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**Beyond university rankings ? Generating
new indicators on European universities
by linking data in open platforms**

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Abstract

The need for new indicators on universities is growing as governments and decision makers at all levels are faced with the huge opportunities generated by new knowledge, but at the same time are pressed hard by budget constraints. University rankings are attracting policy and media attention, but at the same time receive harsh methodological criticism. After reviewing the critical literature on rankings, we suggest that a change in the paradigm of design and production of indicators is needed. The traditional approach is one that leverages on existing data but also suggests heavy investment to integrate existing databases and build up tailored indicators. We show how the *intelligent* integration of existing data may lead to an open linked data platform that permits the construction of new indicators. The power of the approach derives from the ability to combine heterogeneous sources of data in order to derive indicators that address a variety of user needs, without designing the indicators on a custom basis.

Keywords: university, rankings, indicators design, data integration

1. University rankings and the demand for new indicators in higher education and research

The construction of new indicators is a crucial activity in policy making. Governments use numbers to govern complex situations (Porter, 1995; Desrosières, 2008). Researchers in social sciences are increasingly requested to conceptualize, design and implement indicators for various social and policy goals.

Very often user requirements are translated into the design of new indicators. Then the lack of available data forces to make decisions. In most cases the ambitions are abandoned due to the lack of data. In other cases, however, indicators are constructed on the basis of existing data, ignoring or downplaying the limitations coming from the nature of data. A well known example is the construction of university rankings, an exercise that attracts lot of policy and media attention despite the numerous methodological shortcomings. The original goal of these indicators, as it is well known, was to inform potential users of universities worldwide (i.e. Chinese students and their families; government supporting students abroad). This information need was satisfied making the most of existing data on scientific publications and ignoring other aspects of the activities of universities, as well as the limitations of data on publications with respect to disciplinary composition. In Section 2 we summarize a large literature on the limitations of university rankings.

Still in other cases large amount of money are spent in order to build the indicators from scratch. A noticeable case is the integration of existing database on ad hoc basis, i.e. designing queries that relate data extracted from different databases, without changing the structure of data. A noticeable example in the European context is the construction of indicators on the impact of Framework Programme funding, which are repeatedly constructed from scratch.

As it has been rightly emphasized: "Data are not simply addenda or second-order artifacts; rather, they are the heart of much of the narrative literature, the protean stuff that allows for inference, interpretation, theory building, innovation, and invention" (Cronin, 2013, p. 435).

At the same time we note that the user requirements of policy makers are becoming tighter. Policy makers are pressed hard in a difficult dilemma. On the one hand, there are continuously new opportunities generated by the production of knowledge in science and technology, which policy makers are invited to take on board. On the other hand, budget constraints are binding almost everywhere (with few exceptions). This dilemma cannot be addressed without increasing the level of sophistication of indicators used to make informed decisions.

We see two broad trends in the user requirements for indicators that are: granularity and cross-referencing, which are described respectively in Sections 3 and 4. Section 5 illustrates a data infrastructure (Smart.CI.EU) owned by Sapienza University of Rome, and the methodology for its development. Section 6 presents the main user needs which have to be considered in the indicators design phase, while Section 7 proposes an alternative approach to generate new indicators from a platform. Section 8 concludes the paper outlining a list of unsolved policy issues that could be addressed by our approach.

2. Beyond university rankings? A taxonomy of the critical literature

University rankings are an interesting subject for information science and technology. The more they are criticized from a methodological and academic point of view, the more they are covered by the media and diffused among users and decision makers. In this section we aim at classifying the main methodological objections to university rankings, as available in the specialized literature. The classification will help to identify the areas in which there are the most important weaknesses. In the rest of the paper we claim that most of these weaknesses can be addressed by changing the basic methodology, from a composite indicator

approach based only on output measures, to a comprehensive input-output approach made possible by the "intelligent" integration of existing datasets.

The importance of the topics of university rankings is witnessed by the publication of dedicated books (Kehm and Bjorn, 2009; Dehon et al., 2009; Shin et al., 2011; Hazelkorn, 2011) and of several review articles (Bowden, 2000; Provan and Abercromby, 2000; Brooks, 2005; Dill and Soo, 2005; Turner, 2005; Usher and Savino, 2006; 2007; Salmi and Saroyan, 2007; Ioannidis et al, 2007; Taylor and Braddock, 2007; Harvey, 2008: Aguillo et al., 2010; Chen and Liao, 2012; Safon, 2013; Bornmann et al., 2013a, b) since mid-2000s. In addition, policy publications and official reports have been produced directly or under the auspices of UNESCO (Marope et al., 2013), World Bank (Salmi, 2009) or the OECD (Salmi and Saroyan, 2007), as well as by large representative associations such as by the European Universities Association of (Esterman and Nokkala, 2009; Esterman, Nokkala and Steinel, 2010; Rauhvarges, 2011, 2013; EUA, 2012). What follows is our own classification of the main issues discussed.

2.1 Content of indicators

Subject mix

The issue of subject mix and the disciplinary composition of universities has been repeatedly raised. According to Williams and van Dyke (2006) and Buela Casal et al. (2007), there should be separate individual rankings for each school or department, rather than having a composite measure. Marginson (2007) has proposed a general principle: "when comparing research and scholarly capacity or performance, use primarily discipline-basd measures rather than whole of institution measures" (Marginson, 2007, p. 19). One important reason to work in this direction is that rankings give a premium to comprehensive research universities. Isomorphic pressures may reduce the diversity of the system (Fumasoli and Huisman, 2013), penalizing programmatic diversity and specialist universities (Marginson and van der Wende, 2007; van der Wende, 2008). Thus the issue here is not to use several rankings or to check their robustness but to avoid aggregation and rather use separate disciplinary rankings.

Size

It is also often noted that rankings give a premium to large universities, since many indicators are based on past performance (e.g. Nobel prizes), which is associated to current size. In the Shanghai ranking the weight of indicators that are size-dependent is 90%. While size-normalized rankings are also available, it is well known that rankings are biased towards large universities.

Education output

Almost all world league tables are based on research output. Quality of education indicators are included in some of the rankings (for example the Times Higher Education Supplement ranking, THES), but have a limited role altogether. This is a major bias. From a social point of view it is clear that two universities with a similar research output strongly differ if they teach to a largely different number of students, or if the employability of students is different. The argument that there is positive correlation between quality of research and quality of education, which is sometimes advanced, should be tested empirically. The institutions building up the rankings are transparent in claiming that the validity of the final ranking is determined by the constituent indicators, so that it should not be interpreted extensively as stating something like "quality of university". However, several authors have questioned the correspondence between rankings and quality of education, stating that in general "what is incorporated into the rankings is what is measurable, not what is valid" (Cremonini, Westerhijden and Enders, 2008). The validity, reliability and comparability of information incorporated into the measures fail to satisfy properties for acceptance (Bowden, 2000; van Dyke, 2005; Ioannidis et al., 2007). Other authors, such as van Leeuven et al. (2003) have underlined the importance of "using multiple indicators instead of only one" and "investigating which combinations of indicators provide the strongest correlations, thereby indicating the best combinations of indicators in research performance indicators" (van Leeuven et al., 2003, p. 276).

Lack of input data

Some authors have challenged the notion that rankings can be built mainly on the basis of output data, with some limited indication of inputs (e.g. expenditure). Rather, the appropriate notion to be used in order to compare universities is the one of efficiency, or the relation between input and output.

A subtle and important criticism has been proposed by Cremonini, Westerheijden and Enders (2008), who argue that rankings want to reframe higher education as a consumer good, while the appropriate reference model should be one of investment. In other words, rankings offer only information on the output, while they fail to account for the relation between inputs and outputs, and between outputs and social outcomes. Indicators based on input-output relations are more useful to university strategic decision making than simple rankings, because they incorporate considerations of resources. These considerations are crucial insofar as universities must decide their positioning (Maassen and Potman, 1990; Bonaccorsi and Daraio, 2007; 2008; Fumasoli and Huisman, 2013).

2.2 Aggregation of indicators

Statistical robustness

Being based on elementary indicators aggregated into composite indicators, rankings utilize only one of a number of possible combinations of indicators and of aggregation rules. One problem, often raised in the literature, is that the weights used for the aggregation of individual indicators are arbitrary and lack theoretical foundation (Provan and Abercromby, 2000; Brooks, 2005; Lukman et al., 2010). More subtly, what happens is that, given the differences in the range of the distribution of constituent indicators, actual weights differ systematically from intended ones. Saisana and Hombres (2008) and Saisana et al. (2011) have developed a methodology to test the robustness of rankings. Using a simulation technique, they show that, in general, rankings are robust in the top positions but less reliable elsewhere, that Shanghai rankings are more robust than THES rankings, and that for a certain numbers of universities the variability induced by changes in the construction of the composite indicator is so large that all existing rankings are meaningless.

Deterministic ranking

According to Lubrano (2009) an important methodological problem of rankings is that they assume a deterministic setting, while the underlying indicators are average values from distributions. Bibliometric indicators are not exact measures, since they incorporate several sources of errors, such as identification of authors, timing of publication, or name of affiliations. It is better to conceive of the constituent elements of the ranking as a random variable, taken from a distribution. If the problem is conceptualized this way, there is a need to examine the intervals of confidence. As Goldstein and Spiegehalter (1996) puts it, "the mean has no special status" (Goldstein and Spiegehalter, 1996, p. 395). In other words, rankings suppress the intrinsic variability of indicators at lower levels of aggregation, giving an impression of stable hierarchies among universities, without explicitly testing for the statistical representativeness of differences. As it has been noted "an overinterpretation of a set of rankings where there are large uncertainty intervals, can lead both to unfairness and to inefficiency and unwarranted conclusions about changes in ranks" (Goldstein and Spiegehalter, 1996, p. 405).

2.3 Impact and implications of rankings

Rankings and the changing State-university contract

Other authors have tried to trace back the origins of rankings to changes in the relations between universities and the State. Rhoades and Sporn (2002) have carried out a detailed historical analysis of the adoption of Quality Assurance principles in higher education. They show that while in the US the business sector has been the main reference model since the end of XIX century, the borrowing of US models in Europe has followed an adaptive path, moving more from State to State than from market to government. However, the same isomorphic process (in the sense of Di Maggio and Powell, 1983) is at stake. In a similar line of

reasoning, Ferlie, Musselin and Andresani (2008) show that the reform of universities has not followed a unique ideological thrust, but has rather used several narratives in order to justify the changes in the relation between state and universities. Thus, while UK, Netherlands and Norway have embraced New Public Management arguments, in other countries the main narratives have followed rather network governance or neo-weberian arguments, giving more weight to lateral working and intermediate bodies.

Rankings as neoliberal devices

However, other authors show less nuances in their interpretation. A large stream of criticism has tried to demonstrate that the underlying rationale of rankings is ultimately ideological and neoliberal. On one hand, rankings are seen as part of a larger effort to transform higher education into a market sector, and to introduce in the public sector the managerial principles and techniques that govern modern capitalism. Deem and Brehony (2005) have argued that the new managerialism adopted by UK universities amount as an ideology that gives more importance to market results than social outcomes. Hazelkorn (2009) argued that they alter the way university has traditionally performed. Amsler and Bolsmann (2012) sharply argue that they "transform universities around the world from institutions of the public good into corporations and brands, in the construction of education as a "globally traded commodity" "(Amsler and Bolsmann, 2012, p. 284). Adding a geopolitical dimension to the debate, Deem, Mok and Lucas (2008) have suggested that the adoption of the Anglosaxon model in most East Asian countries (e.g. Hong Kong, Taiwan, China, Japan, Singapore) is a manifestation of westernization, implying the acceptance of cultural hegemony.

Rankings as legitimation of categorical inequalities

On the other hand, several authors use concepts from Michel Foucault to show that rankings are part of a more general pattern of modern societies to adopt forms of "disciplinary power" (Foucault, 1977), based on surveillance and normalization, leading to the "indefinite discipline" (Foucault, 2008) of constantly trying to hit the top of the chart (Bruno, 2009; Sander and Espeland, 2009). Another theoretical root of the criticism to rankings is to be found in Pierre Bourdieu, according to which "the symbolic power of academic titles act as institutional rites that reinforce social hierarchies" (Bourdieu, 2001). Rankings give legitimation and reinforce categorical inequalities, institutionalizing them (Rawlings and Bourgeois, 2004; Cantwell and Taylor, 2013). Through a disciplinary power embedded into apparently neutral quantitative measures, "rankings put institutions in a mould" (Thakur, 2007, p. 92).

Rankings as self-fulfilling prophecies

Espeland and Sander (2007) apply to rankings the notion of self-fulfilling prophecies introduced by Robert Merton (Merton, 1968). Since people assume that the meaning of numbers is universal and stable, the transformation of qualitative differences into a measurable difference makes information seem more authoritative. However, small qualitative differences, often subject to considerable statistical uncertainty, are then transformed into highly visible hierarchical differences: "listing schools by rank magnifies these statistically insignificant differences in ways that produce real consequences for schools, since their position affects the perceptions and actions of outside audiences. The distinctions produced by rankings are increasingly important and taken for granted" (Espeland and Sauder, 2007, p. 12). Among the effects produced by rankings for top universities, Ehrenberg (2003) mentions the increase in the number of applicants, the reduction in acceptance rates, the increase in the average SAT scores of the admitted students. Even worse, Bastedo and Bowman (2010a,b) show that published rankings affect the perception of performance: "when certifications are highly legitimate, the formal structure of the evaluation can have institutional effects that are independent of prior reputation and organizational performance" (Bastedo and Bowman, 2010a, p. 6) so that "over time rankings become reputation rather than reputation being an independent indicator that rankings can be used to assess change in quality" (Bowman and Bastedo, 2009, p. 432). Similar effects of distorsion of perceptions are reported by Stake (2006) and Griffith and Rask (2007), who emphasize how very small changes in the rank, which are not distinguishable from noise, are instead interpreted as substantial differences in the underlying quality. Consequently, "a system designed to measure performance dictates what the performance should be- a case of tail wagging the dog" (Taylor and Braddock,

2007, p. 258). Somewhat differently, Greeval, Dearden and Lilien (2008) observe that rankings are rather stable and competition is then localized, taking place among sub-ranks, rather than on the overall ranking.

2.4 Addressing the criticisms
The main criticisms fall in three areas: content of indicators, methodology, and implications. In another paper (Daraio, Bonaccorsi and Simar, 2014) we have addressed content issues (labelled *Monodimensionality*, i.e. lack of data on education, *Input-output structure* and *Size and subject mix*) and methodological issues (labelled *Robustness*). In this paper we try to consider also the criticisms based on political/ideological arguments, discussed above under the heading *Impact and Implications*.

The question we address is the following: which are the abstract requisites for indicators to address the criticisms raised against the university rankings? It must be clear that there are some criticisms that are not bound to be solved by means of existing data: for example, it is clear that existing data on publications have a bias for English language, but no alternative sources of data in other languages are available on a world basis. On the same token, publications in Human and Social Sciences are severely under-represented in existing data sources. We focus on those limitations for which improvements can be implemented on the basis of the existing data. The previous discussion has clearly shown that the minimum standards for acceptability include:

- Coverage of all relevant activities of universities (namely, research and education)
- Consideration of differences in the input structure
- Lack of systematic biases due to size and subject mix
- Statistical robustness of comparison
- Fairness of comparison.

While the first four requisites are clear from the above discussion, the notion of fairness of comparison needs explanation. By fairness of comparison we mean the following requisites: a comparison between universities is fair if and only if: (a) the universities under comparison have a similar input structure; (b) the trade-off between outputs is explicitly recognized in the measurement; (c) a higher ranking is associated to a higher performance, given the input structure and the trade-offs between outputs.

These requisites translate formally the issues discussed in the critical literature that have a political and ideological orientation. In this literature it is generally recognized that all universities differ among themselves in qualitative ways. Only a minority of authors reject the notion of comparison altogether, claiming that universities should be left free from any external judgment (Prado, 2009; Macherey, 2011; Abelhauser, Gori, Sauret, 2011; Bailey and Friedman, 2011; Gori, 2013). These differences can be transformed into quantities only if we recognize that universities have not freedom to access relevant resources, but are constrained by legal, administrative and financial considerations. Thus only universities that are similar in terms of inputs (e.g. staff, funding, expenditure) can be sensibly compared. In addition, it must be recognized that universities are multi-input multi-output producers (Bonaccorsi and Daraio, 2004). This means that universities can produce different mixes between research and teaching outputs and that producing more of one output, given the structure of inputs, may imply producing less of another output. Recognizing this situation means that, once the structure of inputs is fixed in order to compare universities among themselves, it is also needed to compare units with similar mixes of outputs, or to compare units along one output, keeping the other constant. The condition under (c) demands that the measurement used in order to compare universities incorporates conditions (a) and (b). In formal terms, university A is ranked higher than university B if A and B have the same input structure and the same mix of output, and A produces more of at least one output. This condition is satisfied by the notion of dominance.

It is clear that the condition (c) is not satisfied by university rankings built on the basis of composite indicators that incorporate research outputs only. University rankings compare universities with different input structures and without any consideration of outputs different from research. For these reasons they are

likely to induce the negative consequences illustrated in the critical literature: small qualitative differences are translated into different rankings which are highly respected because of the quantitative feature; there is no consideration for different endowments of resources, and there is a pressure to conformity based on research outputs.

Summing up, as it has been observed by Bornmann (2014, p. 428): "Although there are a number of "dos and don'ts" when designing rankings or ratings, there will probably never be one that will do justice to the heterogeneity of the institutions covered and able to produce a valid image of the performance of all institutions."

We suggest that a shift in methodology might address these criticisms.

3. The trend towards granularity of indicators

After the examination of the critical literature on university rankings, we start in this paragraph the description of the first trend in the user requirements for indicators.

We see here what we call a trend towards increased *granularity* of indicators. New indicators are explicitly requested to allow various kinds of aggregation and disaggregation, preserving desirable statistical properties, in order to address new policy needs. Traditional indicators have been mostly developed at a high level of aggregation at national level, more recently with some limited disaggregation at regional level. In addition, traditional indicators do not allow for much disaggregation by nature of actor or by discipline, as we will see below. For the policy needs of democratic governments after Second World War, the traditional OECD aggregate statistical apparatus was quite adequate.

We argue that new policy needs demand a much higher level of granularity, along three directions.

The first direction of increase in granularity is *territorial*. Traditionally, science and technology policies have been the domain of States, whatever their constitutional structure (e.g. in Germany and Spain the funding of universities is mostly done at regional level; in the United States the funding of research is mostly federal while States have a role in funding higher education, etc.). This centralization has been considerably reversed by a number of constitutional reforms, as well as a trend towards regionalization of innovation policies in most OECD countries (OECD, 2011a). This articulation of *loci* of policy making follows a debate that has placed the geographic dimension at the core of public policies for research and innovation.

The second direction of the granularity trend is *institutional*. An important distinction in the public research system is between higher education institutions (among which universities) and Public Research Organizations (PROs). This distinction, which is recorded in official R&D statistics at country level, is then lost in the construction of indicators at lower levels of geographic and disciplinary aggregation. Governments tend to follow separate channels of funding for universities and PROs, in order to avoid disruptive political fights. At the same time, the debate on the relative strenghts and weaknesses of these different institutional forms of public research is very hot. Governments increasingly face the challenge of estimating the differential impact of funding on these subsystems, as well as the opportunities for integration and collaboration among the subsystems (OECD, 2011b).

A related need for institutional granularity comes from the long term evolution of systems of funding of public research. Governments have to decide not only the aggregate level of expenditure (a decision for which the comparative analysis of OECD and Eurostat data is perfectly adequate) but also the allocation of funds among individual actors, e.g. universities and PROs. As it is well known, governments tend to use performance-based funding systems, for which they develop their own internal procedures and datasets, on administrative bases. However, in the long term this practice inevitably creates new policy issues: what is the impact of performance-based funding on the subsequent performance of individual institutions? Is the country performing well, in this perspective, with respect to other comparable countries? Is the distribution

of funding across individual institutions appropriate, or should it be more concentrated, or perhaps less concentrated? These questions cannot be addressed using aggregate indicators.

The third trend is *disciplinary*. Until a few decades ago in most OECD countries the relative shares of funding among disciplines was not considered a highly controversial policy issue. The distinction between mission-oriented research and curiosity-driven research was considered appropriate (Ergas, 1987). Areas of science associated to mission-oriented research (e.g. space, supercomputing) and making use of complex instrumentation (e.g. particle physics, astrophysics) were funded separately on the government budget. Other areas of science associated to curiosity-driven research were funded on the basis of ex ante selection, with relative disciplinary shares following historical patterns and areas of specialization. By and large, funding systems in the steady state were following the disciplinary composition of the underlying research population, with slight variations at the margins. This picture has been challenged in the last three decades for a number of reasons we can only touch here. New broad disciplines, such as information sciences, materials sciences, and life sciences, were born in mid-XX century but exploded in the late '70s and '80s in terms of potential for discoveries and rates of production of new knowledge, creating pressure on funding systems. In the same period in the United States there has been a remarkable shift of priorities from space-related (and subsequently, defense-related) fields to life sciences, starting with the Cancer War launched by President Nixon in 1971. Finally, at the end of the XX century the policy agenda seems to be dominated by concerns about climate change, sustainability and environmental issues, so that many expectations are placed upon sciences that integrate knowledge across many layers of reality (from the molecular level up to large living systems or energy systems). Thus we see a resurgence of sciences that adopt a systemic approach, such as ocean sciences, climatology, ecology, food sciences, and the like. Summing up, governments understand they cannot proceed with steady state allocation of resources, but must build up some rationale for the disciplinary mix (Stewart, 1995). Again, these kinds of questions cannot be addressed using aggregate indicators.

We argue that new indicators must be consistent with a trend towards territorial, institutional and disciplinary granularity. While the need for better granularity is visible and understandable, the state of the art of indicators is not adequate.

4. The trend towards cross-referencing of indicators

Another powerful trend we see in policy requirements is towards *cross-referencing*, or the ability of indicators to be combined in meaningful ways, preserving their statistical properties. For example, governments start to ask why, having spent money on statistics on higher education and on research, the two sources of information cannot be meaningfully matched. Or why information on patents of universities cannot be combined with information on publications of universities, unless a dedicated, and expensive, project is built in order to address this specific question.

There are several important reasons for the cross-referencing trend.

One reason comes from the large literature on research and innovation systems (Lundvall, 1992; Nelson, 1993). Using a variety of approaches and methodological options, this literature has shown that what matters for performance is not only the level of expenditure or the quality of individual actors, but the *interaction* among actors, or the flows within the system. This explains the large interest created by studies on science-technology flows, university-business collaboration, author-inventors, mobility of researchers, international cooperation, impact of research on regional growth, and the like.

In all these cases what is at stake is a relation, or interaction, between systems, or sub-systems, each of which is equipped with its own array of indicators, developed in relative isolation for the purpose of separate policy issues. Thus when governments ask how much interaction with business is generated by funding of

universities, they do not understand why this issue is not only difficult to address, but definitely impossible at the state of the art of existing indicators.

Another reason is somewhat contingent, but powerful. Governments have to come to grip with the impact created by sources of information different from official statistics, such as university rankings. These sources use existing indicators to build up rankings that convey very powerful and clear messages to large audiences. Governments are often presented with the challenge of reconciling the information that comes from official statistics with the information conveyed by rankings. A striking case, largely discussed in the dedicated literature, is the reaction of some European governments, particularly France and Germany, to the relatively poor performance of their universities in Shanghai rankings.

The traditional approach to manage these issues is the design of integration of existing databases, using techniques in database management for data integration, validation and data quality. This approach can no longer sustain the increase in sophistication of requirements for indicators. A change in paradigm is needed.

5. Building the data infrastructure
Before illustrating the methodology it is useful to check whether existing data permit its implementation. In this section we describe a data infrastructure that might be used to address all the requisites illustrated in the above section. The data infrastructure allows the construction of new indicators that can be used in isolation, but also the construction of new ranking indicators based on advanced input-output modeling techniques rather than on composite indicators.

The Smart.CI.EU (Sapienza microdata architecture for education, research and technology studies. A Competence-based data Infrastructure on European Universities) is a data infrastructure created within a research project funded by Sapienza University of Rome and owned at the Department of Computer, Control and Management Engineering Antonio Ruberti, Sapienza University of Rome. The creation of Smart.CI.EU has been made possible by the integration of several data sources. This is entirely based on data on European higher education institutions, thanks to the integration of several projects.

First of all, thanks to the pioneering Aquameth (Bonaccorsi and Daraio, 2007; Daraio et al, 2011) and Eumida projects (Bonaccorsi, 2014) and the subsequent launch of ETER project (European Tertiary Education Register, http://eter.joanneum.at/imdas-eter/), an official census of European higher education institutions has been established. An official list of institutions, validated by National Statistical Authorities (hence compliant with national legislation) is now available. Each institution is characterized by a vector of descriptors, including the geographic location at NUTS 2 level (region). Additional geo-referentiation at NUTS 3 level (province) has been subsequently provided on Eumida data (Varga and Horvath, 2014). The Eumida project made publicly available a dataset limited to basic descriptors of universities (Data collection 1), while Data Collection 2, related to research active institutions, was not published. The new ETER project has updated the Eumida collection for 2012 (and will gather data also for 2013) and has negotiated with National Statistical Authorities the conditions for publication of data. Thus a public dataset on the census of higher education institutions is now available.

Second, the location of institutions can be exploited by associating a number of indicators to the institutions located in the same province (where NUTS 3 data are available) or region (where only NUTS 2 are available). By using Eurostat official data, the economic, social, cultural and demographic context of institutions can be fully characterized. Contextual or environmental variables can also be used to construct indicators of the impact of universities on society.

Third, by using the official name of institutions it is possible to allocate research output to affiliations. We exploited the Global Research Benchmarking System (GRBS) project, which allocated Scopus publications to individual universities in East Asian countries, North America and Europe. With respect to European universities, the affiliations have been cleaned by the same group of experts that worked on the Eumida project. These data are then compared with Scimago data, which are also based on Scopus. The GRBS data

are however more fine-grained, since they have been made available for 251 separate subject categories. These data are available on a complimentary basis and only for a window of time (2007-1010), which nicely overlaps the Eumida dataset (2008-2009). In the future, the availability of publication data by university should be ensured through dedicated investment.

By integrating these three data sources it is possible to obtain the basic indicators listed in Table 1. The indicators in this table are already available in the Smart.CI.EU data infrastructure, that would be useful also as a starting point for future feasibility studies.

Table 1 State of the art of integration of official statistical data on Higher education institutions with output data and territorial covariates

Identifiers	Institutional code
	Name of the institution (in own language)
	Name of the institution (in English)
Basic institutional descriptors	Country
	Legal status
	Type of institution, national definition
	Type of institution standardized
	Foundation year
	Current status year
	University hospital (dummy)
Geographic information	Region of establishment, NUTS2 code
	Province of establishment, NUTS 3 code
Educational activities	Highest degree delivered
	Number of enrolled students at ISCED levels 5
	- by field of education
	- by national/foreign origin
	Number of graduates at ISCED levels 5
	- by field of education
	- by type of degree (diploma, bachelor, master, long cycle)
	- by national/foreign orign
	Distance education institution (dummy)
Research activities (*)	Research active institution (dummy)
	Number of enrolled students ISCED 6
	- by field of education (FoE)
	- by national/foreign origin
	Number of graduates ISCED 6 (doctorates)
	- by field of education (FoE)
	- by national/foreign origin
	R&D expenditures
	Patent applications
	Spin-off companies
Expenditure	Personnel expenditure
	Non-personnel expenditure
	Capital expenditure
Revenues	Core budget
	Third party funding
	Tuition fees
	Total Funding from Private Sector
Personnel	Number of academic personnel in full time equivalent (FTE) and headcount (HC)

	- by field of science (FoS) - by national/foreign origin Number of administrative personnel in FTE/HC
Scientific publications (**)	Number of institution publication output International collaborations: share of publications produced in collaboration with foreign institutions High quality publications: as a share published in the most influential scholarly journals of the world (top 25%) Normalized impact: relationship of an institution's average scientific impact (average citations) and the world average, which is 1 Specialization index: extent of thematic concentration / dispersion of an institution's scientific output (0 for generalistic to 1 for specialized) Excellence rate: % of an institution's output included into the set formed by the 10% of the most cited papers in their respective scientific fields

Scientific publications by subject area (n=250) (***)	Number of publications by subject area
	Percentage publications in top source titles
	   - top 10% journals
	   - top 25% journals
	Number of citations
	Percentage of citations from top source titles
	   - top 10% journals
	   - top 25% journals
	H-index

Regional covariates (****)	Eurostat regional data at NUTS2 level. Selected indicators: Regional gross domestic product (PPS per inhabitant) Employment rate of the age group 15-64 Total intramural R&D expenditure (GERD) Millions of PPS Total R&D personnel and researchers - head count Patent applications to the EPO by priority year - Number Stud ISCED5_6 as % of pop 20-24 years 2008
Local covariates (*****)	Eurostat regional data at NUTS3 level. Selected indicators: Total population (possibly by age group) and population density; Total GDP in PPS and GDP per capita Gross value added at basic prices, possibly by NACE sector (11 sectors) in G€ Employment (in 1000 persons) possibly by NACE sector (11 sectors)

Notes
(*) Items in italics are available for a subset of countries (Eumida Data collection 2)
(**) Source: Scimago based on Scopus data
(***) Source: Global Research Benchmarking based on Scopus data
(****) Possibility to combine with a larger set of regional indicators at NUTS2 level available on Regions and Cities Eurostat dataset
(*****) Possibility to explore also Eurostat data on metropolitan regions and Urban Audit indicators on selected cities

The crucial point here is that these projects have been conceived with a view on the potential for integration of new data. The potential is already visible in two directions: (a) integrating co-variates using the university as the unit of observation; (b) integrating co-variates using the territory as the unit of observation.

The developments in (a) are made possible by the fact that by building up the census of higher education institutions it has been possible to reconcile the data on students, which are in the official domain of higher education statistics, with the data on research, which are in the official domain of S&T statistics. Although the data on research input, such as the R&D expenditure (OECD-Eurostat), are not yet available at microlevel (university level) due to low reliability of allocation of higher education expenditure between research and teaching, it has been possible to integrate the data on research outputs, such as doctorate degrees and scientific publications. With respect to (b) the georeferentiation of higher education institutions offers the possibility to integrate the data available in the census with a host of other data with a territorial dimension, at NUTS 2 but also, with limitations, at NUTS 3 level.

The potential for this approach is already visible in a number of recent developments.

With respect to integrating data at the level of universities, the Eumida data have been integrated with data on publications, and Bonaccorsi, Daraio and Simar (2014) carried out a directional distance analysis of efficiency, economies of scale and specialization. Daraio, Bonaccorsi and Simar (2014), instead, propose a conditional multidimensional ranking, using the same data coming from Smart.CI.EU.

With respect to integrating data at regional level, Vertesy, Annoni and Nardo (2013) have integrated the Eumida data with a number of indicators at regional level.

Combining both directions of integration, in Bonaccorsi (2014) several authors combine Eumida data with co-variates of various kinds, using the university or the territory as the unit of observation (e.g. publications, academic patents, creation of new technology based firms at province level, performance of research teams at university level), showing the potential for empirical research.

As it is shown in Table 2, in future studies it would be possible to integrate other sources of information already available, again following either the direction of integration assuming the university as unit of observation (European funding, U-Multirank, ERA survey) or the territory (Regional Innovation Scoreboard). In some cases the access to these data is not public. However, the gains in integrating such data in an open platform architecture are so great that we believe there might be changes in the access policy in the near future.

Table 2 Feasibility of further integration in the open platform

European funding (^)	EU Framework programmes - participants - funding - role (e.g. coordinator)
Regional Innovation indicators (^^)	Sales of new to market and new to firm innovations Employment in knowledge intensive activities SMEs introducing marketing or organizational innovations SMEs introducing product or process innovations EPO patent applications Innovative SMEs collaborating with others SMEs innovating in-house Non R&D innovation expenditures R&D expenditure in the business sector Population with tertiary education
U- Multirank (^^^)	*Indicators of teaching and learning* Student-staff-ratio Graduation rate Percentage of academic staff with PhD

	Percentage of graduates graduating in norm period
	Rate of graduate unemployment
	Inclusion of work experience
	Indicators from the student survey
	    - Overall learning experience
	    - Quality of courses & teaching
	    - Organisation of program
	    - Contact to teachers
	    - Social climate
	    - Facilities
	o libraries,
	o laboratories,
	o rooms,
	o IT
	- Research orientation of teaching/programme
	- Inclusion of work experience /practical elements
	
	Indicators of research
	External research income (per fte academic staff)
	Doctorate productivity
	Total publication output (per fte academic staff)
	Field-normalised citation rate
	Highly cited research publications
	Research orientation of teaching (student survey)
	
	Indicators of knowledge transfer
	Income from private enterprises (research contracts, service contracts, licenses etc.)
	Joint publications with industry
	Patents (per fte academic staff)
	Co-patenting with industry per fte academic staff)
	
	Indicators of international orientation
	International orientation of programmes (rating indicator)
	Opportunities to study abroad (student survey)
	Percentage of international academic staff
	Percentage of PhDs by foreign students
	International joint publications
	International research income
	
	Indicators of regional engagement
	Percentage of graduates working in the region
	Student internships in local enterprises
	Degree theses in cooperation with local industry
	Regional joint publications
	Income from regional sources

European Research Area indicators (^^^^)	Large array of questionnaire-based data from a large sample of European research performing and research funding organizations

(^) Information on EU programmes funding is publicly available in a database format at http://cordis.europa.eu/projects/home_it.html. Data have been organized by organization in a restricted access website, see https://webgate.ec.europa.eu/e-corda/resources/pdf/BO_XI_Quick_user_guide.pdf. Data are available by subject.

(^^)http://ec.europa.eu/news/pdf/2014_regional_union_scoreboard_en.pdf. Data are available only at regional level (NUTS 2).

(^^^) http://www.u-multirank.eu/#!/home?trackType=home&section=entrance. Data are available for a non-representative sample of universities in Europe and other areas.

(^^^^) See the questionnaires for Research Performing Organizations (RPOs) and Research Funding Organizations (RFOS) and the associated Glossary.
http://ec.europa.eu/research/era/pdf/ERA_Survey_2014_Glossary_v6.pdf

6. User requirements

Indicators should be designed according to the needs of users. However, the needs of users are highly fragmented and idiosyncratic. Universities are multi-input multi-output organizations, with a large number of heterogeneous stakeholders, and with highly differentiated production technologies. Indicators must follow closely the informational needs of sophisticated and heterogeneous users.

Table 3 has been developed by a Group of experts of the European Commission and gives an overview of the sheer variety of needs that indicators should address. The last column offers a preliminary assessment of the feasibility of deriving these indicators from the platform described above. By "Yes" we mean the potential availability of data covering all institutions, excluding the cases in which data are available on a sample (e.g. ERA survey or U-Multirank). In Appendix 1 a list of user groups and usage of research assessment are reported.

Table 3 User requirements for indicators on European higher education

Indicator	Description	Notes	Feasibility
RESEARCH PRODUCTIVITY			
Research publications and outputs	A count of publications and other research outputs.	Depending on purpose only selected types of publications can be counted. Publishing is vital for progress in science scholarship. Different disciplines produce different types of research outputs. Emphasis on quantity of publication. Suitable data bases for a variety of disciplines and research related outputs, especially in social sciences and humanities.	Yes
Research outputs per 'Research Academic' staff	Number of publications and other research outputs per academic staff or full-time equivalent (FTE).	Supports cross-institutional comparisons, adjusted for scale of institution. Comparable definition of 'Academic Staff' and 'Research Time' can be difficult. Agreement on definition of 'Research Academic'.	Yes
QUALITY AND SCHOLARLY IMPACT			
Number and percentage	The number or percentage of journal articles published in	Widely used, especially in the exact sciences which tend to be well covered. Data must be accurate and verified.	Yes

of publications in top-ranked, high impact journals	the top-ranked, high impact journals for the fields of research.	Although one of the most popular indicators, it is not always the most appropriate one. Especially in social sciences and humanities, expert rankings do not correlate very well with impact factors. In these fields and in engineering, other sources are important as well (books, proceedings). Discipline specific journal rankings, especially in social sciences and humanities, based on expert opinion in combination with indicators. Value of developing a ranking or hierarchy of scientific-scholarly publications.	
Citations	Citation data are derived from citation indexes, i.e. databases that do not only contain meta data	In the exact sciences, peers tend to consider citation impact a relevant aspect in assessments of research performance. Citations reflect intellectual influence but do not fully coincide with research quality. Expansion of existing databases and creation of new databases (e.g. based on data from institutional repositories) will include publications but also their reference lists. Principal indexes are Web of Science, Scopus and Google Scholar. Widely used, especially in the exact sciences which tend to be well covered, although the most popular indicators are not always the most appropriate ones. Data must be accurate and verified. Are of limited value in disciplines not well covered by the citation indexes, especially certain parts of social sciences, humanities and engineering. Improve the value of this indicator and coverage of disciplines. Theoretical research into the meaning of citations (clusters) in social sciences and humanities.	Yes
Number Keynote Addresses at National and International Conferences	A count of the number of invited and keynote addresses given at national and international conferences	Used as proxy for quality, impact and peer-esteem. Data can be verifiable by conference programme. No agreed equivalences that apply internationally and facilitate comparison across disciplines. This will probably require direct entry by researchers. A list of internationally comparable items for different disciplines might help a lot.	No
Number Prestigious Nat'l/int'l Awards and Prizes	A count of the number of prestigious national and international prizes won either in total or per academic staff.	Used as an indicator of research quality and impact. Data is verifiable. No agreed equivalences that apply internationally and facilitate comparison across disciplines. Unless lists are publically available this will require direct entry by researchers. A list of internationally comparable items for different disciplines might help a lot.	No
International Visiting Research Appoint	A count of the number of visiting appointment at other academic and/or non-academic	Visiting Appointments provide indication of peer esteem or support by the academic community. Numbers are verifiable. No agreed equivalences that apply internationally and facilitate comparison across disciplines.	No

Ments	agencies and organisations.	Will probably require direct entry by researchers.	
Editorial and Refereeing for Prestigious National/ International journals/ publishers	A count of the number of national and international appointments as editor, member of editorial board or as reviewer	An indicator of the extent to which the researcher's opinion is highly regarded by the academic community. Data is verifiable. No agreed equivalences that apply internationally and facilitate comparison across disciplines. Unless lists are publically available this will require direct entry by researchers. A list of internationally comparable items for different disciplines might help a lot.	No
INNOVATION AND SOCIAL BENEFIT			
External research income	Level of funding attracted by researchers and universities from external sources, including competitive grants and research income from government, industry, business and community organisations.	Comparable data, verifiable through audit, is useful for comparing research performance across the system and within universities. Willingness of industry to pay for research is a useful indicator of its anticipated contribution to innovation and the economy. Levels of external funding vary greatly across disciplines. For example, in countries where over half the total pool of funding is allocated to medical research, universities that do not have Medical Faculties will inevitably secure less funding than those with Medical Faculties. Data collection may be difficult in case of funding by end users because this information is not known to the University administration. Agree international comparative data base.	Yes
Number and percentage competitive grants won	Level of funding won competitively – this is a sub-set of the indicator above.	Comparable data, verifiable through audit, is useful for comparing research performance across the system and within universities. Levels of external funding vary greatly across disciplines. Agree international comparative data base.	No
Research income per academic staff or FTE	Research income per academic staff or FTE	Supports cross-institutional comparisons, adjusted for scale of institution. Important measure of research activity. Comparability is dependent upon institutional mission, context and discipline. Data needs to be adjusted to scale and mission of university.	No
Employability of PhD graduates	Industry employment of PhD graduates	Industry employment of PhD graduates can be an indicator of the contribution of research to society. Used to measure the quality of the graduates, and impact of research on teaching. Career paths and opportunities can differ for different disciplines. Employability can be sensitive to other factors, such as the regional or national economy. Important to develop methods to track graduate employability and career paths. Harmonise the stage(s) post-graduation at educated & skilled workforce.	No

Commercialisation of research generated intellectual property (IP)	Provides measure of the extent of income from commercialisation of intellectual property created through patents, licences or start ups.	This is an area of increasing significance to policy makers. Indicator is an important link between IP, commercialisation and economic benefits. Patents are a very poor indicator of commercialisation. They are sensitive to national context – and to discipline. Databank on university related inventions should be developed.	Yes (^)
End-user Esteem	Includes policy, technical or commissioned reports; consultancy and external contracts; architectural or design awards; etc.	Willingness of external stakeholders to use and/or pay for research is a useful indicator of its anticipated contribution to innovation and the economy. Different opportunities for different disciplines. Lack of agreed basis of capturing data and comparability could undermine legitimacy. Agree basis of international comparability and verifiability.	No
Number and percentage funding from end-users	Provides measure of the extent of income from external-commissioned or contracted work (industry, professions, government, community)	This is an area of increasing significance to policy makers. Indicator is an important link between research and social and economic benefits. Different opportunities for different disciplines. Lack of agreed basis of capturing data and comparability could undermine legitimacy. Agree basis of international comparability and verifiability.	Yes
SUSTAINABILITY AND SCALE			
Post graduate Research Student Load	The ratio of research students (or PhD students) per academic staff or per 'Research Active' staff	Key indicator of research intensity, indicating the scale of the research enterprise. Practices differ across disciplines – large research teams are a common feature of the bio- and medical sciences. Agree basis of international comparability and verifiability.	Yes
Involvement of early career researchers in teams	Number or percentage of early stage researchers involved in research	An indicator of research intensity, the scale of the research enterprise, and future activity. Practices differ across disciplines – large research teams are a common feature of the bio- and medical sciences. Agree definition of 'early career researcher', and basis of international activity.	No
Number of collaborations and partnerships	A count of national and international collaboration with other universities and/or with public-private and NGOs, etc.	Because research is increasingly conducted in collaborative teams, nationally and internationally, this is an important indicator of research involvement and scale of activity. Can be difficult to capture and verify the data due to lack of clarity as to what is being measured. Agree precise definition, inter alia: university-university, university-external stakeholder, national, European or international.	No (*)
Doctoral Completions	The number PhD and equivalent research doctorates and, as	Data is verifiable by universities although there can be a time lag. Rates of completion may differ across disciplines.	Yes

	appropriate, research Masters degree completions.	Different disciplines may prioritise masters and PhD activity. Require common standard for doctorates.	
RESEARCH INFRASTRUCTURE			
Research active academics	Number or equivalent full-time (FTE) of 'research active' academics employed by a university.	'Research active' is established by setting threshold levels of performance for a specific period. Important indicator of research capability. No clear definition of 'Research Active'. Common definition and international comparability of 'Research Active'.	Yes
Percentage 'Research Active' per total academic staff	Ratio of the number of 'Research Active' per total academic staff.	Indicator of research intensity. No clear definition of 'Research Active'. Common definition and international comparability of 'Research Active'.	Yes
Total R&D investment	Total investment in university-based R&D from all sources, including external research income and university resourcing of research	Strong predictor of research performance. Difficult to get valid, comparable institutional data, even within the same institution. Agree basis on which to calculate full cost of research investment, salaries and overheads. Can be difficult to fully calculate university resourcing of research.	No
Research Infrastructure and Facilities	Number of research laboratories, books in the library and/or electronic journal access, supercomputing access	Information provided at the level of the institution. Difficult to get valid, comparable data. Favours older, well-endowed universities. Develop appropriate comparative indicators.	No
Research Ethics	Comprehensive process ensuring good ethical practice is promoted and promulgated.	Important measure of research rigour and integrity, and the effect and purpose of the research. Peer Review would be most useful. Ethical statements regarding the use of research and the source of research funding, e.g. tobacco or armaments, can be very controversial. Develop appropriate indicators to ensure good ethical practice is promoted without interfering in processes of discovery.	Yes

Source: our elaboration on AUBR (European Commission, 2010)

It is clear from the above discussion that indicators cannot be built on a custom basis, unless one is prepared to spend a substantial amount of time and money.

In addition, the construction of indicators on a custom basis does not satisfy the requirement of comparability and interoperability at European level. We therefore must shift the paradigm:

- from proprietary sources to open linked data sources
- from custom-designed indicators to indicators that can be generated reliably by combination of existing data in a platform
- from indicators mainly based on research to a comprehensive set of indicators including several outputs and taking into account the structure of input.

This is not to say that all issues of availability and comparability have been solved. However, the trend towards the integration of existing datasets on a public basis is clearly set. What is needed is a shift in the overall philosophy.

7. Generating new indicators from a platform

Faced with the need for integration of information, there is a natural approach, which however would lead to wrong decisions. The natural approach is one of building up projects for the integration of existing databases, working on definitions and conventions *given* the data structure of information systems. This approach takes for granted the existence of vertically separated databases (silos) and achieves integration working at a low level- i.e. at the level of databases. The limitation of this approach is that it is extremely expensive and, above all, it requires ad hoc solutions. From a technical point of view, this approach amounts to define the admissible queries on databases.

It is extremely important to realize the danger in this approach, which looks on the contrary quite obvious. The development of new technologies in database design, data analysis, data quality, data integration, data visualization and related fields- all areas in computer science that have seen impressive achievements in recent years- allow a conceptual jump in the search for a solution.

The first step is conceptualizing research and innovation systems as complex systems formed by more elementary *entities*. There are several possible way of doing this, as witnessed in the literature. One distinction is between an actor-centered perspective, which defines elementary action units in the system, and a function-based perspective, which on the contrary works more on structural relations and flows within the system. We will try to reconcile these two perspectives. A starting point for conceptualizing this issue is to think in terms of *actors*, e.g. universities, non-university higher education institutions, PROs, firms, governments, funding agencies, government agencies, NGOs and several others. The large literature on systems of innovation and the systematic mapping of European landscapes carried out in recent years allows to build up almost complete maps of actors.

The second step is to develop *concepts* associated to entities. The development of concepts may be helped by the users requirements discussed above. Rather than following strict definitions, actors should be conceptualized in terms of a list of associated concepts. For example a university is associated to concepts such as students, professors, disciplines, location, publications etc. Each of these concepts is, in turn, susceptible of further conceptualization. For example students are associated to concepts such as nationality, country of the last degree, gender, field of education, etc. For each of the concepts we should carry out extensive abstract analysis of the underlying definitions and the relations with other concepts. Its is not important that definitions are formally similar, since higher level concepts will be generated by variable degrees of membership of lower levels concepts. This is a crucial point. While in the integration of databases what is needed is a perfect matching between the concept and the definition, in order to carry out a query, in this approach this issue does not prevent integration, as we shall see below. The similarity of definitions can formally be defined on the basis of the articulation of concepts. If two definitions are equal, their concepts overlap perfectly. If two definitions are different (for example, a "foreign student" might be considered a student of foreign nationality, or a student who has attended the secondary school in a different country), then the associated concepts will reveal the difference. Given this approach, it is always possible to identify the subset of concepts that make two definitions similar. This abstract definition gives flexibility to the information system.

The third step is to look for lists and standards, or more generally in the database language, Authority Files. The existence of a list is enormously important, because it allows exhaustive search. Lists are flexible tools, in the sense that are associated to procedures for update and correction. For example, having an Authority File of companies investing into R&D, or a list of higher education institutions, or of Public Research Organisations (PROs) is an important step. As the example developed in the paper shows, having built the official list of higher education institutions (HEI) in Eumida, associated with basic indicators, has permitted the detailed geo-referentiation and the attribution of further information to the same entity.

Standards are also extremely important. For example, one would take on board standard definitions adopted at international level as to what constitute an author of scientific publication (ORCID, see www.orcid.org), or a research organisation (CERIF, see www.eurocris.org).

The fourth step is to establish links between concepts. For example an important link between the concept of "university" and the concept of "scientific publication" is via the concepts of "author" and of "affiliation". Publications are conceptualized, by necessity, as produced by authors. Authors are conceptualized, by necessity, as associated to institutions (affiliation). The list of affiliations has then a non empty overlap with the list of universities. Similarly, there is a link between "funding agency" and "university". A funding agency, by necessity, funds research. A university, by necessity, carries out research based on funding received from someone else (i.e. universities do not self-finance). The link between these two concepts should then be articulated, for example through the concept of "grant". A grant might be conceptualized as having a source and a beneficiary. The list of beneficiaries has then a non empty overlap with the list of universities.

The abstract notion of link between concepts allows the incorporation of the functional perspective. In this perspective, flows describe the functions that actors of the system perform. For example priority selection, or ex ante project evaluation are necessary functions of a research funding system, whatever the concrete actor will perform them. The functional perspective is useful because it offers an abstract view of the extremely complex landscape of actors. We incorporate this perspective using the even more abstract notion of "link between concepts".

Once these steps are carried out what we obtain is a graph of actors, each with associated a graph of concepts (direct and indirect link). The links between actors are represented as links between concepts associated to actors.

Remember that at this stage we have an abstract representation, for which the actual content of information might be variable. For example, we might have a perfect concept of "university" but not having a list of universities at all. Or we might have a clear notion of "R&D performing firm" but not being able to link their list to the list of patent assignees.

We then are ready to implement a principle for the integration of research and innovation information systems. The informal principle we follow is this: *put your information in the region of the graph in which the potential for generation of other information is greater*.

For example the concept of "location" is linked to the concept of "university" (all universities have a physical location in a place). But the concept of "location" is also related to a host of other concepts such as "R&D expenditure" (it is possible to sum up all expenditures in a given region), "high tech firms" (it is possible to count all firms in a region beloning to a category), or "patents" (patents have inventors whose location is registered), and many others.

This is not always so for other regions of the graph. For example, one might be interested in understanding the extension of patents to other countries. But the location of the countries in which firms or universities extend their patents is not conceptually linked (unless in very general terms) with the entities of the research and innovation system in Europe. Thus this information would be extremely interesting, but weekly connected.

By using this approach a number of new indicators can be generated. Table 4 illustrates the potential of the approach. We combine actors (or entities) in the graph by listing (some of) the concepts associated to them. When two entities share the same concept, it is important to examine at which level of abstraction the overlapping takes place. For example, universities and PROs share the concept "location" (they have a geographic location where their activity is carried out) but universities are in most cases single-site organizations (hence the location of the headquarters is the same of the departments or schools), while PROs are multi-site organizations, so that the location of the headquarters does not provide information on the actual location of research activities. By discovering this mismatch, it is clear that there is a need for

investing into the production of new information in allocating research activities of PROs at territorial level. Once this information is provided, the fact that universities and PROs share the concept of "location" at all relevant levels of abstraction implies that their publications- another concept they share- can be aggregated at location level. From this observation new indicators can be generated, e.g. number of publications at province or region level.

Furthermore, publications can be classified by discipline, or field of science. Again, it is important to check at which level of abstraction the concept is shared. The general concept of "discipline" may in fact be instantiated, at lower levels of abstraction, by different classifications. Therefore it is important to examine whether the two entities share the concept of discipline down to the appropriate level of granularity given by standard classifications. If this is true, then we can again aggregate publications of universities and PROs and generate new indicators that show the production at location level by discipline, or that use the literature on specialization (e.g. Technological Revealed Advantage, or Balassa index) to build up new indicators.

Finally, the concept <location at geographic level is associated to other concepts, such as population (or inhabitants), GDP, or R&D expenditure (e.g. GERD). All these associations of concepts come from a thorough conceptual analysis to be carried out before the construction of indicators. From the previous analysis we have seen that both universities and PROs share the concept of location. Hence all concepts associated to location can be linked to them. As an example, we can build up new indicators that relate the number of publications of universities, added to those of PROs at location level (province or region), divided by the number of inhabitants, or divided by the monetary value of R&D expenditure. In this way we build up new indicators made possible by the underlying shared concept structure, i.e. location.

The advantage of this approach is that new indicators are built following the logical structure of entities and their internal hierarchy of concepts. In this way, entities that share concepts at the appropriate level of abstraction can be combined fruitfully.

Note that this approach is orthogonal to the current approach to indicators, which starts from user requirements (usually very demanding) and builds up an ad-hoc integration of existing databases, without changing the conceptual structure of data. Rather, we advocate a thorough conceptual analysis of entities, after which the combination of data becomes almost automatic. In this way the integration of datasets becomes a smooth process, because the underlying conceptual structure has been clarified ex ante. In our approach, once a new indicator is identified, there is guarantee that it will be feasible. If this is not true, we identify with great clarity the areas where an additional investment in the creation of information is needed. This is a major step forward for the construction of indicators.

In the paper we go ahead with a number of examples of creation of new indicators. In all cases new indicators are generated through a structured process, which ensures the feasibility of the indicator.

New indicators are not generated automatically, but following close inspection of all combinatorial opportunities that have semantic value and add information for the final users.

Table 4 Generation of new indicators through the analysis of shared concepts of elementary entities

Entity	Associated concepts	Shared concepts	Information needs	New indicators
University	Location of site Publications	*Location* is shared but only at higher level of abstraction: universities are single-site, PROs are multi-site	Need to allocate publications of PROs at locational level , e.g. region (NUTS 2) or province (NUTS 3)	Number of publications per region/province
Public Research Organization	Location of headquarters Publications	*Publications* is shared		

University	Location of site Publications by discipline	*Location* is shared (see above) *Publications* is shared *Discipline* is shared but only at higher level of abstraction: need to examine lower levels of granularity of classifications	Need to establish a standard for comparability of classification of disciplines	Number of publications per discipline per region/province Map of scientific activity per discipline Scientific Specialisation Index at region/province level (Balassa index)
Public Research Organization	Location of headquarters Publications by discipline			
University	Location of site Publications	*Location* is shared (see above) *Publications* is shared		Publications per inhabitant at region/province level Publications per euro of HERD
Public Research Organization	Location of headquarters Publications			
Location	Inhabitants HERD			

Source: our elaboration

8. Conclusions

We aim at introducing a change in the way indicators are designed. We suggest a departure from the traditional approach:

- start top down with a thorough conceptual analysis of entities in the research and higher education system
- draw all linkages between concepts, particularly the sharing of concepts between entities
- examine the linkages down to the lowest possible level of granularity, in order to ensure that the sharing is complete
- generate new indicators through the combination of concepts shared across entities
- implement the new indicators with existing data, or invest into the areas that may produce the largest increase in connectivity among entities.

Following this approach, once indicators are created the feasibility is immediately visible. If there is a hole in the data, then it is clear where to invest in production of data.

Furthermore, the process is recursive. Once new indicators have been generated, they will share the concepts that have originated them. Then they enter again in the process of identification of shared concepts. Indicators built over other indicators become feasible.

We argue that this approach might help to address a number of unsolved policy issues that are currently discussed at European level. We offer examples from the European perspective to make the point clear, although similar arguments might be offered to address some of the highly debated issues in US science policy (as witnessed by the Science of Science and Innovation Policy initiative) or Far Eastern countries' policies. Consider the following:

- What is the model of excellence of European universities? Are excellent positions in scientific disciplines concentrated in a few universities or spread across a large number of universities? What are the implications of alternative excellence models?
- Do we see territorial concentration of research activities over time? What are the implications?
- Is it possible to estimate the territorial impact of science policies oriented towards excellence at European level? Are cohesion policies strongly oriented towards research and innovation able to mitigate, if any, the geographic concentration of research activities?
- Is there complementarity or substitution between research and third mission activities, as witnessed for example by publications and patents? Is the emphasis of governments on third mission and technology transfer detrimental to scientific performance?
- Are the patterns of specialization of science (as measured through publications), of technology and innovation (as measured through patents or CIS data) and of industry (as measured by employment or value added) correlated? If yes, at which territorial scale (NUTS 2, NUT 3, country)? If not, what are the implications?
- Is it possible to estimate the long term impact of public expenditure in research on indicators of innovation, productivity, and growth at various territorial scales?
- Is it possible to model the impact of public expenditure in research using a multilevel model using detailed data at all levels of aggregation?

Most of these questions cannot be addressed adequately at the state of the art of indicators. We believe that large improvements are possible by framing the overall problem in a new and broader perspective.

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Appendix 1. Summary of User Groups and Uses of Research Assessment Data
Source: AUBR (European Commission, 2010)

HE MANAGEMENT AND GOVERNANCE
Governing Bodies/Councils
    Policy and planning
    Strategic positioning
    Research strategy development/management
    Investor confidence/value-for-money and efficiency
    Quality assurance
    Institutional and discipline/field data re. level of intensity, expertise, quality and competence
    Benchmarking against peer institutions, nationally and worldwide
    Efficiency level: how much output vis-a-vis funding
    Quality of academic staff and PhD students
    Attraction capacity: recruitment of students, academics
and researchers from outside region and internationally
HE Executives/Management
    Policy and planning
    Strategic positioning
    Research strategy development/management
    Investor confidence/value-for-money and efficiency
    Quality assurance
    Publicity
    Student and academic recruitment
    Improve and benchmark performance and quality
    Institutional and discipline/field data re. level of intensity, expertise, quality and competence
    Benchmarking against peer institutions, nationally and worldwide
    Efficiency level: how much output vis-a-vis funding
    Quality of academic staff and PhD students
    Attraction capacity: recruitment of students, academics and researchers from outside region and
internationally
    Identification of Partnerships (academic, public/private sector, NGOs, research organisations, etc.)
HE Research Groups
    Strategic positioning
    Research strategy development/management
    Investor confidence/value-for-money and efficiency
    Student and academic recruitment
    Discipline data re. level of intensity, expertise, quality and competence benchmarked against peer
institutions
    Quality of academic staff and PhD students
    Attraction capacity: recruitment of students, academics and researchers from outside region and
internationally
    Identification of Partnerships (academic, public/private sector, NGOs, research organisations, etc.)

GOVERNMENTS AND GOVERNMENT AGENCIES
EU and National Governments
    Define policy and inform decisions about HE system and HEIs
    Determine national/international competitiveness
    Quality, sustainability, relevance and impact of research activity
    System and institutional data re level of intensity, expertise, quality and competence
    Performance of HE system and individual institutions
    Benchmarking between nationally and worldwide
    Indicator of national competitiveness
    Investor confidence/value-for-money and efficiency
    Improve performance and quality

Improve system functionality

Attraction capacity: recruitment of students, academics and researchers from outside region and internationally

Quality of academic staff and PhD students

Efficiency level: how much output vis-a-vis funding

Research infrastructure: level of use and efficiency

Ministries of Education/Higher Education or Enterprise and Employment

Policy and planning

Strategic positioning of HE institutions

Quality, sustainability, relevance and impact of research activity

Research strategy development/management

Investor confidence/value-for-money and efficiency

Quality assurance

Institutional and discipline/field data re. level of intensity, expertise, quality and competence

Benchmarking against peer institutions, nationally and worldwide

Indicator of national competitiveness

Performance of HE system and individual institutions

Attraction capacity: recruitment of students, academics and researchers from outside region and internationally

Efficiency level: how much output vis-a-vis funding

Research infrastructure: level of use and efficiency

Local and Regional Governments

Define local/regional policy and competitiveness

Quality, sustainability, relevance and impact of research activity

Improve integration/collaboration between universities, government and private sector

Improve attraction capacity

Benchmarking performance and quality of HE system/institutions nationally and worldwide

Indicator of national competitiveness

Attraction capacity: recruitment of students, academics and researchers from outside region and internationally

Efficiency level: how much output vis-a-vis funding

HE Agencies

Define policy and inform decisions about HE system and HEIs

Quality, sustainability, relevance and impact of research activity

Determine national/international competitiveness

Investor confidence/value-for-money and efficiency

Improve performance and quality

Improve system functionality

System and institutional data re level of intensity, expertise, quality and competence

Performance of HE system and individual institutions

Benchmarking between nationally and worldwide

Indicator of national competitiveness

Attraction capacity: recruitment of students, academics and researchers from outside region and internationally

Quality of academic staff and PhD students

Efficiency level: how much output vis-a-vis funding

Research infrastructure: level of use and efficiency

Other Government Agencies

Improve and benchmark performance and quality

Aid resource allocation

Investor confidence/value-for-money and efficiency

Benchmarking performance and quality of HE system institutions nationally and worldwide

ACADEMIC ORGANISATIONS AND ACADEMIES

Benchmark professional and academic performance and quality

Academic and discipline/field data re. level of intensity, expertise, quality and competence

Student and Academic Recruitment   Benchmarking against peer institutions, nationally and worldwide
Quality of academic staff and PhD students

INDIVIDUALS
Academics and Researchers
Identify career opportunities
Identify research partners
Identify best research infrastructure and support for research
Institutional and field data re level of intensity, expertise, quality, competence and sustainability
Performance of individual institution benchmarked against peers in field of interest
Employment conditions
Impact of research on teaching, Staff/student ratio
Institutional research support
Students
Inform choice of HEI
Identify career opportunities
Institutional and field data re level of intensity, expertise, quality, competence and sustainability
Performance of individual institution benchmarked against peers in field of interest
Research capacity of institution and research team, e.g. graduate students/academic ratio, age of PhD students, time to completion, structure/characteristics of PhD programme and support
Graduate career and employment trends
Quality of the research infrastructure
Staff/student ratio
PEER HEIS
Identify peer HEIs and best research partners
Institutional and field data re level of intensity, expertise, quality, competence and sustainability
Performance of individual institutions and researchers benchmarked against peers in field of interest
Research capacity of institution and research team
Potential for partnership

INDUSTRY PARTNER ORGANISATIONS
Private firms and entrepreneurs
Quality, sustainability, relevance and impact of research activity
Identify potential partners and expertise
Identify consultancy, technology transfer and knowledge transfer partners and expertise
Identify potential employees
Institutional and field data re level of intensity, expertise, quality, competence and sustainability
Performance of individual institution benchmarked against peers in field of interest
Competitive positioning of institution and researchers
Trends in graduate employment and competence
Quality of HE programme, and link between research and teaching
Public Organisations
Quality, sustainability, relevance and impact of research activity
Identify potential partners and expertise
Identify consultancy, technology transfer and knowledge transfer partners and expertise
Identify potential employees
Institutional and field data re level of intensity, expertise, quality, competence and sustainability
Performance of individual institution benchmarked against peers in field of interest
Competitive positioning of institution and researchers
Trends in graduate employment and competence
Quality of HE programme, and link between research and teaching
Employers
Quality, sustainability, relevance and impact of research activity
Identify potential partners and expertise
Identify consultancy, technology transfer and knowledge transfer partners and expertise
Identify potential employees

Institutional and field data re level of intensity, expertise, quality, competence and sustainability
Performance of individual institution benchmarked against peers in field of interest
Competitive positioning of institution and researchers
Trends in graduate employment and competence
Quality of HE programme, and link between research and teaching

CIVIC SOCIETY AND CIVIC ORGANIZATIONS
Identify specific expertise and information
Identify potential collaborator
Identify consultancy, technology transfer and knowledge transfer partners
Institutional and field data re expertise, quality and competence
Peer esteem indicators

MINISTRIES OF HIGHER EDUCATION IN DEVELOPING COUNTRIES
To help determine which foreign higher education institutions are applicable for overseas scholarships studies.
To help determine research partnerships for knowledge and technology transfer
Institutional and discipline/field data re. level of intensity, expertise, quality and competence
Competitive positioning of institution and researchers
Trends in graduate employment and competence
Quality of academic staff and PhD students

SPONSORS AND PRIVATE INVESTORS
Benefactors/Philanthropists
Determine institutional performance vis-a-vis national and international competitors
Investor confidence/value-for-money and efficiency
Quality, sustainability, relevance and impact of research activity
Quality of academic staff and PhD student
Contributor to own brand image
Institutional data re level of quality and international competitiveness
Benchmarking between nationally and worldwide
Quality of academic staff and PhD students
Alumni
Determine institutional performance vis-a-vis national and international competitors
Institutional data re level of quality and international competitiveness
Investor confidence/value-for-money and efficiency
Quality, sustainability, relevance and impact of research activity
Quality of academic staff and PhD student
Reflect pride and career aspirations/reputation
Benchmarking between nationally and worldwide
Quality of academic staff and PhD students
PUBLIC OPINION
Determine institutional performance vis-a-vis national and international competitors
Quality, sustainability, relevance and impact of research activity
Student choice and career opportunities
Investor/parental confidence and value-for-money
Institutional data re. level of intensity, expertise, quality and competence
Benchmarking against peer institutions, nationally and worldwide
Indicator of national competitiveness
Performance of HE system and individual institutions
Efficiency level: how much output vis-a-vis funding