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Visualizing the intellectual structure and evolution of innovation systems research: a bibliometric analysis

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Abstract Despite increasing awareness of the need to trace the trajectory of innovation system research, so far little attention has been given to quantitative depiction of the evolution of this fast-moving research field. This paper uses CiteSpace to demonstrate visually intellectual structures and developments. The study uses citation analysis to detect and visualize disciplinary distributions, keyword co-word networks and journal cocitation networks, highly cited references, as well as highly cited authors to identify intellectual turning points, pivotal points and emerging trends, in innovation systems system research from 1975 to 2012.

Keywords Innovation systems · Scientific visualization · Cityscape · Intellectual development · Bibliometrics

Introduction

It is generally acknowledged that in the contemporary globalizing economy innovation is a key driver of the competiveness of firms, industries, places and nations (Freeman 1994; OECD 2002). The role of innovation in driving economic growth was incisively examined by Schumpeter (1934), who defined innovation as the introduction of a product, a method

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of production, a form of industrial organization or a mode of commercial management, the opening up of a new market, and the conquest of a new source of raw materials or semi-manufactured goods (Schumpeter 1942, pp. 82–93). As Schumpeter himself admitted, innovation is not driven solely by individual enterprises. This idea was however not developed intensively in his writings.

At the start of the 1980s, innovation scholars called for a systemic perspective on innovation and strongly argued that innovation is a complex, social process involving many actors including governments, universities, private and public enterprises and intermediate organizations (Dosi et al. 1988; Freeman 1982; Lundvall 1992; Nelson 1993) which together make up innovation systems (ISs). Since that time IS approaches have become widely used as conceptual frameworks for understanding economic growth (Lundvall et al. 2002), and also as policy tools for promoting economic and social development. At the same time a range of related and complementary concepts have been introduced to capture the different dimensions of ISs including "national innovation system" (Freeman 1987; Lundvall 1988; Nelson 1992, 1993), "regional innovation system" (Asheim and Isaksen 1997; Cooke 1992), "sectoral innovation system" (Carlsson 1995; Malerba 2002), and "technological innovation system" (Bergek et al. 2008; Carlsson 1995) amongst others.

Although their focus differs, these approaches all share the view that innovation is the result of a complex interaction between various actors and supporting institutions. These interactions go beyond the traditional "linear-model of innovation" in which innovation involves a linear sequence from basic research to applied research, industrial development and application (OECD 2002). These IS approaches have been widely adopted by policy makers as well by scholars across the world. As of the end of August 2012, searches using the term "innovation system" and its variants in titles, abstracts or indexing terms identified more than 69,000 publications on Google Scholar, while topic searches for the same terms generated 1,565 records in the Web of Science (WoS). The number of publications relevant to IS research continues to grow explosively. There is thus a need to examine the intellectual development of this relatively new but rapidly growing research field.

The intellectual progress of a problem solving oriented knowledge domain in the social sciences is on the one hand influenced by the inner intellectual research tradition/paradigm/research programme of this research community itself (Kuhn 1962; Lakatos et al. 1978). On the other, it is also driven by developments in neighboring and related knowledge domains. For example, many works in the knowledge domain under study have drawn inspiration from evolutionary economics (Metcalfe 1995; Perez 2010). Moreover, the development trajectory and concrete research topics of ISs scholars are affected by the social, economic, political and ideological contexts in which ISs scholars are embedded. For example, as awareness of environmental degradation increased, and as environmental and energy-related issues emerged as subjects of ISs research (Klagge et al. 2012; Smith et al. 2010), new concepts and frameworks, such as IS functions (Hekkert et al. 2007) and multi-level approaches (Markard and Truffer 2008), were introduced to analyse sustainable transitions. More importantly, the death or semi-retirement of scholars who made substantial contributions to this research field (such as Keith Pavitt of the University of Sussex in 2002 and Christopher Freeman also of Sussex University in 2010) and the emergence of a new generation of scholars with fresh thoughts and methods suggests that the objects of enquiry, and the conceptual and methodological tools IS scholars employ might vary through time.

After nearly 40 years of development there is also increasing intuitive awareness of the need to trace the trajectory of IS research in general (Galli and Teubal 1997), and of its subfields (Cruz and Teixeira 2010; Teixeira 2014). And yet little attention has so far been given to the objective and quantitative depiction of the evolution of ISs research. The majority of literature surveys are qualitative and personalised. This approach tends to lead to over- or under-valuation of the contributions of certain scholars, intentionally or unintentionally. In addition, existing surveys often focus on specific IS subfields and themes, such as national IS (Freeman 1994; Lundvall 2007; Nelson 1992; Teixeira 2014), technological IS (Garcia and Calantone 2002) and territorial/regional IS (Doloreux and Parto 2005; MacKinnon et al. 2002; Moulaert and Sekia 2003; Oinas and Malecki 2002; Iammarino 2005), internationalization of IS (Carlsson 2006), local ISs (Breschi and Lissoni 2001), industrial cluster innovation (Cruz and Teixeira 2010) and analytical and methodological aspects of IS (Carlsson et al. 2002). These fertile surveys offered a focused (and in-depth) perspective. However, they did not generally provide an overall picture of the IS literature.

A manual compilation and systematic review of publications on ISs research seems to be impossible due to the evolving definition of ISs (Lundvall et al. 2009), the ever-increasing number of publications and the diversity of the academic disciplines involved. It is against this background that we offer a longitudinal and comprehensive survey of the evolution of the IS literature using a quantitative method, based on a bibliometric survey, which empirically complements existing qualitative literature reviews.

Bibliometrics is the application of quantitative tools to the study of scientific communications (Pritchard 1969; Leydesdorff 1995), and has been applied in various forms for a century or more (Pritchard and Wittig 1981; for the brief history of bibliometrics, see Hood and Wilson 2001; Osareh 1996a, b). Since Eugene Garfield founded the Institute for Scientific Information in 1958 (an organization that subsequently created the first ever large database of references, the Science Citation Index) and introduced the Impact Factor (the first ever prestige indicator for scientific journals), an increasing number of bibliometric indicators and tools have been developed to assess quantitatively the research performance and the scientific contributions of authors, journals, regions or specific works, analyze the dissemination and cognitive process of scientific knowledge, monitor scientific developments, and identify emerging topical areas and intellectual structures (Osareh 1996a, b; van Raan 1996; Silva and Teixeira 2008; Chen et al. 2012; Cruz and Teixeira 2010). Bibliometric studies have been widely conducted in many natural and social sciences, including ISs research (Lee and Su 2010; Teixeira 2014). A recent bibliometric analysis of IS research for example identified productive authors, institutions and countries, and the most cited journals for the period from 1975 to 2009, using 773 full length articles published in Thomson Reuters's Web of Science Social Sciences Citation Index (SSCI)-listed journals (Uriona-Maldonado et al. 2012). The analysis in this paper is however different in several respects.

The study itself involved, first, the retrieval of IS publications for the period up to August 2012 from the three databases of the WoS provided by Thomson Reuters (formerly the Institute for Scientific Information) with a view to getting a better overall picture of IS research. Uriona-Maldonado et al. collected bibliometric IS research data only from the SSCI database. IS papers were largely published in SSCI-indexed journals, but they also appeared in the Science Citation Index (SCI)-listed journals, and sporadically in Arts and Humanities Citation Index (AHCI) journals.

Second, this paper goes beyond traditional citation counts and employs CiteSpace to identify and visualize the intellectual structure, turning points and dynamics of IS research. CiteSpace is a freely available software package used for visualizing and analyzing trends and patterns in scientific literature retrieved from the WoS (Chen 2006; Chen et al. 2012). This program makes it possible to identify systematically the intellectual origins and developments of the IS research field. This analysis offers researchers, in particular research students and "newcomers" to the field, a more comprehensive picture of its overall intellectual development.

Third, the disciplines which have contributed to IS research, its emerging trends and critical turns will also be detected. The former will be useful for would-be IS scholars interested in which disciplines should be studied, while the latter might enable researchers to identify research gaps and research frontiers, where they might contribute to this field.

Visualizing the intellectual structure and evolution of a scientific field with CiteSpace

The collective scientific advancement of a given research field relies not only on the research skills and abilities of individual researchers, but also on continuing communication among them, which is in turn helpful in improving the research performance of individuals and of the whole scientific community. Although there are other equally important ways of spreading academic ideas, including monographs, conference proceedings and personal blogs or web pages, scholarly journals remain one of the most important media for scientists to communicate with their (invisible) colleagues.

Scientific advance is essentially a dynamic and cumulative process, since any contribution to a given research field need to build upon previous theoretical approaches, research methods and research findings (Shafique 2012). In other words, when scholars write scientific documents, they need to cite the scholarly work of others. Earlier research outputs that are frequently cited collectively constitute the intellectual base of a knowledge domain. A set of primary attributes of the intellectual base, including its disciplinary composition, research traditions, content-bearing keywords, and their interrelationships jointly comprise the intellectual structure of a scientific domain (Chen 2006; Shafique 2012). But the intellectual structure changes, as new publications are unceasingly added to intellectual base. Sometimes the result is structural variation (Chen et al. 2012). Studying changing intellectual structures accordingly affords a holistic understanding of the intellectual origins and developments of a chosen scientific domain over time.

The rapid advances in computer graphics and related sciences in the past two decades make scientific visualization possible. An array of science mapping software tools has been developed to illustrate graphically structural and dynamic aspects of scientific research (Börner 2010). These tools use rigorous scientific techniques for mapping large amounts of bibliometric data and are very useful for researchers and analysts wanting to capture the structural and dynamic aspects of scientific research. These methods complement traditional narrative-based literature reviews that are typically qualitative and based on personal judgment.

Frequently used scientific visualization software tools include IN-SPIRE (Wise 1999), VantagePoint (Porter and Cunningham 2004), CoPalRed (Bailón-Moreno et al. 2005), Leydesdorff's SoftwareCiteSpace (Leydesdorff and Schank 2008), Bibexcel (Persson et al. 2009), VOSViewer(Van Eck and Waltman 2010), Network Workbench Tool (Börner et al. 2010), and Science of Science (Sci2) Tool (Sci2 Team 2009). Each has its own advantages and drawbacks. Some of them are stronger in data preprocessing, while others focus more on visualization (for a detailed and comprehensive comparison of different bibliometric tools, see Cobo et al. 2011).

The analysis tool used in this paper is CiteSpace, a Java-based scientific visualization software package, developed by Dr. Chaomei Chen at Drexel University (USA). It is freely available at http://cluster.cis.drexel.edu/~cchen/citespace/. As with other science mapping software tools (e.g., Bibexcel and VantagePoint), CiteSpace can be used to produce and analyze co-occurrence network of key words and subject categories (co-word analysis), and co-citation networks of authors, documents and journals (co-citation analysis). More important, it facilitate the analysis of temporal patterns of a knowledge domain, including identifying fast-growth topical areas and citation hotspots, and the finding of intellectual turning points, because CiteSpace can not only construct the bibliometric networks for different time periods, but can also detect and visualize burst terms and betweenness centrality to identify emerging trends and radical changes, and turning points, respectively (Cobo et al. 2011; Chen 2006). Furthermore, CiteSpace embodies good visualization techniques enabling users to choose different display modes (cluster views or time-zone views), to control the display of visual attributes and labels, and so on. In short, CiteSpace makes it easier for users to detect and visualize the structural and temporal patterns and trends, especially intellectual turning points, of a particular knowledge domain.

In this survey, two distinctive bibliographc techniques provided by CiteSpace are used: co-word analysis and co-citation analysis. Both co-word and co-citation analysis are based on co-occurrence analysis techniques, which are used to measure the frequency of co-occurrence of pairs of keywords or noun phrases and other terms in the same document. Co-occurrence analysis is based on the assumption that when two items appear in the same context, they are related to some degree. Keyword co-word analysis is a frequently used content analysis technique. It tends to be employed to explore changes in research themes in a research field by measuring the frequency of pairs of items (i.e., words or noun phrases) occurring in the entire body of literature in a selected field. This method assumes that a set of signal-words reflect the core contents of research literature (He 1999). Co-occurrence analysis can be also used for studying which disciplines are involved in constructing the intellectual base of a specific research field.

Since simple citation counts merely identify the contributions of key authors, but are not able to identify more detailed interconnections among scholars, CiteSpace utilizes co-citation analysis to detect the interconnections among scholars and the intellectual structure of a scientific research field (Chen 2006; Cobo et al. 2011). Co-citation analysis is based on the assumption that when two documents (or authors and journals) are both cited by a third one, they are related in some way, even though they don't directly cite each other (Braam et al. 1991a, b; Small 1973). The co-citation frequency is defined as the frequency with which two documents (or authors and journals) are cited simultaneously. The larger the frequency, the stronger is their relationship.

The co-citation analysis methods that CiteSpace provides are document co-citation analysis (Chen 2006; Leydesdorff 2005), author co-citation analysis (Chen and Carr 1999; Nerur et al. 2008; White and McCain 1998) and journal co-citation analysis (Hu et al. 2011; Liu 2005; Tsay et al. 2003). These methods complement each other. Citespace is used to represent visually these three co-citation networks. Document co-citation networks provide insights into connections among co-cited documents, while author co-citation network focuses on interrelationships among authors. Thus, these co-citation analyses enable the identification of groups of intellectually interrelated scientists and their publications. The group of co-cited documents tends to represent the collective knowledge base of a given knowledge domain. Document co-citation and author co-citation analysis all help understand the cumulative tradition and movement of disciplinary paradigms (Braam et al. 1991a, b; Small 1973, 1980) and "invisible colleges" of scientific research from the micro-level (Crane 1972; Wagner 2008), while journal co-citation networks reveals the macro-structure of scholarly disciplines through the macro level analysis of journal titles.

After data collection, clean-up, pre-processing, and parameter setting, CiteSpace can identify individual networks of co-occurrence or co-citation in articles published in a given time interval, known as a time slice, and then merge them to form an general picture that visually shows how a scientific field has been evolving over time. In this paper, an individual network is derived from the 30 most cited articles published in each 2 years time slice. Color map—a spectrum of colors in a visualization—represents temporal patterns of paper publication and citation links among papers.

Thomson Reuters's WoS is often considered to be an ideal data source for bibliometric investigations (van Leeuwen 2006), because it covers approximately 12,000 leading journals worldwide, with citation references across 256 disciplines and also because it provides powerful web-based access to bibliographic and citation information. The WoS encompasses three databases, the Science Citation Index Expanded (SCI-EXPANDED), the SSCI and the AHCI databases.

Documents published with the words "Innovation System", "Innovation Systems", "System of Innovation" and "Systems of Innovation" in titles, abstracts, author keywords and keywords were downloaded. The same search words were used by Uriona-Maldonado et al. (Uriona-Maldonado et al. 2012). But because we retrieve IS literature not only from the SSCI database used by Uriona-Maldonado et al., but also from SCI and AHCI databases, the number of the journal articles identified is much larger. More specifically, 1,565 publications were identified in the WoS web database as of 30 August 2012, with ten document types.

There are 1,364 journal articles, accounting for 87.16 % of the total, followed by proceedings papers (153, 9.78 %), book reviews (78, 4.98 %), reviews (70, 4.47 %) and editorial materials (42, 2.68 %). Other less significant outputs were letters (3), meeting abstracts (3), book chapters (2), news items (2) and biographical items (1).

The bibliometric analysis is based on the 1,364 journal articles, since the major document type is peer-reviewed journal articles, and they have references, which enable tracing of the intellectual roots of the field under study. The bibliographic records (including titles, authors, dates, author addresses, subject categories, reference lists, etc.) of the 1,364 journal articles were downloaded, along with a total of 43,304 cited references.

These journal articles were distributed across 325 journals, contributed by 2,142 scholars from 1,050 institutions in 74 countries/territories. The top four productive countries were the UK, the USA, Netherlands and Germany, each of which produced more than 100 articles. It is worth noting that some Asian countries/territories such as the People's Republic of China, Japan, South Korea, Taiwan, and Singapore were all among the list of the 30 most productive areas.

The 1,364 journal articles were published in ten different languages, although English was the predominant language of articles on IS research (1,299), making up 95.2 % of the total. English is therefore the 'official' international academic communication language for IS research. The predominance of the English language can also be observed in many other natural science (van Leeuwen et al. 2001), and social science and humanities disciplines (van Leeuwen 2013). Among non-English languages, Spanish and German were the second and most widely used (12 and 32, respectively), comprising 2.3 and 8.8 % of the total. French (5), Czech (5), Russian (4), Croatian (3), Portuguese (2), Hungarian (1) and Polish (1) were also contributing languages, although their shares were all below 0.4 %. According to our data, Brooks (1975) was the first work related to IS research. The analysis was therefore based on peer-reviewed journal articles spanning the period from 1975 to

2012. Since the data was downloaded at the end of August 2012, the data for 2012 was not complete. The sample of 1,364 articles was then exported to CiteSpace for further analysis.

The aim of this paper is to demonstrate visually for the period 1975–2012 the intellectual structures and developments in IS research, and in particular its intellectual turning points and emerging trends from the following perspectives: subject categories and major journals, highly cited references and highly cited authors, as well as keywords analysis.

Empirical results

Disciplinary distribution

The disciplinary composition of a given research field reveals to what extent the research field is shaped by the confluence of disciplines and their respective roles. Each article in the Thomson Reuters Web of Knowledge database is assigned to one or more subject categories, according to the journal in which it was published. Using the journal subject classification system, all articles in a journal are assigned to one or more subject categories (as some journals are assigned to more than one category). For example, all articles published in the "Research Policy" are assigned to two categories: Management and to Planning and Development.

Subject category co-occurrence analysis makes it possible to detect the disciplines involved in the intellectual development of a certain knowledge domain and can be visualized using CiteSpace. Figure 1 plots the co-occurrence relationship of subject categories involved in IS research after simplification by Pathfinder network scaling. Pathfinder network scaling, together with the minimum spanning tree algorithm, is a structural modeling technique commonly used to eliminate redundant or counter-intuitive connections and to retain the most salient ones (Samoylenko et al. 2006). Each node in the network represents a category involved in IS research. The area of each node is proportional to the co-occurrence frequency of the respective subject category, and the small number located around the center of a node is the co-occurrence frequency of the relevant category throughout the entire time interval. The width of the line between two categories indicates the citation relationship between categories.

The co-occurrence network of subject categories in IS research consists of 67 nodes and 113 links, meaning that 67 disciplines in total are involved in this research field. The most common category is Management, which is the largest circle with a frequency of 524, followed by Planning and Development (388), Economics (248), Environmental Studies (243), and Geography (230). Other important disciplines with co-occurrence frequencies of less than 200 but more than 100 include Engineering, Urban Studies and Operations Research and Management Science. Although Information Chemistry, Health Care Science and Services, and Energy and Fuels are much smaller, they are marked for reference. But as the different colours of each node show, the earliest IS research outputs were published initially in Engineering, then in Management, Planning and Development, and then in Economics, suggesting the chronological sequence of involvement in ISs research of scholars from different disciplines.

It is worth noting that Management and Operations Research and Management Science are the subject categories with red inner rings, which indicate that the number of articles in these categories has changed considerably. More specifically, the number of articles in the Management subject category fluctuated sharply between 1996 and 1999. This number declined abruptly from 10 in 1996 to 5 in 1997, jumped to 17 and dropped to 10 in the

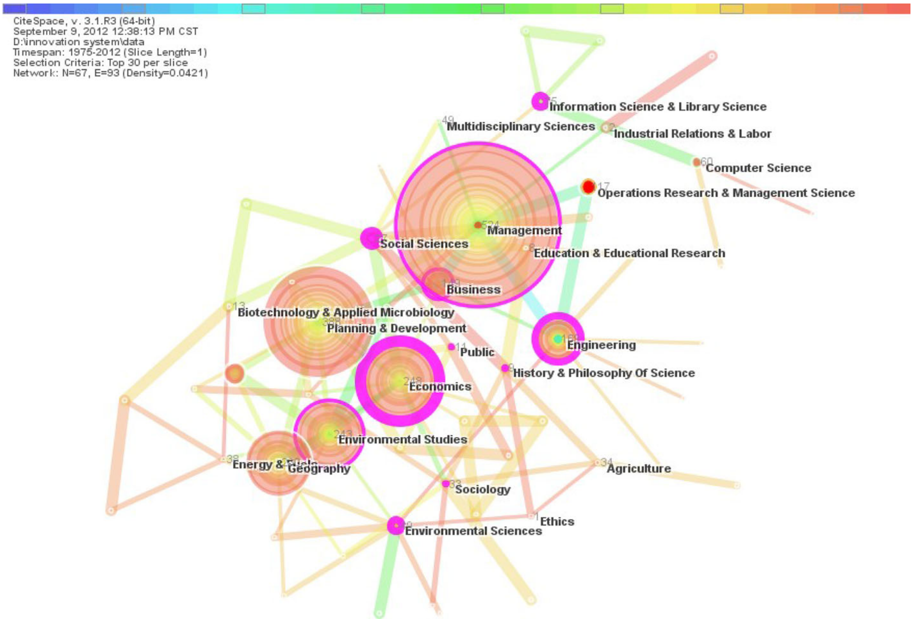

Fig. 1 Disciplines involved in IS research [colour figure can be viewed in the online issue]

following 2 years and saw a stable increase after 1999, implying IS research did not receive continued and increasing attention from management scholars until the new millennium. Moreover, the number of the articles in the Operations Research and Management Science category went up and down between 1990 and 2007.

Keyword co-word analysis

Since keywords provide information about the core content of articles, a keyword co-word network analysis can be used to monitor research topics, as well as the evolving research frontiers of a knowledge domain (Callon et al. 1991; He 1999; Lee and Su 2010). Thomson Reuters's WoS provides two alternatives for the selection of keywords: the original keywords provided by contributor(s), which is called "author keywords"; and the indexing keywords provided by WoS ("Keywords Plus"). Note that WoS provides no keywords for articles published before 1991. Our analysis of the change in research frontiers and topics is therefore confined to post-1990 ISs research.

After standardizing for similar words or different words with the same meaning (for instance, the words "national systems of innovation", "national system of innovation", or "national innovation systems" are mapped to "national innovation system", and "r-and-d", or "research-and-development" are mapped to "research and development"), we used CiteSpace to produce the keyword co-word network of articles published between 1991 and 2012. The simplified merged network that results from use of the minimum spanning tree algorithm consists of 117 nodes and 267 links (Fig. 2). A node represents one author keyword or keyword plus. The size of each node is proportional to the co-occurrence frequencies of the corresponding keywords. Each node is depicted with a series of tree-rings across the series of time slices. A spectrum of colors indicates the temporal orders of co-occurrence links among keywords: oldest in blue, and newest in orange.

Since the term "innovation system" and its variants are used as search keywords, it is not surprising that "innovation" and "innovation systems" have the largest frequencies, 332 and 323 respectively. Other high frequency keywords include "technology" (164), "knowledge" (156), "firms" (133), "policy" (124), "systems" (122), "research and development" (121), "networks" (116), "industry" (112), "national innovation system" (112) and "science" (108). Such keywords as "dynamics" (81, starting in year 2005) and "evolution" (51 starting in 1999) have frequencies of more than 50, revealing that ISs research around the new millennium already paid much attention to process and evolution, in part thanks to the influence of evolutionary economics. As far as sectors of study are concerned, "biotechnology" has become a hot research topic since 1998, with a frequency of 81, and "renewable energy" emerged as an emerging research topic in 2007 (a frequency of 33). Alongside some "conventional" geographical foci of research such as US (28), Europe (40), and Japan (16), China has become a hot study area recently, with a frequency of 56.

Journal co-citation network

As already mentioned, subject category co-occurrence analysis is conducted by classifying the journals in which articles were published, while journal co-citation analysis is carried out for journals in which the cited articles appeared (cited journals). By identifying frequently cited journals, journal co-citation analysis provides important insights into the journals that collectively formed the intellectual base of a knowledge domain.

The merged journal co-citation network in the collection of IS research articles contains 128 journals and 1,378 co-citation links among them. The simplified journal co-citation network, consisting of the most frequently cited 128 journals and 229 co-citation links for

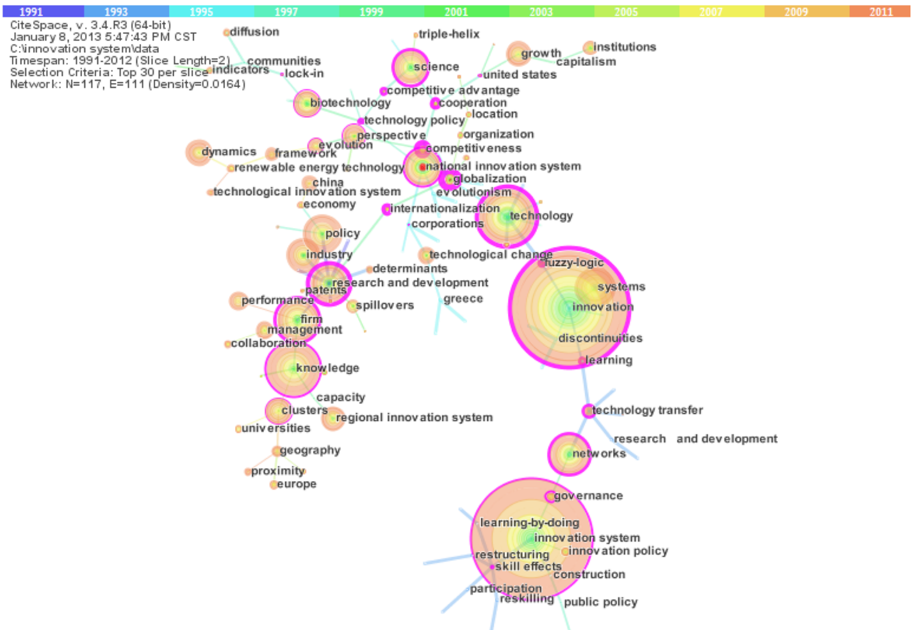

Fig. 2 The keywords co-occurrence network from 1991 to 2012 [colour figure can be viewed in the online issue]

the IS research field, can be produced after employing the minimum spanning tree algorithm. Figure 3 shows the co-citation patterns of highly cited journals. The top three journals in terms of co-citation frequency are Research Policy, Industrial and Corporate Change and Regional Studies (see Table 1). This figure reveals that these top three journals are the primary publishing outlets as well the dominant sources of cited works for IS researchers (Fig. 3).

More interestingly, nodes have purple rings around the outer rim in Fig. 3, signifying that some highly cited journals have high betweenness centrality. These journals make connections to others in the journal co-citation network (see Table 1). Among them, Regional Studies has the highest betweenness centrality ratio (0.26), and publications which have appeared in this journal have been cited since 1997 by IS scholars. Other highly cited journals with high betweenness centrality include Technology Analysis and Strategic Management (0.24), Strategic Management Journal (0.19), Administrative Science Quarterly (0.14), Industrial and Corporate Change (0.11), Cambridge Journal of Economics (0.11) and Journal of Economic Literature (0.10). The Journal of Economic Geography is the one journal with red inner rings, suggesting that its citations have rapidly increased, jumping from 25 in 2007 up to in 62 in 2009. From the subject category perspective, journals in the Economics, Management and Business category received far more citations. Knowledge from Economics, Management and Business is therefore a

Table 1 Frequency distribution and between centrality of the highest cited Journals

Frequency	Centrality	Journal	IF in 2011	Subject
962	0.09	Research Policy	2.520	M, P&D
387	0.11	Industrial and Corporate Change	1.372	B, E, M
379	0.26	Regional Studies	1.187	E, Es , G
260	0.11	Cambridge Journal of Economics	1.447	E
250	0.05	Technovation	3.287	M
235	0.14	Administrative Science Quarterly	4.212	B, M
211	0.06	European Planning Studies	0.679	Es, G, P&D , Us
207	0.24	Technology Analysis and Strategic Management	0.701	M
197	0.03	Science and Public Policy	N/A	N/A
193	0.05	Industry and Innovation	0.750	E, M
193	0.19	Strategic Management Journal	3.783	B, M
186	0	Technological Forecasting and Social Change	1.709	B, P&D
185	0.03	Journal of Technology Transfer	1.176	M
177	0	Environment and Planning A	1.888	Es, G
174	0.02	Management Science	1.733	M
169	0.09	Economic Journal	1.945	E
166	0.03	Journal of Economic Geography	3.261	E, G
154	0.10	Journal of Economic Literature	9.243	E
153	0	Quarterly Journal of Economics	5.920	E
153	0.00	World Development	1.537	E, P&D

Source: Own elaboration based data from the Web of Science and Journal Citation Reports 2011

E economics, *M* management, *G* geography, *P&D* planning and development, *Es* environmental studies, *B* business, *Us* urban studies, *NA* not available, *IF* impact factor in 2011

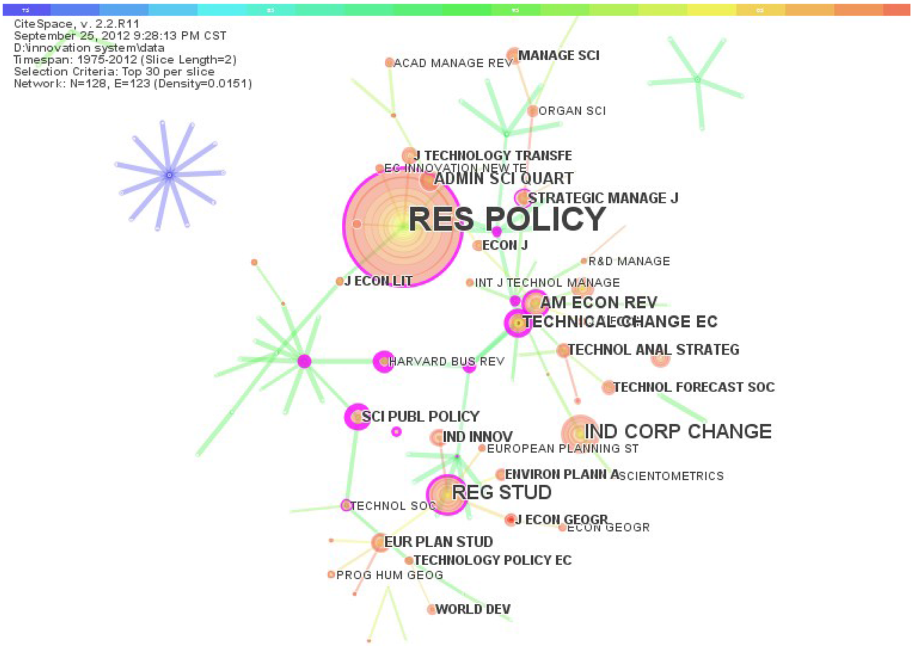

Fig. 3 Journal co-citation network with 128 journals and 229 co-citation links [colour figure can be viewed in the online version]

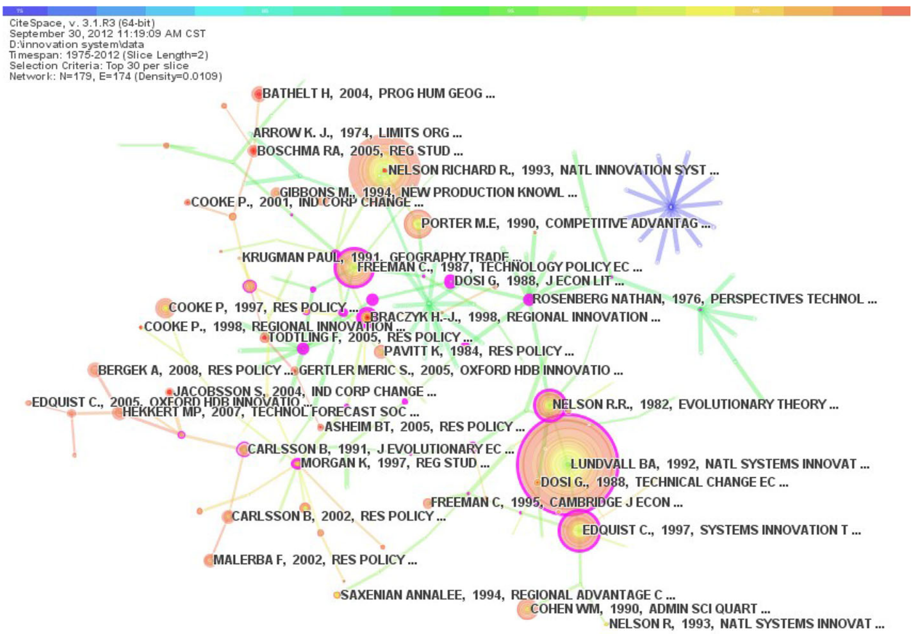

Fig. 4 Document co-citation network with 179 nodes and 289 inks [colour figure can be viewed in the online version]

Table 2 The top 20 most co-cited documents by co-citation frequency

Frequency	Author	Publication year	The title of document	Document type	Subfield
398	Lundvall	1992	National Systems of Innovation	Edited book	National innovation system
314	Nelson	1993	National Innovation Systems: A Comparative Study	Edited book	National IS
180	Freeman	1987	Technology Policy and Economic performance: lessons from Japan.	Monograph	National IS
176	Edquist	1997	Systems of Innovation: Technologies, Institutions and Organizations	Edited book	The first review paper
148	Porter	1990	Competitive Advantage of Nations	Monograph	Cluster
147	Nelson	1982	An Evolutionary Theory of Economic Change	Monograph	Evolutionary approach
120	Cohen	1990	Administrative Science Quarterly	Journal article	Absorptive capacity
111	Cooke	1997	Research Policy	Journal article	Regional innovation system
94	Pavitt	1984	Research Policy	Journal article	Sectoral patterns of technical change
87	Freeman	1995	Cambridge Journal of Economics	Journal article	National innovation system
86	Braczyk	1998	Regional Innovation System	Edited book	Regional innovation system
84	Carlsson	2002	Research Policy	Journal article	Methodological issues
84	Malerba	2002	Research Policy	Journal article	Sectoral innovation system
83	Etzkowitz	2000	Research Policy	Journal article	Triple helix mode
82	Carlsson	1991	Journal of Evolutionary Economics	Journal article	Technological innovation system
82	Gibbons	1994	The New Production of Knowledge	Monograph	New mode of knowledge production
77	Bathelt	2004	Progress in Human Geography	Journal article	Spatiality of knowledge creation
72	Dosi	1982	Research Policy	Journal article	Technological change
69	Nonaka	1995	The Knowledge-Creating Company	Monograph	Knowledge conversion mechanisms
69	Storper	1997	The Regional World	Monograph	Regional evolution

Author is the first author when a highly cited document is multi-authored

IS stands for innovation system

major intellectual resource for IS scholars. This result coincides with the macro-level analysis of subject categories (see "Disciplinary distribution" section).

Document co-citation network

Highly cited documents

A document co-citation network is a network of co-cited references, and is useful in studies of the structure, dynamics, and paradigm developments of a given research field. Figure 4 shows the salient network structure of co-cited references derived from the citing behavior of authors writing on IS from 1975 to 2012, with global pruning by using the minimum spanning tree algorithm.

This network, which is a result of merging 19, 2-year document co-citation networks covering the last 38 years (from 1975 to 2012), comprises of 179 nodes and 289 links. Each node in Fig. 4 represents one cited document, and is depicted with a series of citation tree-rings across multiple time slices. The size of each node is proportional to the total co-citation frequency of the associated reference, while the thickness of a ring is proportional to the co-citation frequencies received in the corresponding time slice (Chen 2006). Each line connecting two nodes in the visualization represents one and more co-citation links involving the two references. The colors of co-citation links shows the first year the connection between the two documents was made.

As Fig. 4 indicates, the most frequently cited work in IS research, the node with the largest citation rings is a 1992 book, edited by Lundvall. This ground-breaking book put interactive learning at the centre of national IS analysis, highlighting that learning is a social process embedded in institutional and cultural contexts. It opened an intense debate about the social construction of IS. The second most frequently cited document is a 1993 book edited by Nelson. This landmark book compared the similarities and differences of national institutions and mechanisms which support technical innovation, and showed that national institutional difference in relation to technical innovation determine to a certain extent national competitiveness. Freeman's (1987) monograph entitled "Technology Policy and Economic Performance: Lessons from Japan" is in third place with 180 citations. Freeman is the first scholar to coin the expression "National Innovation System" through studying Japan's successful catch-up after the Second World War. It is widely accepted among IS scholars that the above three seminal works jointly constructed the conceptual and theoretical foundations for IS research, especially with respect to national systems of innovation (Cooke et al. 1998; Freeman 1995; Lundvall 1999). The fourth document is a 1997 book edited by Edquist, which presented a concise review and defined the characteristics of IS. Porter's 1990 book on "The competitive advantage of nations" occupies fifth place with 148 citations. Porter suggested that the geographical concentration of firms in related industries was a key driver of national competitiveness, popularized the concept of industry cluster and gave a considerable impetus to the study of the geographical dimension of ISs. The sixth most important document is the Nelson (1992) book, which was a milestone on the path towards an evolutionary approach to IS.

Table 2 lists the top 20 highly cited documents by co-citation frequency. Only five single authored publications were included in the list of the top highly cited documents. The others were all multi-authored. These single authored but high cited works include the 1982 Dosi article, the 1990 Porter book, the 1997 Storper book, the 1984 Pavitt article and the 2002 Malerba article. Dosi (1982) article interpreted the determinants and directions of technological trajectories, and Storper's 1997 book proposed an evolutionary approach to regional economies, while the latter two articles focused on sectoral dimensions of IS. It is clear that the high impact research outputs are largely a result of the collaboration of two or more authors, suggesting that research collaboration might lead to greater influence in IS field. This result also applies to many other research fields (Aksnes 2003; Katz and Martin 1997; Luukkonen et al. 1992, 1993; van Leeuwen 2009; Ortega 2014; Leydesdorff et al. 2014). Collaboration does however not necessarily lead to high impact articles, as some single authored IS documents are also included in this list of highly cited publications. It is worth noting that books are the dominant publication type for high impact research outputs, as Table 2 shows. Specifically, books, in the forms of edited books and monographs, accounted for one-half of the top 20 most highly cited documents, and for all of the top six most cited documents. Furthermore, 10 among the 16 most highly cited documents published before 2000 were books (four edited books and six monographs), which means that high quality books were more much cited than journal articles before the arrival of the new millennium. In addition, the journal articles in the top 20 most cited IS documents were largely published in Research Policy, with two exceptions (one in Progress in Human Geography, anther in the Cambridge Journal of Economics) (see Table 2). Note that the journal Research Policy received the largest co-citation frequency (see Table 1), and also

Table 3 Intellectual turning point documents

Centrality	Frequency	Cited reference
0.79	25	Rosenberg (1976)
0.77	2	Pavitt (1992)
0.60	29	Dosi et al. (1988)
0.60	24	Piore (1984)
0.51	23	DeBresson (1991)
0.50	8	Koschatzky (1998)
0.47	86	Braczyk and Heidenreich (1998)
0.37	147	Nelson and Winter (1982)
0.32	180	Freeman (1987)
0.32	67	Lundvall (1988)
0.31	31	Freeman (1988)
0.28	398	Lundvall (1992)
0.28	68	Morgan (1997)
0.27	32	Florida (1995)
0.24	176	Edquist (1997)
0.16	82	Carlsson (1991)
0.16	7	Aoki (1988)
0.15	48	Cooke et al. (2000)
0.13	56	Cooke (2004)
0.13	5	Dalum (1992)
0.12	44	Jacobsson and Johnson (2000)
0.12	42	Lundvall (1994)
0.12	9	Nelson (1993)
0.12	3	Granstrand et al. (1992)
0.12	2	Bowonder and Miyake (1991)
0.10	72	Dosi (1982)
0.10	28	Lundvall (1988)

had a relatively high impact factor (2.52 in 2011). These results—Research Policy is not only the most frequently cited journal, but also the scholarly journal in which the most cited work appeared—indicate that this journal is generally acknowledged to be the leading journal in the field of innovation studies, which is in line with the results of a recent innovation-related journals ranking analysis conducted by Thongpapanl (2012).

Intellectual turning point documents

Turning point documents tend to be critical in intellectual transitions from one time slice to another. The nodes with purple rings around the outer rim in the node-and-link visualization provided by CiteSpace tend to be intellectual turning point documents, which act as bridges in the development of a scientific field linking research in different time periods. The thickness of the purple ring is proportional to the degree of centrality: the thicker the ring, the stronger the betweenness centrality. As Fig. 4 shows, some nodes have thicker purple rings, but the sizes of these nodes are small, indicating that intellectual pivotal documents do not necessarily have high citation scores.

The monograph written by Nathan Rosenberg has the highest betweenness centrality (0.79). This book strongly argued that technological development was at the centre of the long-term economic growth processes of industrializing societies, and that a deeper understanding of technological phenomena needed to go beyond the doctrines of neoclassical economics. Other documents with a strong betweenness centrality include Pavitt (1992) article, Dosi et al. (1988) article, Sabel and Piore (1984) book, DeBresson (1991) book, Koschatzky (1998) article and so on. Michael Piore and Charles Sabel's 1984 book argued that in the early 1980s industrial organization involved a second industrial divide when flexible specialization started to outperform mass production which had supplanted craft production in the early nineteenth century. Although written by sociologists, it had a strong impact in a number of other subject areas acting in particular as a bridge between socio-economic and spatial analysis. These intellectual pivotal documents however received <30 citations from IS scholars.

Certainly it is not the case that all intellectual pivotal documents do not receive high citation scores. The studies of Nelson, Freeman and Lundvall, and others are intellectual turning points in IS research, and also received a large number of citations (see Table 3) perhaps as they were positioned within some of the nodes representing developed foci of research.

Overall the analysis of intellectual turning points (Table 3) proves statistically that the founding fathers of the IS concept and others including Braczyk, Edquist, Carlsson, Cooke and Dosi are leading scholars in IS research (for a more detailed discussion, see "Author co-citation network" section dealing with the Author co-citation network). Their impact does not in every case emerge from the analysis of citation scores, indicating the importance of the use of a wider range of indicators as used in this study.

References with citation bursts

A node with red inner rings in the visualization has a significant citation burst, indicating that citations of this document increased rapidly in a given time period. The size of the red rings represents the strength of its burst property. There are 45 nodes with red inner rings in Fig. 4, meaning that there were 45 references with citation bursts in IS research from 1975 to 2012. Table 3 lists the documents published after 2000 with citation bursts. These documents might become new intellectual turning point documents with profound future effects on the development of IS research or may simply reflect the rapid take-up of IS ideas in a cognate field of study (Table 4).

Amongst them, Bergek et al. (2008) article has highest burst strength (15.2763), followed by Hekkert et al. (2007) article (14.3078). These two documents proposed and developed a framework for understanding the functions of IS. The 2008 Markard article, ranked in third place, combined technological IS and a multi-level perspective for a better understand of radical innovation processes and socio-technical transformations. The two frameworks—functions of ISs and a multi-level framework—have been applied to innovation studies of emerging sustainable technologies (Coenen et al. 2012). The 2005 Asheim article and 2005 Boschma article received increased citations after 2010. The former went beyond the traditional classification of knowledge as tacit and codified to distinguish analytical and synthetic knowledge. In 2007 symbolic knowledge was added (Asheim et al. 2007). This work stressed the way an industry-specific knowledge base shapes the role and workings of different types of regional ISs in a globalising economy. The Boschma article strongly argued that geographical proximity is neither necessary nor sufficient for innovation, and that cognitive, organizational, social, and institutional proximity may play a more significant role.

Author co-citation network

Author co-citation analysis focuses on interrelationships among individual authors in a research field. By measuring the co-occurrence frequencies of individual works by different authors in bibliographies, the interconnections between authors can be identified. The more two authors are co-cited, the closer they are intellectually related. CiteSpace is employed here to produce an overall picture of author co-citation networks and to represent visually "invisible college networks" among IS scholars. Figure 4 plots the co-citation network of the 30 most cited authors in each time slice after being simplified by using the minimum spanning tree algorithm. It consists of the 150 most cited contributors and 245 co-citation links.

In Fig. 5, the size of each node corresponds to the total number of citations for the relevant authors. A purple ring around a node indicates betweenness centrality and means that this author tends to be a pivotal scholar whose work links different development stages

Table 4 Post-2000 references with citation bursts

References	Year	Strength	Begin	End
Jacobsson (2004)	2004	5.731	2007	2012
Bathelt (2004)	2004	4.6867	2007	2012
Edquist (2005)	2005	4.7301	2008	2012
Asheim (2005)	2005	7.6441	2009	2012
Gertler (2005)	2005	6.3626	2009	2012
Cooke (2001)	2001	4.6123	2009	2012
Markard and Truffer (2008)	2008	11.9323	2010	2012
Boschma (2005)	2005	6.6884	2010	2012
Todtling (2005)	2005	6.3231	2010	2012
Bergek et al. (2008)	2008	15.2763	2011	2012
Hekkert et al. (2007)	2007	14.3078	2011	2012

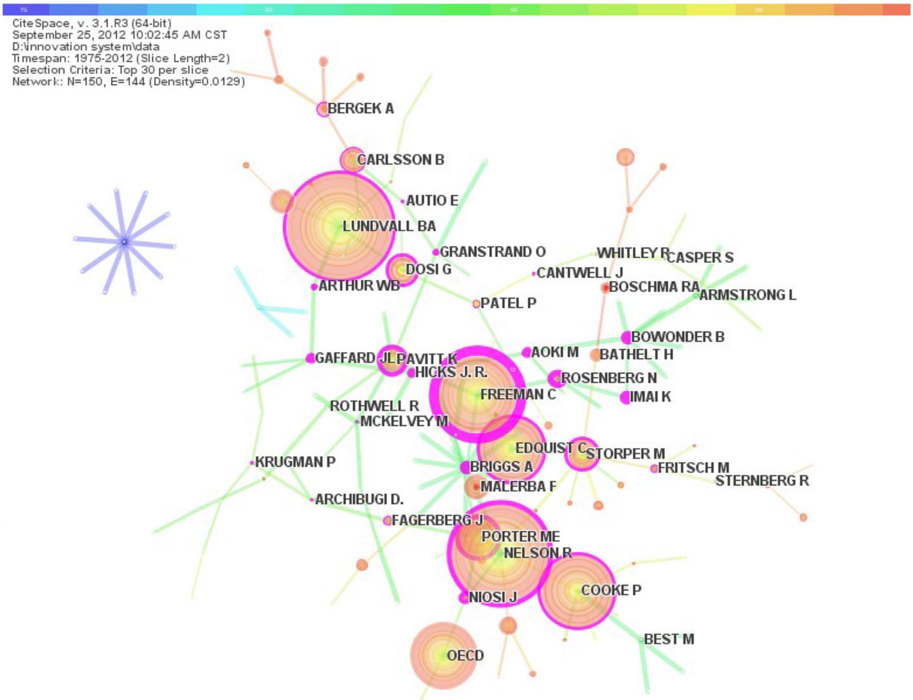

Fig. 5 Author co-citation network with 150 nodes and 245 links [colour figure can be viewed in the online version]

in a scientific field. Note that a highly cited author is not necessarily a scholar with high betweenness centrality. Only when nodes simultaneously have high citation and high betweenness centrality does it imply that they tend to be a leading scholar who has had a fundamental influence on the development and evolution of IS research.

In addition, some nodes in Fig. 5 have red inner rings, meaning that the authors concerned had rapidly increased citations in some time period. Authors whose citations in recent years have grown considerably will probably have a profound impact on the future development of IS research. This consideration means that their work is worthy of more attention, because it may change the development direction of IS research. The most striking cases are Ron A Boschma who developed evolutionary economic geography and contributed to the understanding of the territorial dimension of ISs, and Franco Malerba who worked on sectoral systems of innovation.

Table 5 lists the most cited IS pioneers by co-citation frequency. These highly cited authors include the generally recognized pioneers who first developed the concept of a national IS, such as Bengt-Åke Lundvall, Richard R. Nelson, Christopher Freeman, Giovanni Dosi and Charles Edquist. Among them, Freeman has highest centrality, suggesting that Freeman's work is more groundbreaking in overall IS research. The leading scholars in sub-fields of IS research have high citation scores as well. Examples are Philip Cooke for regional ISs, Bo Carlsson for technological ISs, Michael E. Porter for industrial clusters and Henry Etzkowitz for university–industry–government relations. Other top 20 highly cited scholars include Franco Malerba, Bjørn T. Asheim, Adam B. Jaffe, Peter

Table 5 The profile of the 20 most co-cited pioneers

Author	Frequency	Centrality	Employer institution[a]	Ph.D
Lundvall	599	0.36	Univ Aalborg, Dept Business Studies, Denmark	Economics
Nelson	564	0.58	Columbia Univ, Earth Inst, USA	Economics
Freeman[b]	471	1.12	SPRU,Univ Sussex, UK	Economics
Cooke	408	0.22	Cardiff Univ, Ctr Adv Studies, UK	Geography
OECD	388	0.02		
Edquist	357	0.37	Univ Lund, CIRCLE, Sweden	Economic History
Porter	269	0.51	Harvard Uni, Sch Business, USA	Business Economics
Dosi	224	0.22	LEM, Scuola Super Sant Anna, Italy	Economics
Storper	198	0.35	Dept Geog and Environm, London Sch Econ, UK	Geography
Cohen	193	0.02	Fuqua Sch Business, Duke Univ, USA	Economics
Carlsson	191	0.18	Case Western Reserve Univ, Dept Econ, USA	Economics
Malerba	187	0	Dept Management and Technol,Bocconi Univ, Italy	Economics
Pavitt[c]	177	0.51	SPRU, Univ Sussex, UK	
Etzkowitz	152	0.05	Triple Helix Res Grp, Stanford Univ, USA	Sociology
Asheim	131	0.00	Dept Human Geog, Lund Univ, Sweden	Geography
Jaffe Ab	119	0.02	Fac Arts and Sci,Brandeis Univ, USA	Economics
Maskell	115	0	Dept Ind Econ and Strategy, Copenhagen Sch Business, Denmark	Economics
Morgan	109	0	Sch City and Reg Planning,Cardiff Univ, UK	Geography
Patel	107	0.18	SPRU, UNIV SUSSEX, UK	Economics
Bathelt	105	0.09	Dept Polit Sci, Univ Toronto, Canada	Geography

Source: Web of Knowledge and personal web pages

[a] Validity guaranteed until August 2012, with exceptions of Chris Freeman, and Keith Pavitt

[b] Chris Freeman passed away in 2010, and he received an honorary doctorate from Linköping University in 1977

[c] Keith Pavitt passed away in 2002

Maskell, Kevin Morgan, Parimal Patel and Harald Bathelt. They contributed a lot to different domains within ISs research.

From a geographical perspective, the 20 most cited authors were all from Europe and North America. The presence of six from the USA, eight from the UK and one from Canada shows that this research is overwhelmingly dominated by Anglo-American Scholars. Other highly cited authors came from Demark (2), Sweden (2) and Italy (1). Note that the affiliation of these highly cited scholars changed over the past decade, while the information on their institutional affiliation was collected at the end of August, 2012. Authors with multiple affiliations were allocated to their primary (listed first) affiliation. For example, Richard R. Nelson is a professor at Columbia University, and is also a part-time faculty in the Manchester Institute of Innovation Research, but he was allocated merely to the first one. More interestingly, two highly cited scholars came from the same institution, namely, Chris Freeman and Keith Pavitt from Science and Technology Policy Research Unit (SPRU) of University of Sussex, while other highly-cited scholars such as Richard R. Nelson, Giovanni Dosi and Kevin Morgan once worked there. This result partially reflects the world-leading status of this research centre.

Anglo-American dominance also reflects however the dominant role of the English language and Anglo-American journals. Innovation studies and science and technology research is published in very many countries in foreign languages and in journals that are not listed in the Thomson Reuters's WoS. These other countries include Francophone countries where in the past French rather than English was the language most widely used in social science research.

Most co-cited scholars hold a doctorate or equivalent degree, indicating that doctoral training is an important but not necessary condition for academic leadership. Thirteen highly co-cited scholars hold doctorates in Economics or its sub-disciplines such as Economic History and Business Economics, five in geography and one in sociology. A closer examination of these highly cited authors' educational background shows that Economics and Geography are the most significant disciplinary backgrounds although much of the research is done in interdisciplinary environments.

Conclusions

In this paper we have drawn on bibliometric data relating to 1,364 journal articles listed in the Thomson Reuters's WoS and the co-word analysis and co-citation methods of the CiteSpace bibliometric software to examine the development of ISs research. Key co-word analysis enabled us to explore the evolving content of IS research, co-occurrence analysis permitted the identification of the disciplines and institutions that were the source of major contributions, journal co-citation and author co-citation analysis depicted the networks connecting journals and authors.

The most important disciplines by some way were Business and Management, Regional subject areas (Environmental studies, Geography, Planning and Development and Urban studies), and Economics, reflecting in part the institutional setting for social science research into applied science, technology policy, knowledge and innovation. The content as revealed by keywords was unsurprising although the recent interest in dynamics and evolution is indicative of the emergence of relationships with evolutionary economics.

The top three journals in terms of co-citation frequency were Research Policy, Industrial and Corporate Change and Regional Studies with the latter having a high betweenness centrality indicating its interdisciplinary bridging role with research on regional ISs.

Document co-citation analysis picked out three publications by Lundvall, Nelson and Freeman, identified the importance of joint publication and of monographs or collections. The publications analysis also permitted the identification of turning points at which new directions emerged and of burst frequencies indicating the speed with which new ideas were taken up, and we noted that some of the turning point publications with high betweenness centrality have relatively low citation scores, indicating the importance of using multiple indicators of impact.

Author co-citation analysis finally allowed the identification of invisible colleges, the figures that connected one sub-field and one phase of the IS research programme with another. Not surprisingly it picked out the scholars who first developed the national IS concept (Lundvall, Nelson, Freeman, Dosi and Edquist) as well as the scholars who dominated different sub-fields (Cooke for regional ISs, Carlsson for technological ISs, Porter for industrial clusters and Henry Etzkowitz for university–industry–government relations).

The analysis also highlighted the dominance of Anglo-American journals and scholars in part reflecting the choice of data source (WoS) and document type (journal articles). This predominance also reflects the economic weight and scientific and technological advancement of Anglo-America and the influence of the English language. It also raises questions about the sociology and history of social science, about access to the institutional and social networks that underpin shared academic research programmes and academic publishing, about the drivers of paradigm shifts (Kuhn 1962) and about the possibilities for the co-existence of the principles of tenacity and of a prolific generation of new theories (Feyerabend 1975).

The study finally is restricted by virtue of the choice of publications. The chosen research deals with the production and diffusion of new applied scientific knowledge and with direct impacts on industrial, regional and national economic development. It connects weakly with research into endogenous growth, it has little to say about technology transfer, about emerging as opposed to developed economies and (with the exception of the work of Freeman) about the institutions that support or hinder innovation and economic progress.

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