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Academic landscape of *Technological Forecasting and Social Change* through citation network and topic analyses

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Abstract

Technology and innovation management are vital emerging research fields. *Technological Forecasting and Social Change* has worked as a major forum in this field and is currently regarded as the leading journal. However, an increasing number of publications hamper a comprehensive understanding of the field and journal. In this study, we conducted a systematic review of bibliometric support. We used citation network analysis and topic models to extract research landscapes and trends. Our results illustrate how technology and innovation management research has developed through the interactions among theories, methods, and cases, both qualitatively and quantitatively. Based on our analysis and findings, we discuss the major branches of research, topics in the journal, and future perspectives.

1. Introduction

Technological Forecasting and Social Change (*TFSC*) was founded in 1969 under the title *Technological Forecasting*, to cover the ever-increasing literature on normative and exploratory forecasting and planning (Linstone, 1969). Soon after, editors realized the need to recognize the coupling of technological and social forecasting and hoped for the journal to facilitate dialog between the different disciplines involved in long-term planning, thus updating the title to its current form (Linstone et al., 1970). Although originally placed within economics, current classification schemes place the journal within the scope of the management of technology and innovation, business and international management, and applied psychology (Scimago[1]); business, management and accounting, and psychology (Scopus[2]); or business, regional, and urban planning (Web of Science[3]), highlighting the broad scope of the journal.

In particular, the *TFSC* publishes articles on technology as an economic driver, innovation diffusion, scenario planning, innovation systems, and transition, among others, with an increasing interest in environmental sustainability, biology, and artificial intelligence (Phillips,

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[1] https://www.scimagojr.com/journalsearch.php?q=14704&tip=sid&clean=0

[2] https://www.scopus.com/sourceid/14704?origin=resultslist

[3] https://jcr.clarivate.com/jcr-jp/journal-profile?journal=TECHNOL%20FORECAST%20SOC&year=2020

2019). These topics are offered as guidelines for aspiring and recurrent authors, but there is still no accounting on how these topics have been covered through the history of *TFSC*. This article aims to surface its academic landscape by pointing to major and emergent topics and trends covered by the journal over its 53 years of existence. Therefore, we relied on bibliometric methods based on complex network analysis and text mining.

Bibliometrics refers to the use of data analysis tools and statistical methods for different types of publications, including academic articles (Thelwall, 2008). They facilitate the comprehension of large amounts of data and enable the discovery of hidden patterns. Bibliometrics is applied to the study of academic disciplines, topics, or journals (Mejia et al., 2021).

The *TFSC* is included as a target journal in bibliometric studies covering the field of technology and innovation management (TIM) or management of technology (MOT). Early bibliometric studies contributed by creating journal ranks in these fields through citation analysis. For instance, Cheng et al. computed the number of times different TIM journals were referenced in other authoritative journals in the field, finding *TFSC* ranking within the top 10 in subsequent studies (Cheng et al., 1999, 1997). Linton and Thongpapanl replicated the study by incorporating additional citation indicators resulting in *TFSC* as number six in their original ranking (Linton and Thongpapanl, 2004) and number nine in their updated version (Thongpapanl, 2012). In addition to rankings, other studies have compared *TFSC* to other TIM journals in terms of their impact factors (Sarin et al., 2018). *TFSC* is currently becoming the leading journal with the highest impact factor in 2020 among TIM journals. In a similar direction but focusing on ranking authors instead of journals, Cancino et al (2017) analyzed publications on the topic of innovation by computing author-level indicators to reveal a list of the most influential authors in the field. In this study, *TFSC* was identified as one of the most specialized journals.

In addition to these rankings, content analysis has attracted research interest. The first bibliometric study introduced a topical analysis and classified the articles from ten MOT journals into any of 13 expert-validated categories to later conduct a keyword frequency and country concentration analysis per category (Choi et al., 2012). A later study introduced advanced bibliometrics to automatically extract categories from TIM articles published between 2000 and 2014 based on bibliographic coupling networks and text similarity, where *TFSC* and research policy dominated the topic of innovations in sociotechnical systems (Meyer-Brötz et al., 2018). A more recent study further expands the target analysis to cover

20 years of TIM research by sourcing data from the 10 most acknowledged TIM journals, including the *TFSC*. This study focuses on revealing key actors (authors, institutions, and countries) and topics from the study of co-occurrence networks, focusing on the TIM field without a particular focus on *TFSC* characteristics (Pitt et al., 2021).

Bibliometric studies have focused exclusively on *TFSC*. Sarin et al. studied the articles of the *TFSC* from 1970 to 2018 by applying a variety of methods to reveal the most frequent authors, institutions, and keywords. A factor analysis of the co-citation frequency of all references found in the *TFSC* articles revealed 10 trends: "technological innovation, competitive advantage, innovation diffusion, methodology, technology acceptance, new product, technological transition, knowledge creation, scenario technique, and innovation systems". These trends were inferred based on the most cited authors resulting from factor analysis (Singh et al., 2020).

On the 50th anniversary of the *TFSC*, a two-part bibliometric study was conducted on its corpus. The first part focuses on the knowledge flow in and out of the journal by exploring journals that cite and are cited by *TFSC* grouped into different Web of Science and Scimago categories. Additionally, keyword analysis has found that patent analytics, climate change, sustainability, and energy are among the key topics of the last decade (Sarin et al., 2020). The second part revealed the most frequent authors, institutions, countries, and keywords with results closely mirroring those of Singh et al. (2020) (Mas-Tur et al., 2021).

The latest study on *TFSC*, conducted by Zhu and Cunningham (2022), applies a new variant of topic models (Blei et al., 2010) to text data from the title, abstract, and keywords of the articles, resulting in a hierarchical topic representation of *TFSC* contents. Seven topics were identified: innovation, change, transition, technological, social, forecasting, and market. They conform to a 3-level hierarchy with "social" at the top, and "innovation" and "forecasting" in the intermediate layer. Although they are called topics, they represent knowledge components that cascade down the hierarchy. In this framework, *TFSC* articles can be classified into branches depending on the relevance of each component to a given article.

However, in topic models, academic knowledge is assumed to be represented by terms and vectors. However, in our opinion, academic knowledge is not just a combination of terms, and is represented in a paper. Therefore, it is worthwhile to analyze *TFSC* using a paper as a unit of analysis, in addition to topic models. Even when we treat a paper as the unit of analysis, we can adopt both citation- and text-based approaches to model the relationships among the units. However, the citation-based approach is superior to text-based similarity measurements for measuring the relevance among papers (Shibata et al., 2011). Hence, this study complements these studies by focusing exclusively on the academic landscape of *TFSC* using citation network analysis. We also supplement the topic analysis and discuss the commonalities and differences in the results.

2. Data and Methods

2.1 Data

Metadata, including title, abstract, keywords, and cited references for articles published by *TFSC* was obtained from the Web of Science, one of the major data providers and search engines of academic literature. We searched for all articles since the journal's inception in 1969 for a total of 6214 articles by the date of retrieval on August 1, 2022. The list of articles, including their document object identifier and database identifier, is included as supplementary material.

2.2 Methods

To analyze this collection of *TFSC* articles, we applied two types of methods: one based on citation networks and the other based on advanced text mining techniques. Both methodologies help uncover a snapshot of the knowledge structure created over the year by the *TFSC*, each taking advantage of different data features resulting in complementary landscapes in which differences and similarities are further discussed.

2.2.1 Citation Network Analysis

The first approach surfaces the academic landscape of *TFSC* through direct citation network analysis. Direct citations are known to better represent knowledge fronts (Boyack and Klavans, 2010; Shibata et al., 2009). Direct citation networks are constructed by treating each article as a node and connecting it to any other node that they cite (de Solla Price, 1965). It is expected that articles in our dataset cite articles from other journals, but these citations are not considered because we aim to study only the knowledge contained in the *TFSC*.

Once the network was built, we applied a clustering algorithm to extract groups of articles with a relative concentration of citations among them. These clusters represent topics that *TFSC* has focused on throughout the years, and they obey the natural citation patterns followed by authors that have been published in this journal (Velden et al., 2017). We applied the Louvain algorithm (Blondel et al., 2008), which belongs to a family of algorithms based on modularity maximization. Modularity is a measure of the network structure. This measures the strength of the clustering solution. Networks that are densely connected within clusters, but sparsely connected to nodes in other clusters, have higher modularity (Newman, 2006). The Louvain algorithm has been shown to scale well in large networks and is widely used for clustering citation networks of academic articles (Lancichinetti and Fortunato, 2009).

Finally, clusters were measured by size, with the number of articles, relevance being the ratio between nodes and edges, and average publication year. The clusters were profiled based on their keywords and the most-cited articles.

2.2.2 Topic Analysis

To analyze this collection of *TFSC* publications from the perspective of topic analysis based on text mining, we applied two sets of approaches, hierarchical topic tree (HTT) and scientific evolutionary pathways (SEP), to identify the scientific topics discussed in these articles and explore two types of relationships among these topics, that is, hierarchical relationships and evolutionary relationships. Note that a topic refers to a collection of terms representing similar semantic contents, but HTT and SEP have ways of identifying topics and measuring the relationships among topics.

Because both approaches facilitate terms retrieved from titles and abstracts of the collected *TFSC* articles, we applied a natural language processing (NLP) approach to extract 92,474 raw terms and exploited a term-clumping process (Zhang et al., 2014) to remove noise and consolidate synonyms and collected 3,577 terms as our final input.

HTT, initially developed by Wu and Zhang (2021), was used to discover the hierarchies of topics through a co-term network. Conceptually originating from community detection, HTT starts a community (i.e., a tree branch) by identifying the highest-density node and then unfolds this community by iteratively analyzing and ranking the neighbors of this node via their densities. In HTT, each branch represents a major research area, with leaves representing specific research topics.

SEP (Zhang et al., 2017) highlights the evolutionary relationships between scientific topics over time, assuming that scientific innovation is the recombination of existing knowledge (Fleming, 2001). By introducing streaming data analytics techniques, SEP monitors the change in term composition and frequency within a topic over time, and a new topic will be spilled from an old one when such changes trigger certain thresholds. Thereafter, the relationship between the new and old topics is defined as a "predecessor-descendant" relationship, indicating the evolution of scientific topics.

3. Results

Table 1 summarizes the citation network analyses. The constructed network comprises 4,764 nodes and 17,369 edges. In Table 1, *N, E,* and *Y* denote the numbers of nodes and edges in each cluster, and the average publication year, respectively. After adopting the Louvain method, we have 20 clusters. In Table 1 and Fig. 1, we present the results for clusters whose nodes exceed 50. Figure 1 shows the relative position of each cluster, where the vertical axis is *E/N* and the horizontal axis is *Y*. Here, we regard clusters with a high *Y* as emerging clusters. We also regard clusters with high *E/N* as a research field with high relevance in *TFSC* because higher *E/N* means higher citations per paper within *TFSC*, and research achievements in those cited papers are repeatedly utilized in other papers in *TFSC*. The area of the circles in each plot in Fig. 1 is proportional to *N*. As can be observed in Fig. 1, cluster 1 occupies a large fraction of *TFSC* but becomes mature. Cluster 1 seems to have high relevance considering its methodological contribution, but this is partly due to the oldness of papers in this cluster because old papers can have more citations than recent papers. The relevance of Cluster 4–6 and 12 was relatively high. The relevance of Clusters 14–16 was not very high. The relevance of Clusters 7 and 8 also seems to be not very high, but this might be due to their emergence. Cluster 2 was the most emerging. In contrast, cluster 9 was mature. Below, we describe the details of each cluster whose size is more than 200.

Table 1. Summary of citation network analysis.

Cluster	Name	Y	N	E	E/N	Extracted Key Terms
1	Innovation Diffusion Model	2000	647	1894	2.93	Model, diffusion, Bass, Volterra, Lotka, Kondratieff
2	Digitalization and related topics	2016.4	513	1015	1.98	Smart city, Crowdfunding, Sharing economy, Social medium
3	Transition and Innovation System	2014.4	417	1073	2.57	Transition, Technological innovation system, Energy, Niche, Sustainability transition
4	Emerging Technologies, Opportunity Assessment, and Planning	2011.4	366	1475	4.03	Patent, Potential discovery, Technology, Citation, Analysis, Text mining
5	Foresight and Scenario Planning	2012.6	359	1378	3.84	Scenario, Foersight, Strategic foresight, Scenario planning, Backcasting
6	Delphi and Foresight	2004	333	1479	4.44	Delfi, Foresight, Opinion change, Expert
7	Globalization and Knowledge Economy	2013.8	332	594	1.79	Open innovation, knowledge, firm, network, performance, inter-regional
8	Innovation and Economic Development	2014.9	324	585	1.81	Firm, Financial development, Entrepreneurship, Grassroots, Country ,Saharan
9	Technology Assessment, Forecasting, and Technometrics	1991.5	282	520	1.84	OTA, Technology assessment, TFDEA, Risk
10	Commercialization of University Technologies and Future Industries	2015.8	268	537	2.00	Printing, university, Blockchain, Entrepreneurship, Third mission, Industry
11	Green Innovation	2014.9	262	517	1.97	Carbon emission, Green, Eco-efficiency, CO2
12	Technology Roadmap	2012.7	249	891	3.58	Roadmapping, Roadmaps, disruptive technology
13	Cross Impact Analysis	1985.6	143	261	1.83	Cross impact, KSIM, TIA
14	Digital Transformation and Employment	2008.7	95	133	1.40	Social theory, Global brain, Improved maize, Telecommuting, Job security
15	ICT, Healthcare, and Aging	2014.3	79	127	1.61	Smart home, Older people, ageing ,Care
16	Big Data Analytics and Trend	2016.1	55	89	1.62	Google trends, Serach traffic, Crude oil, Hype Cycle

Figure 1. Scatter plot of each cluster.

Cluster 1 focuses on the innovation-diffusion model. This consists of several research topics. One of these is Kondratieff and the long wave of the economy, which focuses on the interactions between the long-term macroeconomic cycle, social, and innovation factors. It also focuses on modeling the phenomena and cycles, and analyzing the underlying mechanisms. For example, in a recent study, Coccia (2018) discussed the role of general-purpose technology in long waves. de Groot et al. (2021) analyzed economic multi-cycle structure cycles using Fourier analysis. Another trend is the mathematical modeling of innovation diffusion and the analysis of technological substitution. The hub papers in this stream are Blackman (1974, 1972). Although recently, this stream of modeling has not been active, developed models have been applied to cutting-edge topics, such as alternative vehicles (Qian and Soopramanien, 2015), information and communication technologies (ICT) (Lechman and Marszk, 2015; Oughton et al., 2018), diffusion of financial innovation (Marszk and Lechman, 2018), and COVID-19 (Debecker and Modis, 2021). Compared with case analysis, research on methodological development is relatively less active, but continuous efforts still exist. Examples include the grey forecasting model, which adopts the grey model to the Lotka Volterra equation (Wu et al., 2012), and automata network modeling of market potential, extending the generalized Bass model (Guseo and Guidolin, 2009). In summary, research in Cluster 1 matures, especially in modeling, and the research trend has shifted from methodological development to applications in emerging cases.

Cluster 2 comprises the hottest topic, digitalization, and related topics. Research in this cluster tends to adopt both qualitative and quantitative analyses and holistic approaches, including technological advancements, business models and ecosystems, and societal changes. A major stream of research in this cluster is smart cities. For example, Lee et al. (2014) identified six factors: urban openness and proactiveness, smart city infrastructure and governance, service innovation, and partnership formation, and validated these with case studies. Appio et al. (Appio et al., 2019) developed a comprehensive and extensional framework to understand the ingredients of a smart city and its quality of life. The related topic is mobile. Both studies have investigated supply-side and demand-side factors; hub papers focus on demand-side factors, such as user demography, user community, and technology acceptance (Gurtner et al., 2014; Mütterlein et al., 2019). Mobile, e-commerce, social commerce, and social media are emerging research topics (Hajli, 2014; Osei-Frimpong and McLean, 2018). Another cutting-edge stream is COVID-19 (Brem et al., 2021; Yoo and Managi, 2020). This stream appears in Cluster 2, which seems to be because a branch of this cluster is the Internet of Things (IoT), and investigated the application of IoT in the healthcare sector (Ben Arfi et al., 2021; Martinez-Caro et al., 2018). Other topics in this cluster are crowdfunding, sharing economy, and virtual team performance. In sum, research in this cluster is a topic-specific analysis rather than a general theoretical and methodological development, and adopts a holistic approach by integrating existing theories and methods. A typical example is that of a smart city. The adoption of a holistic approach is straightforward when we consider the intersections among innovation, business, and digital ecosystems (Gupta et al., 2019). It is noteworthy that we can observe the appearance of health and related issues in this cluster, and even in smart city research, technology and innovation are the only issues, and start to reconsider quality of life and well-being in this context.

Cluster 3, the transitional management and innovation system, has both high relevance and emergence. This cluster includes both methodological and framework development and case applications, particularly in the energy, electricity, and mobility sectors. The mainstream research in this cluster focuses on transition management. The transition management framework is a systematic and comprehensive integration of the existing expertise in the innovation diffusion process. It is described as a multilevel structure of niches, regimes, and landscapes (Geels, 2005). There have been ongoing efforts to develop sophisticated frameworks. For example, Holtz et al. (2008) described a multi-scale structure, which consists of actors and interventions, even on a single layer from a multi-level perspective. They also expanded the regime to include the natural system and its subsystems. Farla et al. (2012) focused on actors, strategies, and resources for transition. While some studies have used transition management to interpret past cases, Matschoss and Repo (2020) conducted a thought experiment for future energy systems and plausible paths. Another stream of research is innovation systems. A seminal contribution of this stream is a functional approach to innovation systems (Hekkert et al., 2007). Compared to the transition management framework used to analyze emerging technology and innovation diffusion, an innovation system is used to design an innovation policy and policy mix to support or hamper emerging technology and innovation diffusion. Here, a policy does not only mean regulation, but also includes economic transfer and soft instruments, such as voluntary standardization, codes of conduct, public–private partnerships, and voluntary agreements (Borrás and Edquist, 2013). There are overlaps between these two theoretical approaches, and both have been developed through interactions between theory and cases. Most cases used in innovation system research are also in the energy, electricity, and mobility sectors. Thus, it is natural for them to appear in the same cluster.

In Cluster 4, emerging technologies, opportunity assessment, and planning are highly relevant. Research in this cluster focuses on the targeted innovation process from the upstream of innovation (e.g., science and technology) to the downstream (e.g., industry and nation) (Huang et al., 2014). In the upper stream, literature-based discovery (LBD) and trend analysis are useful approaches for identifying emerging technologies and technological opportunities (Daim et al., 2006; Kajikawa et al., 2008; Kostoff et al., 2008). LBD has been adopted in a variety of fields, such as materials science, health, medical research, and computer science. Academic publications and patents were major sources of analysis.

Publications and patents are analyzed independently, but some studies have analyzed the gaps and relationships among them (Lee et al., 2009; Ogawa and Kajikawa, 2014; Shibata et al., 2010). This information can be used as a fundamental basis for technology road mapping (Kajikawa et al., 2008; Lee et al., 2009). The identification of emerging technologies is insufficient for strategic planning. Thus, patent portfolio analysis (Grimaldi et al., 2015) and patent value assessment (Hsieh, 2013), exploration of potential application areas (Nakamura et al., 2015; Song et al., 2017), and market (Song et al., 2018) have also been studied. Research in this cluster has an orientation toward data analytics and methodological development, and prospective analysis and design rather than retrospective interpretation.

Cluster 5 (scenario planning and foresight) had the highest relevance. The research in Cluster 5 can be regarded as having a function similar to that in Cluster 4. While Cluster 4 adopted a quantitative data-driven and evidence-based approach, Cluster 5 adopted qualitative, logical, critical, and intuitive approaches. Wright et al. (2013) described the process of scenario thinking and planning using intuitive logic. Evidence-based extrapolation leads to a plausible scenario; however, for risk management and adaptive management, an essential step is to illustrate an alternative scenario. Scenario planning and foresight have been widely used by corporations (Gordon et al., 2020; Rohrbeck et al., 2015). As evidenced by Rohrbeck and Kum

(Rohrbeck and Kum, 2018), firms that prepare for the future outperform both in their growth and profitability. In addition to corporate foresight, technology foresight is another research topic in this cluster. Technology foresight and foresight have been part of governmental activities (Miles, 2010) and are linked to industrial policy and strategy (Pietrobelli and Puppato, 2016). A computer-assisted approach (Bryant and Lempert, 2010) and multi-stakeholder deliberation and decentralized decision-making (Swanson et al., 2010) were used in this cluster.

Cluster 6, Delphi, and forecasting have the highest relevance, but are rather old compared to Cluster 5, targeting a similar aim. The key elements of the Delphi technique are expert participation, anonymity, questionnaires, feedback, and iteration of the process (Nowack et al., 2011). A major stream of this cluster is methodological research and the other is case applications. In methodological research, researchers have conducted both methodological improvements and evaluation of methods. Enhancing rigor in Delphi is a major topic (Hasson and Keeney, 2011). Examples of methodological improvements include the dissensus-based approach (Steinert, 2009), real-time Delphi (Gordon and Pease, 2006), and integration of Delphi and participatory backcasting (Varho and Tapio, 2013; Zimmermann et al., 2012). On evaluation, Fye et al. (2013) analyzed the accuracy of forecasts and found difficulty in longer time prediction, the advantage of using quantitative rather than qualitative methods, and the variance of accuracy among different topics (higher accuracy in computers and autonomous or robotics than in materials and photonics, implying larger uncertainty in development for the latter). Methodological development is an iterative process of improvement and evaluation. Belton et al. (2019) formulated a Delphi process based on integrating expertise for practical use. Delphi is now applied to a variety of topics, including emerging technologies; human issues, such as health and employment; and social issues, such as sustainability and resilience.

Cluster 7, globalization and knowledge-economy, is a younger cluster, although its relevance is not very high. One stream in this cluster is open innovation and collaboration. It has also been studied in the context of globalization, geographic scale, networks, and public policy. For example, Zouaghi et al. (2018) investigated how the global financial crisis impacted firms' innovation performance and how open innovation and knowledge capability mitigated these effects. Related branches in clusters especially focus on a geographic scale, where regional clusters and intra- and inter-regional collaborations are investigated. A recent trend in this branch of research is the study of China. For example, Sun and Cao (2015) and Xie and Su (2021) investigated intra- and inter-regional research collaboration in China. In their systematic review, Lopes et al. (2018) summarized constructs, antecedents, subsequent performance, and contingent variables (controls and moderators) in open innovation research. Compared to descriptive and empirical works on collaboration, there are few studies on contingent factors and theoretical thoughts on the conditions that determine the success of collaboration and open innovation. Another stream in this cluster is capability in the knowledge economy, which is studied at both the individual and organizational levels. Examples of the former include Conceicao et al. (2003), who proposed a new typology of the university to meet societal requirements and discussed the contribution of education and research in universities to innovation and industrial growth, and Heitor and Bravo (2010), who investigated science policies to promote brain gain to develop human capital. Demirbag et al. (2021) analyzed the relationship between firms' internationalization status and technology acquisition mode, and discussed the importance of knowledge management as a microfoundation of internationalization. The former and latter are intertwined. As discussed by Albats et al. (2020), individual-level characteristics contribute to organizational-level relational capability, and a company's strategic partnerships with universities require specific human capital. In sum, while other clusters focus on the technological aspects of innovation, this cluster focuses on organizational and human capabilities for innovation, which is especially important in the knowledge economy; open innovation is an effective tool for those.

Cluster 8, innovation and economic development, is also a young cluster, although its relevance is not very high. Most of the research in this cluster focuses on Africa, especially sub-Saharan Africa, although it is not limited to Africa. Factors distinguishing research in *TFSC* and development economics in other journals are technology focus, which is also stressed in Amankwah-Amoah et al. (2018). They study innovation and economic development at different scales. At the macroscopic level, the measurement of national innovation capability ex., (Archibugi et al., 2009; Khedhaouria and Thurik, 2017) and capability enhancement through knowledge and technology transfer (Botchie et al., 2018; Costantini and Liberati, 2014) are active research topics. At the mesoscopic level, firms' innovation capability and performance, as well as their business environment, have been investigated. Innovation, internationalization, and export behavior are central topics, especially in the context of this cluster (Martinez-Roman et al., 2019; Rodil et al., 2016). Political and social capital has gained interest in the business environment. Policy and governmental factors on firm innovation include public subsidy (Zhang and Guan, 2018; Zhao et al., 2018), regulation (Jiang and Ma, 2021; Pan et al., 2019), and political constraints and connections (Jiao et al., 2015; Krammer and Jiménez, 2020) and are also research concern in this context. Another branch is the role of social capital in innovation (D'Este et al., 2016; Landry et al., 2002; Ruiz-Ortega et al., 2018), which is not limited to developing countries but will vary among countries. For example, Grzegorczyk (2019) conducted a comparative study of the role of culture in technology transfer. At the microscopic level, entrepreneurship and grassroots innovation are the major research topics. For example, Sarkar and Pansera (2017) conducted multiple case studies and extracted grassroots innovation processes by entrepreneurs who overcome resource scarcity and leverage traditional knowledge, cost-conscious science, and local capabilities, with a focus on the triple bottom line. In addition to the above multiscale research, some branches of this cluster focus on specific technologies. Especially, ICT is the vital research fields among those. A series of research by Asongu et al. (Asongu et al., 2018; Asongu and Le Roux, 2017; Asongu and Nwachukwu, 2018) and Tchamyou et al. (2019) are typical accomplishments in this context, who clarified the relationships among ICT, financial access, entrepreneurship, and human development. Cryptocurrency is an emerging branch of ICT. Su et al. (2020) investigated the relationship between financial liquidity caused by Bitcoin and oil prices. Research on specific technology is not limited to ICT. One example is research on the detrimental effects of electronic waste (e-waste) in emerging economies (Amankwah-Amoah, 2016).

Cluster 9, technology assessment, forecasting, and technometrics, is the oldest among the top 16 clusters. The topics in this cluster seem to have a strong relationship with other clusters. For example, technological forecasting using the advanced Bass model and the Lotka Volterra equation frequently appears in Cluster 1. The LBD and related scientometric and informetric approaches used in Cluster 4 can be regarded as straightforward extensions of technometrics. We can regard Technology Assessment as having a close relationship with Science, Technology, and Society (STS) studies and, thus, with transition management literature in Cluster 3. The appearance of this cluster implies the origin of the *TFSC*. However, papers in this cluster are seldom cited, and each cluster derived from the origin is developing autonomously. Readers interested in the historical development of the topics can refer to a comprehensive review of technometrics (Coccia, 2005) and technology assessment (Tran and Daim, 2008).

Cluster 10, the commercialization of university technologies and future industries, is a highly emerging cluster. One of the streams in this cluster is the commercialization of university technologies via technology transfer, academia-industry collaboration, and start-ups. For example, Hsu et al. (2015) analyzed success factors in the commercialization of university technology from the following four perspectives: human capital, financial resources, commercial resources, and institutional/cultural resources; they elucidated that faculty quality, industry funding, patent portfolio, and incentive policy are the prior factors in each perspective. Somsuk and Laosirihongthong (2014) analyzed factors affecting the performance of incubators in universities and identified paths among four enabling factors (organizational, technological, financial, and human resources), performance of incubation (incubator growth, incubate growth, continuous sponsoring, and community-related impacts), and overall performance of incubation. This stream reflects the third mission of the university, reviewed by Compagnucci and Spigarelli (2020). A central topic in Cluster 10 is the academic entrepreneur and the technology transfer of university technologies. However, other topics also appear in this cluster, for example, Industry 4.0 (Büchi et al., 2020; Frank et al., 2019; Mariani and Borghi, 2019), 3D printing (Rayna and Striukova, 2016) and circular economy (Despeisse et al., 2017), and blockchain (Marsal-Llacuna, 2018; Pazaitis et al., 2017). This might imply that in these technological and industrial fields, expectations of university technologies for future industries are high, and academic research can contribute not only to technological development but also to a shift in institutional settings for opportunity entrepreneurship (Aparicio et al., 2016) and social innovation (Cajaiba-Santana, 2014; Petersen and Kruss, 2021).

Cluster 11 (green innovation) is an emerging cluster. One stream in this cluster is the circular economy and data analytics, which is an emerging topic. This is because green transformation is now required for a single entity but throughout the supply chains. Collaborative associations among all supply chain members, information sharing, big data analytics, and new business models are required to enable circulation and reduce emissions (Gupta et al., 2019; Jabbour et al., 2019). The research and development (R&D) of green technologies (Fujii and Managi, 2019, 2016) and its impact on firm performance (Nirino et al., 2021; Yu et al., 2017), economic growth and sustainability, and social impacts (Jin et al., 2020; Kraus et al., 2020; Viguie et al., 2015; Wang and Feng, 2020; Xie et al., 2016) is another stream. The transformation to a green and sustainable economy is driven not only by push factors, such as technology, but also by pull factors, such as science-based targets. In the latter, there have been continuous efforts in energy scenarios and assessments (Nakićenović, 2000). In particular, recent studies by Kriegler et al. (2015) and Riahi et al. (2015) have played an essential role in credible goal setting.

Cluster 12, the technology roadmap, and disruptive technology and business are emerging and have high relevance. The main focus of this cluster is technology roadmapping and its application to specific sectors. The hub paper is Phaal et al. (2004), which systematized the roadmap process and organized the roadmap into three layers: technology, product, and market. There is no universal method for roadmapping, but it can be customized to adjust the roadmap's purpose (Lee and Park, 2005). This cluster appears as an independent cluster, while it seems to have relationships with some branches in other clusters, including scenario planning in Clusters 4 and 5, Delphi in Cluster 6, and modeling and simulation in Cluster 1. This may reflect the different research orientations described in a recent review (de Alcantara and Martens, 2019; Park et al., 2020). Innovation is an uncertain process, and multiple future scenarios can be envisioned. Roadmaps are a powerful tool for obtaining the commitment of stakeholders to the selected scenario, which contributes to an increased probability of the realization of the scenario. It will work well when we are on a continuous path along with the envisioned scenario, but the occurrence of unexpected events can pose a fundamental risk for planning based on a scenario. Thus, it is straightforward that another research stream of this cluster is a disruptive and emerging technology and business (Kostoff et al., 2004; Phaal et al., 2011; Robinson and Propp, 2008; Sabatier et al., 2012; Walsh, 2004). A related branch of this stream, future technology analysis (FTA) (Featherston and O'Sullivan, 2017; Georghiou and Harper, 2013; Porter et al., 2004), is expected to increase preparedness for disruptive scenarios.

4. Discussion

4.1 Classification schema of citation clusters

To analyze the relationships between citation clusters, we visualized the structure of the citation network. The results are shown in Fig. 2. Some clusters appeared in close proximity. A typical example is Cluster 5 (foresight and scenario planning) and Cluster 6 (Delphi and Foresight), which is a reasonable result. Other clusters appearing in similar positions are Cluster 2 (digitalization and related topics), Cluster 7 (globalization and knowledge economy), Cluster 8 (Innovation and Economic Development), and Cluster 10 (commercialization of university technologies and future industries). However, the papers in Cluster 11 are scattered across the entire network, which might reflect that this issue includes a wider scope.

Based on the visualized results, we classified the main clusters into the following five categories:

- Branch 1: Theory (Quantitative Model)
- Branch 2: Theory (Qualitative Model)
- Branch 3: Method (Quantitative Orientation)

- Branch 4: Method (Qualitative Orientation)
- Branch 5: Emerging Issues

The mainstream branches of *technological forecasting and social change* are pathways from technology to social change. This is well modeled by the quantitative innovation diffusion model and described by the qualitative framework of transition and innovation systems. Thus, we regarded Branches 1 and 2 as the core of the *TFSC*. We simplify research in these as theory, but we must note that clusters also include case studies because theoretical models and frameworks have been developed by interactions and feedback among theories and cases. Branches 3 and 4 offer methodologies to researchers and practitioners. We cannot conclude that Branch 3 is purely quantitative and Branch 4 is qualitative, but it is apparent that they have these tendencies. In Branch 5, Clusters 2 and 7 share a similar context. Clusters 8 and 10 also partially share context because ICT, digital technologies, and universities have played essential roles in development.

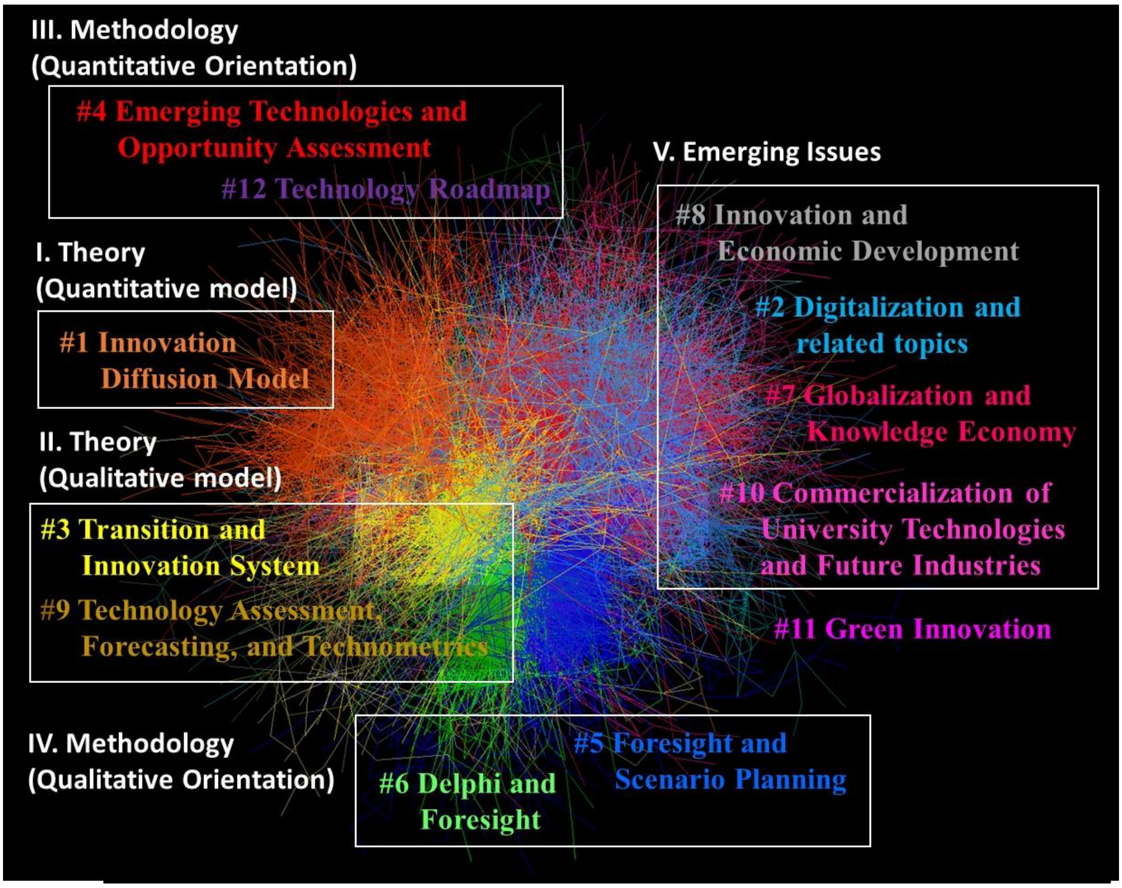

Fig. 2 Citation network structure of *TFSC*.

4.2 Cross-sharing topics among citation clusters

As supplementary support for citation clusters, Figure 3 shows a hierarchical topic tree (HTT) generated by the collected *TFSC* articles. Rooted in "technologies" with three key branches, including "technological development," "opportunities," and "government", the HTT highlights *TFSC*'s technological foci and the interactions among technologies and social, economic, societal, and environmental implications.

Compared with the results of citation network analysis, where the focus is on the whole pathway from technology to social change, the branches of HTT shed light on different stages and aspects of the pathways.

Specifically, in the "technological development" branch, topics, such as "technological forecasting," "roadmapping," "technological innovation," "technological change," "disruptive technologies," and "innovation systems" refer to the theoretical bases, approaches, tools, and research directions of *TFSC*'s interests in science, technology, and innovation studies. This branch also lists certain rising interests of the *TFSC* community, such as "technological convergence," "nanotechnology," "Industry 4.0," and "sustainable development". This branch focuses on the upstream of the pathway from technology to social change.

The "opportunities" branch focuses on the middle or downstream of the pathway. That is, they recognize the competitive advantages and disadvantages of technologies and their holders by responding to questions, such as "who – where – when – what – why – how" (Porter and Detampel, 1995). This branch also mixes topics with "entrepreneurship" and "business model", which in some sense overlaps with Citation Cluster 3 and moves further from technology opportunity analysis to seek approaches to facilitate these "opportunities" to support technology transfer and commercialization.

The "government" branch focuses on the complex interactions among different actors. It is an umbrella covering *TFSC*'s broad interests in external factors that pull and/or push technological development. This branch, on one hand, contains studies on understanding the stakeholders of technologies, such as "developing countries/economies," "industries" "enterprises," "policymakers," and "universities," and on the other hand, it particularly highlights quantitative and qualitative approaches for decision-making support, e.g., "scenario planning," "organizational learning," "patent data," "uncertainty," and "empirical results". In addition, "R&D", as a highlight in this branch, bridges the two parts within an interactive framework.

We can add cross-sharing topics to the branch as:

- Branch 1: Theory (Quantitative Model)
- Branch 2: Theory (Qualitative Model)
- Branch 3: Method (Quantitative Orientation)

- Branch 4: Method (Qualitative Orientation)
- Branch 5: Emerging Issues
- Topic 1: Technological Development
- Topic 2: Opportunity for Commercialization and Social Change
- Topic 3: Actors, Organizations, and Interactions.

It is also interesting to compare HTT with the seven themes identified by Zhu and Cunningham (2022) from a technical perspective; despite both belonging to text analytics, HTT is based on network analytics, which highlights the hierarchical topological structure of a co-term network and identifies topics by recursively detecting densely connected term communities layer by layer, while Zhu and Cunningham's study facilitated hierarchical topic models, in which all topics are identified by conducting a one-off non-negative matrix factorization on a document-term matrix, and the topic hierarchy is calculated based on topic co-occurrence. Different methodological designs yield results with different emphasis. For example, Zhu and Cunningham's results provide a bird's eye view of the seven dominative themes and their associations at the macro level. Complementarily, the results from the HTT profile the research landscape with fine-grained topics from top to bottom, with more stratified branches that indicate the specific details of the topic composition. However, similar to “all roads lead to Rome,” we can easily link Zhu and Cunningham’s seven themes with HTT’s three branches and sub-topics. For example, Themes “technological” and the majority of “innovation,” “change,” and “transition” can be linked with the “technologies” branch, Themes “social,” “forecasting” and parts of “transition” may belong to the “government” branch, and, then, the “opportunities” branch covers the main body of Theme “market”.

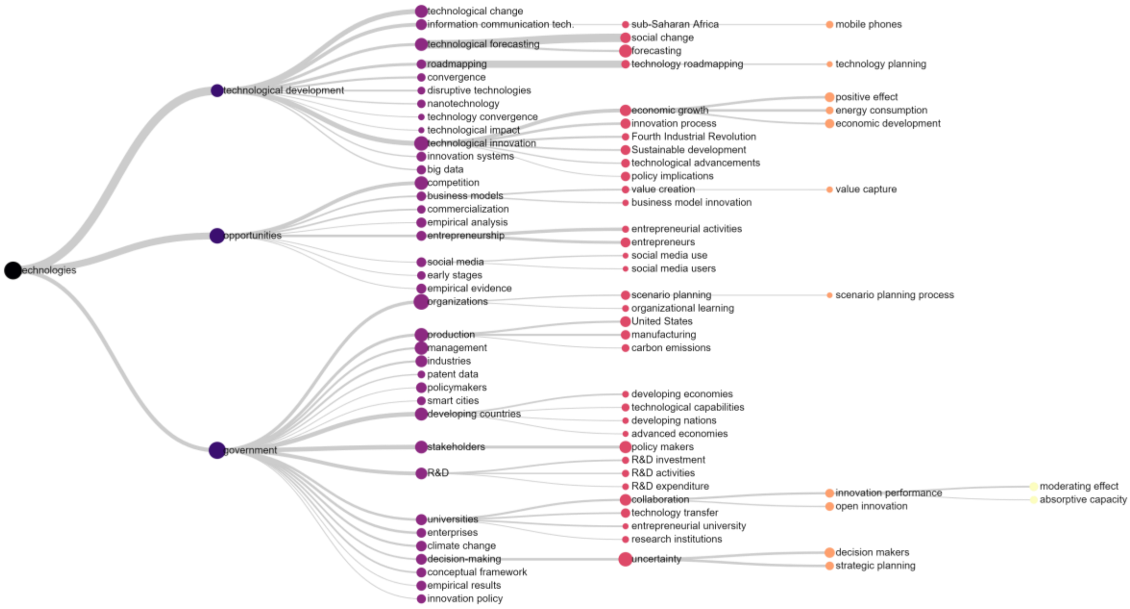

Figure 3. Hierarchical topic tree of *TFSC* articles

4.3 Perspectives on the future direction of *TFSC*

What is or should be the future direction of *TFSC*? When we consider the current trend, Branch 5 is promising and will develop by incorporating future new issues. On the theoretical and methodological aspects, transition and innovation system is the most emerging field and quantitative methods seem to still have room for development by incorporating achievements in the other branches. In addition to such developments along the current path of the trend, we expect the revitalization of the origins of *TFSC*. An example is technology assessment. Although Cluster 9 is the oldest, considering the increasing importance of impact bonds and social entrepreneurship, there should be a resurgence of interest in impact assessment of technologies on social issues. Integrating assessment of technologies and social issues will be a promising topic. Another is innovation diffusion. Although Cluster 1 is rather old, long economic waves can be also liked with technology and societal impacts. ICT has caused the long wave, and what is the next? Some candidates of general-purpose technologies causing the next wave might be gene editing, quantum computing, etc. Economic impact assessments of those technologies and modeling their diffusion and impact path are challenging and attractive research topics.

We also anticipate the future direction of *TFSC* through a SEP created by *TFSC* articles published in the past five decades. The following shows two directions for *TFSC* development: convergence and divergence among branches and topics, and the extension of topics in emerging issues. As a slight extension from the HTT's three big branches in Figure 4, SEP draws seven communities to cover *TFSC*'s interests in various technology-related topics, such as "technological forecasting," "roadmapping," and "tech mining," and their broader scope in science, technology, and innovation studies, e.g., "innovation system," as well as social, political, economic, and environmental implications, e.g., "social system," "social capital," and "climate policy". One of the highlights of SEPs is to foresee potential emerging topics raised in recent years, and such topics are at the end of those pathways. Therefore, we conclude the following future directions for the *TFSC* community: (1) The interactions among technologies and a broad range of social factors – e.g., "human capital," "sustainable development," "public opinion," "entrepreneurial university," and "organizational ambidexterity" delve into urgent real-world concerns and issues, and their outcomes empirically inform related technological stakeholders and policymakers. (2) Novel models to support decision-making in R&D scenarios indicate the pursuit of the *TFSC* community in data/problem-driven methodological development and business model innovation. Particularly, advanced techniques in artificial intelligence and data science (e.g., "text mining" and "fuzzy set") and large-scale data sources (e.g., "social media") become attractive and handleable for the community. (3) Timing topics demonstrate the *TFSC* community's sensitivity and quick reaction to real-world issues, concerns, and problems, including "COVID-19," "emission reduction," and certain emerging technologies and concepts, such as "Industry 4.0," "blockchain technology," and "big data".

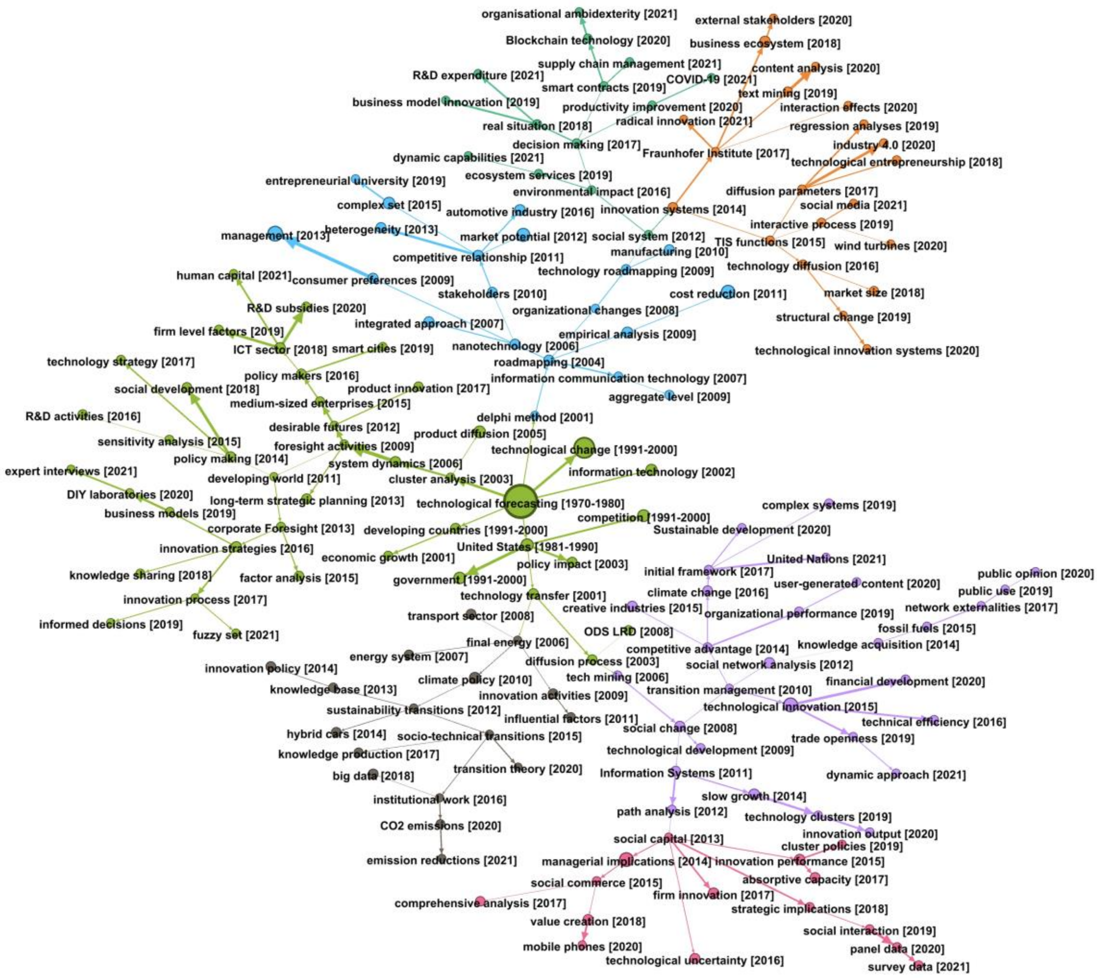

Figure 4. Scientific evolutionary pathways of *TFSC* articles between 1970 and 2021

5. Conclusion

In this study, we analyzed the citation network structure of publications in technological forecasting and social change since 1969 using citation network analysis. We identified major 16 citation clusters and characterized them as emerging and relevant. Based on a systematic review of the papers in each cluster, we classified these clusters into five branches. Branch 1 focuses on the theory and quantitative model of innovation diffusion. Branch 2 is a qualitative theory and model of transition and innovation systems, the origin of which appears to be technology assessment, forecasting, and technometrics. Branch 3 is a methodology with a quantitative orientation, including emerging technologies, opportunity assessment, and a technology roadmap. Branch 4 is a methodology with a qualitative orientation, including foresight, scenario planning, Delphi, and foresight. Branch 5 is rather application-focused and includes digitalization, globalization and the knowledge economy, innovation and economic development, and the commercialization of university technologies and future industries. Green innovation is an emergent cluster with strong connections to diverse branches. We also used a hierarchical topic tree and scientific evolutionary pathways to analyze their appearance and evolution. By adopting topic models, we identify cross-sharing topics among citation clusters. These topics are threefold. Topic 1 is technological development, Topic 2 is an opportunity for commercialization and social change, and Topic 3 is actors, organizations, and their interactions. This study is expected to work as an intellectual foundation to discuss and envision future directions and development pathways for *Technological Forecasting and Social Change*, and our community of technology and innovation management.

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