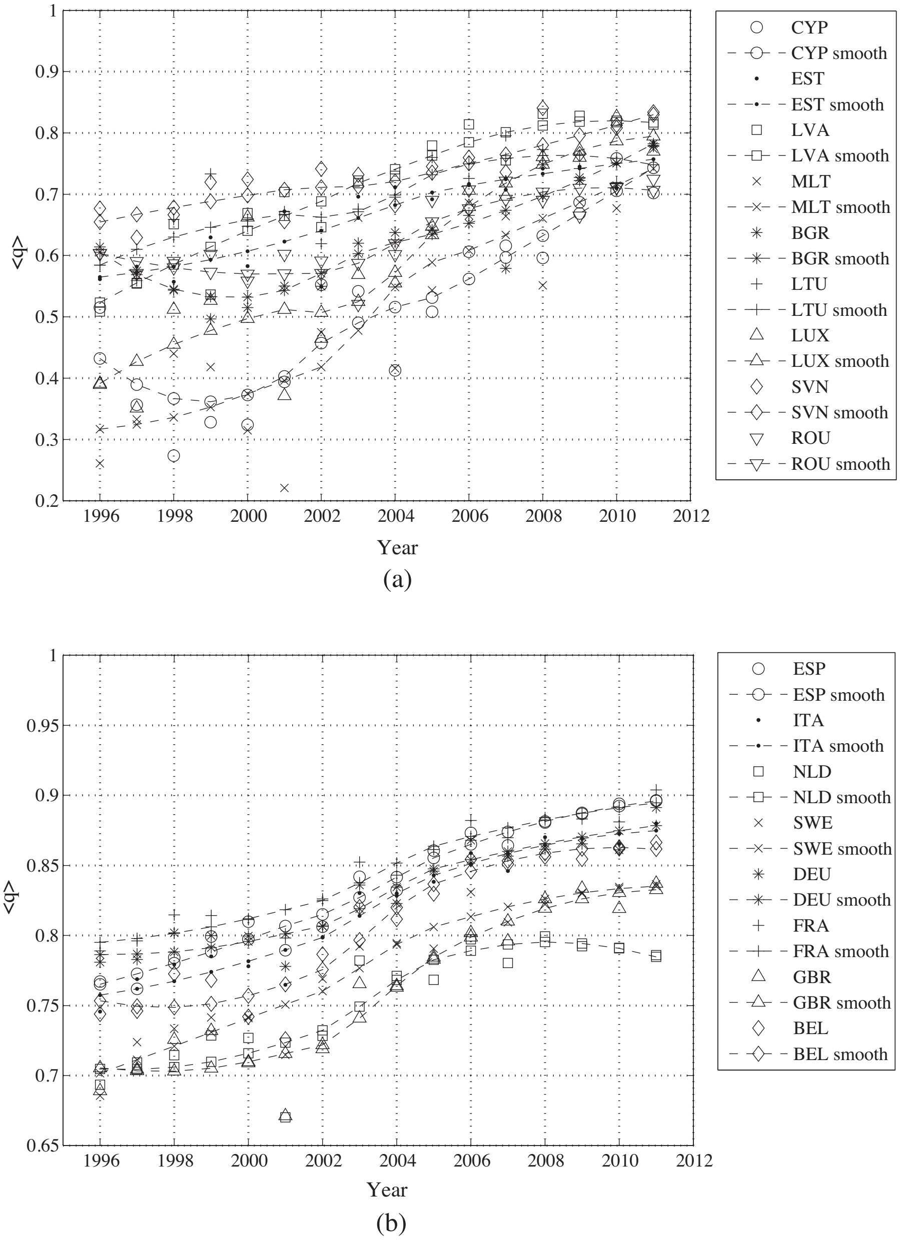

Fig. 7. Dynamics of overlaps for the HCPUB indicator. Selected catching up countries (a) and selected leading countries (b).

Interestingly, we observe that while catching up countries are converging toward the ‘European model’ for all the indicators reported in Figs. 6–8, leading countries, and in particular United Kingdom and the Netherlands, are progressively departing from the ‘European model’, particularly when the indicator PUBf is considered.

Finally, Table 5 shows the closeness or distance of countries from the ‘European model’ for each scientific discipline (for each Scopus subject category). In Table 5 the column ‘Europe’ reports the geometric mean calculated over all the EU countries values of the percentages of PUBf and C indicators. It represents, then, the *typical* European disciplinary profile. *TO* and *BO* in Table 5 show the disciplinary composition of countries in the top 10% overlap, i.e. the 10% of countries with highest overlap values (*TO*) and in the bottom 10% overlap, i.e. the 10% of countries with lowest overlap values (*BO*).

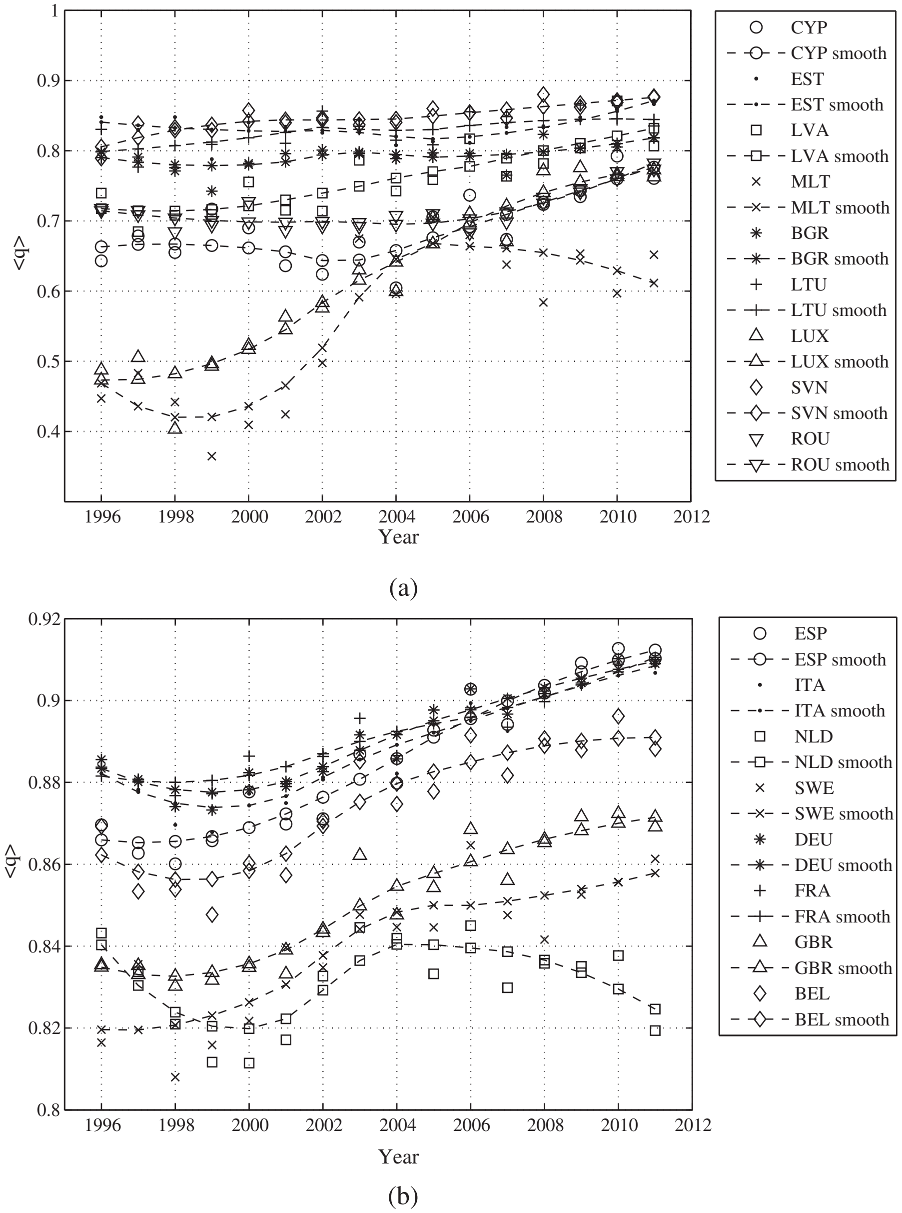

Fig. 8. Dynamics of overlaps for the PUBINT indicator. Selected catching up countries (a) and selected leading countries (b).

Table 5
Disciplinary composition of countries in top 10% overlap (TO) and bottom 10% overlap (BO) compared with the European standard [Europe] for PUBf and C indicators.

Discipline	PUBf			C		
	Europe	TO	BO	Europe	TO	BO
AGRI	5.16	5.02	2.69	4.91	4.55	2.75
ARTS	0.89	1.00	0.86	0.10	0.10	0.13
BIOC	8.22	9.75	4.67	14.63	17.31	8.79
BUSI	0.95	0.67	1.54	0.31	0.27	0.28
CENG	2.43	2.09	3.18	2.01	1.48	4.30
CHEM	5.74	5.51	6.87	6.47	5.83	9.65
COMP	6.02	5.57	9.56	2.21	2.17	3.02

Table 5 (*Continued*)

Discipline	PUBf			C		
	Europe	TO	BO	Europe	TO	BO
DECI	0.46	0.52	0.57	0.24	0.18	0.39
EART	2.73	2.87	1.41	3.62	3.68	3.10
ECON	0.80	0.82	0.91	0.34	0.35	0.31
ENER	1.17	1.00	1.90	0.71	0.56	1.44
ENGI	10.21	9.24	16.48	3.95	3.54	6.11
ENVI	3.22	2.75	2.51	3.21	2.28	2.74
IMMU	2.29	2.96	0.94	4.48	5.50	2.08
MATE	5.59	5.23	8.06	4.28	3.24	7.21
MATH	4.59	4.42	7.21	2.31	1.95	5.13
MEDI	14.41	19.61	6.34	18.61	24.00	10.79
NEUR	1.45	2.24	0.50	2.64	4.14	1.23
NURS	0.36	0.54	0.14	0.40	0.58	0.28
PHAR	2.12	2.38	1.01	2.54	2.74	1.68
PHYS	8.31	8.71	10.88	10.61	9.02	20.65
PSYC	0.89	1.28	0.76	0.77	0.98	0.63
SOCI	3.10	2.72	3.63	0.92	0.77	0.97
VETE	0.60	0.81	0.14	0.42	0.47	0.18
DENT	0.16	0.25	0.05	0.16	0.26	0.05
HEAL	0.73	1.18	0.51	0.59	0.87	0.35
GENE	0.20	0.25	0.17	1.64	2.40	1.01
TOT	100.00	100.00	100.00	100.00	100.00	100.00

6. Conclusions

In this paper we applied the theory developed for spin-glasses to model the behavior of disciplinary profiles of research systems. Once this framework was established, we used the mathematical tools developed in this field of the physics of complexity to empirically compare the disciplinary profiles of research systems and analyze their evolution over time.

We then showed that our approach encompasses the assessment of similarities *between* systems and *within* systems in a unified framework. Moreover, we discussed how our method links with previous studies.

By modeling disciplinary structures of research systems as 'disordered systems', we provide a quantitative approach that permits an analysis of the *regime* of the overall system, that is whether it converges toward a unique disciplinary pattern or it diverges to a differentiated configuration.

Finally, we illustrated the usefulness of our approach through a detailed analysis on the comparison of the disciplinary profiles of European countries and their evolution over the period 1996–2011.

Generally, we found that there is a globalization of science in Europe because the European system is converging toward a *unique* disciplinary structure, even if there is still evidence of consistent differences among the nonleading and most developed European countries. The trend of scientific production over time shows that while catching up countries are converging toward the European model, leading countries, such as the UK and the Netherlands, are progressively departing from it.

Whether the convergence toward a unique disciplinary pattern is good or bad for European science is a relevant policy question that should be addressed but is beyond the scope of the present paper.

The analysis conducted in this paper paves the way for additional numerous future developments. For instance, we could extend the geographical horizon of the analysis to include all other non-European countries. Moreover, we could reverse the objectives of the analysis and estimate the interactions that apply among countries (J) as well as the efforts needed to change the pattern. We leave all these developments to future studies.

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Appendix A. Technical note on spin glasses

In this section we provide further technical details on spin glasses.

As described in Section 2, we are interested in studying a set of N research systems, our 'units' of analysis labeled by the running index a (= 1, . . ., N). Each unit a has a specific pattern of 'research activities', $P_a(i)$. This quantity represents the share of a given kind of research results produced in a subject category i (= 1, . . ., D) over the sum of the results in a given time span for unit a.

To set up a simple model able to describe the time evolution and the stationary states of the set of units under investigation, we can therefore associate to each couple of units a and b an 'energy' given by $J_{ab}\overline{P}_a \cdot \overline{P}_b$ (here the scalar product indicates $\overline{P}_a \cdot \overline{P}_b = \sum_{i=1}^{D} P_a(i) \ \ P_b(i)$). If the system is in equilibrium at a given 'temperature' T, then the energy distribution of the units follows the Boltzmann law given by

$$F(E) = \frac{1}{Z} \ \ e^{-E/k_B T}, \tag{A.1}$$

where $Z = \sum_{\text{all configurations}} e^{-E/k_B T}$, where $e^{-E/k_B T}$ is called Boltzmann factor and k_B is Boltzmann's constant. This assumes the ergodicity of the system, that is, the time average of functions on these random variables equals the average of these same functions over their probability distributions.[13]

Overall, we can sum up the complex social interaction between units a and b by a numerical coefficient J_{ab} (that can assume positive or negative values), which determines the tendency of the two patterns $P_a(i)$ and $P_b(i)$ to become closer or to become very different.

The tendency of the system to minimize this 'social energy' will lead to an alignment of the patterns $P_a(i)$ and $P_b(i)$ if J_{ab} is negative and to an orthogonalization if J_{ab} is positive. The whole system is thus described by a total social energy:

$$\mathcal{H} = \sum_{ab} J_{ab}\overline{P}_a \cdot \overline{P}_b - \overline{h}_a \cdot \overline{P}_a, \tag{A.2}$$

where $h_a(i)$, that is an external 'magnetic' field in the spin-glasses literature, could be viewed as a kind of an external drive pushing on the unit a for enhancing research in discipline i (e.g. the cold war that pushed the strengthening of space research in 1955 in the USA). Let's call this quantity 'Hamiltonian' in analogy with the true Hamiltonian introduced in the physical sciences to describe the macro behavior of the system. In the present case the quantity $P_a(i)$ represents the i-th component of a D dimensional (D is the number of categories) spin a, interacting with all the other spins of the system (the spin is embedded in an 'infinite' dimensional space[14]) via the *quenched* (time independent) quantities J_{ab}.

In the context of research systems, like the one analyzed here, the temperature T represents a small perturbation or noise of small entity which affects the patterns $P_a(i)$; the physical energy E is the energy available for a system to do useful work (Stein & Newman, 2013, p. 271) related to the patterns $P_a(i)$, and the social energy H is a kind of generalized cost function of the system of $P_a(i)$ configurations.

Among the three main models of spin glasses (namely finite-dimensional spin glasses, mean-field spin glasses and spin glasses on random graphs[15]) we apply the *mean-field* spin-glasses model that is closest to the actual dynamics of research systems in which interactions are assumed among all pairs of 'spins'-elementary units of the model. An underlying assumption of this model is that disorder is explicitly present in the system through random couplings J, which are quenched (constant) over time (quenched disordered system). This assumption appears reasonable for the investigation of S&T systems over a short period of time (in our case from 1996 to 2011). Nevertheless, for longer series, this assumption should be carefully considered.

The time evolution (dynamics) of the pattern of a research system (P_a), described by the Hamiltonian in Eq. (A.2), is determined by the set of the following N stochastic differential equations:

$$\frac{d(P_a)}{dt} = -\frac{\partial \mathcal{H}}{\partial (P_a)} + \eta(t) \quad for \quad a = 1, \ldots, N, \tag{A.3}$$

where $\eta(t)$ is a Gaussian noise, with $\langle \eta(t) \rangle$=0 and $\langle \eta(t)\eta(t') \rangle$=2$T\delta(t-t')$, where $\langle \circ \rangle$ stands for the average of $\circ$ and T is the temperature in the spin-glasses context. In our framework, T could represent exogenous shocks of low entity on the system. Given that our purpose is to search for the fundamental state of the system, considering a temperature equal to zero provides a good approximation.

The 'solution' of this problem (the quenched equilibrium state of a general disordered system) is ensured (at least in a statistical sense) once the set of variables J_{ab} is given.[16] Our goal is to show that once the 'Hamiltonian' model has been supposed to hold, one can take advantage from the theoretical tools widely used in the physics of complex systems to treat such a class of Hamiltonian, to derive some general features of the stationary states from first principles. Indeed, without knowing details about J and its distribution we can compare these features with the empirical observation. Depending on the

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13 This assumption is taken to be true for many processes that involve human systems and is commonly made in several fields of study, such as in the econometrics of time series.

14 The dimensional space is infinite for $N \rightarrow \infty$. Nevertheless, in the real case N is large enough and results are not expected to be affected by N.

15 See e.g. Contucci and Giardina (2012) for a comprehensive presentation. A nice introduction can be found in Stein and Newman (2013).

16 It is far beyond the aim of the present paper to describe a possible deterministic evaluation of the variables J_{ab}, as it is also beyond our aim to give their statistical description.

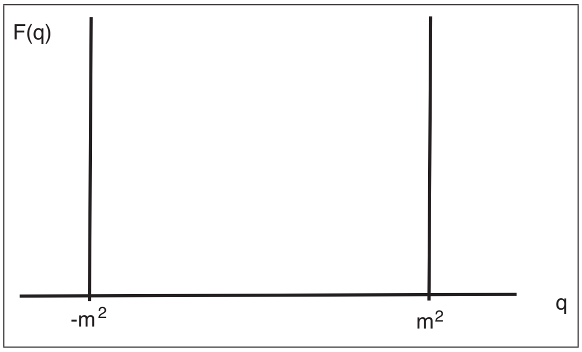

Fig. A.9. An illustration of the overlap distribution of the Ising model.

actual value of J_{ab} or on their statistical distribution as well as on the span of categories (D), the system may have different *regimes*, which can be:

- *convergent* or aligned pattern ('ferromagnetic' pattern, all the units have the same shares of research activities or *disciplinary profile*),
- *divergent* pattern ('paramagnetic' pattern, no visible influence among different units and then different disciplinary profiles),
- *more complex configuration* (induced by multiple, competing interactions, like *frustration*, that is the situation of a unit blocked between two opposing profiles, which is not able to choose the profile to follow).

As described in Section 3, the main property of the overlaps of interest for our method is related to their distribution. According to Parisi (1983), the probability distribution of the 'overlaps' is given by

$$F(q) = \sum_{ab} F_a \; F_b \; \delta(q - q_{ab}), \tag{A.4}$$

where F_a and F_b are the probabilities of the system to be in state (or 'valley') a and b, respectively. In this formula the sum is extended over all the possible pairs of states, including pairs of the same states (states' self-overlap). To understand this formula the Ising model can be helpful.[17] At a low temperature we have two pure states and hence four possible 'overlaps': [18]

$$q_{++} = \frac{1}{N}\sum_i \langle\sigma_i\rangle_+^2 = \frac{1}{N}\sum_i m_i^2 = m^2, \tag{A.5}$$

$$q_{--} = \frac{1}{N}\sum_i \langle\sigma_i\rangle_-^2 = \frac{1}{N}\sum_i m_i^2 = m^2, \tag{A.6}$$

$$q_{+-} = q_{-+} = \frac{1}{N}\sum_i \langle\sigma_i\rangle_+ \langle\sigma_i\rangle_- = -\frac{1}{N}\sum_i m_i m_i = -m^2, \tag{A.7}$$

therefore, the distribution function $F(q)$ has two peaks, at $-m^2$ and at m^2, each with weight 1/2. See Fig. A.9 for an illustration. It is important to emphasize, as pointed out in Castellani and Cavagna (2005), that "the number of peaks of the $F(q)$ is not equal to the number of states, but to the number of possible values taken by the overlap (with a large number of states all with the same self-overlap and mutual overlap, we would still have a bimodal $F(q)$)".

Interestingly, Parisi demonstrated that the 'overlap' is the order parameter of the system (see Parisi, 1983). Moreover, he showed that, far from being a parameter, it is a function, interpreted as a probability law. The elements of the overlap matrix (in the stationary state) are the physical values of the overlap among pure states, and the number of elements of the overlap matrix equal to q is related to the probability of q. This structure of the overlap matrix implies that the average overlap distribution is given by

$$\langle F(q)\rangle = \delta(q - q_0), \tag{A.8}$$

[17] The Ising model is a mathematical model of ferromagnetism in statistical mechanics. The model consists of discrete variables that represent magnetic dipole moments of atomic spins that can be in one of two states (+1 or −1). The spins are arranged in a graph, usually a lattice, allowing each spin to interact with its neighbors. The model allows the identification of phase transitions as a simplified model of reality.

[18] Here the presentation follows Castellani and Cavagna (2005). See also Mezard, Parisi, Sourlas, Toulouse, and Virasoro (1984b) and Mezard, Parisi, and Virasoro (1987) for a comprehensive presentation.

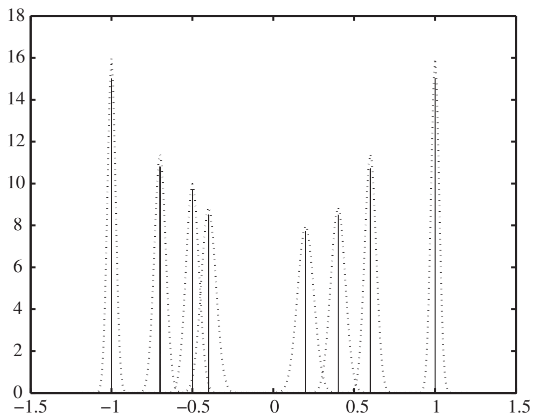

Fig. A.10. A general overlap distribution function $F(q)$.

Table B.6
List of the abbreviations used for the European countries in the paper.

Country code	Country name
AUT	Austria
BEL	Belgium
BGR	Bulgaria
CYP	Cyprus
CZE	Czech Republic
DEU	Deutschland
DNK	Denmark
ESP	Spain
EST	Estonia
FIN	Finland
FRA	France
GBR	United Kingdom
GRC	Greece
HUN	Hungary
IRL	Ireland
ITA	Italy
LTU	Lithuania
LUX	Luxembourg
LVA	Latvia
MLT	Malta
NLD	The Netherlands
POL	Poland
PRT	Portugal
ROU	Romania
SVK	Slovakia
SVN	Slovenia
SWE	Sweden

where q_0 is the self-overlap; it means that there is only one single possible value of the overlap among states.

An interesting property of these probability distributions (the overlaps) is then their *universality*: they depend on the different parameters of the problem (temperature, magnetic field, particular value of q) only through the mean value of the distribution (see Eq. (A.8)).

Owing to the normalization made in (10), the resulting distribution of our overlap measure will be supported on all values of q in the interval $[-1, 1]$.

Therefore, the distribution of the overlaps of a system of research units modeled as a spin-glasses system allows us to investigate the *slow* dynamics of the system, that is whether the system converges toward a unique disciplinary structure (showing a pick on one) or to a differentiated pattern (showing two picks). Even more complex configurations could emerge (when broad overlap distributions appear). See Fig. A.10 for an illustration of a general $F(q)$.

Another interesting property of spin glasses is related to the *ultrametric* structure[19] of the distance between states, which is measured by the overlaps (see Mezard et al., 1984b for more details). It has to be noted that this is typical of hierarchical

[19] An ultrametric space is a metric space in which the triangle inequality is replaced by the strong triangle inequality.

Table B.7
List of the abbreviations used for disciplines in the paper.

Subject category	Description
AGRI	Agricultural and Biological Sciences
ARTS	Arts and Humanities
BIOC	Biochemistry, Genetics and Molecular Biology
BUSI	Business, Management and Accounting
CENG	Chemical Engineering
CHEM	Chemistry
COMP	Computer Science
DECI	Decision Sciences
EART	Earth and Planetary Sciences
ECON	Economics, Econometrics and Finance
ENER	Energy
ENGI	Engineering
ENVI	Environmental Science
IMMU	Immunology and Microbiology
MATE	Materials Science
MATH	Mathematics
MEDI	Medicine
NEUR	Neuroscience
NURS	Nursing
PHAR	Pharmacology, Toxicology and Pharmaceutics
PHYS	Physics and Astronomy
PSYC	Psychology
SOCI	Social Sciences
VETE	Veterinary
DENT	Dentistry
HEAL	Health Professions
GENE	Multidisciplinary

	AUT	BEL	BGR	CYP	CZE	DEU	DNK	ESP	EST	FIN	FRA	GBR	GRC	HUN	IRL	ITA	LTU	LUX	LVA	MLT	NLD	POL	PRT	ROU	SVK	SVN
BEL	0,992																									
BGR	0,829	0,837																								
CYP	0,603	0,593	0,530																							
CZE	0,930	0,939	0,941	0,590																						
DEU	0,976	0,975	0,916	0,591	0,959																					
DNK	0,956	0,967	0,745	0,451	0,881	0,912																				
ESP	0,976	0,982	0,853	0,574	0,964	0,958	0,959																			
EST	0,712	0,737	0,778	0,593	0,844	0,763	0,696	0,763																		
FIN	0,970	0,973	0,786	0,667	0,916	0,940	0,942	0,958	0,790																	
FRA	0,981	0,981	0,908	0,627	0,964	0,996	0,919	0,967	0,776	0,952																
GBR	0,964	0,974	0,740	0,601	0,865	0,928	0,958	0,944	0,692	0,955	0,936															
GRC	0,976	0,965	0,789	0,709	0,912	0,940	0,908	0,954	0,735	0,980	0,954	0,936														
HUN	0,909	0,923	0,927	0,575	0,970	0,939	0,880	0,951	0,796	0,887	0,948	0,855	0,874													
IRL	0,973	0,982	0,801	0,698	0,925	0,944	0,940	0,967	0,758	0,985	0,961	0,967	0,976	0,904												
ITA	0,994	0,989	0,841	0,567	0,929	0,981	0,954	0,972	0,711	0,958	0,984	0,957	0,961	0,922	0,961											
LTU	0,625	0,629	0,812	0,722	0,756	0,728	0,459	0,611	0,767	0,646	0,729	0,549	0,668	0,679	0,654	0,624										
LUX	0,834	0,805	0,717	0,839	0,804	0,796	0,712	0,807	0,665	0,852	0,826	0,758	0,886	0,778	0,859	0,792	0,680									
LVA	0,545	0,546	0,775	0,721	0,695	0,655	0,359	0,537	0,699	0,583	0,657	0,444	0,614	0,636	0,590	0,542	0,948	0,683								
MLT	0,864	0,859	0,535	0,711	0,705	0,778	0,818	0,816	0,553	0,880	0,802	0,917	0,899	0,665	0,898	0,834	0,478	0,782	0,396							
NLD	0,976	0,978	0,727	0,537	0,861	0,929	0,975	0,951	0,651	0,955	0,933	0,987	0,942	0,849	0,956	0,970	0,495	0,750	0,395	0,895						
POL	0,901	0,906	0,976	0,587	0,975	0,964	0,818	0,915	0,825	0,872	0,959	0,824	0,878	0,949	0,876	0,912	0,822	0,767	0,762	0,649	0,816					
PRT	0,820	0,824	0,892	0,750	0,924	0,863	0,721	0,847	0,861	0,864	0,877	0,737	0,866	0,890	0,856	0,809	0,855	0,870	0,864	0,641	0,716	0,917				
ROU	0,589	0,579	0,795	0,741	0,720	0,687	0,382	0,580	0,659	0,599	0,688	0,484	0,652	0,656	0,611	0,577	0,943	0,728	0,969	0,454	0,441	0,789	0,866			
SVK	0,842	0,864	0,954	0,518	0,969	0,904	0,810	0,894	0,872	0,843	0,905	0,772	0,814	0,948	0,842	0,847	0,769	0,737	0,726	0,560	0,760	0,959	0,924	0,730		
SVN	0,791	0,801	0,859	0,805	0,875	0,840	0,666	0,799	0,809	0,831	0,852	0,741	0,846	0,834	0,841	0,778	0,899	0,849	0,898	0,693	0,694	0,884	0,965	0,911	0,866	
SWE	0,984	0,990	0,800	0,534	0,908	0,960	0,981	0,967	0,715	0,970	0,961	0,978	0,948	0,895	0,966	0,982	0,570	0,764	0,484	0,851	0,986	0,872	0,784	0,514	0,837	0,755

Fig. B.11. Overlap values among European countries for the PUBf indicator.

structures, and the study of its usefulness for the comparison of the disciplinary structures of research systems is left for future works.

Appendix B. Countries, disciplines and detailed results

In Table B.6 the list of the abbreviations for the 27 European countries used in the paper is given. In Table B.7 the list of scientific disciplines used in the paper is reported.

In Fig. B.11 the detailed values of overlaps among European countries is reported for the PUBf indicator.

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