



UvA-DARE (Digital Academic Repository)

Trajectories and regimes in research versus knowledge evaluations

Contributions to an evolutionary theory of citation

Leydesdorff, L.; Zhang, L.; Wouters, P.

DOI

[10.3145/epi.2023.ene.03](https://doi.org/10.3145/epi.2023.ene.03)

Publication date

2023

Document Version

Final published version

Published in

Profesional de la Informacion

License

CC BY

[Link to publication](#)

Citation for published version (APA):

Leydesdorff, L., Zhang, L., & Wouters, P. (2023). Trajectories and regimes in research versus knowledge evaluations: Contributions to an evolutionary theory of citation. *Profesional de la Informacion*, 32(1), Article e320103. <https://doi.org/10.3145/epi.2023.ene.03>

General rights

It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).

Disclaimer/Complaints regulations

If you believe that digital publication of certain material infringes any of your rights or (privacy) interests, please let the Library know, stating your reasons. In case of a legitimate complaint, the Library will make the material inaccessible and/or remove it from the website. Please Ask the Library: <https://uba.uva.nl/en/contact>, or a letter to: Library of the University of Amsterdam, Secretariat, Singel 425, 1012 WP Amsterdam, The Netherlands. You will be contacted as soon as possible.

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

Loet Leydesdorff; Lin Zhang; Paul Wouters

Nota: Este artículo se puede leer en español en:
<https://revista.profesionaldelainformacion.com/index.php/EPI/article/view/87143>

Recommended citation:

Leydesdorff, Loet; Zhang, Lin; Wouters, Paul (2023). "Trajectories and regimes in research versus knowledge evaluations: Contributions to an evolutionary theory of citation". *Profesional de la información*, v. 32, n. 1, e320103.
<https://doi.org/10.3145/epi.2023.ene.03>

Manuscript received on 15th October 2022
Accepted on 04th December 2022



Loet Leydesdorff
<https://orcid.org/0000-0002-7835-3098>
University of Amsterdam, Amsterdam
School of Communication Research
(ASCoR), PB 15793
1001 NG Amsterdam, The Netherlands
loet@leydesdorff.net



Lin Zhang
<https://orcid.org/0000-0003-0526-9677>
Wuhan University, School of Information
Management, Center for Science,
Technology & Education Assessment
(Cstea)
Wuhan, China
linzhang1117@whu.edu.cn



Paul Wouters ✉
<https://orcid.org/0000-0002-4324-5732>
Leiden University, Centre for Science and
Technology Studies (CWTS)
Leiden, The Netherlands
p.f.wouters@cwts.leidenuniv.nl

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*.



Acknowledgments

The first author is grateful to *Clarivate* for JCR data. We thank Hongyu Zhou for his contribution; and Inga Ivanova, Gabriele Bammer, and a number of other colleagues for comments on previous drafts.

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 communications are not given naturally. However, inter-subjectively 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).

Knowledge can be expected to develop as the result of co-evolutions and tensions among the various subdynamics in the communication

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

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

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)

“[...] 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).

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, Råfols (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

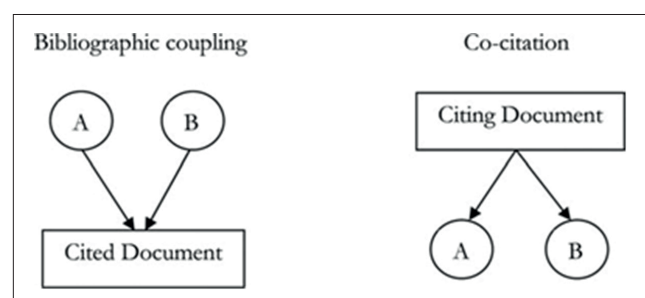


Figure 1. Bibliographic coupling and co-citation. Source: Meireles, Cendon & De-Almeida (2004).

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.

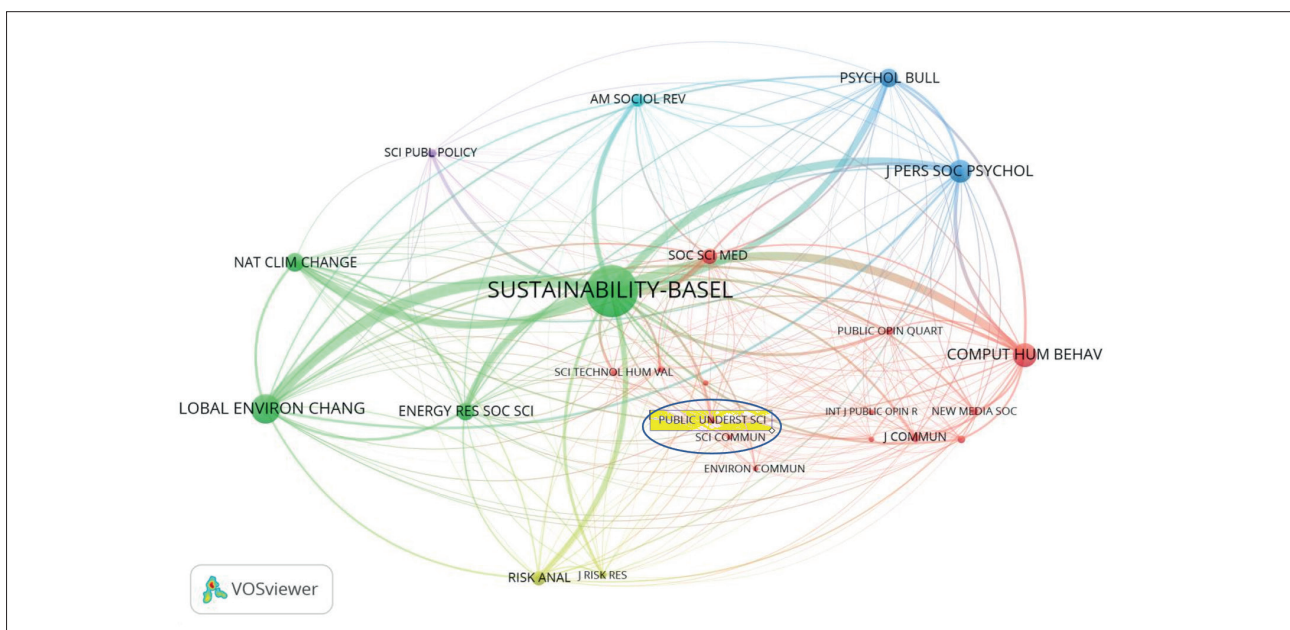


Figure 2. Citations in the *cited* direction for *Public Understanding of Science*, mapped and grouped using VOSviewer.

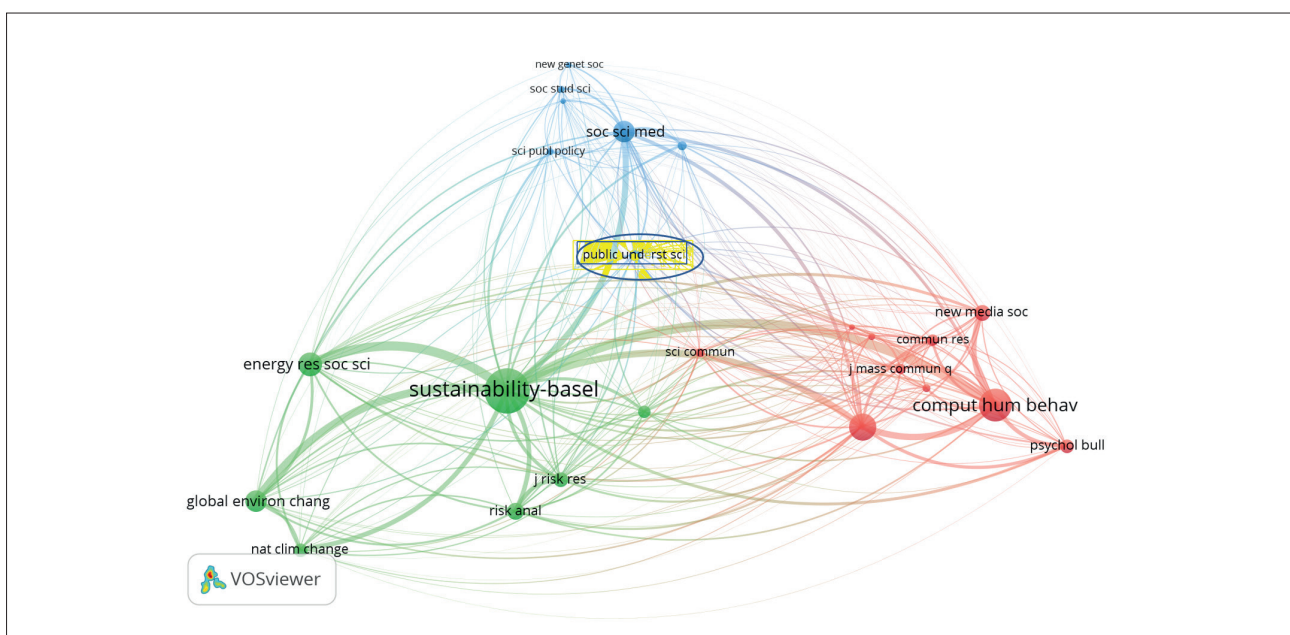


Figure 3. Citations in the *citing* direction for *Public Understanding of Science*, mapped and grouped using VOSviewer.

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 (Råfols; 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.

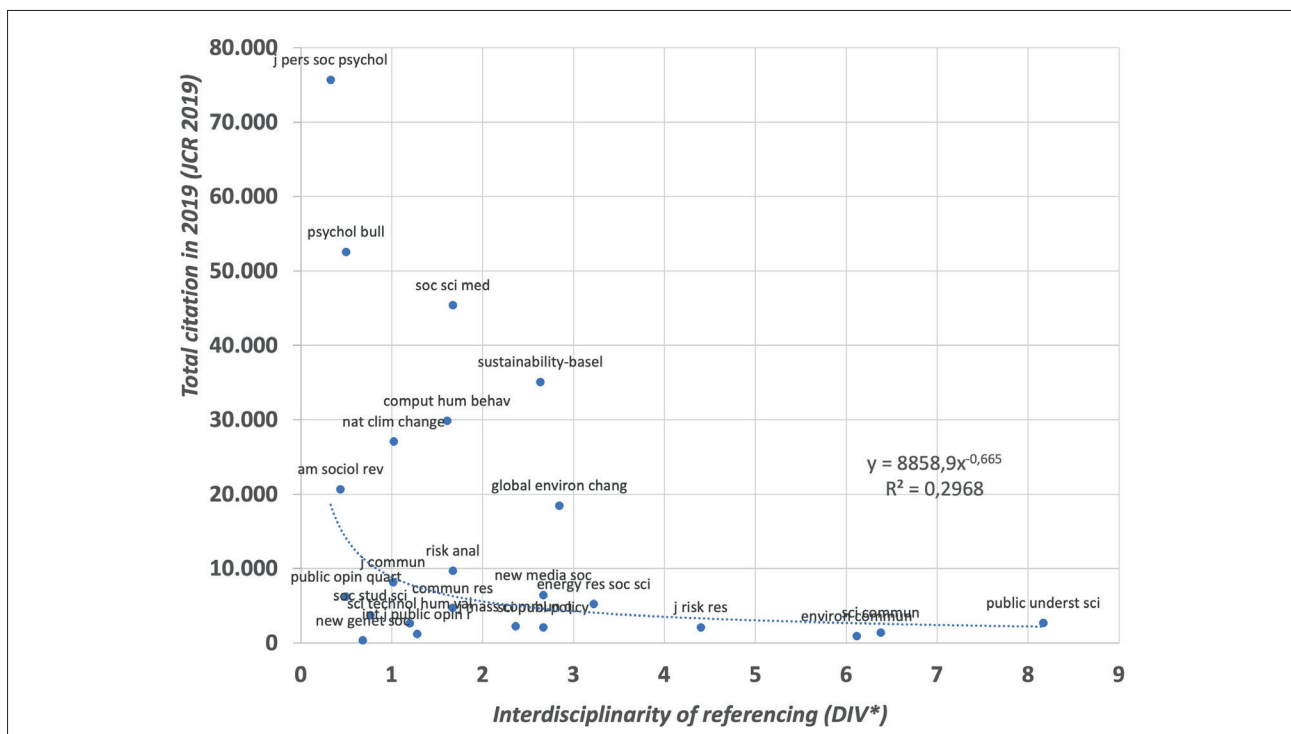


Figure 4. Twenty-four journals citing from and cited by *PUS* during 2019 in terms of interdisciplinarity (*DIV**) on the x -axis and times impact (times cited; TC) on the y -axis.

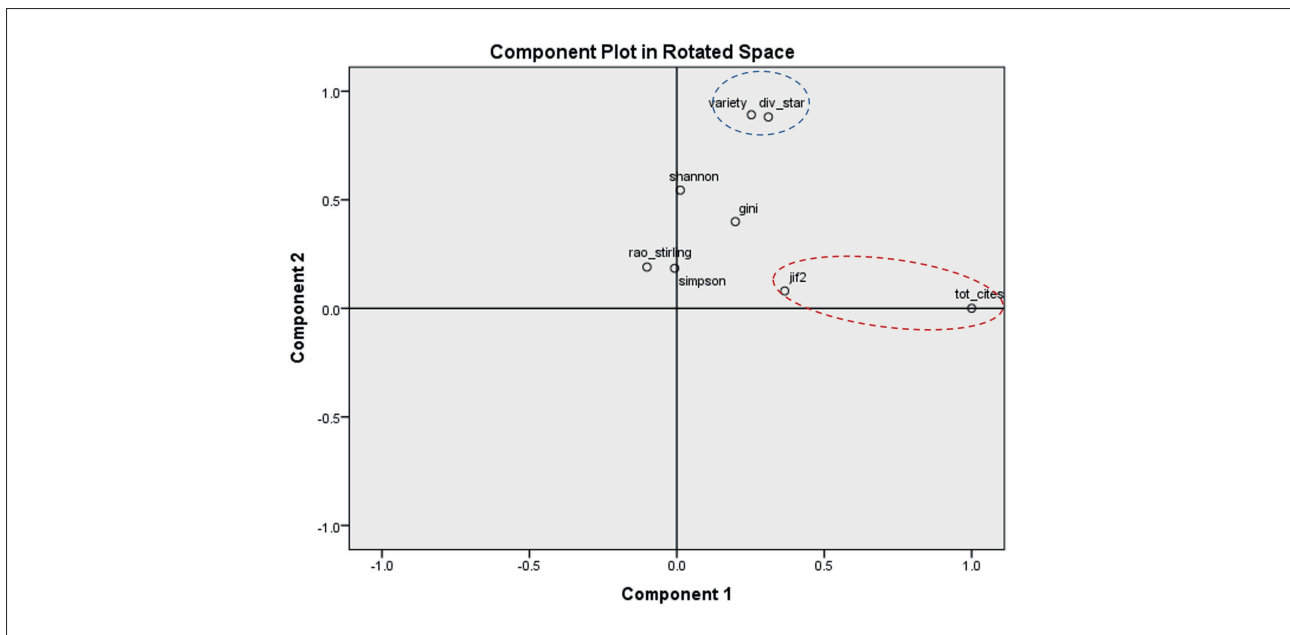


Figure 6. Visualization of the two-factor solutions (*SPSS v.22*) of the matrix of indicators versus 11,487 journals (without the network measures; oblique rotation). Structure matrix.

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.

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

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

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.

8. References

- Abbasi, Alireza; Hossain, Liaquat; Leydesdorff, Loet** (2012). “Betweenness centrality as a driver of preferential attachment in the evolution of research collaboration networks”. *Journal of informetrics*, v. 6, n. 3, pp. 403-412. <https://doi.org/10.1016/j.joi.2012.01.002>
- Andersen, Esben-Sloth** (1992). *Artificial economic evolution and Schumpeter*. Aalborg: Institute for Production, University of Aalborg.
- Audretsch, David B.; Feldman, Maryann P.** (1996). “R&D spillovers and the geography of innovation and production”. *The American economic review*, v. 86, n. 3, pp. 630-640. <http://links.jstor.org/sici?sici=0002-8282%28199606%2986%3A3%3C630%3ARSATGO%3E2.0.CO%3B2-Z>
- Bak, Per; Tang, Chao; Wiesenfeld, Kurt** (1987). “Self-organized criticality: An explanation of the 1/f noise”. *Physical review letters*, v. 59, n. 4, pp. 381-384. <https://doi.org/10.1103/PhysRevLett.59.381>
- Boschma, Ron; Balland, Pierre-Alexandre; Kogler, Dieter** (2014). *Relatedness and technological change in cities: The rise and fall of technological knowledge in U.S. metropolitan areas from 1981 to 2010*. No 1316, Papers in evolutionary economic geography (PEEG), Utrecht University, Department of Human Geography and Spatial Planning, Group Economic Geography. <https://econpapers.repec.org/paper/eguwpaper/1316.htm>
- Boulding, Elise** (1978). “Futuristics and the imaging capacity of the West”. In: Maruyama, Magoroh; Harkins, Arthur M. (eds.). *Cultures of the future*. De Gruyter Mouton. <https://doi.org/10.1515/9783110800067>
- Brooks, Daniel R.; Wiley, Edward O.** (1986). *Evolution as entropy*. Chicago/London: University of Chicago Press. ISBN: 978 0 226075747
- Bruckner, Eberhard; Ebeling, Werner O.; Miguel A. Jiménez-Montano; Scharnhorst, Andrea** (1994). “Hyperselection and innovation described by a stochastic model of technological evolution”. In: Leydesdorff, Loet; Van-den-Besselaar, Peter (eds.). *Evolutionary economics and chaos theory: New directions in technology studies*, pp. 79-90. London: Pinter. ISBN: 978 0 312122188
- Carter, Vicki** (1996). “Do media influence learning? Revisiting the debate in the context of distance education”. *Open learning: The journal of open, distance and e-learning*, v. 11, n. 1, pp. 31-40. <https://doi.org/10.1080/0268051960110104>
- Casson, Mark** (1997). *Information and organization: A new perspective on the theory of the firm*. Oxford: Clarendon Press. ISBN: 978 0 198297802
- Dosi, Giovanni** (1982). “Technological paradigms and technological trajectories: A suggested interpretation of the determinants and directions of technical change”. *Research policy*, v. 11, n. 3, pp. 147-162. [https://doi.org/10.1016/0048-7333\(82\)90016-6](https://doi.org/10.1016/0048-7333(82)90016-6)
- Feldman, Maryann; Storper, Michael** (2016). *Economic growth and economic development: Geographic dimensions, definition & disparities*. https://maryannfeldman.web.unc.edu/wp-content/uploads/sites/1774/2011/11/Economic_Growth_and_Economic_Development_2016_Feldman_Storper.pdf

- Fujigaki, Yuko** (1998). "Filling the gap between discussions on science and scientists' everyday activities: Applying the autopoiesis system theory to scientific knowledge". *Social science information*, v. 37, n. 1, pp. 5-22.
<https://doi.org/10.1177/053901898037001001>
- Garfield, Eugene** (1964). "Science Citation Index - A new dimension in indexing". *Science*, v. 144, n. 3619, pp. 649-654.
<https://doi.org/10.1126/science.144.3619.649>
- Garfield, Eugene** (1971). "The mystery of the transposed journal lists - wherein Bradford's Law of Scattering is generalized according to Garfield's Law of Concentration". *Current contents*, v. 3, n. 33, pp. 5-6. Reprinted in *Essays of an information scientist*, v. 1. Philadelphia: ISI Press, pp. 222-223, 1977.
<http://www.garfield.library.upenn.edu/essays/V1p222y1962-73.pdf>
- Gibbons, Michael; Limoges, Camille; Nowotny, Helga; Schwartzman, Simon; Scott, Peter; Trow, Martin** (1994). *The New production of knowledge: The dynamics of science and research in contemporary societies*. London: Sage. ISBN: 978 0 803977945
- Giddens, Anthony** (1984). *The constitution of society*. Cambridge: Polity Press. ISBN: 978 0 520057289
- Gleick, James** (2011). *The information: A history, a theory, a flood*. Knopf Doubleday Publishing Group. ISBN: 978 0 307 37957 3
- Godin, Benoît** (2006). "The knowledge-based economy: Conceptual framework or buzzword?". *Journal of technology transfer*, v. 31, n. 1, pp. 17-30.
<https://doi.org/10.1007/s10961-005-5010-x>
- Griliches, Zvi** (1994). "Explanations of productivity growth: Is the glass half-empty?". *American economic review*, v. 84, n. 1.
- Husserl, Edmund** ([1935/36] 1962). *Die Krisis der Europäischen Wissenschaften und die Transzendente Phänomenologie*. Den Haag: Martinus Nijhoff. ISBN: 978 9401013369
- Ivanova, Inga A.; Leydesdorff, Loet** (2014). "Rotational symmetry and the transformation of innovation systems in a triple helix of university-industry-government relations". *Technological forecasting and social change*, v. 86, pp. 143-156.
<https://doi.org/10.1016/j.techfore.2013.08.022>
- Kessler, Maxwell-Mirton** (1963). "Bibliographic coupling between scientific papers". *American documentation*, v. 14, n. 1, pp. 10-25.
<https://doi.org/10.1002/asi.5090140103>
- Kuhn, Thomas S.** (1977). *The essential tension: Selected studies in scientific tradition and change*. Chicago: University of Chicago Press. ISBN: 978 0 226458052
- Langford, Cooper H.; Hall, Jeremy K.** (2005). "Complexity in cluster development: Towards an evolutionary theory to guide policy development".
<https://www.semanticscholar.org/paper/49cd670d11aafc8d2e20df0ce3ade7bd2b1ec7ef>
- Langford, Cooper H.; Hall, Jeremy K.; Josty, Peter; Matos, Stelvia; Jacobson, A.** (2006). "Indicators and outcomes of Canadian university research: Proxies becoming goals?". *Research policy*, v. 35, n. 10, pp. 1586-1598.
<https://doi.org/10.1016/j.respol.2006.09.021>
- Leydesdorff, Loet** (2000). "Luhmann, Habermas and the theory of communication". *Systems research and behavioral science*, v. 17, n. 3, pp. 273-288.
[https://doi.org/10.1002/\(SICI\)1099-1743\(200005/06\)17:3<273::AID-SRES329>3.0.CO;2-R](https://doi.org/10.1002/(SICI)1099-1743(200005/06)17:3<273::AID-SRES329>3.0.CO;2-R)
- Leydesdorff, Loet** (2007). "Betweenness centrality as an indicator of the interdisciplinarity of scientific journals". *Journal of the American Society for Information Science and Technology*, v. 58, n. 9, pp. 1303-1319.
<https://doi.org/10.1002/asi.20614>
- Leydesdorff, Loet; Ivanova, Inga A.** (2014). "Mutual redundancies in interhuman communication systems: Steps toward a calculus of processing meaning". *Journal of the Association for Information Science and Technology*, v. 65, n. 2, pp. 386-399.
<https://doi.org/10.1002/asi.22973>
- Leydesdorff, Loet; Ivanova, Inga A.** (2021). "The measurement of 'interdisciplinarity' and 'synergy' in scientific and extra-scientific collaborations". *Journal of the Association for Information Science and Technology*, v. 72, pp. 347-402.
<https://doi.org/10.1002/asi.24416>
- Leydesdorff, Loet; Ràfols, Ismael; Milojević, Staša** (2020). "Bridging the divide between qualitative and quantitative science studies". *Quantitative science studies*, v. 1, n. 3, pp. 918-926.
https://doi.org/10.1162/qss_e_00061

- Leydesdorff, Loet; Wagner, Caroline S.; Bornmann, Lutz** (2018). "Discontinuities in citation relations among journals: Self-organized criticality as a model of scientific revolutions and change". *Scientometrics*, v. 116, n. 1, pp. 623-644.
<https://doi.org/10.1007/s11192-018-2734-6>
- Leydesdorff, Loet; Wagner, Caroline S.; Bornmann, Lutz** (2019). "Interdisciplinarity as diversity in citation patterns among journals: Rao-Stirling diversity, relative variety, and the Gini coefficient". *Journal of informetrics*, v. 13, n. 1, pp. 255-269.
<https://doi.org/10.1016/j.joi.2018.12.006>
- Leydesdorff, Loet; Wagner, Caroline S.; Zhang, Lin** (2021). "Are university rankings statistically significant? A comparison among Chinese universities and with the USA". *Journal of data and information science*, v. 6, n. 2, pp. 67-95.
<https://doi.org/10.2478/jdis-2021-0014>
- Leydesdorff, Loet; Ward, Janelle** (2005). "Science shops: a kaleidoscope of science–society collaborations in Europe". *Public understanding of science*, v. 14, n. 4.
<https://doi.org/10.1177/0963662505056612>
- Li, Tien-Yien; Yorke, James A.** (1975). "Period three implies chaos". *The American mathematical monthly*, v. 82, n. 10, pp. 985-992.
- Luhmann, Niklas** (1990a). "The cognitive program of constructivism and a reality that remains unknown". In: W. Krohn; G. Küppers; H. Nowotny (eds.). *Selforganization. Portrait of a scientific revolution*, pp. 64-85. Dordrecht: Reidel. ISBN: 978 9 048140732
<https://luhmann.ir/wp-content/uploads/2021/07/The-Cognitive-Program-of-Constructivism-and-a-Reality-that-Remains-Unknown.pdf>
- Luhmann, Niklas** (1990b). *Die Wissenschaft der Gesellschaft*. Frankfurt a.M.: Suhrkamp. ISBN: 978 3 18580653
- Luhmann, Niklas** (1996). "On the scientific context of the concept of communication". *Social science information*, v. 35, n. 2, pp. 257-267.
<https://doi.org/10.1177/053901896035002005>
- Luhmann, Niklas** (2012). *Theory of society*, v. 1. Stanford, CA: Stanford University Press. ISBN: 978 0 804739504
- Malerba, Franco; Nelson, Richard; Orsenigo, Luigi; Winter, Sidney G.** (1999). "'History-friendly' models of industry evolution: The computer industry". *Industrial and corporate change*, v. 8, n. 1, pp. 3-35.
<https://doi.org/10.1093/icc/8.1.3>
- Marres, Noortje; De-Rijcke, Sarah** (2020). "From indicators to indicating interdisciplinarity: A participatory mapping methodology for research communities in-the-making". *Quantitative science studies*, v. 1, n. 3, pp. 1041-1055.
https://doi.org/10.1162/qss_a_00062
- Marshakova, Irena V.** (1973). "Bibliographic coupling system based on references". *Nauchno-Tekhnicheskaya informat-siya seriya, Ser. 2*, n. 6, pp. 3-8.
- Maturana, Humberto R.** (1978). "Biology of language: the epistemology of reality". In: Miller, George A.; Lenneberg, Elizabeth (eds.). *Psychology and biology of language and thought. Essays in honor of Eric Lenneberg* (pp. 27-63). New York: Academic Press. ISBN: 978 1 483258140
<https://sites.evergreen.edu/arunchandra/wp-content/uploads/sites/395/2018/05/BofLanguage.pdf>
- Meireles, Magali-Rezende-Gouvea; Valadares-Cendon, Beatriz; De-Almeida, Paulo E. M.** (2014). "Bibliometric knowledge organization: A domain analytic method using artificial neural network". *Knowledge organization*, v. 41.
<https://doi.org/10.5771/0943-7444-2014-2-145>
- Nelson, Richard R.; Winter, Sidney G.** (1977). "In search of useful theory of innovation". *Research policy*, v. 6, n. 1, pp. 35-76.
[https://doi.org/10.1016/0048-7333\(77\)90029-4](https://doi.org/10.1016/0048-7333(77)90029-4)
- Nelson, Richard R.; Winter, Sidney G.** (1982). *An evolutionary theory of economic change*. Cambridge, MA: Belknap Press of Harvard University Press. ISBN: 978 0 674272286
- Nonaka, Ikujiro; Takeuchi, Hirotaka** (1995). *The knowledge creating company*. Oxford/New York: Oxford University Press. ISBN: 978 0 195092691
- Petersen, Alexander M.; Rotolo, Daniele; Leydesdorff, Loet** (2016). "A triple helix model of medical innovations: supply, demand, and technological capabilities in terms of Medical Subject Headings". *Research policy*, v. 45, n. 3, pp. 666-681.
<https://doi.org/10.1016/j.respol.2015.12.004>

- Popper, Karl R.** ([1935] 1959). *The logic of scientific discovery*. London: Hutchinson. ISBN: 978 0 091117214
- Ràfols, Ismael** (2021). “‘Measuring’ interdisciplinarity: from indicators to indicating”. *Integration and implementation insights* (blogpost).
<https://i2insights.org/2021/2002/2009/measuring-interdisciplinarity>
- Ràfols, Ismael; Leydesdorff, Loet; O’Hare, Alice; Nightingale, Paul; Stirling, Andy** (2012). “How journal rankings can suppress interdisciplinary research: A comparison between innovation studies and business and management”. *Research policy*, v. 41, n. 7, pp. 1262-1282.
<https://doi.org/10.1016/j.respol.2012.03.015>
- Ràfols, Ismael; Meyer, Martin** (2010). “Diversity and network coherence as indicators of interdisciplinarity: Case studies in bionanoscience”. *Scientometrics*, v. 82, n. 2, pp. 263-287.
<https://doi.org/10.1007/s11192-009-0041-y>
- Sahal, Devendra** (1981). *Patterns of technological innovation*. Addison-Wesley. ISBN: 978 0 201066302
- Schumpeter, Joseph A.** (1939). *Business cycles. A theoretical, historical and statistical analysis of the capitalist process*.
<https://www.mises.at/static/literatur/Buch/schumpeter-business-cycles-a-theoretical-historical-and-statistical-analysis-of-the-capitalist-process.pdf>
- Shannon, Claude E.** (1948). “A mathematical theory of communication”. *The Bell System technical journal*, v. 27, n. 3, pp. 379-423.
<https://doi.org/10.1002/j.1538-7305.1948.tb01338.x>
- Small, Henry** (1973). “Co-citation in the scientific literature: A new measure of the relationship between two documents”. *Journal of the American Society for Information Science*, v. 24, n. 4, pp. 265-269.
<https://doi.org/10.1002/asi.4630240406>
- Stirling, Andy** (2007). “A general framework for analysing diversity in science, technology and society”. *Journal of the Royal Society interface*, v. 4, n. 15, pp. 707-719.
<https://doi.org/10.1098/rsif.2007.0213>
- Whitley, Richard D.** (1984). *The intellectual and social organization of the sciences*. Oxford: Oxford University Press. ISBN: 978 0 199240456
- Zhang, Lin; Leydesdorff, Loet** (2021). “The scientometric measurement of interdisciplinarity and diversity in research portfolios of Chinese universities”. *Journal of data and information science*, v. 6, n. 4, pp. 13-35.
https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3798519
- Zhang, Lin; Rousseau, Ronald; Glänzel, Wolfgang** (2016). “Diversity of references as an indicator of the interdisciplinarity of journals: Taking similarity between subject fields into account”. *Journal of the Association for Information Science and Technology*, v. 67, n. 5, pp. 1257-1265.
<https://doi.org/10.1002/asi.23487>
- Zitt, Michel; Small, Henry** (2008). “Modifying the journal impact factor by fractional citation weighting: The audience factor”. *Journal of the American Society for Information Science and Technology*, v. 59, n. 11, pp. 1856-1860.
<https://doi.org/10.1002/asi.20880>