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‘Science of Science’: the thematic landscape and historical roots

S. N. Archana*, P. K. Padmakumar and Shajitha C.

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Abstract

Introduction. This study analyses the status of the global Science of Science (SOS) research to map its spatial and temporal landscape, prominent researchers and their approaches to the subject. It further traces the historical roots of SOS to identify the seminal works and authors who laid the foundation of this research area.

Method. We conducted bibliometric and reference publication year spectroscopy (RPYS) analyses on data extracted from Scopus and Web of Science (WoS) databases, to examine the thematic landscape and the historical roots respectively.

Analysis. Bibliometrix R package was used to analyse and map the productivity and thematic landscapes. CReXplorer was employed to perform RPYS to identify the seminal authors and works that framed the research area of SOS.

Results. Scientometrics and its variants form the central theme of present day SOS and the area will be led forward by Artificial Intelligence (AI) and innovation studies. The historical roots of SOS lies in the works of J.D.Bernal, de Solla Price, Merton and Garfield.

Conclusion. Mapping SOS from inception to its current stature, this study reveals its weak theoretical framework, risking its reduction to mere quantitative science study. We suggest to undertake interdisciplinary collaborative investigations to address this.

Introduction

Originated in Poland in the early 1900s (Kokowski, 2015), Science of Science (SOS) is an interdisciplinary research area that deals with the philosophy, psychology, sociology, history, economics and operations research of science. It covers the study of science policy; planning, conduct and communication of research as well as people power resources of science (Ossowska & Ossowski, 1964; Bernal & Mackay, 1966; Goldsmith, 1967). Maria Ossowska and Stanisław Ossowski coined the term 'Science of Science' ('nauka o nauce' [Polish]) in 1935 (Kokowski, 2015) and the first published literature on SOS appeared in 1936 in the Polish International review, *Organon* Vol.1, No.1 (later republished in *Minerva* 3 [1], 1964); in which Ossowska and Ossowski envisioned a new subject field that comprises the investigations of the problems related to the 'Philosophy of Science', 'Psychology of Science' and the 'Sociology of Science' (The science of science, 1936; Ossowska & Ossowski, 1964).

The Irish scientist J. D. Bernal's thoughts and works are widely credited for the development of SOS as a separate discipline (Goldsmith, 1967; Goldsmith & Mackay, 1964; Lamirel et al., 2020; Zhao et al., 2020). In the treatise, the Social function of science, he discussed the history, sociology and economics of science and predicted the future reorganisation of research and scientific communication (Bernal, 1939). de Solla Price's demonstration of the 'Big Science' (characterised by the exponential growth of scientific literature) by statistical methods, initiated the application of quantitative techniques in studying the phenomena behind science (Price, 1963). The citation index, which analysed and quantified the influence of a scientific paper in a research field (Garfield, 1955) was another breakthrough in the area of SOS. Citation data helped to unveil the sociological evaluation and historical developments of a subject (Garfield, 1963). Several quantitative measures and techniques designed to study the history and process of science, the impact of research and researchers, economics of science, strengthened the field of SOS over the years (Aria & Cuccurullo, 2017; Cobo et al., 2011a; Garfield et al., 2003; Garfield, 2009; Hirsch, 2005; Thor et al., 2016a; Van & Waltman, 2010). Some of the recent papers claim that SOS integrates findings from Scientometrics, innovation studies, sociology of sciences, and employs quantitative techniques to understand and model the process of science (Fortunato et al., 2018; Zeng et al., 2017). The availability of large-scale bibliographical and citation datasets along with the development of several software tools to analyse and visualize these datasets changed the pace of growth of SOS research.

Analysing the studies of Ossowska and Ossowski, de Solla Price and Bernal and MacKay, SOS can be understood as a transdisciplinary research area with many facets, and that involves quantitative as well as qualitative analysis to understand the science behind the scientific enterprise. de Solla Price and Garfield developed the quantitative techniques in SOS which led to the genesis and development of Scientometrics (now a well-developed research area). But some of the recent studies consider SOS as an emerging field that relies upon quantitative methods to analyse the large datasets available from multiple data sources (Clauset et al., 2017; Fortunato et al., 2018; Zeng et al., 2017). Whereas some other studies consider SOS as a research field that employs a mixed methodology (involving qualitative and quantitative techniques) to get a comprehensive understanding of the science behind science (Kawalec, 2019; Lamirel et al., 2020; Zhao et al., 2020).

To understand this, it is pertinent to analyse the research landscape of SOS since its inception. Hence the present study analyses the status of the global SOS research to map its spatial and temporal landscape, prominent researchers and their approaches to the subject and the overall development of the area. The study further traces the historical roots of SOS to identify the seminal works and authors on 'whose shoulders this subject area stands'. In addition, this study reflects on the epistemological transformation of the Science of Science—from sociological and philosophical interpretations of scientific activity to contemporary algorithmic and data-driven approaches

Related studies

The history of SOS in Poland from 1910s-1993 was sketched by Kokowski and discussed the contribution of eminent Polish scholars and institutions towards the genesis and development of SOS. SOS lost its Polish identity and ideology by 1990s due to various geo-political factors (Kokowski, 2015). J. D. Bernal's thoughts and works had a profound influence on SOS research in China which in turn deeply impacted the scientific development of the country particularly in Science Technology and Innovation (STI) planning, policies and processes. Chinese SOS research matured gradually over the years through the constant interactions of the field with related disciplines, and now shifted towards applied research using mixed methodologies (quantitative and qualitative) specifically about the economic and strategic functions of science (Lamirel et al., 2020; Zhao et al., 2020).

SOS helps to understand the origin and source of new knowledge and can inform how scientific research should be oriented to foster innovation of new technologies to solve global challenges (Kim et al., 2024). Several scholars reviewed the developments and trends in the field of SOS systematically (Fortunato et al., 2018; Hou et al., 2019; Liu et al., 2023; Zeng et al., 2017) and bibliometrically (Garfield, 2009; Kawalec, 2019; Lamirel et al., 2020).

The subject area of SOS experienced a critical change during 1980s and got shifted from qualitative studies focused on history and philosophy of science to quantitative studies powered by computational techniques (Kawalec, 2019). The availability of large-scale datasets, new measurement approaches and the expanding range of empirical methods assisted by computational toolkits further accelerated the growth and substantial development of SOS (Hou et al., 2019, 2025; Liu et al., 2023). This trans-disciplinary field is currently driven by the collaboration of natural, computational and social scientists who made use of these datasets for undertaking quantitative studies to understand the factors behind successful science (Fortunato et al., 2018). Application of complex network analysis on scholarly data helped to reveal the conceptual and community structures, evolution of the system and prediction of future research trends of a subject area (Zeng et al., 2017). The systematic review of recent research papers in SOS revealed that most of them were focussed on publication output and the future research in SOS would be led by machine learning and AI. The integration of AI into quantitative science studies will introduce a paradigm shift in SOS, opening new avenues for accurate predictions and a deeper understanding of the dynamics of the process of science (Hou et al., 2025).

The increased focus on evaluative metrics-based studies led to the neglect of some basic old questions of SOS like the social mechanism of science and the societal impact of science. These reviews also pointed out some limitations of the metrics used in current quantitative studies and the need for a systematic validation of the existing algorithms for ranking of authors, papers, etc. Widely used metrics are biased and the authors argued for a new set of metrics in combination with theories and models; that are designed with a proper understanding of the processes and mechanism of science for a holistic exploration of the scientific enterprise (Fortunato et al., 2018; Zeng et al., 2017, Wu et al., 2022).

The availability of large-scale datasets, different bibliometric indicators, and software tools for bibliometric analysis and data visualisation made it easier to demonstrate the spatial and temporal growth, evolution, networks and trends of research in different subject areas. These tools facilitate to analyse the performance of authors, journals, institutions as well as articles and help to map the networks of citations, authors and keywords (Cobo, et al. 2011a; Donthu et al., 2021; Pritchard, 1969). Over the past two decades bibliometric studies gained momentum across disciplines outside library and information science such as environmental sciences, management studies, life sciences, multidisciplinary science and medicine (González-Alcaide, 2021). Bibliometrix (<http://www.bibliometrix.org>) is an opensource software tool written in R-language and developed by Massimo Aria and Corrado Cuccurullo in 2017 to conduct bibliometric analysis and

to visualise science mapping. The tool facilitates collection and conversion of datasets from different data sources like Web of Science (WoS), Scopus, Dimensions, PubMed, Lens.org and Cochrane Library. It also facilitates the merging of datasets from multiple sources as well as the removal of duplicate records from the merged datasets. The 'Biblioshiny' package of this R tool is used for the mapping and visualisation of the bibliometric analyses (Aria & Cuccurullo, 2017). This tool has been used widely by scholars across different disciplines for evaluating the performance of published research, science mapping and visualisation as well as for literature reviewing (Aria et al., 2020, 2022; Belfiore et al., 2022; Di Cosmo et al., 2021; Guleria & Kaur, 2021; Rodríguez et al., 2022; Rodríguez-Soler et al., 2020; Scarano et al., 2023).

The citation data and cited references of papers were used by eminent scholars to study bibliographic coupling, create topological maps and algorithmic historiographs of knowledge domains (Bornmann et al., 2010; Bornmann & Marx, 2013; Kessler, 1963; Garfield, 2004; Garfield et al., 1964, 2003; Laband & Majumdar, 2012; Leydesdorff, 2010). Eugene Garfield visualised the historiography of 'scientometrics' using HistCite software to demonstrate how this research area evolved from 'science of science' and attained growth after the World War II. (Garfield, 2009).

Cited reference analysis is a technique that involves the analysis of reference lists of publications in a specific research field to identify the influential authors and papers who impacted the research in that field (Bornmann & Marx, 2013). Based on this, another quantitative technique, the 'Reference Publication Year Spectroscopy' (RPYS) got introduced in 2014 to identify the historical roots of a research area (Marx et al., 2014). The publication year of the cited references formed the basic unit in this method and based on frequency of citations received by a particular year, the historical roots and seminal works are identified. RPYS was applied by scholars to understand the 'philosophy of science', the origin and historical roots of 'Higgs boson' research, historiography of 'information metrics', detect seminal works in 'global positioning system' and to unveil the myth behind 'Darwin finches' (Barth et al., 2014; Comins & Hussey, 2015; ; Leydesdorff et al., 2014; Marx & Bornmann, 2014; Wray & Bornmann, 2014). Leydesdorff developed a program- RPYS.exe (<http://www.leydesdorff.net/software/rpys/>) to generate RPYS of any dataset downloaded from WoS and later enhanced its features to aggregate the cited reference across variants and misspellings to identify seminal works in a specific research field (Bornmann et al., 2016; Leydesdorff et al., 2014). Further a user interface for this program, the CitedReferencesExplorer (CRExplorer) (www.crexplorer.net) was introduced that facilitated the analysis of cited references (CRs) and presentation of results in a graphical format (Thor et al., 2016a). Later the program was improved by introducing new indicators and by facilitating disambiguation of CRs as well as the analysis of Scopus datasets (Thor et al., 2016b, 2018, 2021).

Research questions

The study addresses four research questions.

- RQ1. How did SOS as a research area develop over the years?
- RQ2. What is the conceptual/thematic structure of SOS?
- RQ3. Who are the current drivers & influencers of SOS?
- RQ4. Who laid the foundation of SOS and which are the seminal works that shaped SOS?

Materials and methods

Science as a subject is being studied under various domains of knowledge such as 'philosophy of science', 'history of science', 'sociology of science', 'psychology of science', 'economics of science', 'quantitative science' and 'scientometrics'. According to a recent study (Krauss, 2024), only 3% of the publications dealing with the study of Science under these subfields use the term 'science of science'. Our review revealed that some of the authors used this term synonymous with

scientometrics, whereas Krauss (2024) pointed out that only 0.6% of ‘scientometric’ papers used the term ‘science of science’. Moreover, there is no evidence in literature to consider Science of Science as a collective name for all those studies that involve ‘science’ as a subject. Since the purpose of this study is to identify the real landscape of SOS as a subject field, we decided to extract only those publications that identified themselves as ‘science of science’.

The materials for this study were collected from two bibliographic databases- WoS and Scopus with the query, ["science of science" OR "SCISCI"] in the search field, *Article Title*, *Abstract*, *Keywords* of Scopus and *Topic* of WoS. The results were then filtered for English language publications and document types limited to articles, review articles, editorials, conference proceedings, datapapers, books and book chapters; further limiting the year of publication to 2023. Finally 286 (WoS) and 503 (Scopus) documents were retrieved.

To combine these two datasets and to eliminate the duplicate items, RStudio package was used and got 521 unique documents. ‘Biblioshiny’ package of the R tool ‘Bibliometrix’ was used for analysing this data to map the thematic structure, influential authors and publications, research trends and networks. For tracing the historical roots of SOS (RQ4), RPYS technique was applied and used the tool ‘CRExplorer’.

Results

Productivity landscape

Productivity plots depict the growth of a research area and the performance of authors, sources, countries, etc. The annual productivity graph of ‘Science of Science’ (Figure 1) reveals that the first indexed publication in the area came out in 1939 and the subject field took a slow pace to establish itself in the knowledge domain. It gained a small growth in the 1960s and 1970s and the growth rate improved during the next two and a half decades. After 2005, the subject field attained a dynamic growth with an exponential hike in the number of publications from 2011. Over these 85 years, from 1939–2023 (only 49 productive years) a total of 1048 authors contributed 521 papers in the field of SOS resulting in an average annual growth rate of 4.93%. During the first 30 years, only seven papers were published and it took 17 years for the second publication to come out. From 1939–1998 (60 years) only 24 years witnessed the publishing of a paper in SOS and a total of 48 publications came out during this period. After 1998, at least one publication in SOS came out in every year and 56 papers were produced during 1999–2011. The number of papers published per year crossed 10 in 2011 and from there onwards the subject field started growing significantly.

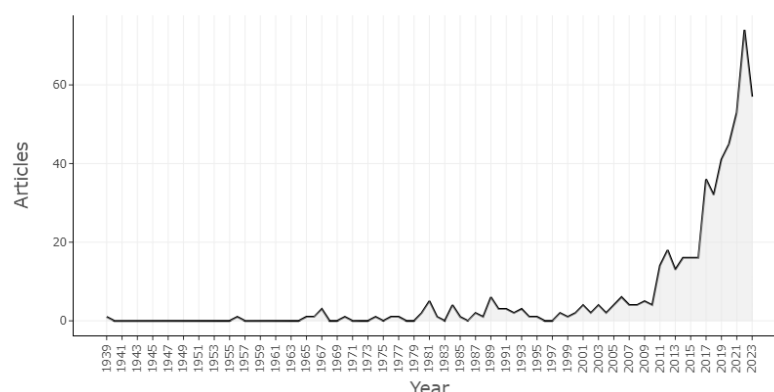


Figure 1. Annual productivity of SOS research

From among the 1048 authors of 521 papers, 143 authors contributed 177 single-authored documents. The remaining 344 papers were published by multiple authors with a ratio of 2.91 co-authors per document and an international co-authorship of 18.04%. The most productive

authors are plotted in Figure 2a and Figure 2b. With the exception of Petersen, who entered the field in 2011, the leading contributors began publishing after 2016, suggesting a recent expansion of research in the Science of Science. The analysis of the country wise productivity (corresponding author's country) shows that USA contributed around 29% of papers (131 documents) in SOS followed by China (10%). Australia leads in international collaboration with 62% of its total publications emerging from international co-authorship, followed by China (37%). Indian papers lacked an international collaboration (Figure 3).

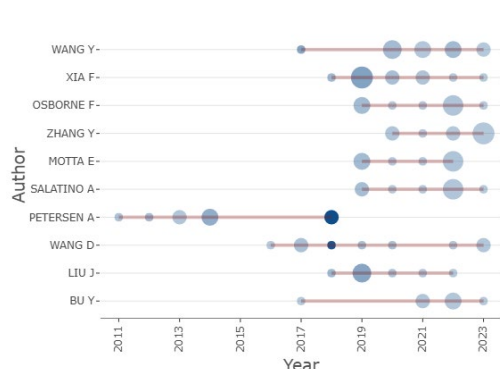


Figure 2a. Performance of top 10 authors over time

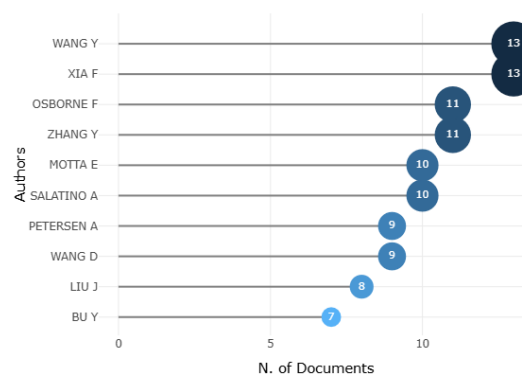


Figure 2b. Publication counts of top 10 authors

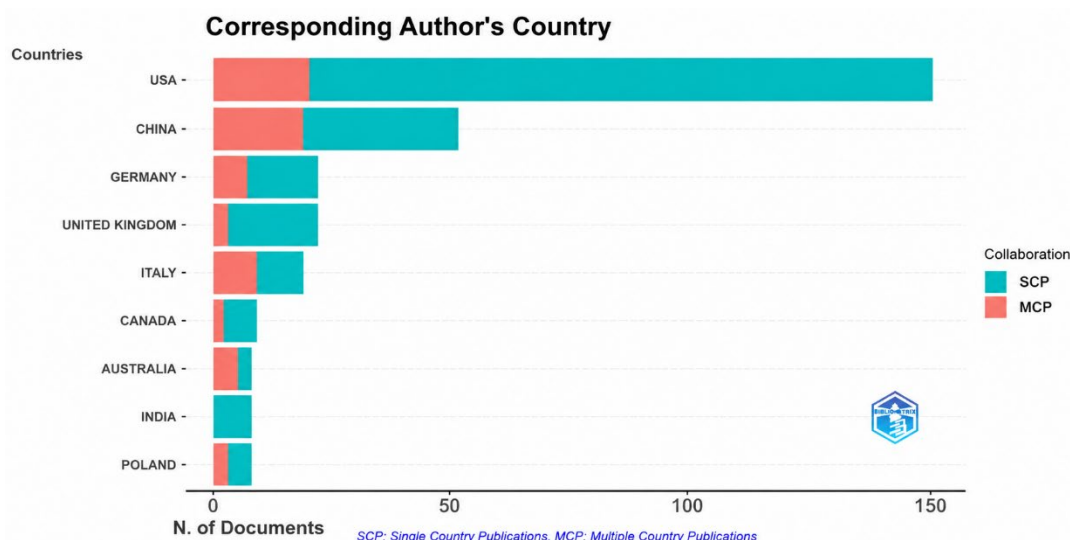


Figure 3. Performance of corresponding author's country

Mapping of the most prominent sources in this subject area (Figure 4) reveals that more than 20% (111 papers) of the publications are centred in three journals of which two are core journals reporting scientometric research and the third one is a multidisciplinary journal, Proceedings of the National Academy of Sciences of the United States of America (PNAS).

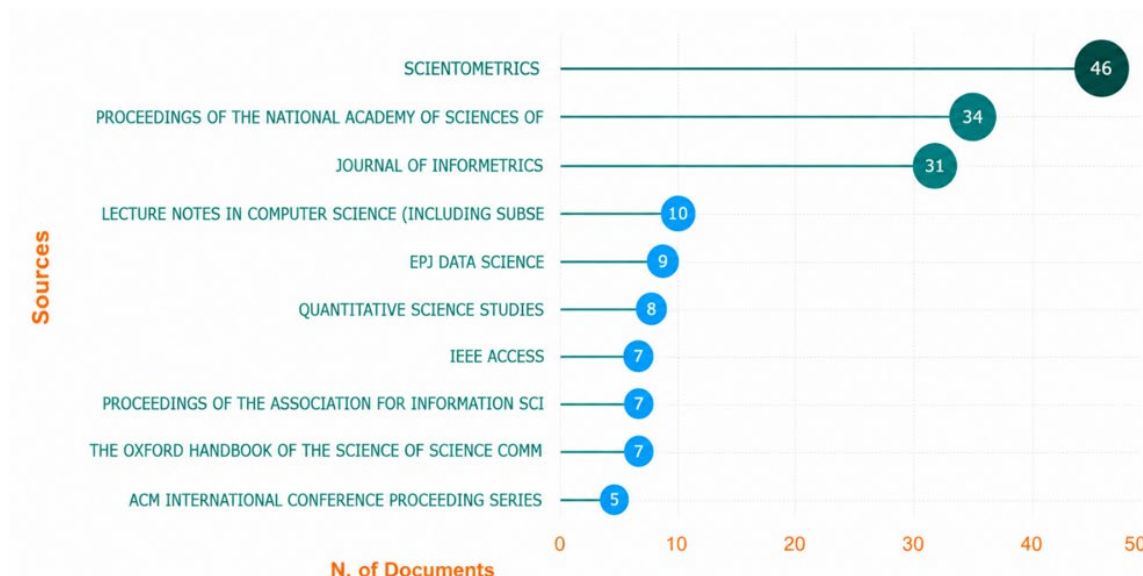


Figure 4. Prominent sources publishing SOS research

The three-field plot for productivity overview presented in Figure 5 visualises the country of affiliation of the top ten productive authors and the sources in which their publications appeared. It can be seen that the majority of authors belong to China and USA; where China ranks first in position. It is also evident that these authors preferred to publish in the top seven productive journals as depicted in Figure 5.

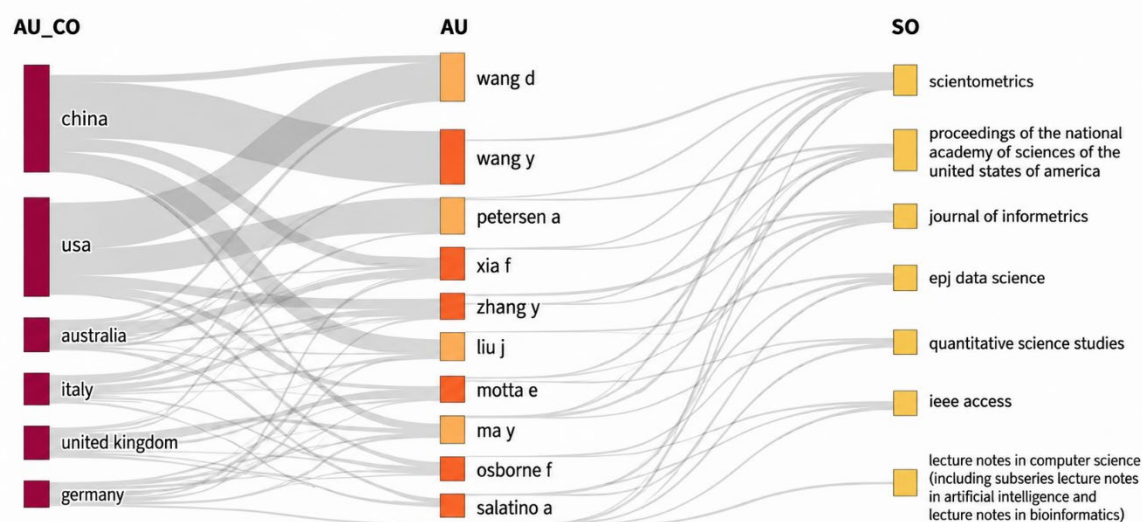


Figure 5. Productivity overview of SOS research

Thematic landscape

For the conceptual or thematic analysis of a research field, keywords such as author's keywords, journal's keywords or keywords extracted by the indexing databases (keywords Plus) are used. The frequency of co-occurrences of these keywords and their similarities are calculated using standard measures like Jaccard index, Salton's Cosine, proximity index and equivalence index, and finally these keywords are clustered using different clustering algorithms to map the thematic landscape (Cobo et al., 2011b). The present study employed Leiden method for clustering the themes, as the

Leiden algorithm has been proved to yield clusters of themes that are supposed to be connected and avoids the clustering of badly connected or disconnected themes (Traag, Waltman and Van Eck 2019). The result is plotted in Figure 6, and it represents the clusters of themes horizontally (along x-axis) and vertically (along y-axis) based on their centrality and density respectively. The clustering based on the increasing level of centrality and density leads to the formation of four quadrants that represent the motor themes (q1), basic themes (q2), emerging/disappearing themes (q3) and niche themes (q4). Among these, q1 and q2 are considered as central themes and the other two as peripheral themes (Callon, Courtial and Laville, 1991).

It is evident from the graph that the field of SOS is being led forward by the ‘motor’ themes (matured, central and driving themes), scientometrics and its related subject fields like bibliometrics and informetrics. ‘Science of Science’ remains as the basic theme and it can be seen that the cluster is moving up towards the top right quadrant (motor theme) which is an indication of the maturity of the field in the coming years. ‘Sociology of Science’ can be viewed as a declining theme which indicates that present scholars in SOS are not interested in studying this area. Themes like science communication is moving towards an isolation. This can be due to the non-usage of such keywords by present day authors. Another major cluster visible is that of scholarly data, innovation and artificial intelligence (AI). This theme is placed centrally and can be considered as a developed theme and is likely to move rightwards in the future owing to the current trends in research in big data and AI. It can be inferred that along with scientometrics, AI and bigdata will drive forward the research in SOS. The major sub-themes associated with each groups and their connections among and between these clusters is visualised in Figure 7.

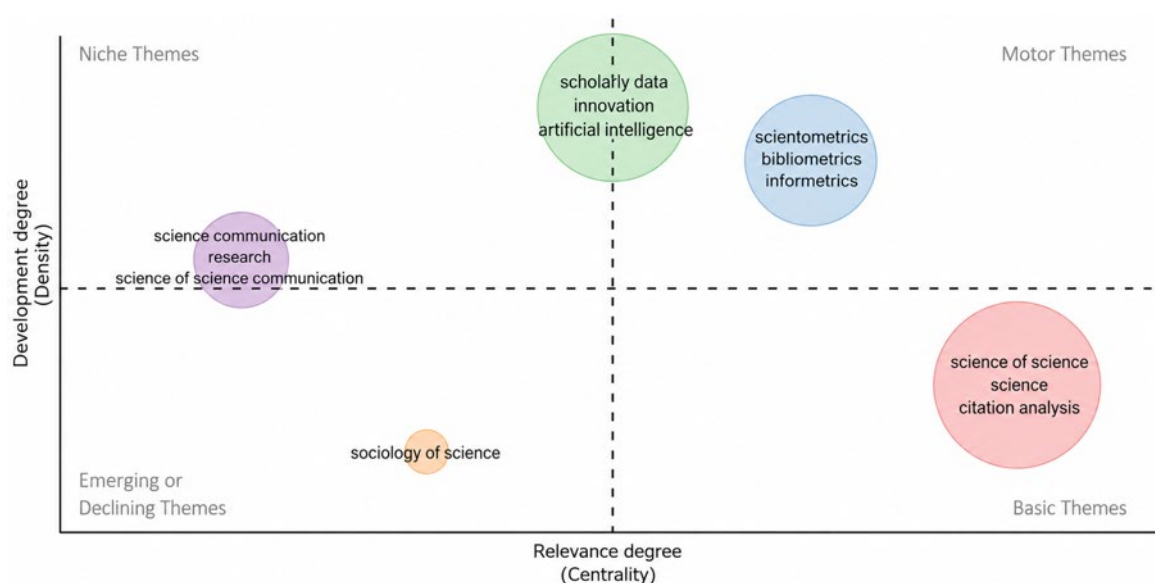


Figure 6. Thematic landscape of SOS research

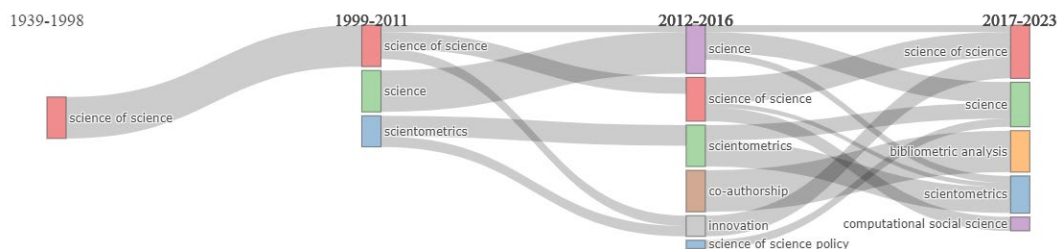


Figure 8. Thematic evolution of SOS over four time slices

Figures 9a-d give a detailed presentation of the various themes that led the research in SOS over the four time slices. The graphs show that 'Science of Science' was the central theme during the first time slice. Over the years, various subthemes flourished, among which some of the themes drive forward the subject field and some declined or contributed little to the growth of SOS. During the second period, scientometrics and its variants, history and sociology of science and studies about scientists led the field. 'Histcite', a tool used to analyse the historical development of a subject, was one of the motor themes during this period that indicated the contribution of Eugene Garfield to this field. The studies related to World War II became niche or isolated themes. The third time slice reveals that science of science policy, team science and collaborations became the basic and motor themes along with citation analysis and impact measures. It is notable that except the 'policy' studies, all other themes are related to the quantitative analysis of published research and the theme 'sociology of science' got isolated. The fourth period that corresponds to the current practices in SOS research is led by 'scholarly data', AI and 'innovation', whereas 'machine learning', 'network science' and 'science communications' form the basic themes. 'Computational Social science' is seen as an emerging theme. It is evident that scientometrics and its different variants like bibliometrics and informetrics form the central theme of present day SOS research or in other words, the SOS research is now mainly focused on the quantitative analysis of published scientific research (big data from bibliographic and full-text databases) augmented with the application of machine learning and AI. The keyword cloud map (Figure 10) substantiates this finding.

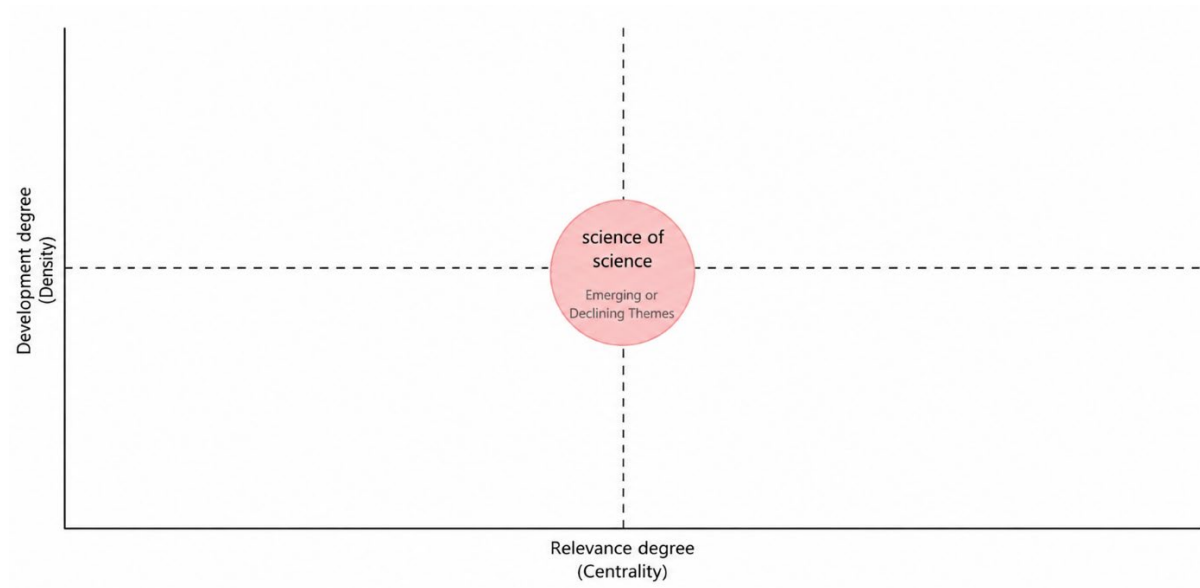


Figure 9a. Thematic structure during 1939-1998

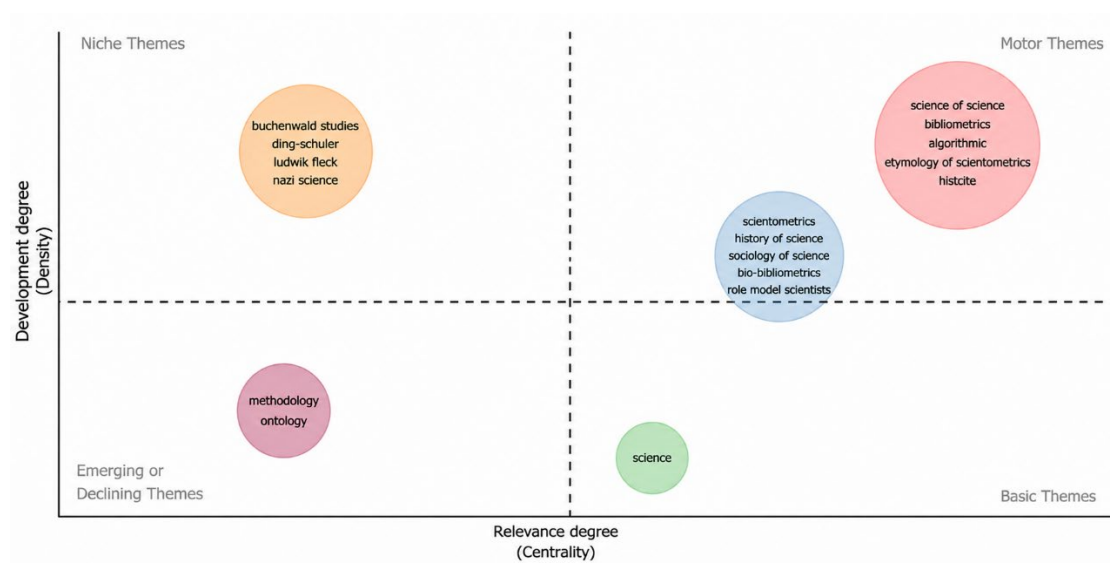


Figure 9b. Thematic structure during 1999-2011

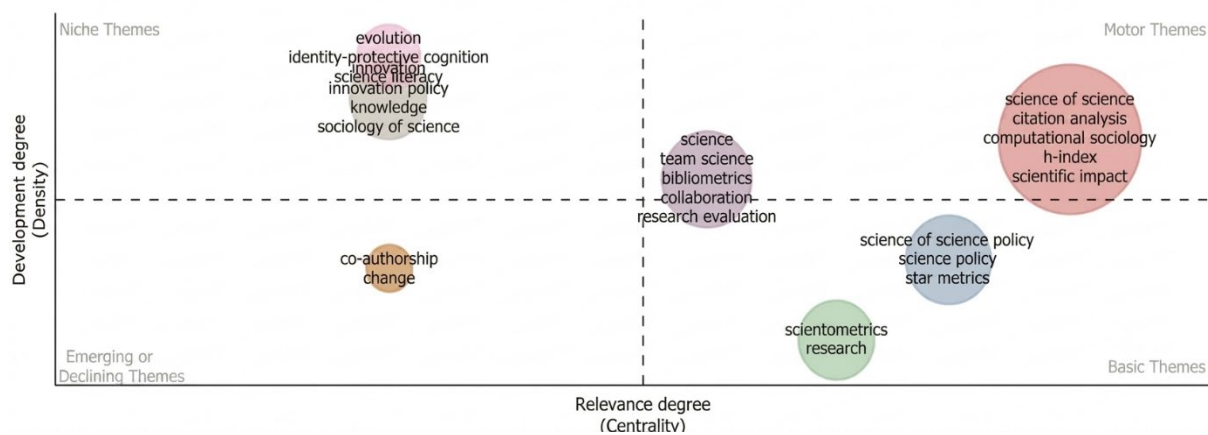


Figure 9c. Thematic structure during 2012-2016

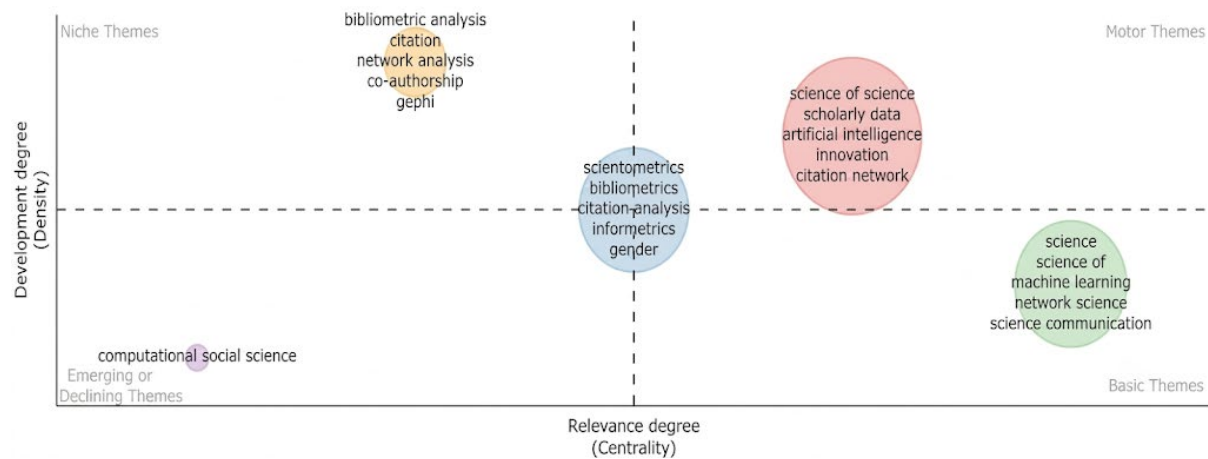


Figure 9d. Thematic structure during 2017-2023

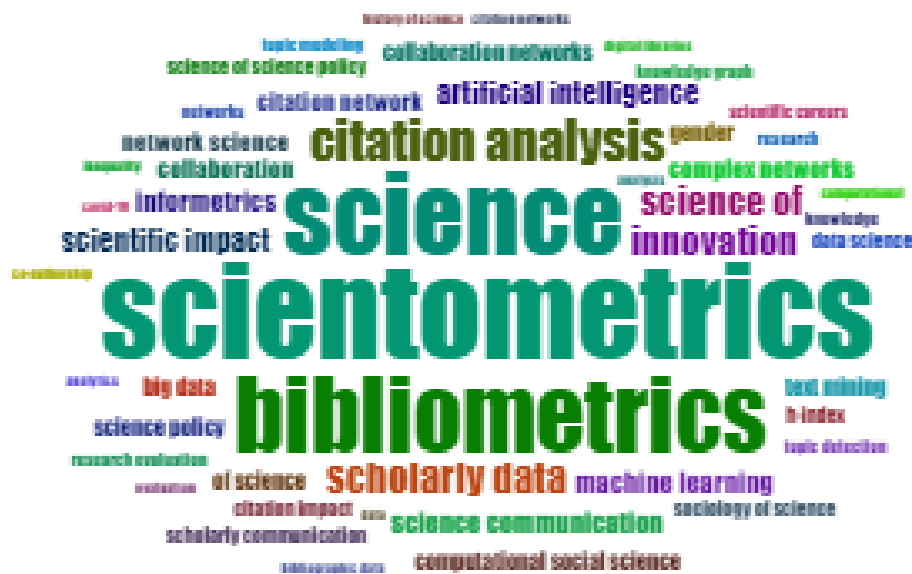


Figure 10. Keyword cloud map of SOS

Analysis of the trend topics helps to predict the forward journey of a research field. Figure 11 predicts the future directions of research in SOS and can be understood that along with scientometrics; machine learning, complex network analysis and AI will take a lead role in the advancement of research in SOS in the coming years.

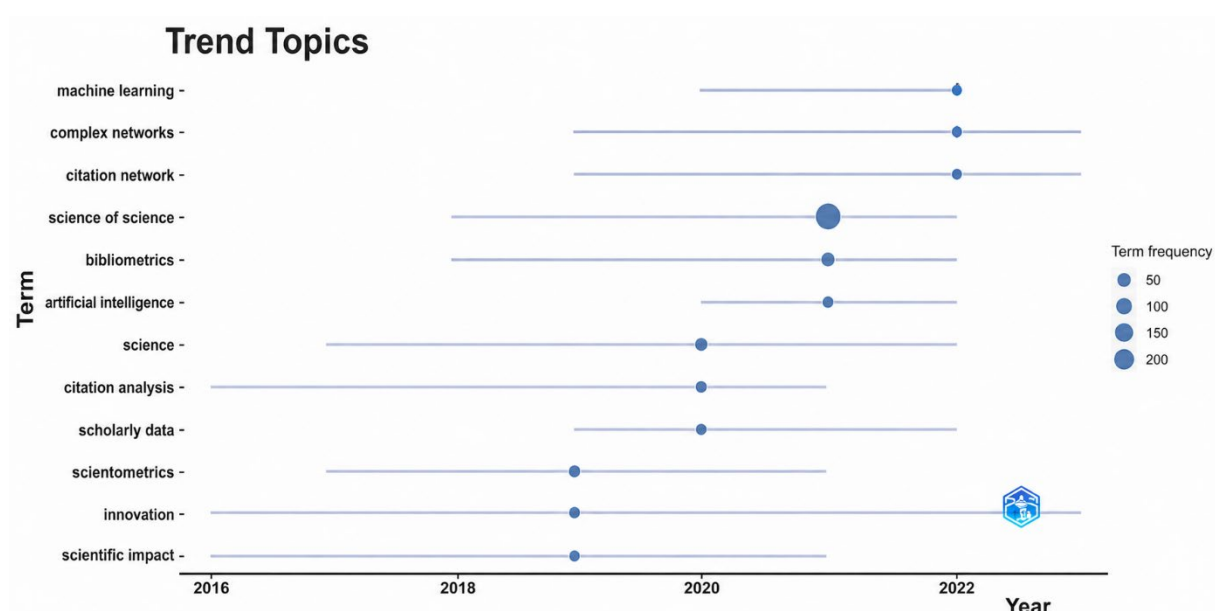


Figure 11. Research trends in SOS

Drivers & influencers of SOS research

In this section, we tried to identify the impactful authors, influential papers and sources which can be credited for the advancement of this research area. The citations received and references made by the publications under study were analysed for this purpose.

Drivers / Impactful authors

Different author level metrics such as h-index, g-index, m-index and total citation count were analysed to identify the current drivers of SOS and are depicted in Figures 12a to 12e. Based on the h-index, Petersen and Xia emerge as the most influential contributors within the dataset, each recording a score of 9 (Figure 12a). When productivity is normalised by career length using the m-index (Hirsch, 2005), Xia ranks highest (1.5), followed by Shao and Yuan (1.25), indicating a relatively rapid accumulation of influence (Figure 12c).

The g-index, which gives greater weight to highly cited publications (Egghe, 2006), further highlights Xia and Wang as the most impactful authors with a score of 13 (Figure 12b). Citation-based indicators also reveal differences between local influence within the SOS dataset and broader disciplinary impact. While Sinatra (67 citations) and Petersen (65 citations) receive the highest local citations (Figure 12d), global citation counts (Figure 12e) place Petersen first (993 citations), followed by Kahan (907) and Evans (867). Interestingly, Kahan receives relatively few citations within the local dataset, suggesting that some influential contributors to SOS are more widely cited across related fields than within the core literature of the domain itself.

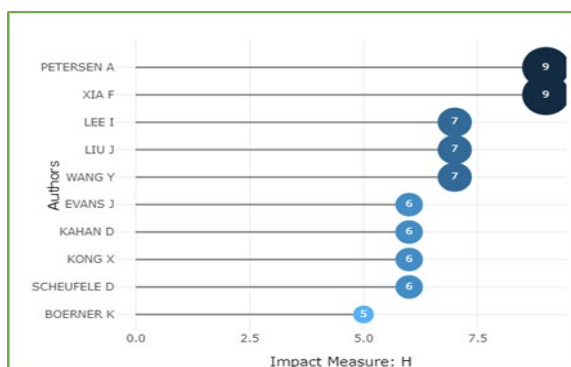


Figure 12a. Author impact: H-index

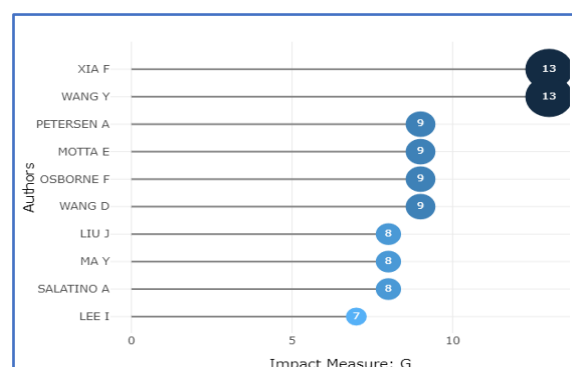


Figure 12b. Author impact: G-index

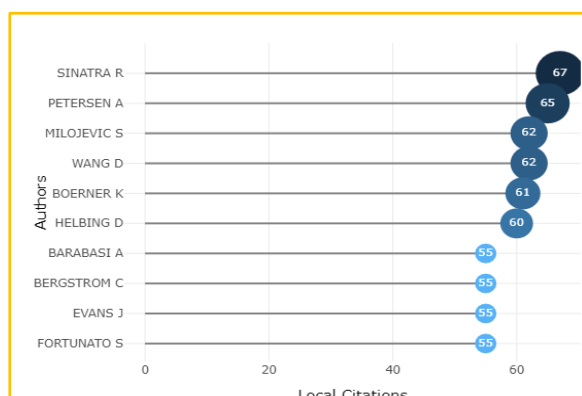


Figure 12c. Author impact: M-index

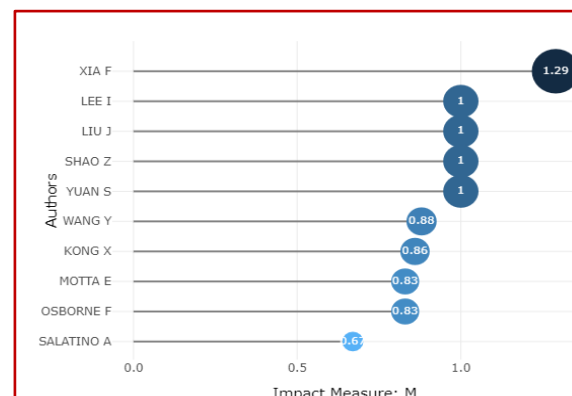


Figure 12d. Author impact: Local Citations

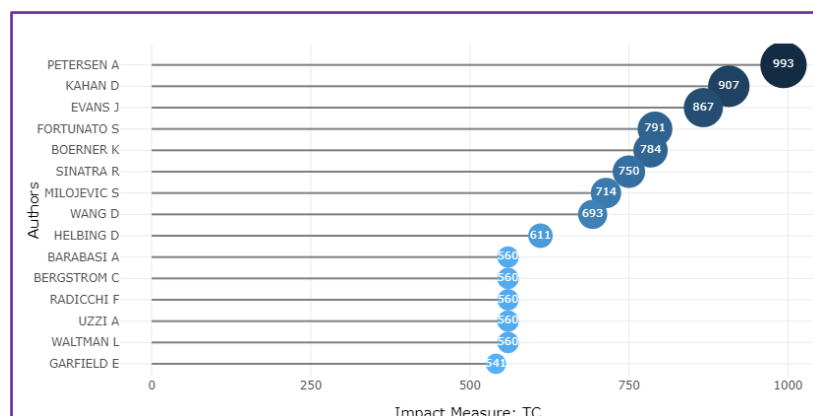


Figure 12e. Author impact: Global Citations

Influential publications

To identify the influential publications, we analysed the cited references of the documents in the current dataset. Figure 13 represents the most influential publications that drive this research field forward.

The review article, *Science of Science* by Fortunato et al. (2018), emerges as the most referenced publication, receiving 55 local citations. Other highly cited works include Uzzi et al. (2013) on Atypical combinations and scientific impact, Hirsch (2005) introducing the h-index, Sinatra et al. (2016) proposing the Q-factor for measuring individual scientific impact, and Wuchty, Jones and Uzzi (2007) on the growing dominance of team science. A common feature of these influential works is their emphasis on quantitative approaches to studying science, particularly through citation analysis, author-level metrics, and large-scale bibliometric datasets. This pattern indicates a shift in the intellectual foundations of contemporary SOS research, rooted in quantitative scientometrics and data-driven analyses of scholarly communication.

Another major observation is that the highly influential paper turned out to be a top cited paper among the documents in the current dataset. Apart from this, no other document from the dataset could find a place in the Figure. Analysis of the top cited documents in the current dataset revealed that eight received a local citation count of 7 or below and the second most cited document received 11 local citations.

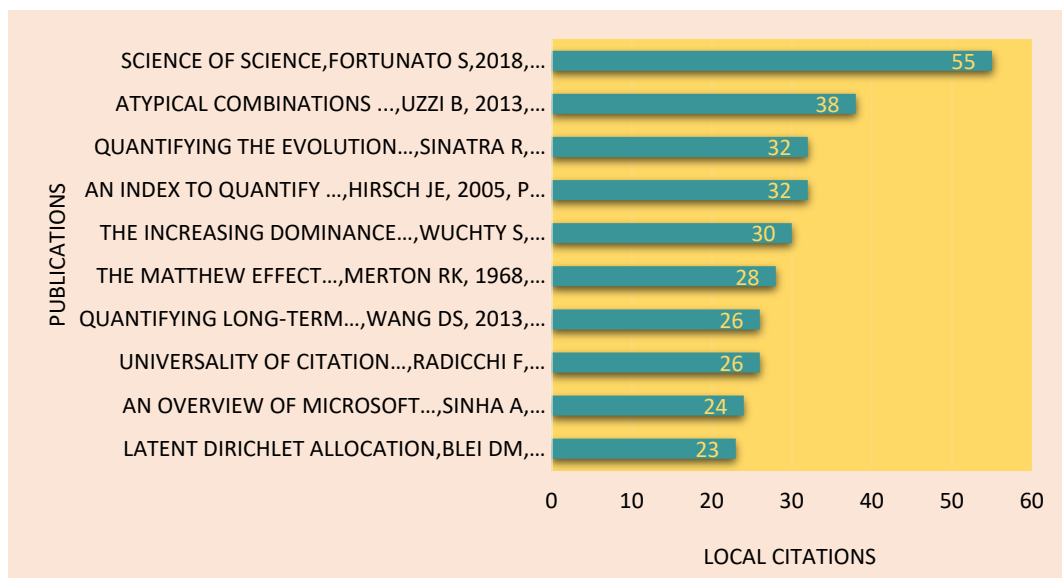


Figure 13. Influential publications of SOS

Figure 14 represents the co-citation network of the papers in the current dataset. Distinct clusters are visible for the influential papers mentioned above, representing studies related to author impact measures (green), citation analysis (blue), sociology of science (purple), and science of science (red). The network diagram gives a clear picture of other influential papers in each of these areas. Strong interlinking among the clusters are also visible in the Figure.

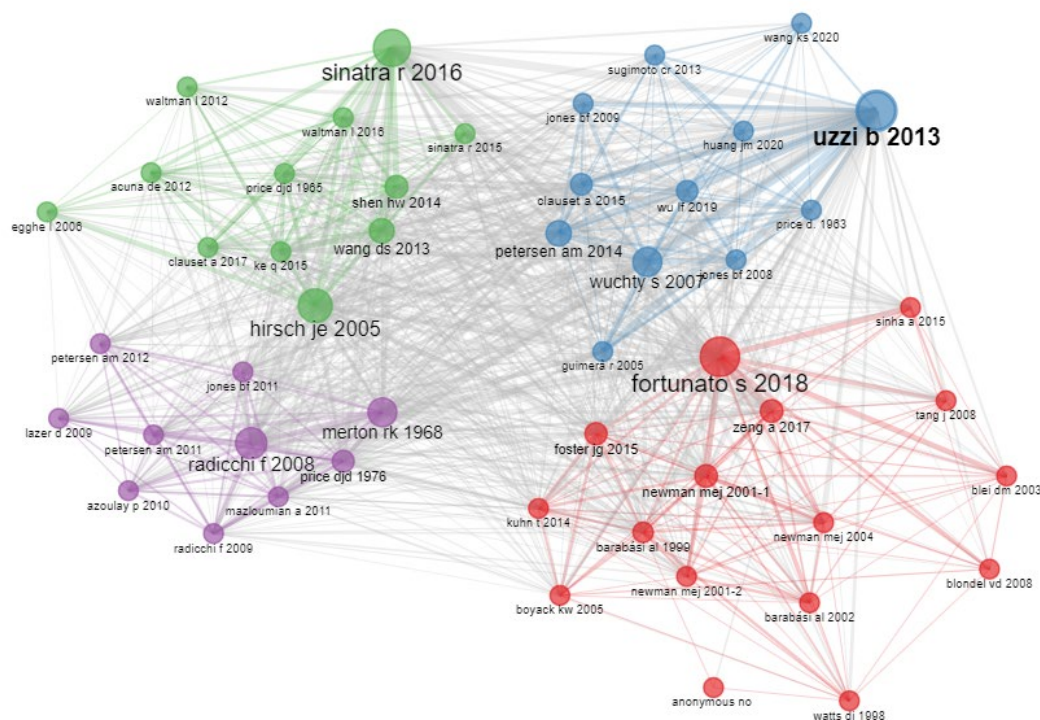


Figure 14. Co-citation network of influential papers

Influential Sources

Influential sources refer to the journals in which the cited references were published. With respect to the influential sources of the field of SOS, Scientometrics is in the first position with 836 citations in the local dataset followed by Science with 720 citations (Figure 15).

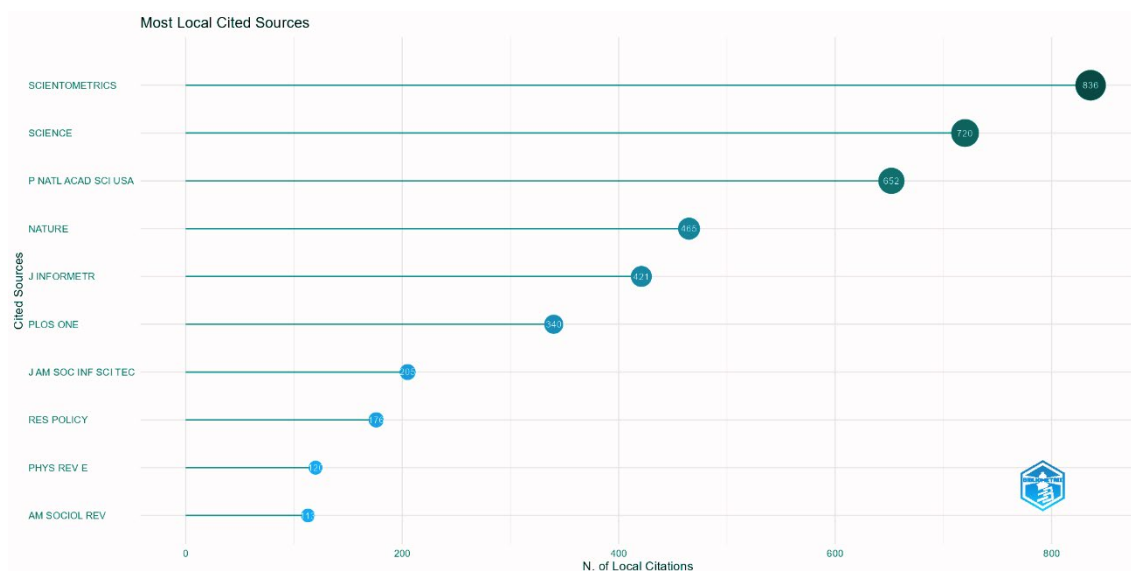


Figure 15. Influential sources of SOS

Historical roots of SOS

Reference Publication Year Spectroscopy (RPYS) was employed to identify the historical roots of the research field and to demonstrate the influencers who set the platform for the genesis and development of SOS. As discussed in the methodology section, the tool 'CRExplorer' was used for this analysis. Even though this tool facilitates the analysis of datasets downloaded from WoS as well as Scopus, it does not support the analysis of a combined dataset as facilitated by 'Biblioshiny'. So, it was decided to go with the Scopus dataset with 503 records for this particular analysis. Scopus provided the cited references (CRs) of only 468 publications that were published after 1974. The omitted content included the CRs of 11 papers (published before 1974). Hence this analysis was done with 21032 CRs that were published from 1620 onwards. Figure 16 represents the landscape of CRs over this period. An exponential hike in the number of CRs is visible in the graph towards the later years that corresponds to the hike in the number of publications in SOS as depicted in the Figure 1.

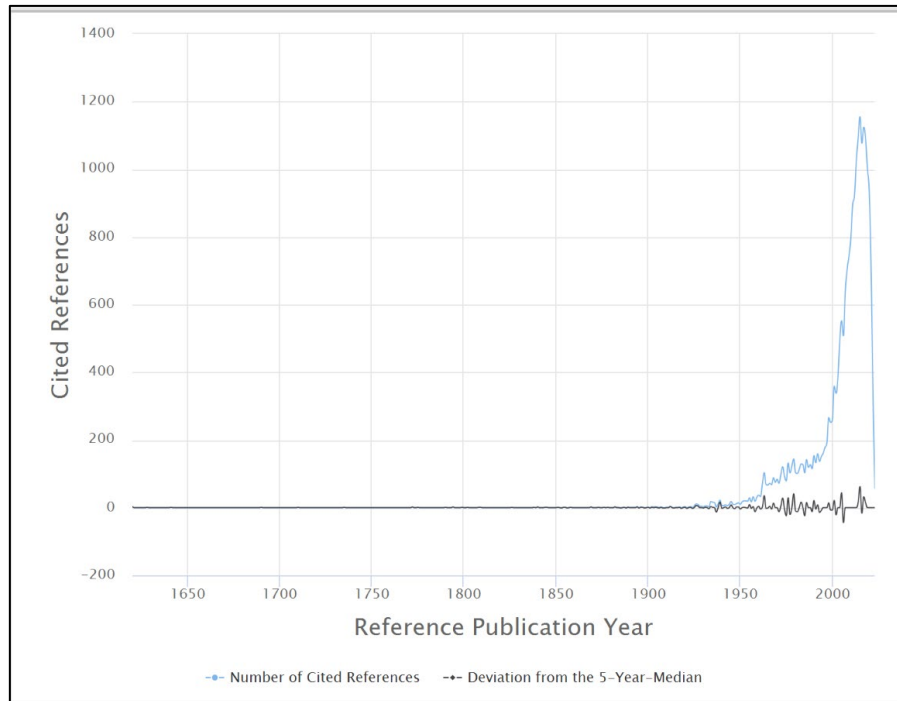


Figure 16. Reference Publication Year Spectroscopy of SOS research

For tracing the historical roots, we limited the year of publication of the CRs to 1990. The cut-off year was set at 1990 as the number of publications in SOS started growing after this period which would also have contributed to the number of CRs and corresponding peaks in the RPYS graph (Figure 16). Hence, we considered the publications before 1990 as the historical publications (Barth et al., 2014; Bornmann et al., 2016; Marx et al., 2014; Wray & Bornmann, 2014).

This was then carried out in two sessions. In the first session, we took the publications from 1620 to 1900 and for the second session, from 1901 to 1990. For each period, the influential authors and papers were identified. The RPYS for the first period is depicted in Figure 17. The maximum number of citations received for a particular year during this period is only three and for the years 1620, 1882 and 1894. All the three citations for 1620 went to Francis Bacon for his book *Novum Organum*. For the other two years the citations were shared by six different authors. It is also noticed that the three citations to Bacon were made after 2000. With the available data, it can be inferred that the publications during this period did not contribute significantly to the genesis and development of SOS.

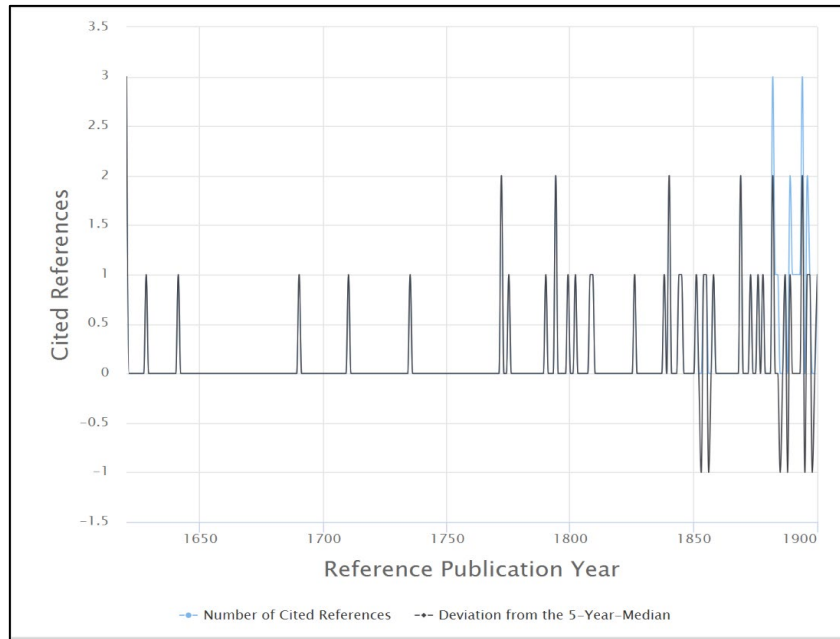


Figure 17. RPYS for 1620-1900

The RPYS for the second session is shown in Figure 18. This was further analysed for three time periods of 30 years each as depicted in Figures 19a, 19b and 19c, to get a clear understanding of the influencers. Moreover, Figure 18 also represents the ‘Little Science’ and ‘Big Science’ periods in which a clear distinction is visible in the citation patterns owing to the changed nature of science in the rise of the ‘Big Science’ era (1950 onwards).

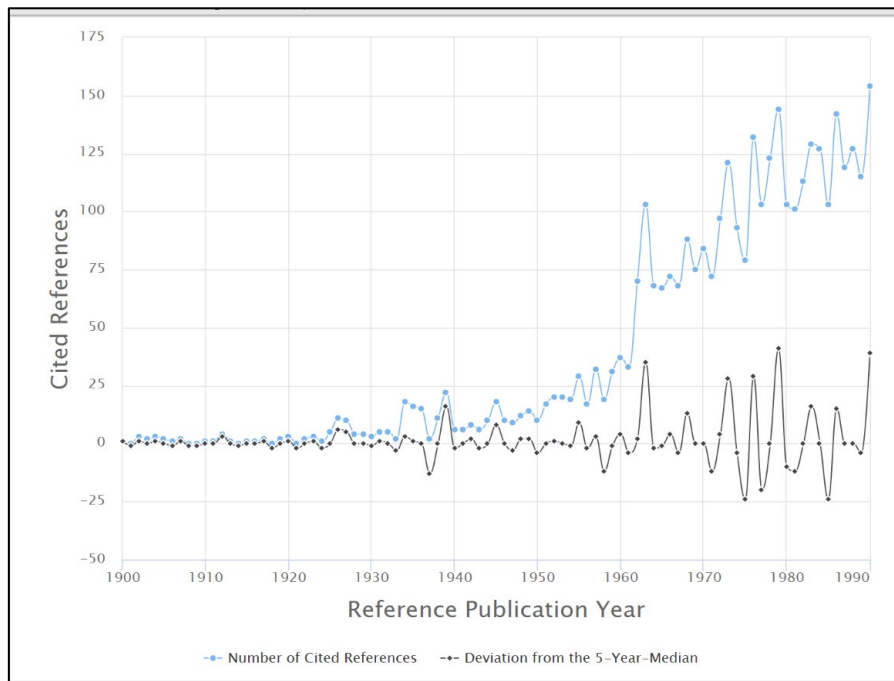


Figure 18. RPYS for 1900-1990

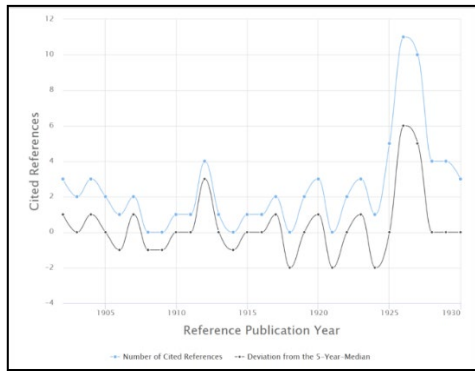


Figure 19a. RPYS for 1901-1930

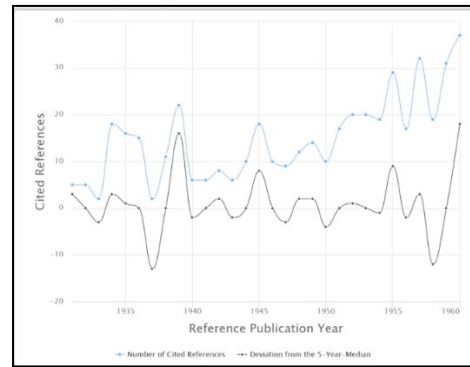


Figure 19b. RPYS for 1931-1960

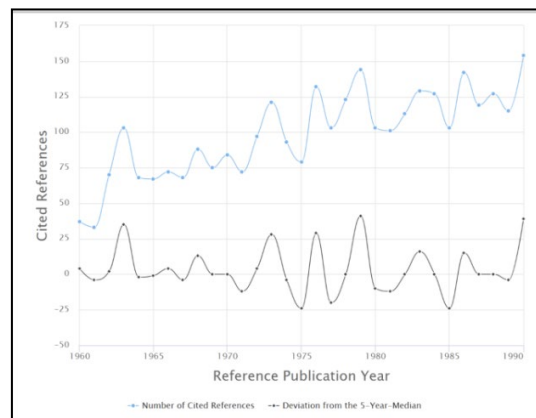


Figure 19c. RPYS for 1961-1990

The largest number of citations a year could receive in the first 30 years is 11 (1926) and for the title, 'The frequency distribution of scientific productivity by A. J. Lotka in which the 'inverse square law of scientific productivity' was proposed (Lotka, 1926). The year 1927 received 10 citations, which was shared by seven papers. It is also observed that the majority of these citing publications came out after 2000.

During the second period from 1931-1960, a rise in the number of citations is generally visible with more than 20 citations during 1939 and 1955 and more than 30 citations during 1957, 1959 and 1960. J. D. Bernal and Eugene Garfield received the most number of citations during this period. Even though the later years of this period received more citations, these were shared by a large number of authors. Those who received four or more citations include K. R. Popper, Burton and Kebler, W. Shockley and D. T. Campbell.

In the last period, the number of citations again escalated crossing 100 citations for most of the years. Rather than journal articles, some landmark books in the area of sociology of science and bibliometrics received many citations. de Solla Price's 'Little Science Big Science', Merton's 'Social Theory and Social Structure' are identified as the most influential books during this period and de Solla Price's 'Networks of scientific papers' is found to be the influential article. Table 1 represents a detailed overview of the historical roots of present-day SOS research.

Seminal authors who laid the foundation of SOS

We made an attempt to identify the most influential authors of the past who laid the foundation for the development of this research area. This analysis was based on the citation counts received by these authors from the local dataset. It is observed that Derek J. de Solla Price, regarded as the father of Scientometrics (Merton & Garfield, 1963) and J. D. Bernal, who is considered as the father

of Science of Science (Zhao et al., 2020) along with Merton and Garfield laid the foundation of SOS. Table 2 represents the seminal authors and their highly cited works. It is also evident that majority of the seminal works in SOS are books.

Period	Year	Author	Title	Article/ Book	Source/ Publisher	Citations received
1900-1930	1926	A. J. Lotka	The frequency distribution of scientific productivity	Article	Journal of the Washington Academy of Sciences, 16(12), pp.317-323	11
1931-1960	1955	Eugene Garfield	Citation indexes for science: A new dimension in documentation through association of ideas	Article	Science, 122 (3159), pp. 108-111	18
	1939	J. D. Bernal	The Social Function of Science	Book	London: George Routledge and Sons, Ltd.	14
1961-1990	1963	Derek J.de Solla Price	Little Science, Big Science	Book	Columbia University Press	40
	1968	Merton R.K.	Social Theory and Social Structure	Book	Free Press	35
	1965	Derek J.de Solla Price	Networks of scientific papers	Article	Science, 149, pp. 510-515	30
	1976	Derek J.de Solla Price	A general theory of bibliometric and other cumulative advantage processes	Article	Journal of the American society for Information science, 27, 5, pp. 292-306	29
	1962	Kuhn T.S.	The structure of scientific revolutions	Book	University of Chicago Press	20
	1973	Merton R.K.	The sociology of science: Theoretical and empirical investigations	Book	University of Chicago Press	20
	1972	Crane D.	Invisible Colleges: Diffusion of Knowledge in Scientific Communities	Book	University of Chicago Press	12
	1963	Kessler M.M.	Bibliographic coupling between scientific papers	Article	American Documentation, 14, 1, pp. 10-25	11
	1970	Kuhn T.S.	The Structure of Scientific Revolutions, 2nd ed.	Book	University of Chicago Press	11
	1972	Eugene Garfield	Citation analysis as a tool in journal evaluation	Article	Science, 178, 4060, pp. 471-479	11
	1973	Small H.	Co-citation in the scientific literature: A new measure of the relationship between two documents	Article	Journal of the American Society for Information Science, 24, 4, pp. 265-269	11
	1979	Eugene Garfield	Citation indexing: Its theory and application in science, technology, and humanities	Book	John Wiley & Sons	10
	1986	Derek J.de Solla Price	Little Science, Big Science... and Beyond	Book	Columbia University Press	10

Table 1. Historical roots and Foundational works of SOS

Seminal Author	Total Local Citations	Works	
		Books	Articles
		Little Science, Big Science, Columbia University Press, 1963	Networks of scientific papers, Science, 149(3683), pp. 510-515, 1965
Derek J.de Solla Price	156	Science since Babylon, Yale University Press, 1961 Little Science, Big Science... and Beyond, Columbia University Press, 1986	A general theory of bibliometric and other cumulative advantage processes, J. Am. Soc. Inf. Sci, 27 (5), pp. 292-306, 1976
Merton R.K.	82	Social Theory and Social Structure, Free Press, 1968 The sociology of science: Theoretical and empirical investigations, University of Chicago Press, 1973	The matthew effect in science: the reward and communication systems of science are considered, Science, 159(3810), pp. 56-63, 1968
Eugene Garfield	76	Citation Indexing: Its Theory and Application in Science, Technology, and Humanities, John Wiley & Sons, 1979	Citation indexes for science: a new dimension in documentation through association of ideas, Science, 133(3159), pp. 108-111, 1955 Citation analysis as a tool in journal evaluation: Journals can be ranked by frequency and impact of citations for science policy studies, Science, 178 (4060), pp. 447-471, 1972
Kuhn T. S.	46	The Structure of Scientific Revolutions, University of Chicago Press, 1962	
Barnes B.	26	Interests and the Growth of Knowledge, Routledge, 1977	
Bernal J.D.	24	The Social Function of Science, London, Routledge & Sons, 1939 Science in History, London, Watts & Co., 1954	

Table 2. Seminal authors and their works

Discussions

This study was framed to address four research questions related to the development, thematic structure, influencers and historical roots of SOS. The analysis of RQ1 revealed that SOS originated during the 'Little Science' (Price, 1963) period and took a slow pace in its development and towards the end of the 20th century, the subject field got established and by 2011, achieved a dynamic growth. This was also evident in the author productivity graphs which showed that almost all the highly productive authors in the area started publishing after 2011 and most of their works came

out after 2016. Analysis of the corresponding author's country revealed that USA contributed almost one-third of the research in SOS followed by China (10%). But the analysis of the country of affiliation of individual authors in the dataset gave another picture with China taking the lead role followed by USA. The study identified Scientometrics, PNAS and Journal of Informetrics as the relevant sources that publish SOS research.

Addressing RQ2, we mapped the thematic structure of SOS and observed that the theme 'scientometrics' is leading this research area. 'AI and scholarly data' is seen as a matured sub-theme of SOS and owing to the recent developments in bigdata analytics and AI, it could be inferred that scientometrics, along with AI and bigdata will drive forward the research in SOS. Another major observation was that 'Sociology of Science' which was considered as one of the basic themes in SOS has now declined. This thematic marginalisation of 'Sociology of Science' indicates a gradual shift in the methodological orientation of SOS research. Analysis of the temporal evolution of various themes in the area by dividing the total time span into four time slices revealed that 'Science of Science' remained as the only central theme till 1998. During 1999-2011 'scientometrics' and its variants, 'history' and 'sociology' of science, and studies about 'scientists' led the field. But studies related to 'war science' was found to be isolated. In the third period 2012-2016, quantitative studies like 'citation analysis', 'teams science', 'bibliometrics', 'computational sociology' took the lead role but 'sociology of science' got isolated (Kawalec 2019). In the last period that corresponds to the current trends in SOS, 'scientometrics' and its facets formed the central theme, and it was evident from the results that currently SOS is led by AI, scholarly data and innovation studies (Fortunato et al., 2018; Zeng et al., 2017, Wu et al., 2022). These results suggest that while early contributions to the field emphasised the theoretical and qualitative analyses of scientific institutions, norms, history and philosophy of sciences, contemporary studies increasingly rely on quantitative approaches including citation analysis, bibliometrics and computational modelling. This change in the methodological direction of the SOS can be attributed to the recent availability of large-scale bibliographic databases and advanced computational tools that allow researchers to analyse scientific activity at unprecedented scale and granularity.

Responding to RQ3, we tried to identify the drivers/impactful authors of present-day SOS research using different author level metrics viz: h-index, g-index, m-index and total citations received. Feng Xia who had the largest number of publications (13), scored high in three metrics (h-index, g-index, m-index) whereas total citation count received from the local data set was only 301 owing to the fact that the first publication was in 2018. Petersen with a total publication count of nine came first with respect to the total citations received. Peterson also shared the top value for h-index (9) with Xia. Search for the influential publications from the current dataset ended up with Science of Science by Fortunato et al. (2018) with 55 local citations. All other papers in the top ten cited documents from this dataset received very low citation counts between 11 and 3. So, in order to identify the publications that influenced SOS research we analysed the cited references of the papers and found that Science of Science by Fortunato et al. (2018) ranked first followed by *Atypical combinations and scientific impact* by Uzzi et al. (2013).

The analysis of CRs with RPYS technique using CReXplorer (RQ4), enabled us to identify the seminal works and authors who laid the foundation for this research area. We limited the publishing year of the cited reference to 1990 to trace the historical roots as the subject area gained a visible growth only after this period. Publications that came out between 1960-1990 contributed much to the development of this area. Among these, de Solla Price's *Little Science, Big Science* and its editions were found to be highly referenced (50 citations) by later researchers. Other seminal works included Merton's *Social Theory and Social Structure*, J. D. Bernal's *the Social Function of Science*, Garfield's paper *Citation indexes for Science*. This analysis also revealed that Derek J. de Solla Price (156 local citations) is the most influential author in this field followed by R. K. Merton (82) and Eugene Garfield (76). Hence it is inferred that Derek J. de Solla Price (the father of Scientometrics) and J. D. Bernal (the father of Science of Science) along with Merton and Garfield

laid the foundation of SOS. Their contributions established the conceptual and methodological basis for subsequent developments in the field.

The cited reference analysis conducted in Bibliometrix R tool with the same data could not reveal these influential publications due to the disambiguation associated with the author names in the CRs. CRExplorer facilitates to identify this disambiguation and cluster same documents to get the actual number of citations. Taking this factor into consideration, it is evident from the above discussion that apart from paving the foundation for SOS, Price, Merton and Garfield are the most influential and highly cited authors by the documents in the current dataset.

From social function to algorithmic patterns: the epistemic transformation of SOS

The transition of the 'Science of Science' (SOS) from its 20th century roots to its contemporary state represents a significant epistemic shift. Our RPYS analysis confirms that the foundation of the field is built upon the works of J.D. Bernal, Derek de Solla Price, and Robert K. Merton. These pioneers viewed science through a socio-historical and functionalist lens. For Bernal, the "Science of Science" was inextricably linked to the "Social Function of Science," emphasising how scientific discovery served or failed to serve humanity. Merton considered science as a social institution and analysed how science operates within social, political, and economic structures.

However, our thematic mapping reveals a stark departure from these qualitative origins. The current dominance of 'Scientometrics', 'Artificial Intelligence' and 'Machine Learning' as central themes indicate that SOS has undergone a computational pivot. In this new paradigm, science is increasingly treated as a high-dimensional data problem rather than a social institution. While this quantitative rigor allows for the analysis of millions of publications it risks marginalising the very human and ethical dimensions that the Polish founders, Ossowska and Ossowski, originally envisioned.

As we gain precision in measuring scientific productivity through AI and big data, we risk losing the interpretive depth required to understand the quality of scientific intellectual life. This paradox suggests a shift towards a 'black-box' epistemology, where the focus moves from the human 'why' of scientific discovery to the predictive 'what' of citation networks. This methodological reductionism needs to be addressed. The devolution of SOS to a mere metric-centric subject area, where the complex social realities of science are flattened into citation counts and h-indices warrants the attention of experts interested in the philosophy, sociology, psychology and economics of science.

Implications

This study presents a comprehensive map of the subject field SOS that originated in the 1930s and revealed that this subject area has not yet matured. Only the quantitative aspects of the subject received the interest of the scholars around the world, owing to the theoretical strengthening of the subject area 'Scientometrics' by Eugene Garfield augmented with the availability of large datasets provided by bibliographic databases and the developments in visualising collaborations and subject networks. Whereas many of the important aspects of SOS like the philosophy of science, sociology of science, policy-level implications of science, psychology behind the scientific enterprise, along with how these different aspects complement each other to study the science behind science; requiring qualitative analysis, remained under-explored. This asymmetry in research interests, limits the field's capacity to understand science comprehensively from multi-dimensional insights. Hence this study implies that there is an urgent need to revisit the theoretical foundations of the subject. Re-engaging the foundational works along with critical discourses and discussions involving theorists from all disciplines that contribute to the study of Science is essential to strengthen the theoretical framework of SOS.

Limitations and dimensions for future exploration

We used limited keywords for data extraction in order to avoid the overload of papers from individual subject areas resulting in a large dataset of which the majority (more than 97%) do not use the term SOS or do not identify themselves as SOS (Krauss, 2024). This is in contrast to the usual practice of employing multiple keywords for data extraction to do bibliometric analysis. Owing to the concerns mentioned in the Materials and Methods section, this study warranted to limit the number of keywords which in turn helped us to map the real landscape of SOS. However, we admit this as a limitation of this study. Another limitation is the dependence on a single bibliometric analytical software (Bibliometrix) for the study. Identifying seminal works with RPYS technique has an inherent limitation as it takes into consideration only the number of citations received and overlook its scientific quality.

For the holistic development of this area, it is highly recommended to concentrate future research on strengthening the theoretical foundations of SOS. Systematic reviews of SOS literature, influence of geo-political factors in the conceptual development of the subject, contribution of SOS in policy formulation etc. can be explored. Multi-dimensional studies may be conducted to identify gaps and areas that require theoretical development. All these warrants interdisciplinary, cross-cultural and international collaborations integrating qualitative and quantitative methods.

Conclusion

This paper reveals that SOS as a research area emerged in the early 1900s. It took a slow pace to get itself established as a research field and is yet to achieve a holistic growth. The thematic analysis reveals that SOS lost its identity as a qualitative study of science midway its evolution and currently relies more on quantitative techniques. Scientometrics and its variants form the central theme of present-day SOS and the research area will be led forward by Artificial Intelligence (AI), scholarly data and innovation studies. The historical roots of SOS lie in the works of J. D. Bernal, de Solla Price, Merton and Garfield. The study could identify many under-explored areas in SOS like the societal impact of science, philosophy of science and economic impact of science. It is also evident that scholars specialising in quantitative science studies increasingly use the term 'Science of Science' as a synonym of quantitative studies, with some of the recent papers reporting SOS as a branch that employs quantitative techniques to analyse large datasets to understand the process of science.

While the "Big Data" approach offers powerful predictive insights into scientific impact and team dynamics, it often lacks the interpretive depth required to understand the underlying epistemic shifts or the evolving norms of the scientific community. The current thematic landscape reflects an increasingly peripheral status of qualitative enquiries about the scientific enterprise as the field pivots towards a more technocratic and algorithmic epistemology. To bridge this gap, future research must move beyond descriptive reporting and re-integrate these quantitative metrics with the theoretical frameworks established by the field's founders, ensuring that SOS remains a study of the nature of science and not just a measurement of its outputs.

This research helped to unveil SOS as a research area since its inception to its current stature. In the absence of a strong theoretical framework, SOS may lose its identity and may be framed as a research area dealing with the quantitative study of science. To strengthen the theoretical foundations of this research area, we suggest to undertake interdisciplinary collaborative investigations involving social scientists, economists, philosophers and psychologists on the conceptual, theoretical and methodological frameworks of SOS. It is important to make more qualitative studies and develop new quantitative techniques to measure the unexplored themes. The lack of academic departments to study and teach Science of Science may hinder this. To ensure a sustainable growth and holistic maturity of the subject, institutionalisation is

recommended. Establishing dedicated research centres, funding schemes and interdisciplinary collaboration would help this.

About the authors

S. N. Archana* currently serves as Assistant Librarian in Cochin University of Science and Technology (CUSAT), Kerala, India. She received her PhD in Library and Information Science from CUSAT. Her expertise includes research data management, research metrics, bibliometrics, and the integration of emerging technologies in libraries. She can be contacted at niharikamanakkil@gmail.com ORCID: 0000-0002-1471-9791

P. K. Padmakumar works as Assistant Librarian in Cochin University of Science and Technology (CUSAT), Kerala, India. He holds an M.Phil. in Library and Information Science. Areas of interest include the use of artificial intelligence in higher education, digital humanities, and information and data literacy. He can be contacted at pappanparam@gmail.com ORCID: 0000-0001-6866-651X

Shajitha C. is an Assistant Professor in the Department of Library and Information Science, Kannur University, Kerala, India. She holds a PhD in Library and Information Science. Her areas of interest include Institutional repository, Digital curation, Cyber Security, Data Literacy, Research support services and Artificial Intelligence. She can be contacted at shajitha.c@gmail.com ORCID: 0000-0002-6946-2380

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