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Uncovering the knowledge flows and intellectual structures of research in *Technological Forecasting and Social Change*: A journey through history

Shikhar Sarin[a,*], Christophe Haon[b,c], Mustapha Belkhouja[b], Alicia Mas-Tur[d], Norat Roig-Tierno[e], Trina Sego[a], Alan Porter[f,g], José M. Merigó[h,i], Stephen Carley[g]

[a] College of Business and Economics, Boise State University, Boise, ID 83725, United States
[b] Grenoble Ecole de Management, F-38000 Grenoble, France
[c] IREGE, Université Savoie Mont Blanc, France
[d] Department of Management, University of Valencia, Av. Tarongers S/N, Valencia 46022, Spain
[e] ESIC Business & Marketing School, Valencia, Spain
[f] Ivan Allen College of Liberal Arts, Georgia Institute of Technology, Savant Building, 631 Cherry Street NW, Atlanta, GA 30332-0525, USA
[g] Search Technology, Inc., 6025 The Corners Parkway, Suite 202, Norcross, GA 30092, USA
[h] School of Information, Systems & Modelling, Faculty of Engineering and Information Technology, University of Technology Sydney, 81 Broadway, Ultimo 2007, New South Wales, Australia
[i] Department of Management Control and Information Systems, School of Economics and Business, University of Chile, Av. Diagonal Paraguay 257, 8330015 Santiago, Chile

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ABSTRACT

Technological Forecasting and Social Change (TF&SC) celebrates its fiftieth anniversary this year. The anniversary represents an appropriate time for an introspective analysis of the journal's history and impact. This study presents a bibliometric analysis of TF&SC in terms of how often TF&SC is cited by other journals (citation outflow), how often other journals are cited by TF&SC (citation inflow), citations by Web of Science and SCImago disciplinary categories, most-cited articles in TF&SC, co-citation of journals, and co-occurrence of author keywords. Analysis is conducted by using the Web of Science (WOS) database and Visualization of Similarities (VOS) viewer software. The incoming versus outgoing citation patterns identified here suggest an asymmetry in the knowledge flows of TF&SC. Papers published in TF&SC have increasingly cited knowledge from journals in Technology and Innovation Management (TIM), Engineering, and Decision Sciences, but the journal impacts a different set of disciplinary categories such as Energy, Environmental Sciences, and Social Sciences. From 1969–2018, Innovation, Foresight and Forecasting feature as the most popular keywords. Focus on topics such as Patents/Patent Analysis, Climate Change, Sustainability, and Energy seems to have intensified in the last decade.

Findings suggest that focus on two countries of interest, India and China, is emerging in research published in TF&SC. Different regions of the world can be expected to place differential emphasis on various topics based on their socioeconomic-technological environments. The journal needs to be receptive to this diversity of perspectives from a growing community of scholars worldwide.

If you don't know where you've come from, you don't know where you're going.

~ Maya Angelou (Poet, Author, Civil Rights Activist)

1. Introduction

TechnologicalForecasting and Social Change (TF&SC) celebrates its fiftieth anniversary this year. Such milestones and commemorative occasions offer an apt time to take stock and look ahead (Di Benedetto et al., 2018). There is a long tradition of disciplines and journals availing of such opportunities to engage in healthy introspection (e.g.,

* Corresponding author.
E-mail addresses: ssarin@boisestate.edu (S. Sarin), christophe.haon@grenoble-em.com (C. Haon), mustapha.belkhouja@grenoble-em.com (M. Belkhouja), alicia.mas@uv.es (A. Mas-Tur), norat.roig@esic.edu (N. Roig-Tierno), tsego@boisestate.edu (T. Sego), aporter@searchtech.com (A. Porter), jmerigo@fen.uchile.cl (J.M. Merigó), stephen.carley@searchtech.com (S. Carley).

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Baumgartner and Pieters, 2003, Green et al., 2003, Huber et al., 2014, Sarin et al., 2018a). Many researchers suggest that it is vital for journals and domain areas to periodically conduct critical self-evaluation of their history, evolution and impact (e.g., Reibstein et al., 2009, Sarin et al., 2018b, Varadarajan and Jayachandran, 1999).

Such longitudinal and macro-level analyses often reveal patterns and long-term trends that would otherwise remain hidden, and point to emerging areas of interest and improvement (e.g., Clark et al., 2014, Sarin et al., 2018b, Shafiq, 2013). Following in this rich tradition, we use bibliometric analysis to examine the evolution, impact, and the intellectual structure of *Technological Forecasting and Social Change* through the first fifty years of its existence. In this paper, we present the first of two parts of a bibliometric analysis of 50 years of TF&SC publications conducted by overlapping author teams. In the second paper that follows (Mas-Tur et al., 2020), the author team explores TF&SC publications and citations by year, the most productive and influential TF&SC authors, the most productive and influential universities contributing to TF&SC, and the most productive and influential countries and supra-regions contributing to TF&SC. Mas-Tur et al. (2020) also analyze co-citation of authors, and bibliographic coupling of authors, institutions and countries.

In this paper, the author team explores how often TF&SC is cited by other journals (citation outflow), how often other journals are cited by TF&SC (citation inflow), citations by Web of Science and SCImago disciplinary categories, most-cited articles in TF&SC, co-citation of journals, and co-occurrence of author keywords. Analysis is conducted by using the Web of Science (WOS) database and visualization of similarities (VOS) viewer software (Van Eck et al., 2010).

This study targets the following queries. First, which journals and disciplinary domains is TF&SC influencing the most? Second, which TF&SC articles and topic areas have been most influential? Third, which journals and disciplinary domains have had the most influence on TF&SC publications? Fourth, which articles/books and topic areas have had the most influence on TF&SC publications? Finally, we also explore how these patterns have evolved over time and by geographic region. Together with the second part of this bibliometric introspection (Mas-Tur et al., 2020), we hope to illuminate the journal's advances and trends, and to guide authors and reviewers to the journal's most influential studies.

The rest of this paper is organized as follows. Section 2 describes the methods used. Section 3 presents our results. Finally, Section 4 offers a discussion with concluding remarks.

2. Methods

Bibliometric analysis involves the examination of a corpus of literature in terms of quantitative indicators such as citations, topical associations, authorships, geographic and institutional patterns, often over a period of time (Ellegaard and Wallin, 2015). Bibliometric techniques provide an objective analysis, as they only consider the statistical results extracted from the selected scientific database, in this case Web of Science Core Collection. Such analyses are standard methodologies for assessing the impact of journals, authors, institutions and disciplinary domains, and for examining patterns of influence among journals or disciplines (e.g., Biemans et al., 2010, Clark et al., 2014, Ellegaard and Wallin, 2015, Sarin et al., 2018a). Bibliometric analysis can rely on a variety of calculations, such as citation counts or publication counts by author, institution, country or region, or citation co-occurrence (Mas-Tur et al., 2019). For the analysis reported here, we examine TF&SC citations of other journals, other journals' citations of TF&SC, the disciplines of journals that influence and are influenced by TF&SC, TF&SC articles that are most often cited, co-citation of journals by TF&SC authors, TF&SC author keywords, co-occurrence of keywords, and keywords by geographic region.

TF&SC's impact on knowledge presented in other journals is indicated by how often other journals cite TF&SC; this is referred to as the *citation or knowledge outflow*. Conversely, how often other academic journals are cited by TF&SC indicates how these journals influence the knowledge being generated in TF&SC (Clark et al., 2014); this is referred to as the *citation or knowledge inflow*.

The disciplinary background of these journals provides an indicator of the knowledge bases TF&SC draws upon. By comparing the disciplines of journals citing TF&SC with those of journals cited by TF&SC, we can explore what Clark et al. (2014) called the "intellectual balance of trade." TF&SC might not influence the same disciplines that it is influenced by.

Keyword co-occurrence or co-word analysis draws on the most common keywords used in the document to elaborate the conceptual framework of a research field (Callon et al., 1983, Ding et al., 2001). Co-citation refers to two documents receiving a citation from the same third document (Small, 1973). Thus, co-citation provides a measure of a relationship between the references cited by the set of documents under study.

The study applies a mapping technique to the bibliographic information by using Visualization of Similarities (VOS) viewer software (Van Eck et al., 2010). Bibliometric mapping, also known as maps of science, monitors a scientific field to determine its cognitive structure, evolution and main actors (Noyons et al., 1999), and provides a clearer visualization of the results (Merigó et al., 2016). According to Small (1999), a map of science is "a spatial representation of how disciplines, fields, specialties, and individual papers or authors are related to one another as shown by their physical proximity and relative locations…" The VOS viewer software (http://www.vosviewer.com/) is often used to map the bibliographic material because it supports all the features under study (Van Eck et al., 2010).

Note that this work uses fractional counting in the analysis of the bibliographic data in the VOS software. That is, it always gives one unit to each article and then fractions the value of each co-author according to the total number of co-authors (Cancino et al., 2017, Gaviria-Marín et al., 2018). The alternative approach in VOS viewer is the full counting method, which gives one unit to each co-author independently of the total number of co-authors. The main advantage of fractional counting is that it measures appropriately the results considering the number of co-authors in each document. Full counting approach gives more importance to those articles that have many coauthors, which has the potential of creating visualization problems in the figures.

3. Results

In the sections that follow, we present the results of the study. In Section 3.1, we explore journals that cite and are cited by TF&SC. In Section 3.2, we report on TF&SC citation impact by discipline. In Section 3.3, we identify the most-cited articles published in TF&SC. In Section 3.4, explore co-citation of journals by TF&SC authors. Finally, in Section 3.5, we analyze author keywords, co-occurrence of keywords, and keywords by geographic regions.

3.1. Journals citing and cited by TF&SC

From 1969–2018, TF&SC published 4794 articles. Bibliometric records from the Web of Science (WoS) identified 31,205 documents that cited at least one TF&SC article over this period. These documents come from 7529 different sources (journal articles, book chapters, conference papers, etc.) and generated 56,233 citations of TF&SC. Fig. 1 shows the number of papers published in TF&SC each year from 1969 to 2018, and the number of citations received by TF&SC each year. After remaining relatively steady for the first three decades, both the number of papers published in TF&SC and citations of TF&SC increase after 2001. Annual citations show a dramatic increase from 1995 to 2007. Although still high, the last decade has seen swings in the citations counts per year. The number of papers published per year in TF&SC increased sixfold from 2005 to 2018, with a majority of that increase coming

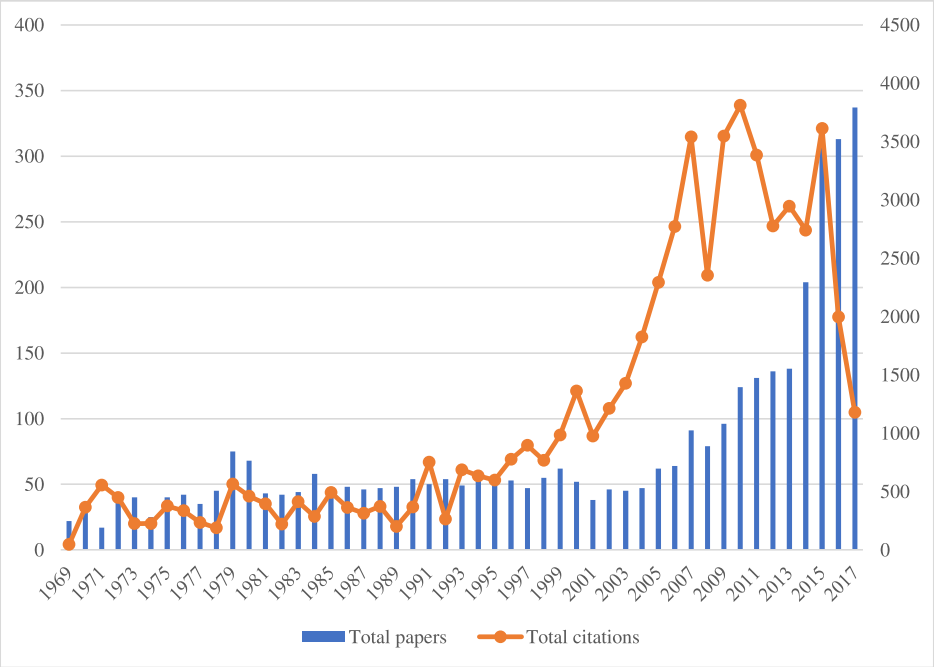

Fig.. 1. Articles Published in TF&SC and Citations Received by TF&SC per Year.

within the last decade.

To investigate the impact of TF&SC (i.e., knowledge outflow), we used the above-mentioned records of citations of TF&SC articles on other journals. To examine the knowledge inflow of TF&SC (i.e., sources cited by TF&SC articles), we extracted citation data from the 4794 articles published in TF&SC between 1969 and 2018. The resulting database contained 170,077 citations from 49,336 different sources (journal papers, book chapters, conference papers, etc.). Tables 1 and 2 list the top 50 citing and cited journals for TF&SC, respectively.

Because of significant increases in TF&SC publications and citations in recent years, a 50-year profile will be skewed in favor of the most recent decade (2009–2018). A decade-by-decade breakdowns of knowledge outflow and knowledge inflow patterns are presented in the Online Appendix Tables A1-A5 and Tables A6-A10 respectively. Tables A5 and A10 suggest that citation outflow and inflow numbers from the most recent decade (2009–2018) dominate those from first four decades since TF&SC began publication.

The journal most frequently citing and cited by articles published in TF&SC has been TF&SC itself (12,206 self-citations over the 50-year period). Such self-citations were particularly frequent in the first three decades (1969–1999). For example, Table A1-A3 on the citing side show that from 1969 to 1978, the highest number of citations of TF&SC were in TF&SC (526 self-citations), followed by *Futures* (29) and *Policy Sciences* (12). This trend continued from 1979 to 1988 with 841 self-citations followed by *Futures* (55) and *Journal of Scientific and Industrial Research* (38); and 1989–1998 with 791 self-citations followed by *Futures* (56) and *Journal of Forecasting* (55).

Over the last two decades (1999–2018), TF&SC impact is distributed over a broader set of journals (see Tables A4-A5). From 1999–2008, the top five journals citing TF&SC focus on technology and innovation management (i.e., *Technovation, Research Policy* and *International Journal of Technology Management*). However, in the most recent decade (2009–2018), journals citing TF&SC most often relate to the environment, energy or sustainability (i.e., *Journal of Cleaner Production; Sustainability*; and *Energy Policy*), signaling a shift in the impact of TF&SC. Interestingly, the multidisciplinary journal *Futures* is not only the second most frequently citing journal of TF&SC over the 50-year period (Table 1), but has faithfully ranked among the top 5 journals citing TF&SC in every decade of its publication (see Tables A1-A5). A closer examination of Tables A1-A10 suggests that the intellectual knowledge structure of TF&SC is growing with time, as cross-citations with other journals increase notably with each decade.

We see notable differences between the journals that influence TF&SC publications and those that are influenced by TF&SC. Of the top ten journals citing TF&SC (Table 1), four are also among the top ten journals cited by TF&SC (Table 2). However, *Strategic Management Journal* and *Management Science* are respectively the fourth and the sixth most frequently cited journals by TF&SC, but neither frequently cites TF&SC in return (i.e., they are not among the top fifty of journals citing TF&SC). Similarly, *Academy of Management Review* (#8), *Academy of Management Journal* (#9), and *Administrative Science Quarterly* (#10) are among the top ten journals cited by TF&SC, but none of them are among the top ten journals citing TF&SC. To summarize, management sciences provide important foundation to the knowledge generated in TF&SC, but the converse seems not to be true.

Conversely, while *Journal of Cleaner Production* (#3) and *Sustainability* (#4) frequently cite TF&SC, they are much less often cited by it. The knowledge outflow and inflow patterns presented in Tables 1 and 2 suggest that energy and environmental interests appear much more on the citing side than on the cited side. We discuss these implications at a more aggregate disciplinary level in the next section.

3.2. TF&SC citation impact by discipline

In this section, we explore the disciplinary domains that journals citing and cited by TF&SC occupy. In Section 3.2.1, we examine these disciplines as defined by Web of Science disciplinary categories. In Section 3.2.2, we examine these disciplines as defined by SCImago disciplinary categories.

3.2.1. TF&SC citation impact by web of science disciplinary categories

We examined the citation exchange patterns between TF&SC and disciplinary categories as classified by the Web of Science. As presented in Table 3, these results suggest that Management, Business, and Planning & Development represent the top three disciplinary categories of works cited by TF&SC publications, accounting for approximately 65% of the citations. The same categories lead in the disciplines citing

Table 1
Top 50 ranking of journals most often *Citing* TF&SC 1969–2018.

Citing journal	Rank	Citations
Technological Forecasting and Social Change	1	12,206
Futures	2	1106
Journal of Cleaner Production	3	1033
Sustainability	4	952
Energy Policy	5	943
Technology Analysis and Strategic Management	6	800
Research Policy	7	646
Scientometrics	8	618
Technovation	9	560
Renewable & Sustainable Energy Reviews	10	548
Energy	11	349
Environmental Innovation and Societal Transitions	12	303
Foresight	13	301
Applied Energy	14	294
Expert Systems with Applications	15	289
International Journal of Technology Management	16	277
R & D Management	17	276
Energy Research & Social Science	18	252
International Journal of Forecasting	19	229
Plos One	20	200
Science and Public Policy	21	199
Journal of Engineering and Technology Management	22	197
Ecological Economics	23	189
Climatic Change	24	188
European Journal of Futures Research	25	181
Global Environmental Change-Human and Policy Dimensions	26	177
IEEE Transactions on Engineering Management	27	171
European Journal of Operational Research	28	169
Telecommunications Policy	29	167
Environmental Modelling & Software	30	160
Journal of Business Research	31	148
Environmental Research Letters	32	146
Environmental Science & Policy	33	144
International Journal of Production Economics	34	141
Computers & Industrial Engineering	35	140
Energies	36	139
Journal of Technology Transfer	37	137
Industrial Management & Data Systems	38	132
Journal of Scientific & Industrial Research	39	125
International Journal of Hydrogen Energy	40	123
Technology in Society	41	122
Agricultural Systems	42	117
Energy Economics	42	117
International Journal of Innovation and Technology Management	44	114
International Journal of Production Research	45	111
Transportation Research Part A-Policy and Practice	46	109
Journal of Informetrics	47	107
Creativity and Innovation Management	48	106
Land Use Policy	48	106
European Planning Studies	50	100

Table 2
Top 50 ranking of journals most often *Cited by* TF&SC 1969–2018.

Cited Journal	Rank	Citations
Technological Forecasting and Social Change	1	12,206
Research Policy	2	5203
Futures	3	1763
Strategic Management Journal	4	1757
Energy Policy	5	1709
Management Science	6	1575
Technovation	7	1489
Academy of Management Review	8	1083
Academy of Management Journal	9	1007
Administrative Science Quarterly	10	937
Technology Analysis and Strategic Management	11	891
Harvard Business Review	12	866
Organization Science	13	849
American Economic Review	14	828
Science	15	770
Scientometrics	16	766
Journal of Product Innovation Management	17	738
Journal of Marketing	18	648
Industrial Corporate Change	19	605
Long Range Planning	20	582
MIS Quarterly	21	540
Journal of Marketing Research	22	528
Journal of Business Research	23	481
Econometrica	24	469
IEEE Transactions on Engineering Management	25	443
Quarterly Journal of Economics	26	423
European Journal of Operational Research	27	401
Journal of Management Studies	28	397
Science and Public Policy	29	394
International Journal of Forecasting	30	392
Economic Journal	31	385
Journal of Business Venturing	31	385
Journal of Cleaner Production	33	384
Journal of Political Economy	34	378
Research Technology Management	35	376
Expert Systems with Applications	36	367
World Development	36	367
Ecological Economics	38	360
International Journal of Technology Management	39	359
California Management Review	40	351
Foresight	41	344
Journal of Management	42	342
Marketing Science	43	337
Nature	44	319
Energy Economics	45	313
Information & Management	46	307
Small Business Economics	47	306
Telecommunications Policy	48	295
Renewable & Sustainable Energy Reviews	49	288
Computers in Human Behavior	50	265

TF&SC as well, accounting for nearly 42% of TF&SC citations. TF&SC relies on the management, business, and planning and development literatures to create new knowledge, which is then largely cited (58%) by works outside of these disciplines. This finding suggests that TF&SC serves as a guidepost at the intersection of technology, economics and social science, and offers hints regarding where other disciplines (e.g., engineering) might be headed. It may be natural that researchers in other fields just take these hints implicitly, as they choose their research topics. This may not necessarily result in citations to TF&SC.[1]

Disciplines with an applied mathematics orientation (12% total), including Operations Research & Management Science (5%), Industrial Engineering (4%), and Mathematics (3%), are among the top cited disciplinary categories. These disciplinary categories are also rather prominent among works citing TF&SC papers, with Operations Research & Management Science, and Industrial Engineering appearing among the top ten citing disciplinary categories.

Disciplines related to the environment or energy (33% total), including Environmental Sciences (11%), Environmental Studies (9%), and Energy & Fuel (7%), as well as the relatively new Green & Sustainable Science & Technology category[2] (6%), are among the disciplinary categories that cite TF&SC most often. Overall, TF&SC seems to be a net exporter of knowledge to environmental, energy and sustainable science disciplines, as these disciplines cite TF&SC works more often than TF&SC works cite them.

Figs. 2 and 3 show a bibliometric mapping of WoS disciplinary categories cited by and citing TF&SC. The nodes in these maps reflect citations for particular WoS disciplinary categories. We organized

[1] We thank an anonymous reviewer for this insightful suggestion.

[2] "Green & Sustainable Science & Technology" is a disciplinary category recently added by WoS and is not included in our concordance and thesaurus for cited journals yet. Sources other than journals are not heavily indexed into WoS disciplinary categories. In general, books, reports, and other non-journal literature are not generally indexed.

Table 3
Most often cited and citing works by web of science categories (WC).

Web of Science Category (WC)	WC Categories Most Cited by TF&SC Papers			WC Categories Most Citing TF&SC Papers		
	Rank	Share	Citations	Rank	Share	Citations
Management	1	24%	30,200	2	15%	5211
Business	2	24%	30,141	1	15%	5237
Planning & Development	3	17%	21,683	3	12%	4113
Economics	4	11%	14,383	5	10%	3476
Operations Research & Management Science	5	5%	5893	8	6%	2082
Environmental Studies	6	4%	4687	6	9%	2995
Industrial Engineering	7	4%	4465	10	5%	1605
Environmental Sciences	8	3%	4251	4	11%	3927
Information Science & Library Science	9	3%	4095	12	4%	1319
Mathematics	10	3%	3561	11	0%	34
Energy & Fuels	11	3%	3196	7	7%	2293
Green & Sustainable Science & Technology	xx	xx	xx	9	6%	2079

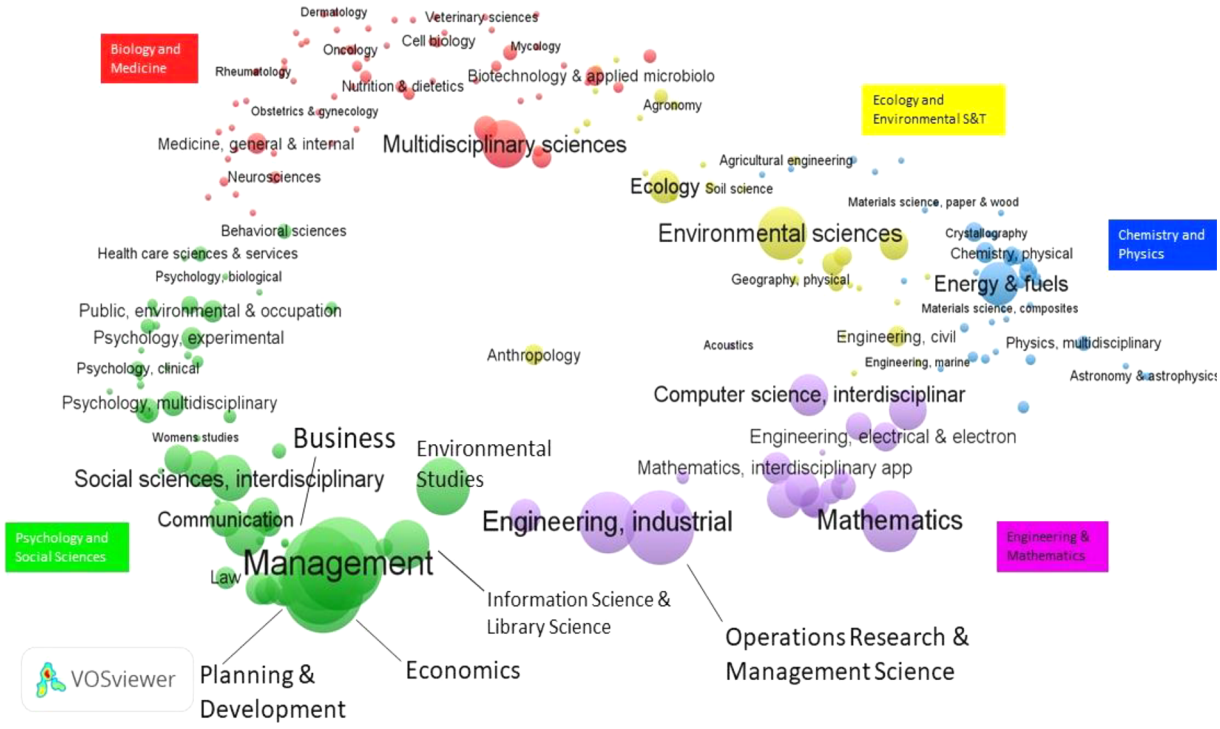

Fig. 2. Web of science categories cited by TF&SC Papers.

citations (both citing and cited by TF&SC) by meta-discipline.[3] Color-coding shows aggregation of citations into five meta-categories: Social Sciences & Psychology, Engineering & Mathematics, Ecology & Environmental Science & Technology, Chemistry & Physics, and Biology & Medicine (also see Table A11 in the Online Appendix). Table A11 shows that the most cited and the most-citing meta-discipline is Social Sciences & Psychology. This is largely explained by the fact that TF&SC belongs to that meta-discipline. However, cites to articles in journals indexed in other meta-disciplines, especially in Engineering & Mathematics, are substantial (18%). Furthermore, 48% of citations received by TF&SC articles come from outside the Social Sciences & Psychology meta-discipline.

Fig. 2 shows that the meta-discipline most often cited by TF&SC publications is Social Sciences & Psychology with more than 78,000 citations (green in Fig. 2). Similarly, Fig. 3 shows that the meta-discipline most often citing TF&SC publications is also Social Sciences & Psychology with more than 30,000 citations (green in Fig. 3). The meta-discipline least often cited by and least often citing TF&SC is Biology & Medicine (red in Figs. 2 and 3).

3.2.2. TF&SC citation impact by SCImago disciplinary categories

To further explore knowledge flows across disciplines, we also used a more detailed categorization of disciplines provided by SCImago.[4] According to SCImago, TF&SC belongs to both the Business and Psychology disciplinary categories. Within Business, TF&SC is categorized

[3] To facilitate recognition of interpretable patterns, several authors have aggregated the 250+ WCs into some 19 or so macro-disciplines, based on disciplinary category to category cross-citation patterns (Leydesdorff and Rafols, 2009, Leydesdorff et al., 2013, Porter and Rafols, 2009). To further consolidate, we have gone on to group these into meta-disciplines, such as the five presented here. On his website, Loet Leydesdorff provides tools to facilitate calculating these measures of interdisciplinarity (www.leydesdorff.net).

[4] SCImago is a research group from the Consejo Superior de Investigaciones Científicas (CSIC), University of Granada, Extremadura, Carlos III (Madrid) and Alcalá de Henares, dedicated to information analysis, representation and retrieval by means of visualization techniques. It includes the journals and country scientific indicators developed from the information contained in the Scopus database (Elsevier B.V.). https://www.scimagojr.com

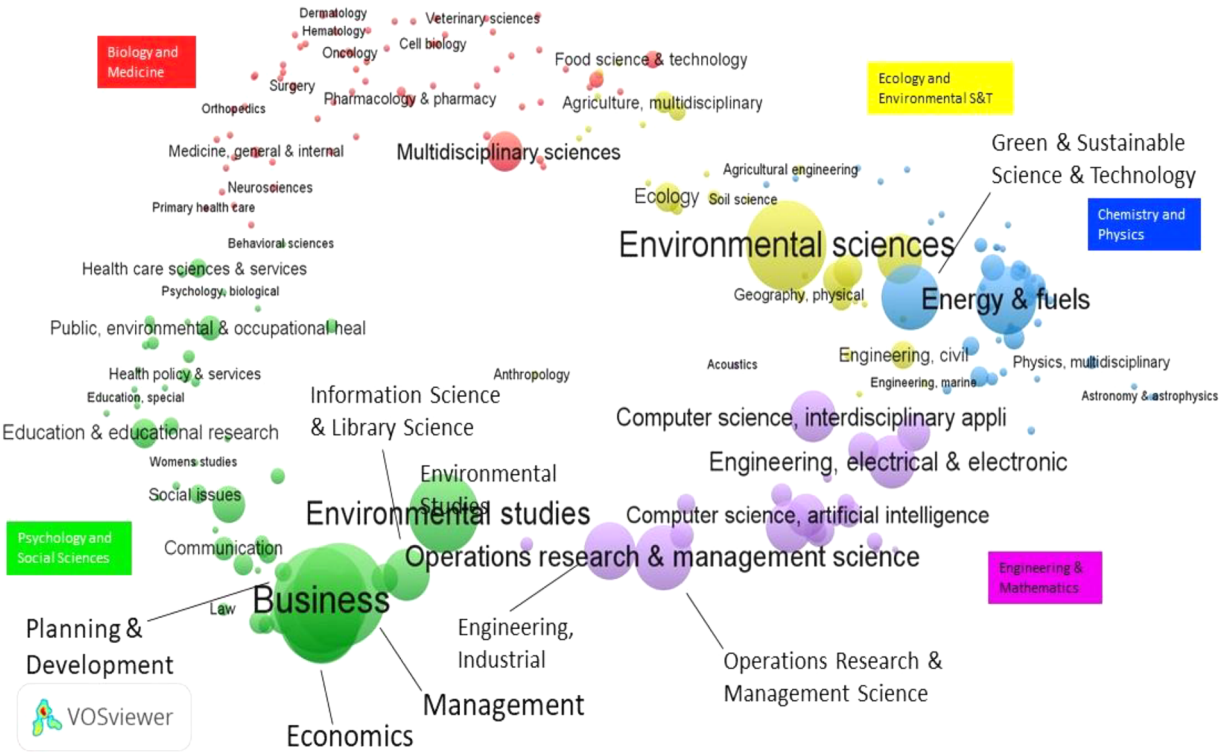

Fig. 3. Web of science categories citing TFSC.

in the Technology and Innovation Management (TIM) subcategory. However, Phillips (2019) notes that TF&SC has long recognized that technological change and socioeconomic change drive each other reciprocally. Phillips adds that TF&SC has stood at the intersection of technology, economics and social science. TF&SC articles have rarely addressed the management of individual or specific companies. While the journal publishes articles addressing the marketing, entrepreneurship, finance, and aspects of technology forecasting & assessment, that does not make TF&SC a business journal.

As such, classification of TFSC strictly as a business journal may not be completely accurate and could have the potential of affecting our analyses.[5] Thus in order to minimize any bias resulting from the way TF&SC is categorized by the WoS and SCImago databases, we isolated TF&SC from any subcategories it is supposed to be linked to (i.e., Business, TIM and Psychology) in subsequent analyses.

Table 4 and Fig. 4 present the SCImago disciplinary categories of works citing TF&SC 1969–2018, in total and by decade. Table 4 shows that once TF&SC is excluded from those (sub) categories to which it belongs, a variety of disciplinary categories rank higher than Business or TIM in terms of works citing TF&SC. As top disciplines citing TF&SC, Energy (#2), Environmental Science (#3), Social Sciences (#4), Engineering (#5), and the more general Business category (#6) highlight the multidisciplinary impact of TF&SC.

Fig. 4 presents SCImago disciplinary categories of works citing TF&SC by decade. Instead of using the raw counts, we divided the number of citations in each disciplinary category by the total citations of TF&SC by journals in the top citing list of each decade (Tables A1-A5 in the Appendix). This approach allows us to measure the relative importance of each disciplinary category. Fig. 4 suggests that the relative importance of self-citation has consistently decreased from 67% in 1969–1978 to 23% in 2009–2018. The figure also suggests that the impact on Engineering, Social Sciences, Decision Sciences and Computer Science has been fairly stable over the last 50 years (varying between 5% to 11%). These findings are consistent with Editor-in-Chief, Professor Fred Phillips, contention that TF&SC has one foot in engineering and the other in social science.[6]

Starting the 1989–1998 decade, TF&SC became an increasingly important source of knowledge for the Energy and Environmental Sciences disciplines, especially over the last two decades (increasing from 2% to 13% of citations since 1999 for both categories; see Fig. 4). TF&SC seems to be playing a similarly influential role in the PICMET Conferences since the 1990s. On the other hand, disciplines such as Engineering, Decision Science, Business (excluding TIM and TF&SC), and Econometrics and Finance show a gradual decrease in their frequency of citing TF&SC research over the last two decades.

Table 5 and Fig. 5 present the SCImago Disciplinary Categories of works cited by TF&SC over the 50-year period. Table 5 shows that TIM journals (excluding TF&SC) are the most frequently cited disciplinary category, followed by self-citation and Business (#3 excluding TIM and TF&SC). Fig. 5 further suggests the decreasing importance of self-citation over this period (from 39% to 13%). The rate of citation of Business journals (excluding TIM and TF&SC) has remained fairly steady over the 50-year period (16% on average; see Fig. 5).

Books are cited less frequently today than they were in the early days of the journal. Social Sciences, once the most influential category on TF&SC, has gradually lost impact, earning less than 7% of TF&SC citations in the most recent decade. After increasing impact over the first two decades, citations of Economics, Econometrics, and Finance journals seem to have peaked in 1989–1998 around 21%, and has shown a steady decrease since then to around 9% in the last decade.

Fig. 5 also shows that the citations of TIM journals have increased from 3% to 17% over 50 years. Engineering and Decision Sciences have followed a similar trend (increasing from 5% to 13%, and from 3% to 13%, respectively).

The analysis of citations by and of SCImago disciplinary categories shows an asymmetry in knowledge exchange patterns related to TF&SC.

[5] We thank an anonymous reviewer for this insightful suggestion.

[6] We thank an anonymous reviewer for bringing this to our attention.

Table 4
Citations of TF&SC by SCImago category of citing journal.

Discipline	1969–2018		1969–1978		1979–1988		1989–1998		1999–2008		2009–2018	
	R	Cit	R	Cit	R	Cit	R	Cit	R	Cit	R	Cit
TFSC	1	12,206	1	526	1	841	1	791	1	1378	1	8670
Energy	2	5199			13	22	11	62	7	259	3	4860
Environmental Science	3	5183	5	19	6	103	9	76	5	333	2	4893
Social Sciences	4	4920	2	77	3	183	3	266	6	309	4	4322
Engineering	5	4892	3	55	5	130	4	250	2	512	5	4014
Business (Excluding TIM and TFSC)	6	3959	4	46	2	203	2	324	3	450	6	3470
TIM (Excluding TFSC)	7	2829	7	18	8	91	5	222	4	395	8	2233
Decision Sciences	8	2581	12	10	4	140	6	221	7	259	7	2247
Computer Science	9	1890	5	19	7	98	7	152	9	144	9	1662
PICMET Conferences	10	1369							11	76	10	1293
Economics, Econometrics, and Finance	11	929	11	12	11	48	8	98	10	133	11	866
Agricultural and Biological Sciences	12	423	16	6	15	7	16	8	17	13	12	403
Mathematics	13	415	8	16	9	52	10	68	12	72	13	347
Medicine	14	346	15	8	12	44					14	344
Biochemistry, Genetics and Molecular Biology	15	200	18	2							15	200
Earth and Planetary Sciences	16	188	18	2			13	27	16	19	16	160
Multidisciplinary	17	125	12	10	10	51	12	35	14	24		
Physics and Astronomy	18	123					17	7	13	31	17	97
Arts and Humanities			17	4	14	18	14	17				
Chemical Engineering			8	16					15	23		
Chemistry			8	16								
Material Science			14	9			17	7				
Psychology (Excluding TFSC)							15	15				

Abbreviations: R = Rank; Cit = Citations.
NB: Ranks and citations of categories are based on the top citing journals for each period. The sum of the numbers for each decade thus do not necessarily correspond to the numbers for the full period.

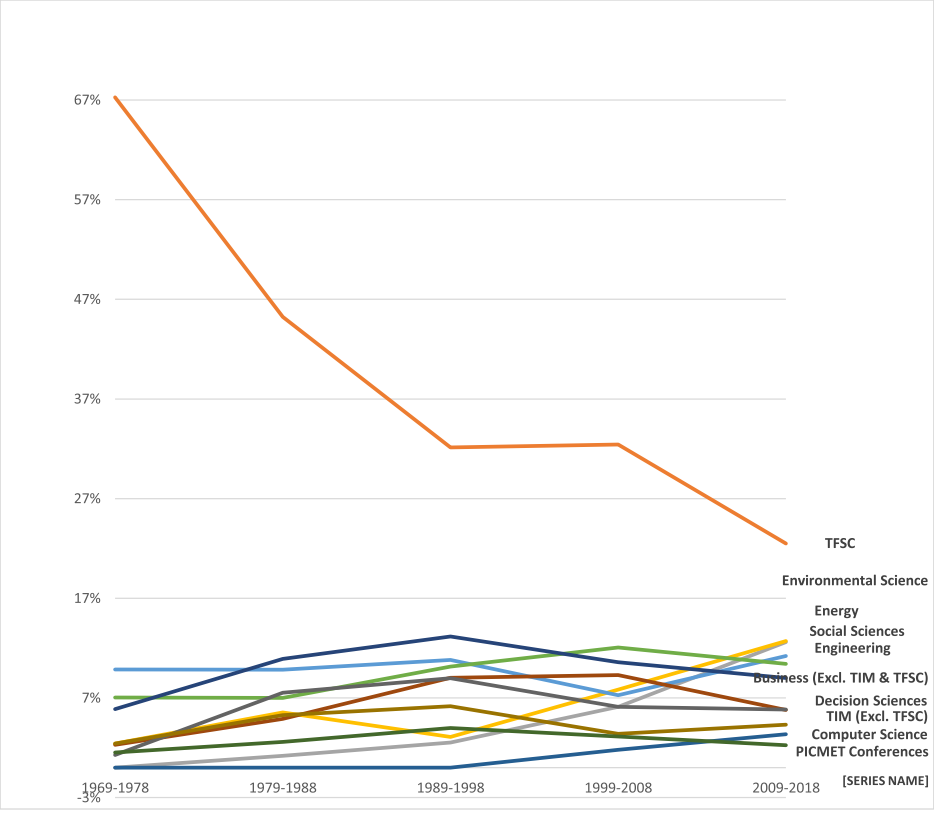

Fig. 4. Incoming citations (Citations of TFSC) by discipline and by decade 1969–2018*
* Threshold 500 citations minimum over 50 years + PICMET conferences.

Again, TF&SC can be seen to act as a guidepost: sourcing knowledge from disciplinary categories such as TIM, business, decision sciences, and economics (all with more than 8000 citations by TF&SC); and hinting where a different set of disciplinary categories such as energy, environmental sciences, and social sciences (all with more than 4000 citations of TF&SC) might be headed. On the other hand, TF&SC seems to be net importer of knowledge from engineering with over 9600 citations of engineering journals in TF&SC relative to only 4800 citations

Table 5
SCImago categories of journals cited by TF&SC.

Discipline	1969–2018		1969–1978		1979–1988		1989–1998		1999–2008		2009–2018	
	R	Cit	R	Cit	R	Cit	R	Cit	R	Cit	R	Cit
TIM (Excluding TFSC)	1	13,539	11	36	8	156	4	348	2	1099	1	11,223
TFSC	2	12,206	1	526	1	841	1	791	1	1378	3	8670
Business (Excluding TIM and TFSC)	3	11,184	3	171	2	385	3	572	3	982	2	9364
Engineering	4	9654	9	63	10	115	5	326	4	887	4	8450
Decision Sciences	5	9261	10	43	6	186	6	298	5	838	5	8058
Economics, Econometrics, and Finance	6	8081	4	135	3	353	2	738	6	809	6	5824
Social Sciences	7	5463	2	187	4	275	7	282	7	637	7	4312
Computer Science	8	2899	15	11			12	66	10	227	8	2744
Environmental Science	9	2847	14	13	13	31	14	37	11	181	9	2614
Energy	10	2694							12	134	10	2560
Arts and Humanities	11	1972	7	79	7	175	10	158	8	293	11	1296
Multidisciplinary	12	1089	6	104	5	195	9	170	9	263	12	578
Medicine	13	866	8	69	11	108	8	252	15	87		
Books	14	430	4	135	9	122	11	81	14	92		
Mathematics	15	401	16	7	15	15	15	31	13	112	13	361
Psychology (Excluding TFSC)	16	265	12	30	13	31	16				14	265
Agricultural and Biological Sciences			16	7	12	32	12	66				
Chemical Engineering			13	14	16		16					

Abbreviations: R = Rank; Cit = Citations.
NB: Ranks and citations of categories are based on the Top citing journals for each period. The sum of the numbers for each decade thus do not necessarily correspond to the numbers for the full period.

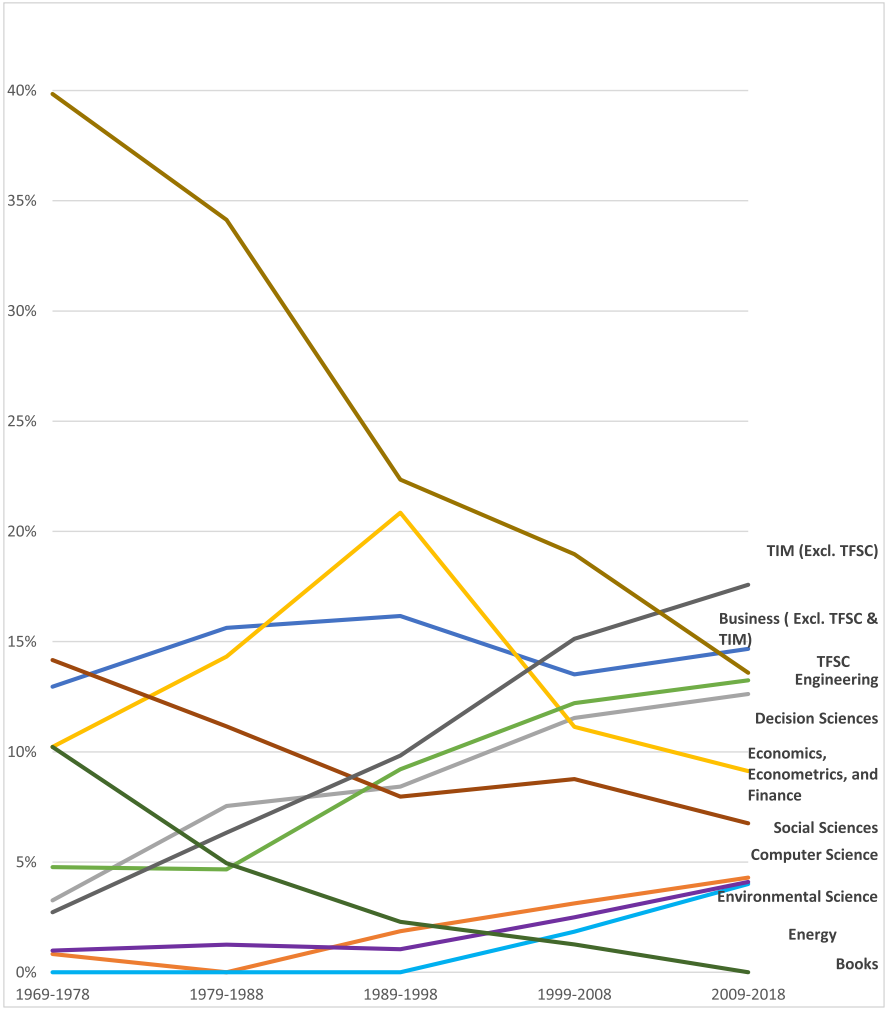

Fig. 5. Outgoing citations (Citations by TFSC) by discipline and by decade 1969–2018*
* Threshold 2000 citations minimum over 50 years + books.

Table 6
The 40 most cited TF&SC articles.

R	TC	C/Y	Year	Title	Author(s)
1	681	56.75	2007	Functions of innovation systems: A new approach for analysing technological change	Hekkert, M., Suurs, R., Negro, S., Kuhlmann, S., Smits, R.
2	476	39.67	2007	Scenarios of long-term socioeconomic and environmental development under climate stabilization	Riahi, K., Gruebler, A., Nakicenovic, N.
3	447	9.31	1971	Simple Substitution Model of Technological Change	Fisher, JC., Pry, R.H.
4	391	26.07	2004	Technology roadmapping - A planning framework for evolution and revolution	Phaal, R., Farrukh, C.J.P., Probert, D.R.
5	370	28.46	2006	Current validity of the Delphi method in social sciences	Landeta, J.
6	361	27.77	2006	Forecasting emerging technologies: Use of bibliometrics and patent analysis	Daim, T., Rueda, G., Martin, H., Gerdsri, P.
7	321	12.35	1993	The Adoption of Agricultural Innovations - A Review	Feder, G., Umali, D.L.
8	284	12.91	1997	The past and future of constructive technology assessment	Schot, J., Rip, A.
9	269	19.21	2005	Analysis of interactions among the barriers of reverse logistics	Ravi, V., Shankar, R.
10	249	8.89	1991	Delphi - A Reevaluation of Research and Theory	Rowe, G., Wright, G., Bolger, F.
11	242	17.29	2005	Processes and patterns in transitions and system innovations: Refining the co-evolutionary multi-level perspective	Geels, F.W.
12	216	18	2007	Climate change impacts on irrigation water requirements: Effects of mitigation, 1990–2080	Fischer, G., Tubiello, F., Van Velthuizen, H., Wiberg, D.
13	203	29	2012	Consensus measurement in Delphi studies - Review and implications for future quality assurance	Von der Gracht, H.
14	191	3.9	1970	Design of a Policy Delphi	Turoff, M.
15	182	10.71	2002	Does social capital determine innovation? To what extent?	Landry, R., Amara, N., Lamari, M.
16	178	17.8	2009	Establishment and embedding of innovation brokers at different innovation system levels: Insights from the Dutch agricultural sector	Klerkx, L., Leeuwis, C.
17	178	9.89	2001	Internationalization of services: A technological perspective	Miozzo, M., Soete, L.
18	173	9.11	2000	The art of scenarios and strategic planning: Tools and pitfalls	Godet, M.
19	173	6.18	1991	An Evaluation of Delphi	Woudenberg, F.
20	156	9.75	2003	A review of selected recent advances in technological forecasting	Martino, J.P.
21	154	17.11	2010	Understanding the determinants of RFID adoption in the manufacturing industry	Wang, Y., Wang, Y., Yang, Y.
22	151	10.07	2004	Roadmapping a disruptive technology: A case study - The emerging microsystems and top-down nanosystems industry	Walsh, S.T.
23	149	10.64	2005	How to improve scenario analysis as a strategic management tool?	Postma, T., Liebl, F.
24	149	9.31	2003	Applying the gray prediction model to the global integrated circuit industry	Hsu, L.C.
25	147	14.7	2009	Functions of innovation systems as a framework to understand sustainable technological change: Empirical evidence for earlier claims	Hekkert, M., Negro, S.
26	146	14.6	2009	Intellectual capital and new product development performance: The mediating role of organizational learning capability	Hsu, Y., Fang, W.
27	143	15.89	2010	Thinking inside the box: A participatory, computer-assisted approach to scenario discovery	Bryant, B., Lempert, R.
28	141	9.4	2004	Disruptive technology roadmaps	Kostoff, RN., Boylan, R., Simons, G.R.
29	140	15.56	2010	Identifying and evaluating robust adaptive policy responses to climate change for water management agencies in the American west	Lempert, R., Groves, D.
30	138	23	2013	The choice of innovation policy instruments	Borras, S., Edquist, C.
31	137	68.5	2017	The future of employment: How susceptible are jobs to computerization?	Frey, C., Osborne, M.
32	137	6.23	1997	Innovation forecasting	Watts, R.J., Porter, A.
33	135	7.94	2002	National Learning Systems - A new approach on technological change in late industrializing economies and evidences from the cases of Brazil and South Korea	Viotti, E.B.
34	133	7.82	2002	Combining neural network model with seasonal time series ARIMA model	Tseng, F.M., Yu, H.C., Tzeng, G.H.
35	130	10	2006	Forecasting emerging technologies with the aid of science and technology databases	Bengisu, M., Nekhili, R.
36	129	5.61	1996	Timing, diffusion, and substitution of successive generations of technological innovations: The IBM mainframe case	Mahajan, V., Muller, E.
37	128	14.22	2010	Exploring sustainability transitions in the electricity sector with socio-technical pathways	Verbong, G., Geels, F.
38	126	15.75	2011	Enhancing rigor in the Delphi technique research	Hasson, F., Keeney, S.
39	125	8.93	2005	A systematic approach for identifying technology opportunities: Keyword-based morphology analysis	Yoon, B., Park, Y.
40	124	17.71	2012	Sustainability transitions in the making: A closer look at actors, strategies and resources	Farla, J., Markard, J., Raven, R., Coenen, L.

Abbreviations: R = Rank; TC = Total citations; C/Y = Citations per year.

of TF&SC in engineering journals. This differential is likely to increase going forward as the long-term pattern suggests decreasing frequency of citations of TF&SC by engineering journals, while the citations of engineering journals by TF&SC seem to be increasing.

Phillips (2019) notes that the fields of Operations Research (OR) and TIM seldom reference each other these days. However, our analysis shows that TF&SC seems to buck this general trend within the TIM journals. Table 3 shows that according to the Web of Science Categories (WC), Operations Research & Management Science (MS) is in the Top 5 disciplinary categories most cited by TF&SC papers (5% of the cited papers), and in the Top 10 of the disciplinary categories citing TF&SC papers (6% of the citing ones). Suggesting that there is a fairly balanced inflow and outflow of citations between OR/MS and TF&SC.

While lamenting the disconnect between OR/MS and TIM, Phillips (2019) notes that Decision Science is likely to act as a bridge between the two disciplines. Consistent with this observation, we find that an analysis of citation inflow and outflow patterns based on SCImago Categories of Journals shows that OR/MS journals have consistently ranked in the Top 10 disciplinary categories citing TF&SC (Table 4); as well as in the Top 10 disciplinary categories of journals cited by TF&SC (Table 5). Both these patterns show remarkable consistency over the decades. Thus within the broader category of TIM journals, TF&SC remains an exception in maintaining a close bi-directional knowledge exchange between OR/MS and TIM, quite often through Decision Science. This is undoubtedly due to the influence of the two long-term Editors-in-Chief of TF&SC, Dr. Hal Linstone and Dr. Fred Phillips, both of whom had degrees in mathematics and worked in Operations Research before moving to technology management.[7]

3.3. Most cited articles in TF&SC

To complement our analysis of knowledge exchange patterns, we examined the data more closely at the level of individual articles.

[7] *We are grateful to an anonymous reviewer for bringing this to our attention.*

Table 7
Top 40 works most often cited by TF&SC publications.

R	TC	Year	Title (Journal)	Author(s)
1	162	1969	A new product growth for model consumer durables *(Management Science)*	Bass, F.M.
2	150	1982	*An evolutionary theory of economic change*	Nelson, R.R., Winter, S.G.
3	120	1990	Absorptive capacity: A new perspective on learning and innovation *(Administrative Science Quarterly)**	Cohen, W.M., Levinthal, D.A.
4	101	1971	A simple substitution model of technological change *(Technological Forecasting and Social Change)*	Fisher,J.C., Pry R.H.
5	95	1982	Technological paradigms and technological trajectories: A suggested interpretation of the determinants and directions of technical change *(Research Policy)*	Dosi, G.
6	91	1975	*The Delphi Method: Techniques and applications*	Linstone, H.A., Turoff, M.
7	88	1961	Technical change and the rate of imitation *(Econometrica)*	Mansfield, E.
8	87	1989	Building theories from case study research *(Academy of Management Review)*	Eisenhardt, K.M.
9	76	2003	*Diffusion of innovations*	Rogers, E.M.
10	73	2007	Functions of innovation systems: A new approach for analyzing technological change *(Technological Forecasting and Social Change)*	Hekkert, M.P., Suurs, R.A.A., Negro, S.O., Kuhlmann, S., Smits, R.E.H.M.
11	71	2002	Technological transitions as evolutionary reconfiguration processes: A multi-level perspective and a case-study *(Research Policy)*	Geels, F.W.
12	68	1992	*National systems of innovation. Towards a theory of innovation and interactive learning*	Lundvall, B.A.
13	64	1981	Evaluating structural equation models with unobservable Variables and Measurement Error *(Journal of Marketing Research)*	Fornell, C., Larcker, D.F.
14	62	2006	Forecasting emerging technologies: Use of bibliometrics and patent analysis *(Technological Forecasting and Social Change)*	Daim, T.U., Rueda, G., Martin, H., Gerdsri, P.
15	61	1985	*Competitive advantage: Creating and sustaining superior performance*	Porter, M.E.
16	60	1990	Patent statistics as economic indicators: A survey *(Journal of Economic Literature)*	Griliches, Z.
17	60	2004	Technology Roadmapping—A Planning Framework for Evolution and Revolution *(Technological Forecasting and Social Change)*	Phaal, R., Farrouk, C.J.P., Probert, D.R.
18	59	1972	*The limits to growth*	Meadows, D.H., Meadows, D.L., Behrens, J.R.W.W.
19	57	1993	*National innovation systems: A comparative analysis*	Nelson, R.R.
20	55	1991	Firm Resources and Sustained Competitive Advantage *(Journal of Management)*	Barney, J.
21	55	1957	Hybrid Corn: An Exploration in the Economics of Technological Change *(Econometrica)*	Griliches, Z.
22	55	1990	New Product Diffusion Models in Marketing: A Review and Directions for Research (Journal of Marketing)	Mahajan, V., Muller, E., Bass, F. M.
23	54	1995	*Diffusion of innovations*	Rogers, E.M.
24	53	2001	Science and technology roadmaps *(IEEE Transactions on Engineering Management)*	Kostoff, R.N., Schaller, R.R.
25	52	2007	Typology of sociotechnical transition pathways (*Research Policy*)	Geels, F.W., Schot,J.
26	51	1984	Multiple perspectives for decision making*: Bridging the gap between analysis and action*	Linstone, H.A
27	50	2005	The origins and evolution of scenario techniques in long range business planning *(Futures)*	Bradfield, R., Wright, G., Burt, G., Cairns, G., and Van Der Heijden, K.
28	48	1967	*Technological forecasting in perspective: A framework for technological forecasting, its techniques and organization*	Jantsch, E.
29	48	1980	*Competitive strategy: Techniques for analyzing industries and competitors*	Porter, M.E.
30	48	1990	*The competitive advantage of nations*	Porter, M.E.
31	48	1934	*The theory of economic development*	Schumpeter, J.A.
32	48	1997	Dynamic capabilities and strategic management *(Strategic Management Journal)*	Teece, D.J., Pisano, G., Shuen, A.
33	48	1986	Technological discontinuities and organizational environments *(Administrative Science Quarterly)*	Tushman, M.L., Anderson, P.
34	48	1994	*Mastering the dynamics of innovation*	Utterback, J.M.
35	47	2003	*Open innovation: The new imperative for creating and profiting, from technology*	Chesbrough, H.
36	46	2008	Analyzing the functional dynamics of technological innovation systems: A scheme of analysis *(Research Policy)*	Bergek, A., Jacobsson, S., Carlsson B., Lindmark, S., Rickne, A.
37	46	1997	*The innovator's dilemma*	Christensen, C.M.
38	46	1963	An experimental application of the Delphi Method to the use of experts (Management Science)	Dalkey, N.
39	46	1986	Profiting from technological innovation: Implications for integration, collaboration, licensing and public policy *(Research Policy)*	Teece, D.J.
40	45	1985	Clio and the economics of QWERTY *(American Economic Review)*	David, P.A.

Abbreviations: *R* = Rank; TC = Total Citations.

* Cohen and Levinthal might have revived interest in absorptive capacity and applied it to the firm level, but the notion can trace its origins to Rostow's earlier works: Rostow, W.W. (1956). The Take-Off Into Self-Sustained Growth. Economic Journal, (March); Millikan, M.F. and Rostow, W.W. (1957). A Proposal: Key to an Effective Foreign Policy, New York: Harper; Rostow, W.W.(1963). The Economics of Take-Off Into Sustained Growth. ed., New York: St. Martin's Press. We are grateful to an anonymous reviewer for bringing this to our attention.

Table 6 presents a list of the 40 most-cited TF&SC publications from 1969 to 2018. During this period, the most-cited paper (Hekkert et al., 2007) received 681 citations and has been cited at the rate of almost 57 citations per year since its publication. Overall, thirteen articles have received more than 200 citations and seven have received more than 20 citations per year. Over half of articles receiving more than 200 citations have been published since 2004. Tables A12 through A16 of the Online Appendix identify the most cited TF&SC articles by decade.

Table 7 lists 40 documents (i.e., articles and books) that were cited the most by works published in TF&SC between 1969 and 2018. Not surprisingly, the list features many seminal articles and books in forecasting, technology and innovation management, economics, decision-making and strategy. Topping this list with 162 citations is the groundbreaking article by Frank Bass introducing the Bass Diffusion Model (Bass, 1969). Seminal books feature prominently on this list (16 out of 40), with *An Evolutionary Theory of Economic Change* by Nelson and Winters ranked at the second most cited publication in TF&SC. This would be followed by Everett Rogers classic book *Diffusion of Innovations*, whose 2003 edition and 1995 editions would rank #3 on the list with a combined 130 citations. However, for citation purposes these are counted as separate entries at #9 and #23 in Table 7. However, the share of books as a prominent source of the intellectual underpinnings of the articles published in TF&SC has decreased steadily over the years (see Fig. 5). These trends suggest a broadening of the intellectual base of the TF&SC as the body of knowledge and the interdisciplinary nature of the journal have grown.

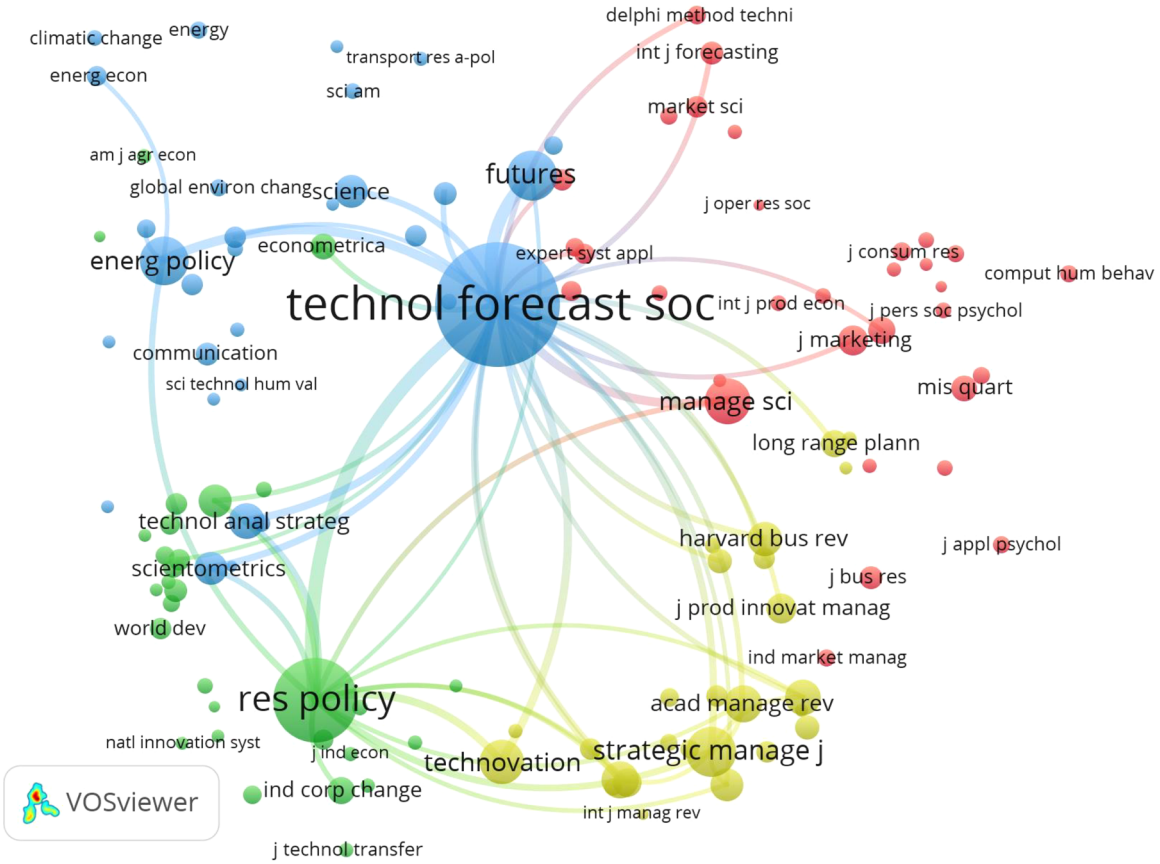

Fig. 6. Co-citation of Journals in TFSC: Minimum citation threshold of 100 and 50 links.

3.4. Co-citation of journals in TF&SC

Co-citation refers to two documents receiving a citation from the same third document (Small, 1973). Fig. 6 presents a bibliometric mapping analysis of which journals tend to be cited together by TF&SC authors. In this figure, the size of the node reflects total citations by TF&SC over the 50 years, and the connections reflect co-citations. In Fig. 6, circling clockwise from top left, we find prominent nodes for *Energy Policy, Futures, TF&SC, Management Science, Administrative Science Quarterly, Academy of Management Review, Academy of Management Journal, Strategic Management Journal*, and *Research Policy*.

Data underlying the co-citation of journals in TF&SC is presented in Table 8. The table presents totals (covering 1969–2018) as well as breakdowns for the most recent three decades (i.e., 2008–2017, 2007–1998, and 1997–1988). The number of articles published in TF&SC (and consequently the citations of and in TF&SC) grew considerably starting in 2007 (see Fig. 1). As such, the average figures for the "50 years" outlined in Tables 1, 2 and 8 are likely to be skewed in favor of the most recent decade (2008–2017). Indeed, decade-by-decade breakdowns presented in Table 8 show that the 40 most cited journals for the 50 years corresponds closely with those most cited in the most recent decade. Not surprisingly, TF&SC figures at the top when comparing the lists of the most citing and cited journals. Such self-citation was dominant in the first decade (1969–1978) of journal publication (Table A1 in the Online Appendix). Over time, the cross-citations with other journals has increased notably. The Appendix provides a detailed decade-by-decade breakdown of the top incoming and outgoing citations by TF&SC (Tables A1 through A10 and Figures A1 through A9 in the Online Appendix).

3.5. Analysis of author keywords

Next, we turn out attention to topics and keywords appearing in TF&SC articles, and how they have evolved over the years. Drawing on the WoS searches of TF&SC abstract records, we tabulated the most frequently occurring 40 keywords offered by the authors. Table 9 presents these keywords in total (i.e. 1969–2018) and for the two most recent decades (i.e., 2008–2017 and 1998–2007).[8]

From 1969–2018, "innovation," "foresight," and "forecasting" feature as the most popular keywords, appearing 144, 82 and 58 times, respectively. These three keywords consistently featured among the top five keywords in both 2008–2017 and 1998–2007 decades as well. Recall that the tremendous growth in TF&SC publication from 2007 onwards means that the global profile tends to highly resemble the recent decade (2008–2017). Frequencies of the top keywords appears to follow this pattern.

Observations of data presented in Table 9 suggests some interesting patterns:

- Interest in staple topics like *Diffusion, R&D, Technology Transfer* and *Technological Change* appears to be consistently strong among TF&SC authors;
- TF&SC authors have strong and enduring interest in methodologies such as *Scenario Planning, Delphi, Text Mining, Bibliometrics, System Dynamics*, and *Roadmapping*;
- Two areas of geographical/national foci seem to be emerging in *China* and *India*, with interest in China becoming particularly strong

[8] The WoS database only starts showing keywords for papers published in TF&SC starting 2001. For TF&SC papers published 2000 and earlier, no keywords appear in the WoS database.

Table 8
Co-citation of journals in TFSC: Global (1969–2018) and temporal analysis of the most recent three decades.

	Global (1969–2018)			2008–2017			1998–2007			1988–1997		
R	Journal	Cit	CLS	Journal	Cit	CLS	Journal	Cit	CLS	Journal	Cit	CLS
1	Technol Forecast Soc	9896	6822	Technol Forecast Soc	7418	5329.41	Technol Forecast Soc	963	546.35	Technol Forecast Soc	578	341.04
2	Res Policy	4544	3691.74	Res Policy	4011	3252.89	Res Policy	360	280.24	Res Policy	132	96.54
3	Futures	1664	1319.64	Energy Policy	1456	1131.7	Manage Sci	152	135.81	Futures	111	84.78
4	Strategic Manage J	1568	1402.24	Strategic Manage J	1385	1239.02	Futures	147	117.29	Manage Sci	105	91.67
5	Energy Policy	1556	1215.72	Futures	1193	972.09	Strategic Manage J	147	123.6	Science	94	76.6
6	Manage Sci	1376	1277.23	Technovation	1156	1052.95	Admin Sci Quart	140	120.17	NY Times	90	41.57
7	Technovation	1276	1162.44	Manage Sci	1002	946.28	Science	129	77.94	Am Econ Rev	80	67.82
8	Acad Manage Rev	919	871.61	Acad Manage Rev	806	768.54	Harvard Bus Rev	91	85.22	Admin Sci Quart	66	51.95
9	Admin Sci Quart	873	807.25	Acad Manage J	759	714.99	Energ Policy	88	54.46	Am J Agr Econ	63	34.21
10	Acad Manage J	851	803.13	Technol Anal Strateg	746	691.81	Technovation	85	78.58	Econometrica	61	52.62
11	Technol Anal Strateg	812	757.31	Organ Sci	677	640.68	J Prod Innovat Manag	83	73.2	Harvard Bus Rev	54	45.92
12	Harvard Bus Rev	745	710.05	Scientometrics	663	574.11	Am Econ Rev	80	75.53	Communication	44	22.82
13	Organ Sci	729	690.93	Admin Sci Quart	631	605.77	Nature	69	56.47	Econ J	43	36.56
14	Science	726	596.18	Harvard Bus Rev	571	549.14	J Marketing	67	61	J Marketing	42	35.61
15	Scientometrics	711	615.53	J Prod Innovat Manag	513	481.13	Q J Econ	64	52.06	Business Week	40	30.97
16	Am Econ Rev	705	667.18	Am Econ Rev	493	470.25	IEEE T Eng Manage	62	59.1	Sci Am	39	33.56
17	J Prod Innovat Manag	607	567.59	R&D Manage	461	436.29	J Forecasting	60	46.12	Wall Street J	39	31.22
18	J Marketing	580	541.72	J Marketing	449	423.77	Acad Manage Rev	57	53	Acad Manage Rev	38	33.57
19	R&D Manage	538	510.44	Ind Corp Change	447	431.96	Technol Anal Strateg	55	52.61	IEEE T Syst Man Cyb	38	17.25
20	Ind Corp Change	483	467.44	MIS Quart	429	385.33	J Marketing Res	52	46.33	Strategic Manage J	36	33.89
21	J Marketing Res	467	447.44	Long Range Plann	377	356.31	R&D Manage	52	49.04	Technovation	35	26.95
22	Long Range Plann	465	437.3	J Marketing Res	366	354.6	Market Sci	51	43.82	J Polit Econ	34	31.33
23	MIS Quart	445	401.13	J Bus Res	351	336.97	Int J Forecasting	50	44.96	Delphi Method Tech	33	24.48
24	Econometrica	436	405.92	J Manage Stud	334	323.43	Int J Technol Manage	50	47.06	J Forecasting	33	28.17
25	IEEE T Eng Manage	381	364.82	Science	324	305.71	Organ Sci	49	45.71	Rev Econ Stat	32	29.54
26	J Manage Stud	381	368.14	Foresight	319	295.18	Acad Manage J	48	44.4	Economist	30	23.21
27	Q J Econ	366	342.75	Ecol Econ	300	282.21	Long Range Plann	48	44.09	Fortune	30	26.67
28	J Bus Res	364	350.33	J Clean Prod	292	260.54	Econometrica	47	45.47	IEEE T Eng Manage	29	24.01
29	Int J Forecasting	360	330.28	Res Technol Manage	292	268.82	Econ J	45	42.88	J Marketing Res	29	25.92
30	Communication	344	233.07	J Bus Venturing	289	269.53	Scientometrics	44	32.04	Q J Econ	29	24.74
31	Res Technol Manage	335	310.03	Int J Forecasting	285	260.31	J Polit Econ	42	38.3	Long Range Plann	28	24.68
32	Foresight	332	307.98	J Manage	282	274.89	Sci Publ Policy	42	26.58	Acad Manage J	27	26.12
33	Econ J	329	318.36	Eur J Oper Res	280	263.81	Calif Manage Rev	40	38.8	Sci Publ Policy	27	22.46
34	Sci Publ Policy	329	300.67	Int J Technol Manage	269	261.69	Rev Econ Stat	39	36.42	Technology Transfer	27	23.65
35	Eur J Oper Res	323	305.19	Expert Syst Appl	262	237.8	Diffusion Innovation	38	35.73	J Econ Lit	26	24.06
36	Int J Technol Manage	322	311.99	Energ Econ	261	227.11	J Econ Lit	37	36.11	Market Sci	26	23.42
37	World Dev	322	293.82	IEEE T Eng Manage	261	253.79	Sci Am	37	29.13	Multiple Perspective	26	25.69
38	J Bus Venturing	317	295.61	World Dev	261	241.29	Ind Corp Change	36	34.95	Technical Change Ec	26	21.5
39	Ecol Econ	316	298.63	Telecommun Policy	260	209.9	Communication	34	22.47	Am Sci	25	20.52
40	J Manage	315	306.65	Q J Econ	254	243.89	Res Technol Manage	34	31.41	Int J Forecasting	24	22.48

Abbreviations: *R* = Rank; Cit = Citations; CLS = Citation link strength.

in the last decade;

- TF&SC author interest in topics such as *Patents/Patent Analysis, Climate Change, Sustainability*, and *Energy* seems to have intensified in the last decade;
- New topics like *Open Innovation, Innovation Policy, Social Media, Climate Policy,* and *Renewable Energy* have emerged on the most common keyword list within the last decade;
- In addition to those mentioned above, there seems to be an increasing interest in specific technologies of note: *Nanotechnology, Information Technology, Learning,* and *Emerging Technologies*; and
- Interest in topics related to *Terrorism, Biotechnology, Computational Linguistics, Complexity*, and *Core Competencies*, seems to have waned from the 1998–2007 decade to the next.

Topical foci can be further examined by considering how often terms appear together in the same abstract. Fig. 7 shows the frequent author keywords (larger nodes indicating occurrence in more papers) and the strengths of their connections (based on co-occurrence in those papers). Bibliometric mapping of the co-occurrence of keywords in abstracts is a way of exploring topics and themes in TF&SC publications. For instance, “text mining” (upper right corner) shows strong link to literature-based discovery (i.e., bibliometrics) and patent analysis. Also, in its neighbourhood are “tech mining,” “clustering,” “computational linguistics” and “data mining.” Similarly, “climate change” (lower left of the topical network map) shows connections to “energy policy,” “sustainable development,” “climate policy,” and “energy efficiency”.

To explore further, we analyzed additional topics mentioned in the abstract records. We used Natural Language Processing (NLP) to extract Title and Abstract noun phrases, and then combined those with author keywords and WoS Keywords Plus. We consolidated those terms (as per Porter et al., 2018), then calculated highly emergent terms – those meeting thresholds of novelty, persistence, community usage, and specificity, and exhibiting accelerating usage over the recent decade. Consolidating those reveals the following emergent topics for 2008–2017, which we expect to garner emphasis in TF&SC for the next few years:

- Socio-technical systems & transitions
- Institutional context and social entrepreneurship
- Industry-university collaboration and “Triple Helix” (industry-government-university relations)
- Social responsibility
- Innovation performance
- Preparedness and leadership
- Patent data
- Absorptive capacity and open innovation
- Various analytical tools

These topics suggest an emphasis on innovation in context. Note that they are consistent with the author keyword emphases tallied in

Table 9
Most common author keyword occurrences in TFSC.

R	Global Keyword	Oc	Co	2008–2017 Keyword	Oc	Co	1998–2007 Keyword	Oc	Co
1	Innovation	144	115	Innovation	121	92	Innovation	23	17
2	Foresight	82	68	Foresight	68	55	Forecasting	15	6
3	Forecasting	58	43	Scenarios	49	41	Foresight	14	11
4	Scenarios	57	48	Delphi	43	36	Technology	14	13
5	Delphi	49	42	Forecasting	43	32	Text Mining	12	11
6	China	48	36	China	41	29	Technology Assessment	10	7
7	Text Mining	44	35	Patent Analysis	37	27	Bibliometrics	9	9
8	Patent Analysis	39	30	Scenario Planning	36	25	Science & Technology	9	6
9	Scenario Planning	39	28	Text Mining	32	23	Nanotechnology	8	8
10	Technology	39	33	Patents	30	25	Scenarios	8	6
11	Nanotechnology	35	30	Sustainability	29	24	China	7	7
12	Sustainability	33	25	Innovation Policy	27	20	Delphi Method	7	4
13	Diffusion	32	25	Nanotechnology	27	20	Information Technology	7	4
14	Bibliometrics	31	30	Diffusion	26	21	Technological Change	7	2
15	Innovation Policy	31	23	Climate Change	25	22	Technology Forecasting	7	6
16	Climate Change	30	27	Technology	25	20	Terrorism	7	5
17	Patents	30	25	System Dynamics	23	14	Complexity	6	5
18	Energy	27	25	Bibliometrics	22	19	Delphi	6	6
19	Technology Forecasting	27	22	Open Innovation	22	15	Diffusion	6	4
20	System Dynamics	25	18	Energy	21	20	Energy	6	5
21	Technological Change	24	14	Strategic Foresight	21	19	Factor Analysis	6	5
22	Uncertainty	24	18	Technology Forecasting	20	15	India	6	5
23	Information Technology	23	17	Uncertainty	20	14	Logistic Growth	6	4
24	India	22	21	Renewable Energy	19	14	Biotechnology	5	4
25	Open Innovation	22	16	Patent	18	12	Climate Change	5	5
26	R&D	21	15	Social Media	18	11	Clustering	5	5
27	Strategic Foresight	21	19	Emerging Technologies	17	13	Computational Linguistics	5	5
28	Technology Assessment	21	15	Technological Change	17	9	Innovation Diffusion	5	1
29	Technology Foresight	21	18	Technology Roadmapping	17	14	Internet	5	4
30	Technology Transfer	21	18	Climate Policy	16	12	R&D	5	1
31	Delphi Method	20	17	India	16	16	Research Evaluation	5	5
32	Emerging Technologies	20	16	Information Technology	16	10	Technological Forecasting	5	4
33	Technological Forecasting	20	17	Learning	16	13	Technology Foresight	5	4
34	Innovation Diffusion	19	12	R&D	16	13	Technology Transfer	5	1
35	Patent	19	13	Scenario	16	13	Core Competencies	4	4
36	Renewable Energy	19	14	Technology Foresight	16	14	Decision Making	4	3
37	Technology Roadmapping	19	15	Technology Transfer	16	12	Diffusion Model	4	4
38	Learning	18	15	Roadmapping	15	13	Disruptive Technologies	4	2
39	Roadmapping	18	16	Technological Forecasting	15	12	Document Clustering	4	4
40	Scenario	18	15	Technological Innovation	15	7	Economic Growth	4	4

Abbreviations: *R* = Rank; Oc = Author keyword occurrences; Co = Author keyword co-occurrences links.

Table 9 and viewed in Fig. 7. The Appendices offer additional perspectives on topical emphases. Single-decade variants of Fig. 7 are provided in Figure A5 (1998–2007) and Figure A6 (2008–2017).

A more detailed breakdown of the top author-supplied keywords by geography is provided in Table 10. The table lists the top 40 keywords for the geographical regions of North America, Europe, and Asia. The graphic visualizations of the prominence and co-occurrence connections among these keywords for North America, Europe, and Asia are presented in the Online Appendix Figures A7-A9 respectively. We invite the interested reader to contrast the figures in greater detail, but offer a few observations on Table 10 here:

- *Innovation* is the most frequently-appearing keyword across each of the regions, with the greatest emphasis coming from Europe, followed by Asia;
- Search-based discovery is a source of a significant amount of interest from Asia in the form of *Patent Analysis, Text Mining, Bibliometrics*, and *Patents*; this also shows up in North America to a lesser extent, but is a much lower priority in papers from Europe;
- *China* shows as a prominent topic in all three regions (Table A16);
- Papers from Europe tend to focus on *Foresight, Scenarios, Scenario Planning*, and *Forecasting*, most prominently, followed by North America and Asia;
- *Climate Change, Sustainability, Energy* and *Energy Policy* feature more prominently in TF&SC research from North America and Europe; and
- *Nanotechnology* also features more prominently in TF&SC research from North America and Europe than in research from Asia.

4. Discussion

Over the fifty years of its existence, *Technological Forecasting and Social Change* has come to be regarded as one of the top journals in technology and innovation management (Sarin et al., 2018a). This essay seeks to examine the intellectual structure of the journal by studying the citations patterns, topical associations, and their temporal and geographic patterns from 1969 to 2018 (Ellegaard and Wallin, 2015). Such analyses are standard methodologies for assessing the impact of journals and disciplinary domains, and for examining patterns of knowledge flow among them (e.g., Biemans et al., 2007, Sarin et al., 2018a).

From modest beginnings, the journal has come a long way. The number of papers published in TF&SC has increased substantially starting in 2005. An examination of the incoming and outgoing citations of TF&SC reveals that citation of books and social science journals, along with self-citations by TF&SC have decreased from the first decade of the journal's publication to the most recent one. This suggests the maturing of a body of knowledge, and a broadening of the knowledge base that the journal draws upon (Sarin et al., 2018a, Sarin et al., 2018b).

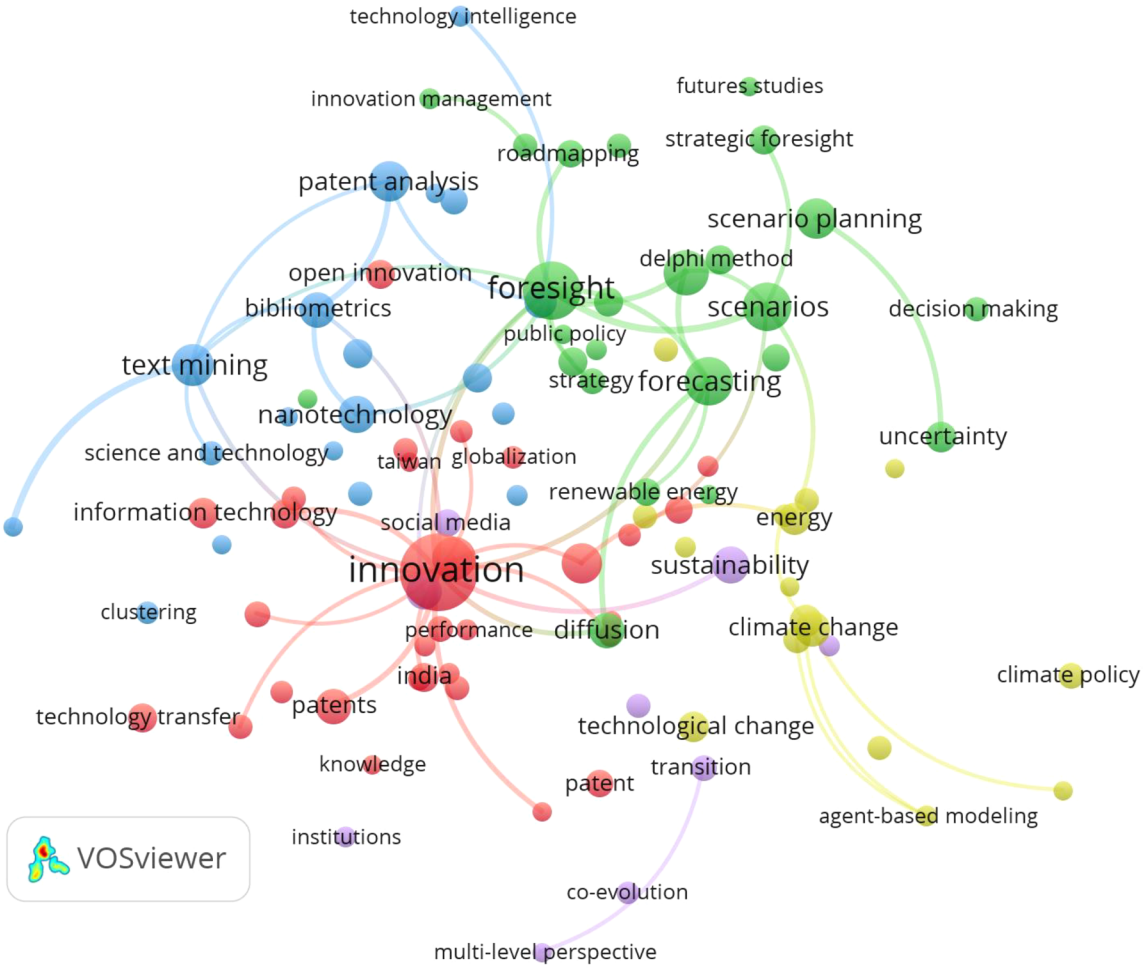

Fig. 7. Co-occurrence of author keywords in TFSC: Minimum occurrence threshold of 10 and 50 links.

The incoming versus outgoing citation patterns suggest an asymmetry in the knowledge flows of TF&SC. Over the last five decades, papers published in TF&SC have increasingly cited knowledge from journals in Technology and Innovation Management (TIM), Engineering, and Decision Sciences. At the same time, TF&SC has become an increasingly important source of knowledge for works published in Energy and Environmental Sciences. The journal has also shown itself to be an important source of knowledge for the PICMET Conferences.

In a manner, TF&SC appears to serve as a guidepost: sourcing knowledge from disciplinary categories such as TIM, Business, Decision Sciences, and Economics (all with more than 8000 citations by TFSC); and suggesting where a different set of disciplinary categories such as Energy, Environmental Sciences, and Social Sciences (all with more than 4000 citations of TF&SC) might be headed. Engineering is the only disciplinary category that shows a balance in terms of serving as a source knowledge as well as a place of influence for TF&SC.

Biemans et al. (2007) note that while the are highly informative, bibliometric analyses are limited in their ability to distinguish between citations that truly reflect intellectual indebtedness versus those are largely perfunctory in nature. Thus, we further examined the topic foci of the research published in TF&SC over the last fifty years by examining the keywords provided in the abstracts.

From 1969–2018, *Innovation, Foresight* and *Forecasting* feature as the most popular keywords. These three keywords also consistently featured among the top five keywords in the most recent two decades of TF&SC publications. However, significant differences are seen across geographies with respect to interest in these topics. In terms of keywords, research from North America shows a broader focus. On the other hand, emphasis in *Innovation* was the highest in papers coming from Europe, followed by Asia and then North America. Papers from Europe also tended to focus more prominently on *Foresight* and *Forecasting,* followed by North America and Asia.

Interest in staple topics like *Diffusion, R&D, Technology Transfer* and *Technological Change* remains high among TF&SC authors. Interest in methodologies such as *Scenario Planning, Delphi, System Dynamics*, and *Roadmapping* is also enduring. Focus on topics such as *Patents/Patent Analysis, Climate Change, Sustainability*, and *Energy* seems to have intensified in the last decade. Keywords *Climate Change, Sustainability, Energy* and *Energy Policy* featured more prominently in research from North America and Europe. Research from Asia shows less frequent interest in topics related to climate change, sustainability, and energy; this might be the result of regional priorities of economic development rather than sustainability. Consistent with such an orientation, TF&SC authors from Asia more frequently use keywords *Patents* and *Patent Analysis*. Asian authors also use keywords *Text Mining*, and *Bibliometrics* more frequently than authors from North America or Europe do; this may reflect a growing research focus in Asian universities.

Our analysis suggests that focus on two countries of interest, *India* and *China*, is emerging in research published in TF&SC. This is a testament to the growing international importance of both countries. In particular, the interest in China features prominently across all three geographical regions of North America, Europe and Asia, and has become particularly strong in the last decade. On the other hand, interest in topics related to *Terrorism, Biotechnology, Computational Linguistics, Complexity*, and *Core Competencies*, seems to have waned from the

Table 10
Most common author keyword occurrences in TFSC: Geographic classification.

R	North America Keyword	Oc	Co	Europe Keyword	Oc	Co	Asia Keyword	Oc	Co
1	Innovation	31	25	Innovation	92	66	Innovation	42	26
2	Text Mining	26	25	Foresight	66	52	China	29	18
3	China	17	14	Scenarios	43	35	Patent Analysis	29	23
4	Nanotechnology	17	15	Delphi	39	30	Forecasting	26	15
5	Bibliometrics	15	14	Scenario Planning	29	19	Text Mining	22	17
6	Climate Change	15	12	Innovation Policy	27	17	Bibliometrics	16	15
7	Foresight	14	10	Sustainability	23	17	Technology Forecasting	16	13
8	Technological Forecasting	11	9	Forecasting	22	19	Patent	12	7
9	Technology	11	6	Technology	22	19	System Dynamics	12	6
10	Forecasting	10	6	China	21	16	Diffusion	11	8
11	Literature-Based Discovery	10	10	Nanotechnology	20	18	India	11	10
12	Patents	10	9	Technological Change	20	8	Patents	10	9
13	Sustainability	10	8	Open Innovation	19	12	Taiwan	10	9
14	Delphi	9	7	Energy	18	16	Technology Roadmapping	10	5
15	Scenario Planning	9	5	Uncertainty	18	13	Bass Model	9	6
16	Scenarios	9	6	Strategic Foresight	17	16	Economic Growth	9	5
17	Science And Technology	9	8	Transition	16	12	Foresight	9	9
18	India	8	8	Climate Change	15	14	Information Technology	9	8
19	Technology Forecasting	8	7	Delphi Method	15	12	Iran	9	7
20	Terrorism	8	6	Diffusion	15	12	Network Analysis	9	7
21	Biotechnology	7	5	Emerging Technologies	15	12	Patent Citation	9	8
22	Energy	7	5	Learning	15	12	R&D	9	8
23	Energy Policy	7	6	Technology Assessment	15	11	Technology	9	9
24	Information Technology	7	4	Technology Foresight	15	12	Technology Roadmap	9	9
25	Innovation Policy	7	3	Patent Analysis	14	9	Climate Change	8	7
26	Patent Analysis	7	6	Patents	14	10	ICT	8	7
27	Technology Diffusion	7	6	Scenario	14	12	Innovation Diffusion	8	3
28	Climate Policy	6	4	System Dynamics	14	9	Nanotechnology	8	7
29	Clustering	6	6	Corporate Foresight	13	11	Technology Foresight	8	6
30	Decision Making	6	3	Roadmapping	13	12	Emerging Technologies	7	6
31	Document Clustering	6	6	Social Media	13	6	Korea	7	3
32	Energy Efficiency	6	6	Sustainability Transitions	13	8	Social Capital	7	5
33	Globalization	6	4	Climate Policy	12	11	Technology Adoption	7	2
34	Information Retrieval	6	6	Co-Evolution	11	6	Technology Transfer	7	6
35	Policy	6	6	Innovation Diffusion	11	6	Big Data	6	5
36	Renewable Energy	6	4	R&D	11	7	Citation Analysis	6	6
37	Technological Change	6	4	Strategy	11	10	Competition	6	6
38	Technological Innovation	6	3	Technology Transfer	11	6	Creative Economy	6	5
39	Technology Roadmapping	6	3	Absorptive Capacity	10	7	Entrepreneurship	6	6
40	Uncertainty	6	4	Entrepreneurship	10	8	Lotka-Volterra Model	6	4

Abbreviations: R = Rank; Oc = Author keyword occurrences; Co = Author keyword co-occurrences links.

1998–2007 decade to the next. This could be attributed to the emergence of new areas of research and policy interest.

Within the last decade, new topics like *Open Innovation, Innovation Policy, Social Media, Climate Policy,* and *Renewable Energy* have emerged on the most frequent keywords list for the first time. There also seems to be an increasing interest in specific technologies of note, such as *Nanotechnology, Information Technology, Learning,* and *Emerging Technologies. Nanotechnology* features more prominently in research from North America and Europe, relative to Asia.

Our analysis suggests that TF&SC readers can expect future emphasis on research related to socio-technical systems and transitions, and to social responsibility. Addressing such complex problems will require multifaceted solutions with increasing interest in: preparedness and leadership, established as well as emerging analytical tools, social entrepreneurship, open innovation, triple-helix (i.e., industry-government-university) collaborations, and innovative performance. Different regions of the world can be expected to place differential emphasis on various topics based on their socioeconomic-technological environments. The journal needs to be receptive to this diversity of perspectives from a growing community of scholars worldwide.

As has been noted by other authors, citation analysis is a flawed indicator of influence. For example, Clark et al. (2014) points out that authors may be critical of articles they cite, authors may cite articles without having read them, and citations may be inappropriate or erroneous. Thus, any bibliometric analysis based on citations has its caveats. Despite such limitations, we believe that this research contributes to our understanding of TF&SC.

The last fifty years have been an exciting ride. The next fifty promise to be even more fun!

Authors statement

The work submitted in the revised manuscript TFS_2019_1793 - *Uncovering the Knowledge Flows and Intellectual Structures of Research in Technological Forecasting and Social Change: A Journey Through History*, represents original research by the authors. This work is not currently under review at any other journals, and none of the co-authors have any conflict of interest with the research presented.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.techfore.2020.120210.

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Dr. Shikhar Sarin is a Professor of Marketing at Boise State University (USA). His research interests include marketing strategy, new product development, innovation, marketing/management of technology, personal selling & sales management, digital commerce and bibliometrics. He has received research awards from the American Marketing Association, Product Development and Management Association, and the Sales Education Foundation. His research has been published in the *Journal of Marketing, Journal of Marketing Research, Journal of the Academy of Marketing Science, Decision Sciences, Journal of Product Innovation Management, Industrial Marketing Management, Journal of Business Research, Journal of Marketing Theory and Practice, Journal of Personal Selling and Sales Management,* and *Engineering Economist*, among others.

Dr. Christophe Haon is a Professor of Marketing at Grenoble Ecole de Management and a researcher at IREGE (Université Savoie Mont Blanc). He conducts research on marketing strategy, new product development, market orientation and customer satisfaction. His research has been published in *Marketing Letters, Journal of Business Research, Journal of Product Innovation Management, Industrial Marketing Management,* and *the European Management Review*, among others. He has also coauthored several books, *including Making Innovation Last: Sustainable Strategies for Long Term Growth*, published by Palgrave Macmillan.

Dr. Mustapha Belkhouja is an Associate Professor of Quantitative Methods at Grenoble Ecole de Management. His research topics focus on academic visibility, knowledge diffusion, reputation and international business. His research has appeared in *Journal of Product Innovation Management, Industrial Marketing Management, M@n@gement, Research Policy, Technological Forecasting & Social Change,* and *Strategic Organization*, among others.

Dr. Alicia Mas-Tur is a Associate Professor in the Management Department at the University of Valencia. She has presented numerous papers at international conferences. She has also published articles and books in international journals including *Service Industries Journal, International Entrepreneurship and Management Journal, and Service Business.* She is or has been the guest editor and referee for international journals. She is or has been on the editorial board of several journals including the *Journal of Business Research* and *Contemporary Economics*.

Dr. Norat Roig-Tierno is a Professor at the ESIC Business & Marketing School, Valencia, Spain. His research is focused on innovation, regional development and the application of qualitative methodologies. His research has appeared in journals such as *Applied Geography, Journal of Human Development and Capabilities, Social and Policy Administration,* and *Journal of Business Research*, among others. He is or has served on the editorial board of several journals.

Dr. Trina Sego is a Professor of Marketing at Boise State University (USA). Her research interests include advertising, consumer behavior, international marketing, and marketing strategy. Her research has been published in *Journal of Consumer Behaviour, Marketing Theory, Journal of Personal Selling & Sales Management*, and *Journal of Marketing Theory and Practice*, among others.

Dr. Alan Porter is Professor Emeritus of Industrial & Systems Engineering at Georgia Institute of Technology (USA), where he also co-directs the Technology Policy and Assessment Center. His current research interests focus on computer-aided exploration of information in electronic Science & Technology databases. He has authored over 160 professional publications and 11 books.

Dr. Jose M. Merigó is a Professor at the School of Information, Systems, and Modelling at the Faculty of Engineering and Information Technology at the University of Technology Sydney (Australia) and Part-Time Professor at the University of Chile. He has published more than 400 articles in journals, books and conference proceedings. He is on the editorial board of several journals. He has also been a guest editor for several international journals, member of the scientific committee of several conferences and reviewer in a wide range of international journals. Since 2015, he has been recognized by the Web of Science Group of Clarivate Analytics (previously Thomson & Reuters) as a Highly Cited Researcher in Computer Science.

Dr. Stephen Carley is a Senior Research Scientist at Search Tech, Inc. His research interest include bibliometrics and nanotechnology. His research has been published in *Technological Forecasting and Social Change, Scientometrics, Technology Analysis and Strategic Management, Research Evaluation, PLoS One, Journal of Nanoparticle Research*, and *Journal of Technology Transfer*, among others.