Trajectories and regimes in research versus knowledge evaluations: Contributions to an evolutionary theory of citation

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Abstract

Citation analysis can provide us with models of the evolutionary dynamics in scholarly and scientific communication. We propose to distinguish between institutional research evaluation (usually, *ex post*) and knowledge evaluation *ex ante*, in relation to directionality in citation analysis. We discuss the theoretical literature on communication systems which distinguishes between information and meaning, in which the concept of redundancy plays an important role as measure of the potential of a communication system. This is the basis for a model of knowledge dynamics which differentiates between observable variation and latent selection environments. We use indicators at the journal level and analyze the citation environments of journals in both the cited and citing directions. Among journals, the citing direction can be analyzed by co-citation and indicates the integration of knowledge from different fields. The cited direction can analogously be analyzed by bibliographic coupling and represents the extent to which the cited journal has become relevant for different disciplines, hence indicates knowledge diffusion. We apply this analysis on three different case studies of journal-journal relations: a small scale study of the journal *Public Understanding of Science*, a random sample of 100 journals, and a large-scale analysis of the set of *JCR* 2016 journals. Combined, the results seem to confirm the hypothesis that interdisciplinarity cannot be captured by one-dimensional citation analysis. Both citing and cited directions are relevant for knowledge and research evaluations, respectively. We raise the question whether indicators of interdisciplinarity can be developed by combining both directions in citation analysis, indicate further research, and discuss the normative implications of our preliminary results.

Keywords

Interdisciplinarity; Synergy; Theory of citation; Bibliographic coupling; Co-citation; Research evaluation; Knowledge evaluation; Evolutionary theory of citation; Scholarly communication; Scientific journals; Indicators; *Journal Citation Reports*; *JCR*.

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1. Introduction

Whereas citation impact can be measured for the purpose of research evaluations, scholars reconstruct boundaries among disciplines and specialties with reference to literatures. The act of referencing can be interpreted as an instance of *knowledge* evaluation, different from the institutionally oriented *research* evaluations. Knowledge evaluations can be expected to have a dynamic different from research evaluations. Although variation in the cited and citing dimensions can be captured in a single (asymmetrical) citation matrix, selections in the two directions involve distinct environments .

The citation matrix shows all variation and co-variation, but *not* necessarily the underlying selection mechanisms. The latter may remain latent. Variation is phenotypical and thus observable, whereas selection environments cannot be observed directly because they are based on virtual codes in human communication: they need to be defined theoretically.

Unlike biological codes (such as DNA), codes in interhuman communictions are not given naturally. However, intersubjectively binding codes can be specified reflexively as theoretical constructs by a (scientific) community. Because communication is dynamically developing, the selections can iteratively operate on one another. The highly-skewed distributions of citations, for example, suggest recursive selections of selections (**Bruckner** *et al*., 1994). Furthermore, the social system is highly differentiated and different selection mechanisms can therefore interact with each other. In social systems, markets operate as selection dynamics differently from political decision-making. Following **Schumpeter** (1939), one can also distinguish between selections on the market with a tendency toward equilibrium and innovations that upset equilibria (**Dosi**, 1982; **Nelson**; **Winter**, 1977; 1982; **Sahal**, 1981). The historical development of social organization can be seen as a retention mechanism in an evolutionary system which stabilizes social and cognitive relations and thereby functions as a localizable selection environment that is analytically different from e.g., global quality control or peer review routine. Without specification of selection environments –that is, genotypical criteria– the reconstruction cannot reach beyond a redescription of phenotypical variation. Understanding the dynamics of communication and knowledge creation, therefore requires models that enable us to specify selection criteria and their development over time.

The complexity of communication can *evolve* in systems which process both information and meaning. First, information is produced in historical processes and is measurable as entropy (**Shannon**, 1948; **Gleick**, 2011); meaning can reflexively be provided with reference to the codes in the information. We understand the providing meaning to information as asking to the selection of a signal from noise (**Leydesdorff**, 2021, p. 7). After all, not all information is meaningful in a particular context. The subsequent processing of meaning mediates between the historical developments and their evolutionary dynamics. While information can be communicated, meanings can be shared (one of the forms of processing meaning). The cycling of meanings on top of the entropy flow can be expected to generate redundancy in the system and thus enlarge the number of options available (although not yet used) (**Leydesdorff**, 2021, pp. 75-76). In information system terms, the maximum information content is then increased without communicating more than zero information (e.g. one can signal the existence of empty boxes) (**Brooks**; **Wiley**, 1976, p. 76). We shall argue below that citation analysis can provide us with access to the complex interaction between information and meaning processing in the evolution of interhuman communications (**Leydesdorff**, 2021).

2. Modelling knowledge dynamics

Knowledge can be expected to develop as the result of co-evolutions and tensions among the various subdynamics in the communication. **Kuhn** (1977), for example, considered science as the result of "essential tensions" between stability and change. **Popper** ([1935] 1959) further distinguished between contexts of discovery and justification as (potentially co-evolving) subdynamics. **Gibbons** *et al.* (1994) added the context of application as typical of the dynamics facilitated by the internet.

Three subdynamics operating upon one another can encompass all species of complex dynamics (**Langford**; **Hall**, 2005; **Li**; **Yorke**, 1975; cf. **Langford** *et al*., 2006). The knowledge structures resulting from such co-evolutions (re)produce, among other things, the observable network structures in which cultural evolutions can historically be retained (**Fujigaki**, 1998; cf. **Giddens**, 1984). By recursively and discursively selecting on historical trajectories with reference to criteria, new regimes of expectations can emerge as a consequence of the existing redundancies in a communication system. In this way, expectations about the future development can "invert the arrow of time" without violating the laws of physics.

Understanding the dynamics of communication and knowledge creation, requires models that enable us to specify selection criteria and their development over time

In physical evolution, this development is a blind interaction between variation and selection (for example when a superfluous piece of biological code is transformed leading to a new property). In cultural evolution, anticipatory systems (such as humans) can introduce a goal-oriented selection which introduces a fundamentally novel dimension in the communication dynamics. This is also the key to understanding the relation between information and meaning: meaning is the second-order linkage between information and anticipatory selection regimes (see **Leydesdorff**, 2021, for further details about the implication for the social sciences).

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In other words: along trajectories, entropy is generated in observable changes; regimes, however, operate in terms of expectations which add to the redundancy in the opposite direction and thus reduce the relative weight of the observed information. Using **Shannon** (1948), redundancy *R* can be measured as the difference between the maximum entropy (H_{max}) and the observed information ($H_{observed}$). Redundancy can serve as an information-theoretical measure of the potential of the systems for options that have not yet been realized (**Brooks**; **Wiley**, 2011; **Leydesdorff**; **Ivanova**, 2014; 2021; **Petersen** *et al*., 2016).

The complexity, recursive dynamics, and nesting of the operations along different axes generate asynchronicities and tensions (**Kuhn**, 1977). These tensions can be relaxed by changing the landscape; for example, as in the case of avalanches. Such discontinuities can be large or small, to variable extents. From this (neo)evolutionary perspective, breakthroughs are a consequence of "self-organized criticality" in communication structures (**Bak**; **Tang**; **Wiesenfeld**, 1987; **Leydesdorff**; **Wagner**; **Bornmann**, 2018).

The evolving knowledge bases are archived and reflected in the literature as the "footprints" of scientific (r)evolutions. In the background the scholarly literature functions both as a repository of these footprints and provides the common ground on the basis of which new dynamics can be generated as variation (**Luhmann**, 1996). This repository can also be seen as an archaeological source which enables the reconstruction of the process of knowledge creation. For this reason, citation indicators can be used as elements in models of knowledge dynamics.

2.1. The processing of meaning

How the processing of meaning (citing) can make a measurable difference for historical information processing was conjectured by Luhmann in his discussion with Habermas in 1971 (1971, p. 34; 1990a, p. 27). At the time, Luhmann formulated programmatically as follows:

> "[…], what is special about the meaningful or meaning-based processing of experience is that it makes possible *both* the reduction and the preservation of complexity; i.e., it provides a form of selection that prevents the world from shrinking down to just one particular content of consciousness with each act of determining experience." (**Luhmann**, 1990a, p. 27)

Notwithstanding the author's explicit *caveat* that this characterization "is still not adequate," Luhmann was ahead of his time by claiming meaning-processing as a selection mechanism that is different from natural selection. The processing of meaning includes a second-order dynamics which feeds both back and potentially forward on the stream of historical events. **Luhmann** (2012, p. 238) speculated that "[w]e need only a sufficiently subtle theory of time that determines the present as the boundary between past and future." Although the relevant question was raised, this program was not elaborated into empirical operationalizations.

For example, Luhmann formulated against Habermas as follows:

> "Social structures do not take the form of expectations about behavior (let alone consist of concrete ways of behaving), but rather take the form of expectations about expectations." (**Luhmann**, 1990b, p. 45 [1971, p. 63])

However, this was not elaborated into historical developments of expectations along trajectories as different from evolutionary mechanisms of the generation and evolution of expectation with reference to horizons of meaning.

2.2. A neo-evolutionary perspective

In the neo-Schumpeterian tradition of evolutionary economics and technology studies, **Dosi** (1982) first addressed the tension between trajectories and regimes in a paper entitled "Technological paradigms and technological trajectories: A suggested interpretation of the determinants and directions of technical change" Dosi formulated the relations between trajectories and regimes as follows:

> "A technological trajectory, i.e., to repeat, the "normal" problem solving activity determined by a paradigm, can be represented by the movement of multi-dimensional trade-offs among the technological variables which the paradigm defines as relevant. Progress can be defined as

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> the improvement of these trade-offs. One could thus imagine the trajectory as a "cylinder" in the multidimensional space defined by these technological and economic variables. (Thus, a technological trajectory is a cluster of possible technological directions whose outer boundaries are defined by the nature of the paradigm itself)." (**Dosi**, 1982, p. 154)

> Whereas interdisciplinarity as co-citation can be interpreted as a measure of interdisciplinary integration of knowledge, interdisciplinarity as bibliographic coupling can be interpreted as a measure of interdisciplinary diffusion

> "[…] In broad analogy with the Kuhnian definition of a "scientific paradigm," we shall define a "technological paradigm" as "model" and a "pattern" of solution of *selected* technological problems, based on *selected* principles derived from natural sciences and on *selected* material technologies." (**Dosi**, 1982, p. 152)

Note the specification of three selection environments. However, Dosi's research program was overshadowed by **Nelson** & **Winter**'s (1982) groundbreaking book *Evolutionary theory of economic change.* Unlike their earlier agenda calling for "a useful theory of innovation" (**Nelson**; **Winter**, 1977), **Nelson** & **Winter** (1982) shifted the focus to the firm as the unit of analysis. They formulated as follows:

> "The heart of the conceptualization problem discussed in the preceding section was to characterize the generation of innovation as purposive, but inherently stochastic." (**Nelson**; **Winter**, 1982, p. 54)

The earlier focus on deterministic *selection environments* was thus abandoned (cf. **Nelson**; **Winter**, 1978, p. 64). **Casson** (1997) noted that the delineation of innovation systems in institutional terms offers the advantage of compatibility with (e.g., national) statistics (**Griliches**, 1994). However, an institutional perspective on innovation leads sooner or later to a theory of entrepreneurship rather than accounting for the dynamics of communication and innovation (**Carter**, 1996; **Godin**, 2006).

The emphasis in evolutionary economics has increasingly been on co-evolutions between regional economics, economic geography, and technological options (**Audretsch**; **Feldman**, 1996; **Boschma**; **Balland**; **Kogler**, 2014; **Feldman**; **Storper**, 2016). This literature suggests a mutual shaping among the various factors of knowledge production, inducing trajectories and niches (**Geels**; **Schot**, 2007). As **Andersen** (1992) and **Boulding** (1978) noted, the evolution-theoretical perspective became secondary to an empirical approach with a focus on the historical development (**Malerba** *et al*., 1999). This paper aims to redress the balance and draw attention again to the evolutionary perspective.

3. Operationalization

The creation and observation of interdisciplinary connections can be used as an empirical case study to analyze the role of future oriented expectations in knowledge dynamics. For this analysis, the difference in direction of the citation is relevant.

Is another perspective on "citation" possible when one studies references ("citing") rather than citations ("cited") (**Garfield**, 1964)?; **Zitt** & **Small** (2008), for example, transposed the aggregated journal-journal citation matrix and thus generated a mirror image of the journal impact factor (JIF), (**Garfield**, 1971), which they called the "journal audience factor." In a similar vein, **Leydesdorff** & **Ward** (2005) suggested "disclosure" to audiences as an objective different from "impact." Whereas impact measures "sending" along the arrow of time, the operation in the opposite direction requires "disclosure" of alternative options.

Figure 1 illustrates the difference in the directionality of co-citations (**Marshakova**, 1973; **Small**, 1973) *versus* bibliographic coupling (**Kessler**, 1963). Co-citations are generated in an historical process; bibliographic couplings are knowledge-based and thus subject to organized knowledge production and control (**Nonaka**; **Takeuchi**, 1995; **Whitley**, 1984).

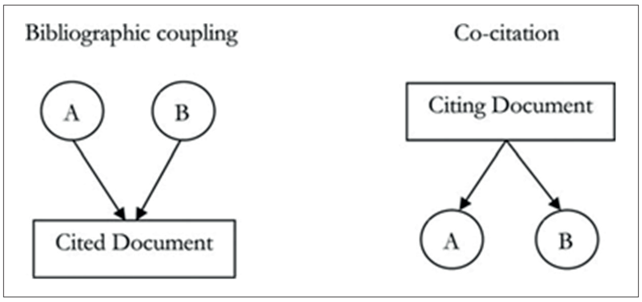

Figure 1. Bibliographic coupling and co-citation. Source: **Meireles**, **Cendon** & **De-Almeida** (2004).

The distinction between referencing to horizons of meaning and citation as references to past performance is not to be equated with the distinction between qualitative story-telling versus quantitative testing. Quantification is an issue of measurement scales. New ideas are first developed qualitatively, but for hypothesis testing and at a more aggregated level one may need statistics.

In a recent blogpost, **Ràfols** (2021) suggested that interdisciplinarity is based on a second *directionality* in citation data –"citing"– and cannot be captured in one-dimensional analyses of "citedness." **Marres** & **De-Rijcke** (2020) have proposed using "indicating," as different from citing or referencing. "Indicating" refers to "horizons of meaning" (**Husserl**, [1935/36] 1962) in addition to informing us about the data. If one wishes to measure elements of the process of "indicating" one will also need indicators that combine the different directions in citation analysis.

Whereas interdisciplinarity as co-citation can be interpreted as a measure of interdisciplinary integration of knowledge, interdisciplinarity as bibliographic coupling can be interpreted as a measure of interdisciplinary diffusion. We are interested in the interplay of both directions as an empirical case of the interplay between trajectories and selection regimes. It is this interplay which may create fundamental novelty in the system. Is it possible to capture this development in an integrated indicator of interdisciplinarity?

4. Exploring potential indicators

4.1. A specific set

Let us first develop the model using a relatively small citation matrix among 24 journals citing articles in *Public Understanding of Science* (*PUS*) during 2019 as an example.[1] Figures 2 and 3 provide (rather standard) visualizations of the co-occurrences matrices in the cited and citing directions, when *PUS* is used as the seed for mapping the relevant citation and referencing environments. We chose *PUS* because this journal is programmatically oriented towards the subject that we theorize.

In Figure 2, *PUS* has a peripheral position as part of a group of small journals (including, e.g., *Science Communication* colored yellow in Figure 2), whereas this journal is central at the crossroads of the citation traffic among three journal clusters in Figure 3. The three journal groups in Figure 3 indicate specialties focusing on (1) sustainability, (2) science communication, and (3) science and public policy, respectively.

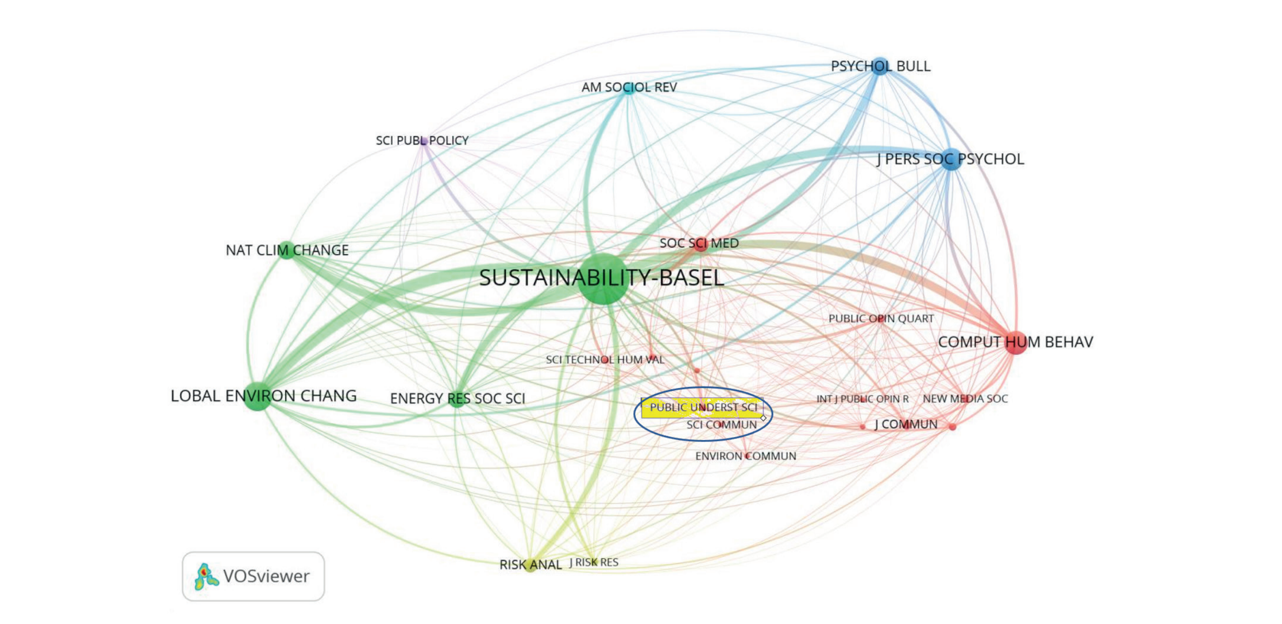

Figure 2. Citations in the *cited* direction for *Public Understanding of Science*, mapped and grouped using *VOSviewer*.

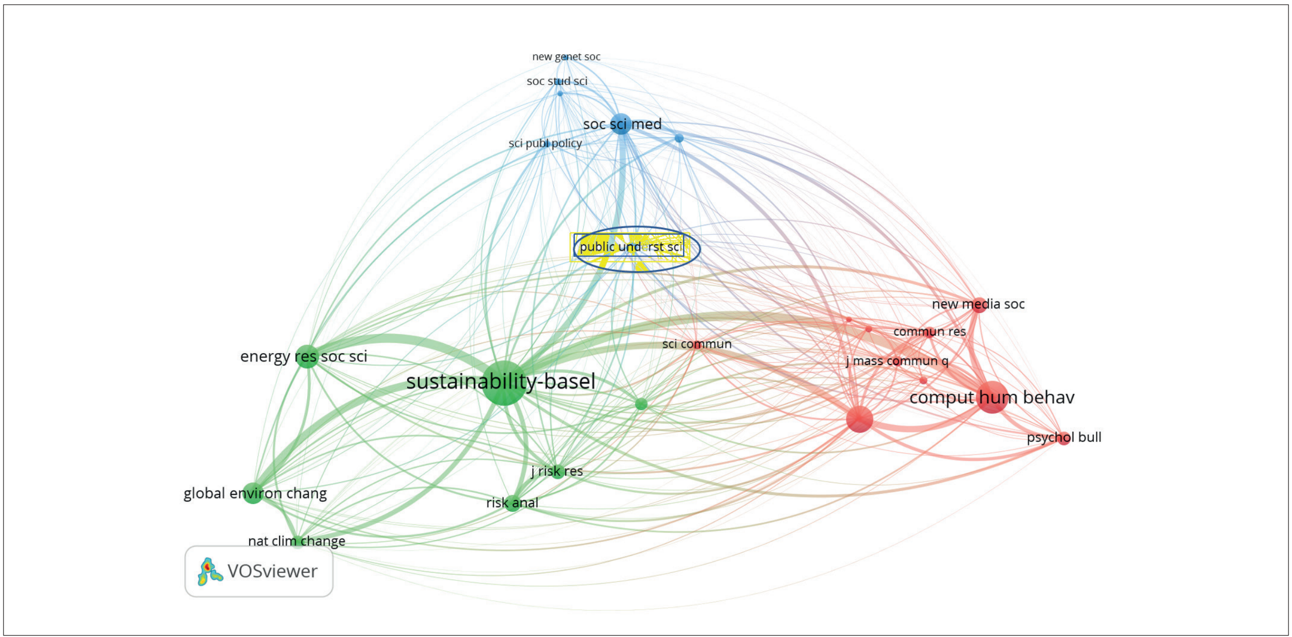

Figure 3. Citations in the *citing* direction for *Public Understanding of Science*, mapped and grouped using *VOSviewer*.

Figures 2 and 3 show that *PUS* is cited as a specialist journal in the field of “science communication,” but papers published in *PUS* cite journals from different disciplines in their relevant environments. A mapping, however, is not a sufficient basis for quantitative evaluation if one wishes to compare different groups, or if one wishes to analyze current and past relations between disciplines. This raises the question: how one can indicate the relations between disciplines from the perspectives of research evaluations *versus* knowledge evaluations?

4.2. Operationalization in terms of indicators

One can consider indicators in the cited and citing directions as two analytical axes *x* and *y* of a map. For example, the journal impact factor (JIF) can be considered as an indicator of prestige and reputation, among other possible indicators in the “cited” direction. Indicators for measuring interdisciplinarity in the “citing” direction have been developed more recently (**Ràfols**; **Meyer**, 2010; **Stirling**, 2007; **Leydesdorff**; **Wagner**; **Bornmann**, 2019; **Zhang**; **Rousseau**; **Glänzel**, 2016; **Zhang**; **Leydesdorff**, 2021).

The most straightforward impact indicator in the cited dimension is “times cited” (TC). One advantage of this indicator is that citations and publications can be counted: counts can be added and subtracted, whereas issues of normalization may lead us astray into discussions about proper statistics and baselines. “Total cites” (TC) is a size-dependent indicator, whereas JIF is size-normalized.

Analogously, one can use a variety of indicators for the measurement of interdisciplinarity. In this second dimension, we chose *DIV** (Figure 4) as one among the advanced indicators of interdisciplinarity. This indicator has advantages when compared with alternative options (**Zhang**; **Leydesdorff**, 2021). As data, we again use the matrix of 24 journals in the citation environment of the journal *PUS*.

Figure 4 shows that the distributions are skewed: some of the 24 journals specialize in one of the two dimensions (along the respective axes). The two indicators are inversely correlated (Pearson’s $r = -.38$, *n.s.*; Spearman’s $\rho = -.41$, $p < .05$): scoring high on TC is related to a low score on *DIV**. One can find *PUS*, for example, represented at the right-most end along the *x*-axis ($x = 8.17$), while the psychology journals lead the ranks along the *y*-axis (TC > 50,000). Closer to the origin, we find journals which are thematically close to *PUS*, but lower on interdisciplinarity. A few journals, such as *Global and Environmental Change* and *Sustainability-Basel* populate the map towards the middle. In these latter journals trade-offs between the two dimensions are indicated. This analysis therefore reveals the different roles of the journals in terms of social network theory –observable relations in history– and latent communication structures –evolutionary. This may inform science policy and the potential targeting of journals for priority programming. The distances to the origin ($\sqrt{x^2+y^2}$) provide a size-dependent statistic.

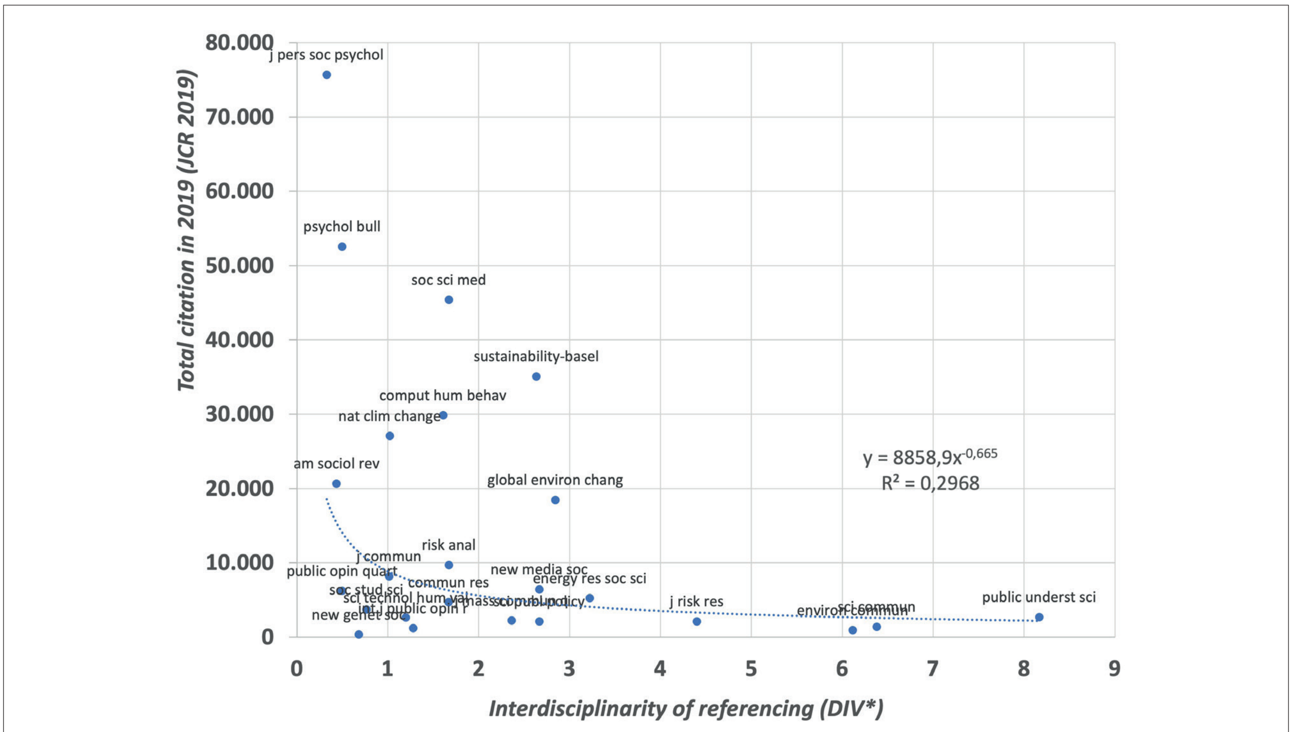

Figure 4. Twenty-four journals citing from and cited by *PUS* during 2019 in terms of interdisciplinarity (*DIV**) on the *x*-axis and times impact (times cited; *TC*) on the *y*-axis.

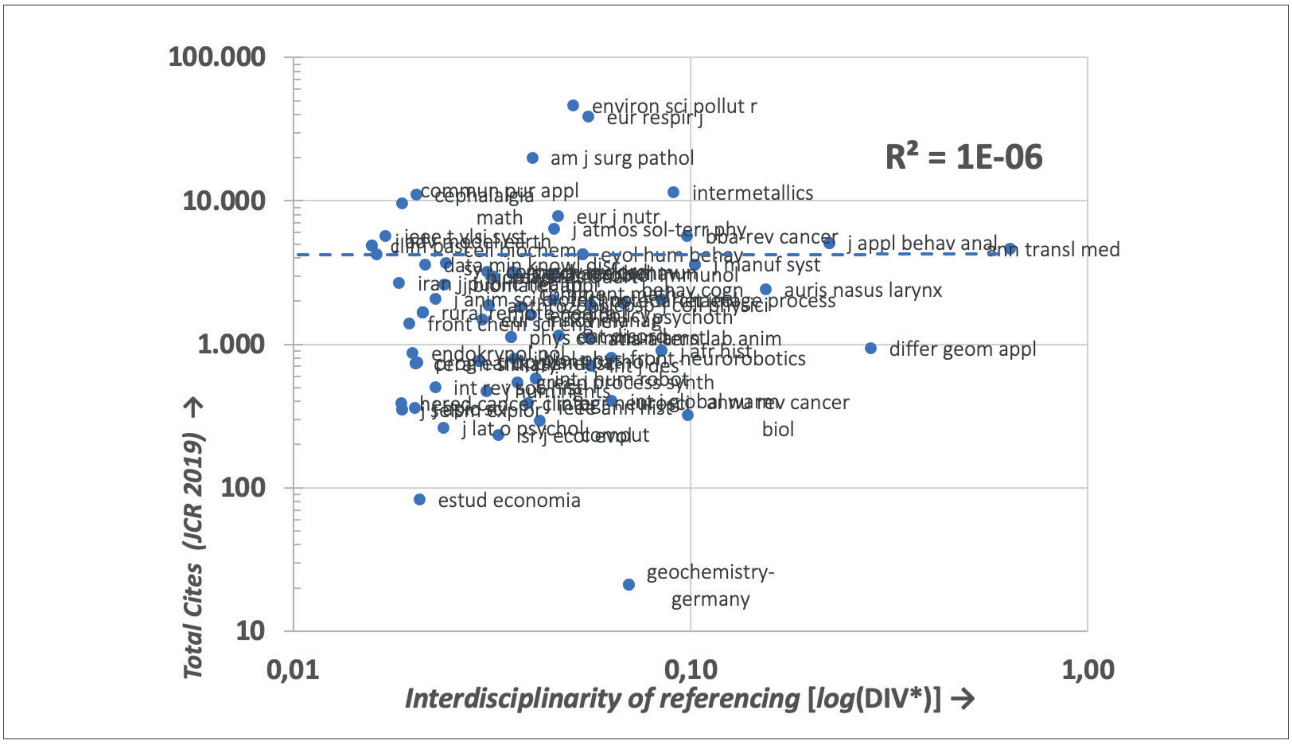

Figure 5. Total Cites plotted against *DIV** for a random sample of 100 journals listed in the *JCR* 2019; $r < 0.01$.

4.3. Random sample

Is the inverse relation found above between the two dimensions specific for *PUS*, or would it be structural and also hold for a random sample of journals drawn from the set of journals in the *Journal Citations Reports* (*JCR*) of *Clarivate*? Since the computation of *DIV** for more than 10,000 journals is time-consuming, we first attempted to work with a random sample of 100 journals.[2] Thereafter (next paragraph), we use 2016 data, for which indicator values were available from a previous project (**Leydesdorff** *et al*., 2019).

Figure 5 shows the results using a random sample ($N = 100$), but otherwise the same methods as in the case of Figure 4. The two dimensions are statistically independent in this sample: $r = 0.001$ ($p > .99$). We may thus conclude as to the absence of correlation or, in other words, orthogonal perspectives.

4.4. *JCR* 2016 journal set

The results of a random sample can be incidental given the sample choice. We therefore enlarged the analysis to the population of 11,487 journals in *JCR* 2016. The *Journal Citation Reports* (*JCR*) have provided journal indicators (impact factors, etc.) based on yearly aggregated journal-journal citation relations since the mid-1970s.[3, 4]. The usual journal indicators are provided with the files for the basic indexes by *ISI/Clarivate*. We have added centrality measures –betweenness, closeness, in- and outdegree, and eigenvector (Table 1)– to each journal in this file because these network measures were sometimes found to be relevant for indicating interdisciplinarity (**Abbasi**; **Hossain**; **Leydesdorff**, 2012; **Leydesdorff**, 2007).

In sum, the input file for the analysis contains the following indicators at the journal level for 11,487 journals included in *JCR* 2016:

Table 1. Indicators included in the analysis of *JCR* 2016 data

Journal indicators (Source: *JCR* 2016)	**Diversity indicators** (Source: **Leydesdorff** *et al*., 2019)	**Network indicators**
- Total cites, *N* of self-citations. - Two and Five-Year Impact Factors. - Immediacy and Eigenvector indicators.	- Rao-Stirling and True Diversity; - *DIV* and *DIV** - Simpson, Shannon, Variety - Disparity, operationalized as (1 – cosine) at the database level	- indegree, - outdegree, - betweenness, - closeness, - eigenvector.

As could be expected, we find complexity in the interactions among the network and diversity measures. Without the network measures, however, the first factor with highest factor loading for TC and JIF is followed by a second factor with highest loadings for *DIV**. This two-dimensional structure confirms **Ràfols**' *et al.* (2012) conjecture: the two components are negatively correlated.

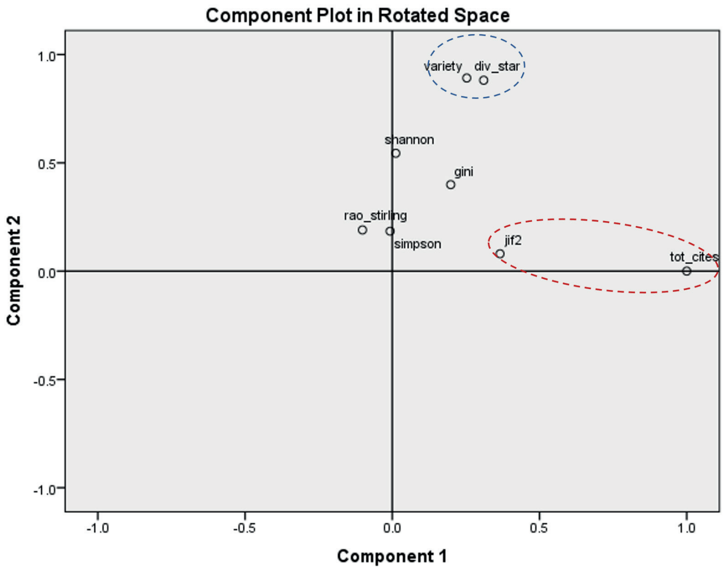

Figure 6. Visualization of the two-factor solutions (*SPSS v.22*) of the matrix of indicators *versus* 11,487 journals (without the network measures; oblique rotation). Structure matrix.

Figure 6 shows the two-dimensional component plot. The figure visualizes the (relative) orthogonality between the two components. "Total cites" correlates completely (r = 1.0) with Factor 1. *DIV** is grouped with variety as a second dimension. Using oblique rotation, the correlation between these two components is 0.232.

Table 2. Two-factor solution (without the centrality measures)

	Rescaled component	
	1	2
Total cites	**1.000**	**.232**
jif-2	.385	.165
DIV*	**.515**	**.953**
variety	.460	.950
Shannon	.138	.547
Gini	.291	.445
Simpson		.183
Rao-Stirling		.167

5. Discussion and further perspectives

The discussion above and the preliminary testing of our hypotheses against empirical data call for the specification of selection environments. Specification of what is evolving may enable us to be more precise (in further research) about what can be tested and how, so that the model can be further filled out empirically. We recall that first answering the question "What is evolving?" should not be skipped, however speculative the initial responses may be.

One of our objectives in this study was to unpack the issues from an analytical perspective. Citation analysis can provide us with models of the (neo)evolutionary dynamics. Considering observable citation as phenotypical variation, one can raise the question of the specification of relevant selection environments. Selection is operating in processes of "mutual shaping" between cited and citing at each moment of time, and dynamically as stabilization and globalization over time. Selection mechanisms tend to develop orthogonally (**Maturana**, 1978). However, codes operate as selection mechanisms upon one another, in addition to operating on variation. Stabilizations provide second-order variety for globalizations as a second-order layer of selections.

Our case study shows that citation analysis which is based on only one direction (be it either citing or cited) may miss the complex interaction between variation and selection regimes. This is especially important in the case of anticipatory systems which recursively redefine the criteria for selection. For example, the rise of interdisciplinary research in the life sciences has completely redefined chemistry, physics and biology.

6. Normative implications

In a knowledge-based economy, not only the state and knowledge-based enterprises should have access to the knowledge production process. Citizen groups and other stakeholders can be relevant reference groups that submit demand (variation). From the perspective of innovation policy, there is a need for the articulation of demand, countervailing the supply-side orientation of academia. In Mode-2 configurations of university-industry-government relations one needs new options resulting from the interactions among novelty generation (in academia), wealth generation (in industry), and governance.

In other words: evaluation of the societal role of knowledge cannot be based on research assessments of past performance. When one focuses on the horizontal interactions among codes, one needs to move beyond an agenda of research evaluation towards an agenda for the evaluation of knowledge –both inside and outside of academia. This orientation would also enable a more inclusive appreciation of the different forms in which research results diffuse socially. Exploring a broader agenda of knowledge evaluation may go along with the move from indicators based on past performance to indicating the interdisciplinary creation and circulation of knowledge in search of possible synergies.

> In a knowledge-based economy, not only the state and knowledge-based enterprises should have access to the knowledge production process. Citizen groups and other stakeholders can be relevant reference groups that submit demand (variation)

7. Notes

1. The data was retrieved from the *Journal Citation Reports* 2019 in the *Web of Science* (*WoS*) of *Clarivate*™.

2. To make a random selection from a list with no repeats, see at
https://www.ablebits.com/office-addins-blog/2020/07/22/random-sample-excel-no-duplicates

3. Of these 11,467 journals included in *JCR* 2016, 11,459 (that is, 99.8%) are included in the analysis.

4. The computation of the interdisciplinarity and diversity indicators for 12,185 journals (*JCR* 2019) is computationally time-consuming. We first tried to work with a random sample, but the results were then not clear.

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