Technological Forecasting & Social Change 78 (2011) 283–293

Contents lists available at ScienceDirect

Technological Forecasting & Social Change

Patent and publishing activity sequence over a technology's life cycle

Heini M. Järvenpää [a,*], Saku J. Mäkinen [a,b], Marko Seppänen [a]

[a] Center for Innovation and Technology Research, Tampere University of Technology (CITER), Tampere, Finland
[b] Department of Industrial Management, Tampere University of Technology, Tampere, Finland

ARTICLE INFO

Article history:
Received 6 October 2009
Received in revised form 31 March 2010
Accepted 26 June 2010

Keywords:
Emerging technology
Technology Life Cycle
Diffusion
Publication
Patents
Media
Sequence

ABSTRACT

The use of multiple indicators in analyzing technological developments and exploiting the increasing availability of information has been recommended widely in order to decrease systematic biases between single measures. One of the few frameworks that take multiple sources into account is the Technology Life Cycle indicators that provide a measure for the totality of sources available for analysis and take their timeliness into account, although the linear model that the framework represents is often questioned. The aim of this paper is to provide bibliometric studies with insight into the timely relevance of using different databases. To assess the reporting sequence between different databases, this paper measures the reporting activity of three case technologies in different databases and analyzes the yearly reporting volumes of a number of items that mention the technology in the databases as suggested by the TLC indicators. The results of this paper suggest that, when science is the source of new ideas and the driver for technological development and innovations, communication can happen in the order suggested by the TLC indicators. However, this model does not seem to be a general model for detecting and forecasting a technological life cycle. In addition, the results of the paper point to the possibility of studying non-linear models of innovation and contexts where this type of dynamics might take place.

1. Introduction

The purpose of technological forecasting is to provide timely insight into the prospects of technological change [1]. In analyzing technological developments, and exploiting the increasing availability of information, bibliometric studies have especially increased in popularity in technological forecasting. In the current literature, however, bibliometric studies are often scientometric studies that rely typically on only a single source such as the Science Citation Index or Compendex to analyze scientific advancements. The use of these sources is so common that bibliometric analysis is even said to be applicable if international journals are the dominant or at least a major means of communication in a particular field under investigation [2]. Similarly, in technological forecasting, patent analyses have been among the most prevalent measures of innovation, although there is a debate in the literature regarding possible problems with using patent data to measure innovation or technological progression, such as Griliches's concept of the "mirage" of patent statistics, which appear to provide a number of proxy measures for analysis that may not be real [3]. In summary, one of the most prolific criticisms concerning technological forecasting, and specifically the use of databases, is the use of one database as a source, which has been noted to lead to biased results, as one database reveals only one side of the story [4]. The often-stated recommendation is to use multiple sources to overcome the biases and weaknesses of single sources [4,5].

In an effort to understand the timeliness of different sources and to remedy the maladies of using a single source, the concept of Technology Life Cycle indicators [1] was created. Technology Life Cycle (TLC) indicators create a holistic picture of the multiple sources used in reporting the various findings in each stage of R&D. TLC indicators suggest an indicator, the number of articles, for

* Corresponding author. P.O. Box 541, FI-33101 Tampere, Finland. Tel.: +358 40 735 5177; fax +358 3 3115 2027.
E-mail address: heini.jarvenpaa@tut.fil (H.M. Järvenpää).

0040-1625/$ – see front matter © 2010 Elsevier Inc. All rights reserved.
doi:10.1016/j.techfore.2010.06.020

each of the R&D stages: the Science Citation Index for basic research, the Engineering Index for applied research, Patents for development, Newspapers for application, and finally the Business and Popular Press for the societal impact stage of R&D. The TLC indicators were developed for technology forecasting, and as the name suggests, the purpose is to track the life cycle of the technology with an indicator pointed for each stage. Nevertheless, the theoretical basis for technological forecasting lies in understanding the processes of technological innovation, and the TLC indicators clearly rely on the heavily criticized linear model, a model that has been even claimed to be "dead" [6], but nevertheless used for its simplicity [7], and for that, the model is a "rhetorical entity" and "gives a sense of orientation when thinking about funding to R&D" [7]. The criticism pointed at the linear model of technological innovation is also valid for the TLC indicators in terms of the claimed order, and an over-emphasis on science as the origin of innovations and technologies. Nevertheless, the TLC indicators as a concept comprise the databases that are the most frequently used in the literature, a means for measuring technological progression in these sources, and finally the relationship between the different sources.

The TLC indicators concept is thus taken as the starting point for this study, as a joint assessment of the magnitude of reporting the technological progression in these databases would help the bibliometric analysis of emerging technologies in technological forecasting. Therefore, the purpose of this paper is to provide assistance to the measurement concerning the temporal evolution of reporting the technological progression in each of the databases as suggested by the TLC indicators. The aim is to provide bibliometric studies with insight into the timely relevance of using different databases, and the following research question emerges for this paper: Do the sources suggested by the TLC indicators to report about a technology follow a sequence that starts with scientific papers, followed by engineering papers, then patents, and finally news? The research question is symmetrical in the way that positive and negative answers will add to our knowledge and help the future of bibliometric studies, especially in relation to technological forecasting.

To assess the reporting sequence between different databases, this paper measures the reporting activity of three case technologies in different databases and analyzes the yearly reporting volumes of the number of items mentioning the technology in the databases as suggested by the TLC indicators. The study provides insight into the orderliness of the publication activity in different databases and hence sheds light on the theoretical grounding of the TLC indicators. In addition, the paper seriously questions the traditional use of only one source in technological forecasting studies.

2. Theoretical background

The purpose of technological forecasting is to provide timely insight into the prospects of technological change [1]. Forecasting research does this by analyzing the past and present, and then forecasting the future. For the analyses of the past and present, information about technological innovations is needed, and this information is commonly tracked from different databases over the technology's life cycle. A method for analyzing text databases quantitatively is bibliometrics, defined as a general means for measuring texts and information [8,9]. Bibliometric analyses help researchers identify "who is doing what and where," give insight into where the technological development is heading, and provide feasible rates of progress along with warning signals of what is to come [10].

As the amount of information available in electronic form continues its logarithmic growth, the number of studies analyzing that information grows. When looking at the ISI Web of Knowledge the number of studies that at least mention bibliometrics has grown steadily since the 1980s (Fig. 1). This is not surprising as information technology has enabled and facilitated a mass of information to reach us; each year, the amount of printed and digital information created in companies grows faster than 65% [11]. This amount of information has thus much potential to be mined and analyzed, also from the technology forecasting point of view.

While more and more databases and electronically accessible sources are available to be bibliometrically analyzed, most of the technology-oriented analyses use only one database as a source [12–14]. In scientometric orientation, the source used is often the Science Citation Index (SCI) or Compendex; these indexes focus on journal publications, and the latter includes conference papers. The Science Citation Index is said to be one of the best sources for publication and citation data [15,16] and is often used as a

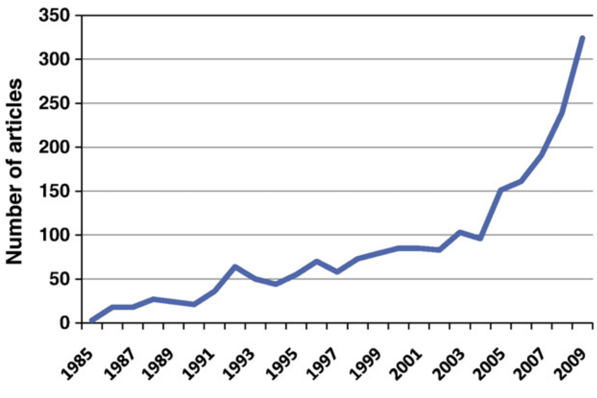

Fig. 1. "Bibliometric*" in the TOPIC field of ISI Web of Science databases.

database for looking up information about emerging technologies [17,18]. Kostoff states that almost all the published scientometric studies that compare countries, as well as most other research units, have used the basic-research-oriented SCI [19]. However, not all kinds of research end up published in journals: Companies can have publications as part of a patenting strategy [4], but mostly university researchers use journals as an output. Another limitation to measuring research output from publication databases such as the Science Citation Index is that only sufficiently recognized journals are indexed by the SCI. A bookkeeping artifice emerges when evaluating growth rate in publications, and not all growth comes from increased sponsorship or increased research productivity but from papers published in journals newly included in the SCI [16].

Compendex, on the other hand, is an engineering publication database, oriented in applied research, and is often used for the index's wide coverage. Compendex has also been described as the "database of choice, although it does not have citation capability" [16]. The use of sources such as the Science Citation Index and Compendex is so common that bibliometric analysis is even said to be applicable if international journals are the dominant or at least a major means of communication in a field [2]. This presumption, however, is due to bibliometrics having a strong orientation in measuring scientific performance although the definition of bibliometrics enables wider use and context.

Another widespread approach to studying technology advancements is to observe the evolution of patent applications. Patents are often used for tracking technologies [20], and the rate of development has been found to be correlated with development activities [21,22]. Some debate exists in the literature regarding possible problems with using patent data to measure innovation, such as Griliches's [3] concept of the "mirage" of patent statistics, which appear to provide a number of proxy measures for analysis that may not be real [5]. The patent indicator misses many non-patented inventions and innovations, some types of technology are not patentable, and in some cases, it is still being debated whether certain items can be patented [5]. Some patents, then again, are patented but never commercially exploited, while some companies, for example, use patenting to prevent and block others from patenting in that area [5]. In addition, in measuring technologies through patents, the policy shifts can generate surges in the number of patents as companies might want to wait to patent until a more favorable policy is about to be put into practice and then patent [4]. This makes it challenging to estimate the number of patents. One has to be aware of different policies, as the regulatory environment also shapes the efficacy of patents as a measure [23]. In addition, the propensity to patent differs across industries depending on the relative costs of innovation versus imitation. In addition, when patents are measured as an innovation indicator, four kinds of systematic mistakes are likely to occur [5]: first, underestimating innovation in low technological opportunity sectors; second, overestimating innovative activity among firms that collaborate on R&D; third, underestimating the rate of small firms that innovate; and fourth, overestimating the innovation intensity of small patent holders. In spite of all the difficulties, patent statistics remain a unique resource for analysis of the process of technical change. Researchers have claimed that nothing else even comes close in the quantity of available data, accessibility, and the potential industrial, organizational, and technological detail [22].

Regardless of the extensive use of these different sources individually, the use of one database as a source leads to biased results, as one database reveals only one side of the story [4]. The often-stated recommendation is to use multiple sources to overcome the biases and weaknesses of single sources [4,5]. However, not many studies systematically analyze the varied sources available or have studied the timeliness of reporting in different sources. One of the few is the concept of Technology Life Cycle (TLC) indicators introduced by Watts and Porter [1]. The concept strives to understand the totality of different kinds of databases from which to mine information about technological innovations and takes the timeliness into account. The indicators describe the typical sources that report the findings in each stage of R&D. The TLC indicators were developed for technology forecasting, and as the name suggests, the purpose is to track the life cycle of the technology with an indicator pointed for each stage. Table 1 shows the indicator listing that takes a look at publications of different types during the technology life cycle.

The conceptual foundation upon which the TLC indicators, and technological forecasting overall, rest is a degree of orderliness in the innovation process [1]. The TLC indicators and original R&D stages succession rely heavily on a linear assumption of research and development work—an assumption that "everyone knows is … dead" [6]. The linear model of innovation consists of four to six phases, depending on the definitions: basic research, applied research, development, (production, marketing), and diffusion. The linear model has been criticized throughout its existence, although many of the critiques have been claimed to be targeted toward an excessively simplified representation of the model [24]. To better depict the interactive nature of technological progress, substitutive complex models have been developed, such as the chain-linked model [25,26] and the multi-channel interactive learning model [26,27]. The

Table 1
Technology Life Cycle indicators [1].

Factor	Indicator
R&D profile	
Fundamental research	No. of items in databases such as Science Citation Index
Applied research	No. of items in databases such as Engineering Index
Development	No. of items in databases such as U.S. Patents
Application	No. of items in databases such as Newspapers Abstracts Daily
Societal impacts	Issues raised in the Business and Popular Press abstracts
Growth rate	Trends over time in number of items
Technological issues	Technological needs noted
Maturation	Types of topics receiving attention
Offshoots	Spin-off technologies linked

linear view on technological development is, nevertheless, claimed still to be alive because of the measurement issues and statistics [7] and because of the intuitive simplicity of the model, which makes understanding the interdependencies easy. Although "today's innovation process is best characterized by nonlinearity and interaction [28]," there are no good and widely utilized ways to measure the complex innovation process: the lack of statistics and widespread measurement has not made them surpass the old linear view. It is a danger that, in the complex models "everything depends on everything else in a non-linear fashion at the same time" [24], hindering the measurement possibilities. Although the linear model is condemned as certainly not a general theory of innovation, this model has been seen as a "rhetorical entity" and giving "a sense of orientation when thinking about funding to R&D" [7]. The linear model is also seen to have potential, for example, in science-based industries or "as a part or a complement of broader, more general theories which recognize more clearly the dynamic interactive nature of the innovative process" [24].

The TLC indicators offer a framework for understanding the totality of databases as this framework takes the most typically used databases and attaches the databases to a specific phase in the R&D process. The TLC indicators also form a linear sequence for reporting activity based on the linear model of innovation. The indicators thus not only heavily rely on linear thinking but also enforce this thinking by differentiating between basic and applied research and claiming basic research to be the origin of technical innovation. Although these assumptions are heavily criticized in the innovation literature, the TLC indicators offer a starting point for measuring the different sources and thus a process that is not typically possible with the complex systemic models. The TLC indicators take different databases into account and provide a framework for understanding their connectedness.

To summarize, the databases that the TLC indicators suggested as indicating the phases in R&D are commonly used in technology forecasting, but mostly individually, not as a whole. The use of multiple indicators has been suggested by, for example, Nelson [4], who argues that using multiple indicators decreases systematic biases between single measures. One of the few frameworks that take multiple sources into account is the TLC indicators that provide a measure for the totality of sources available for analysis and take their timeliness into account, although the linear model that the model represents is often questioned.

3. Research method and data

The Technology Life Cycle indicators are a bibliometric measure for operationalizing the technology's life cycle. White and McCain [29] define bibliometrics as "the quantitative study of literatures as they are reflected in bibliographies. Its task, immodestly enough, is to provide evolutionary models of science, technology, and scholarship." Bibliometric analysis is said to be applicable if international journals are the dominant or at least a major means of communication in a field [2]. This presumption, however, is due to bibliometrics having a strong orientation in measuring scientific performance from scientific journal databases although the definition of bibliometrics enables wider use and context.

To measure the TLC indicators bibliometrically, the actual measurement still needs to be specified as the TLC indicators do not explicitly specify how these indicators should be measured. The "number of items" marking the first four indicators does not yet give instructions on how to analyze these numbers. Many papers that study emerging technologies measure the growth rate in publication activity and assume an S-shaped graph [30,31]. The papers thus take the development into account and expect a certain behavior. These papers, however, very often measure from only one database such as the Science Citation Index or the US Patent and Trademark Office (USPTO) database, missing the totality of different databases and their relation to each other, which, then again, is the message of the Technology Life Cycle indicators.

To answer the research question about the order of appearance of reporting in different sources, an exact measurement was created. The TLC indicators build on bibliometric research, and thus here the starting point was chosen according to the bibliometric tradition. This means that first the yearly number of articles for each of the case technologies was counted, to give an overview of where the reporting activity was happening and to strengthen the later analysis. We studied the yearly activity levels by counting the articles that mentioned the case technology in each of the selected databases for each year, and compared the case technologies' development. The growth trends were found to be exponential so, in addition to plotting the yearly activity levels, we plotted the cumulative number of hits in each database and presented them in a logarithmic scale to be able to compare the graphs better.

The case technologies were searched from the headline or title field of each of the databases. The headline field was selected first to get the most relevant hits. Abrahamson and Fairchild have also suggested using headlines [32]. Second, limiting the search field was the availability of different search fields in some of the databases. Abstracts and keywords in the Science Citation Index records are searchable only from 1991 onwards. The news databases do not offer abstracts to be searched. To have comparable results, we thus selected the headline field from all of the databases.

To analyze the sequence of sources with each case technology, a definition of linearity was needed. As Balconi et al. [24] describe, linearity can be understood in several ways. The first interpretation is to understand linearity to mean sequentiality, as opposed to parallelism or simultaneity, in the time dimension. A second way of understanding linearity sees linearity as lacking feedback (either or both occurring simultaneously or over time). The third meaning of linearity implies that feedback is not self-reinforcing. From these three interpretations, linear models with very different emphases can be formed: the strong form linear model that implies a sequence of activities occurring one after the other with no feedback or, at the other extreme, the weak form linear model that is a fully interconnected system where all the activities interact with each other simultaneously and over time through self-reinforcing mechanisms [24]. The assertion of linearity in the case of TLC indicators is described as follows: "in the 'clean' case, one would expect to see the topic first rise, then decline, in fundamental research; with a similar but lagged pattern in a more applied research database; followed in turn by evidence of development, application, and possibly impact." [1]. Watts and Porter [1] also instruct that "on a technology broaching commercial introduction, one might concentrate on diffusion issues, thus tapping economic and market databases. For a technology still in the laboratory, one would likely concentrate on research databases." These researchers thus imply that linearity means sequentiality and do not comment on possible feedback. In this study, the TLC indicators are assumed to be following the sequential linear model. Thus, to analyze the sequence of reporting in this study, the very first hits of the measured occurrence time series were analyzed, the appearance years are compared, and finally, an order of appearance sequence is formed. The analysis of the first hit was chosen for three reasons. First, as we search for the technology in the headline part, the first appearance signifies that the technology has become recognized enough to be used by its name in the headline. Second, even though the hit is the first one, the meaning of the first hit is significant in terms of later analysis: A published article, patent, or a news piece represents activity that has happened before that piece has become public. The first hit thus means that there is more to be expected. Very seldom does a research field yield only one article, patent, or piece of news. Third, as many of the technologies are not stand-alone solutions but are based on earlier research, the recognition of that specific technology in the research field sets the beginning for that specific technology that differentiates itself from the background technical solutions and research.

Three criteria were used for selecting the case technologies. First, the timing of the development activities needed to fit the availability of sources. Because the Science Citation Index is available only from 1974 onwards, the selection of cases was limited to case technologies that would have their origins after 1974. Although the study is mainly interested in the beginning of the development of a technology, 2008 was selected as the end of the observation period in order to better comprehend the development over time. However, because of the limitations in the patent database, the very last years of the patent data are not reliable. As we searched the technologies in the granted patents by the patent application date, the newest patent applications were not included in the search as they had not yet been granted. The second criterion for the selection of the case technology was the unambiguity of the vocabulary used in the search term. The term had to be unambiguous so that we would get only relevant search results. The third criterion was the scope of the technology's name. To increase the relevance of the results, we selected technologies whose name represented the technical solution, i.e., the name of the technology was not given at a specific moment (for example, Bluetooth), but instead the whole technological development leading to the technology used the same name. Biodiesel, laser cladding, and blue LED were selected as the case technologies.

The search terms for each of the case technologies were defined broadly in order to include the relevant articles, and because the selection of cases was already based on unambiguity of the name of the technology. For biodiesel, the search term was "biodiesel" in all sources. The search term for laser cladding was "laser cladding," although in research by Dubourg and Archambeault [33] the search term was formed iteratively starting with the simple usage of the term "laser cladding," and then terms were added; only two patent classes were included in order to include only the relevant streams of research. However, as we were searching the general appearance of the technology and were not interested in the research streams within the laser cladding research, we searched for laser cladding by the technology's exact name. Blue LED was searched with the terms "blue LED OR blue-light-emitting diode." An option for searching with the representative wavelength of the color blue as well was discarded as adding the wavelength made the search term ambiguous. The abbreviation LED caused some problems as it is also the past tense of the verb leave. To include only relevant articles, a manual check of the articles was required.

The databases used in this study were selected according to the Technology Life Cycle indicators. The TLC indicators set the Science Citation Index to represent fundamental research, Compendex to represent applied research, Patents to represent development, and Newspaper Abstracts Daily to represent applications. Last, for societal impacts, the indicator was set to be "issues raised in the Business and Popular Press Abstracts." This last indicator is left out of the empirical study as the indicator is a very different kind of an indicator in which instead of "number of hits" the indicator is "issues raised." This makes the indicator difficult to compare with the other indicators, but as the indicator for "Application" was the quantitative measure of the news media, the source is thus also included in the study. The databases we selected are presented in Table 2. Next, each of the databases is briefly described.

The Science Citation Index Expanded, owned now by Thomson Reuters, covers more than 6650 major journals across 150 disciplines in science and technology. The database presents an extensive and multidisciplinary source for mining information and covers the world's leading scientific, technical, and medical journals. In our search, we used the Science Citation Index through two services. We used the STN Database service for articles from 1974 to 1986, and we used the ISI Web of Science for articles from 1986 to 2008.

The indicator for applied research was the number of articles in databases such as the Engineering Index [1]. The Engineering Index, now available as a backfile covering the years 1884–1969 and containing more than 1.7 million records, was succeeded by the Compendex database, now owned by Elsevier. Compendex is a comprehensive engineering and applied science database with 11.3 million records from more than 5600 scholarly journals, trade magazines, and conference proceedings, from more than 190 engineering disciplines. The broad subject areas covered in Compendex include civil, mining, chemical, mechanical, electrical, and general engineering. Compendex coverage is from 1970 to the present.

Table 2
The databases used and the innovation process phase they indicate.

Database used	Innovation process phase
Science Citation Index	Fundamental research
Compendex	Applied research
U.S. utility patents	Development
LexisNexis: All English Language News	Application

The next indicator, "the number of patents in databases such as U.S. Patents," was set to represent the development phase [1]. Only U.S. patents are measured because inventors use their home country protection for almost every invention and U.S. protection for those innovations the inventors feel represent significant advances or commercial value [34]. The databases used, however, depend on what kind of information is sought. The U.S. utility patents provide a good starting point when researchers are interested in the overall activity levels. The utility patents are adequate for this, as, according to the USPTO, "approximately 90% of the patent documents issued by the PTO in recent years have been utility patents, also referred to as 'patents for invention.'" The U.S. patents were measured directly from the USPTO.

The later stages of the Technology Life Cycle were indicated first by "the number of items in newspaper abstracts daily" (application) and then "issues raised in the business and popular press" (societal impacts). However, as described earlier in this section, the differences in the type of the indicator makes the "societal impacts" indicator difficult to compare with the other indicators; thus, only the quantitative news media measure, "the number of items in newspaper abstracts daily," is measured here. This is a valid selection because this paper is interested in the timeliness of the news category reporting and because the instructions for technology forecasting suggest minimizing attempts to predict social implications of new technologies [35]. The news and media are not commonly used in academic research for tracking technological development research although, with fast-developing technologies, communication to the stakeholders can be started very early and business databases, such as Business Source Premier or ABI Inform, have been mentioned to provide insight into technologies that have piqued the interest of the marketplace [36]. Overall, the competition in the news media has also made journalists increasingly popularize science. This means that there would be more material to analyze but creates doubt about the reliability of those reports. Holger Wormer, professor of science journalism at Dortmund University in Germany, estimates that "only one in fifty reported scientific breakthroughs is a real breakthrough, if ever" [37].

All in all, the last indicator was set to be "the number of items in databases such as newspaper abstracts daily." The newspapers were accessed through the Nexis database offered by LexisNexis, a part of the Reed Elsevier group. According to the LexisNexis, Nexis is "the world's largest and most trusted collection of news, company, people, industry, regulatory and legal content taken from 35,000 sources from 1975 to present day, covering all the world's major and emerging markets." The LexisNexis online system was originally set up for law firms and financial sources but has now become "the media archive of choice for many academic and political sources" [38]. From the Nexis database, a group source "All English Language News" that contains more than 3000 individual sources was selected.

4. Results

Here, the results for each of the case technologies are presented. First, the graphs representing the activity levels in the TLC indicators are presented and described separately for each of the case technologies. Then the Results section shows the graph depicting the years when the case technologies were mentioned for the first time in each of the databases and the sequence that the years form.

Biodiesel refers to a non-petroleum-based diesel fuel. The general definition of biodiesel in the US defines this fuel as "renewable fuel for diesel engines derived from natural oils like soybean oil, and which meets the specifications of ASTM D 6751" [39]. A more technical definition defines biodiesel as Biodiesel, n—a fuel comprised of mono-alkyl esters of long chain fatty acids derived from vegetable oils or animal fats, designated B100, and meeting the requirements of ASTM D 6751 [39]. The specification ASTM D 6751 was first published in 2002, but the development of biodiesels began in the early 1990s. According to Suurs and Hekkert [40], biodiesel is a so-called first-generation (1G) biofuel, based on conventional technologies, mainly adopted by farming organizations. Agricultural crops are used to produce biodiesel or bioethanol. The 2G biofuels originate from more science-based

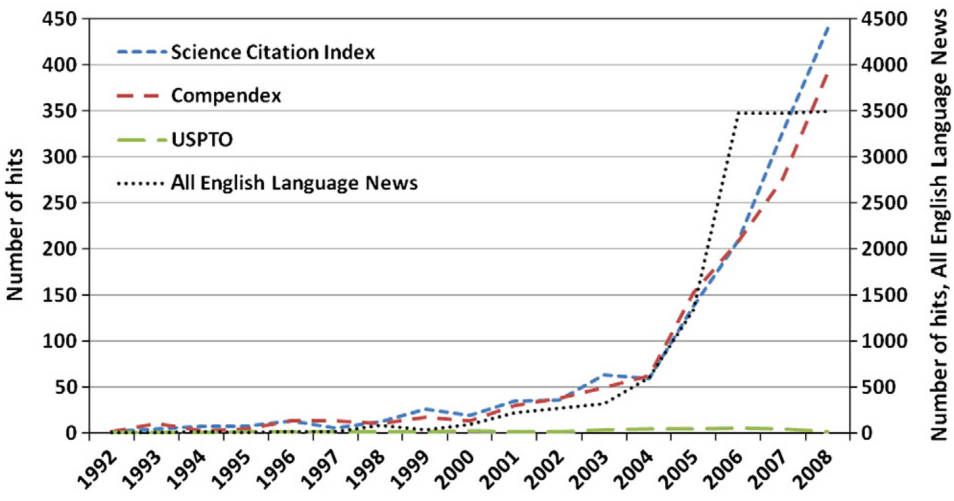

Fig. 2. Number of yearly hits mentioning biodiesel in the Technology Life Cycle indicators.

technologies (chemical and biotechnological) that are mostly advocated by research institutes and oil companies, but also by biotech industries and dedicated entrepreneurs [40]. The case in this study is 1G biodiesel biofuel.

For biodiesel, the overview of the activity in Technology Life Cycle indicators over time is presented first in normal scale in Fig. 2 and then in cumulative form on a logarithmic scale in Fig. 3. The figures show that the three indicators—the Science Citation Index, Compendex, and All English Language News—in addition to having the same starting point have a very similar growth curve. The patenting activity, while lagging behind time wise, is also significantly lower in terms of volume. Interestingly, however, the news indicator, which had been expected to be the last one, shows a dramatically bigger publishing volume throughout the years.

Laser cladding is a metal surface-enhancing process consisting of covering a substrate surface with a coating of a different nature [33]. Laser cladding ensures a bond with minimal dilution, nominal melting, and a small heat-affected zone, and protects components from corrosion far better than competing coating methods [41]. Laser cladding research reached an activity level high enough to be systematically measured after 1985 [33].

An overview of the laser cladding activity in Technology Life Cycle indicators is presented in Figs. 4 and 5. Compendex and the Science Citation Index present clearly observable early reporting activity increasing somewhat at the same time and at the same pace; however, the activity volume in Compendex exceeded the volume in the Science Citation Index. The patent activity starts later, after 1993, although the real increase in activity begins only after 1996 and levels off after a few years. All English Language News, although presenting activity only during the last three years of observation, shows a steep rise in publishing activity levels for laser cladding.

Blue-light-emitting diode (LED) has been popularized as an invention made by Shuji Nakamura in 1993, but the research effort on blue-light-emitting diodes has a much longer history. The now commercialized blue LEDs are based on the wide band gap semiconductors GaN (gallium nitride) and InGaN (indium gallium nitride). It wasn't until 1986 that the needed dramatic improvement in the crystal quality of GaN was achieved after which, in 1989, researchers were able to produce p-type conduction in nitrides and to control the conductivity of n-type nitrides. These achievements led to the invention of the world's first GaN p–n junction blue/UV LED in 1989. These breakthroughs inspired nitride researchers around the world to greater efforts and eventually led to the commercialization of high-performance blue LEDs [42].

The yearly activity levels in blue LED publishing are presented in Fig. 6, and the cumulative logarithmic overview of the blue LED indicator activity is presented in Fig. 7. Also here, the first two indicators Science Citation Index and Compendex present similarly developing communication activity trend with almost simultaneously increasing activity. The next indicator, All English Language News, behaves somewhat similarly although starting eight to nine years later than the first two. The development is not, however, linear but instead demonstrates a steep rise and then slight leveling off for five years before rising steeply again. The last indicator, U.S. Patents, has a low activity level throughout the years.

Overall, the differences in publishing volumes between the case technologies are significant. While the maximum number of yearly hits of the cases in Compendex varies from 391 (biodiesel) and 105 (laser cladding) to 50 (blue LED), the maximum number of yearly hits in All English Language News has an even wider range: 3496 for biodiesel, 16 for laser cladding, and 35 for blue LED.

In addition to the overall reporting development graphs, we analyzed the first articles that mention the case technologies. The TLC indicators state that the reporting order should proceed in a sequence in which the first activity is in the Science Citation Index, then Compendex, followed by U.S. Patents, and finally All English Language News. The years when the case technologies were mentioned for the first time in each of the databases and the sequence that the first-mentions form are presented in Table 3.

For biodiesel, the first appearance in the Science Citation Index, Compendex, and All English Language News was 1992. The first article mentioning biodiesel in the title appeared in the U.S. Patents database in 1995. The sequence of appearance is thus not in the proposed order; three of the four indicators appear at the same time, 1992, while one (patents) lags three years behind.

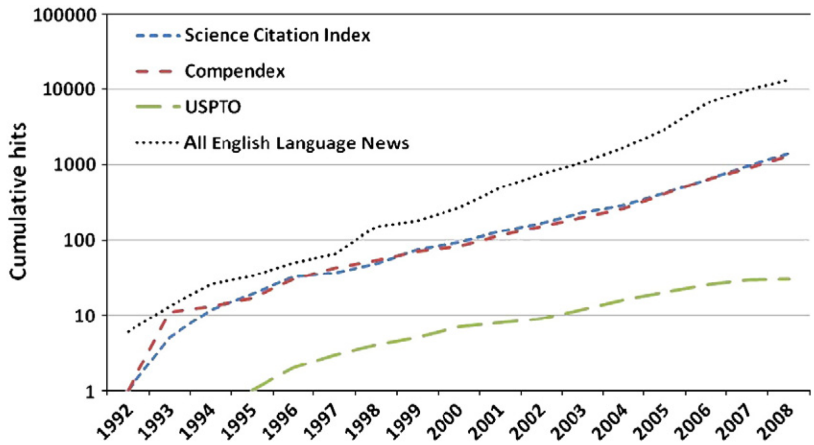

Fig. 3. The cumulative number of hits on a logarithmic scale for biodiesel in the Technology Life Cycle indicators.

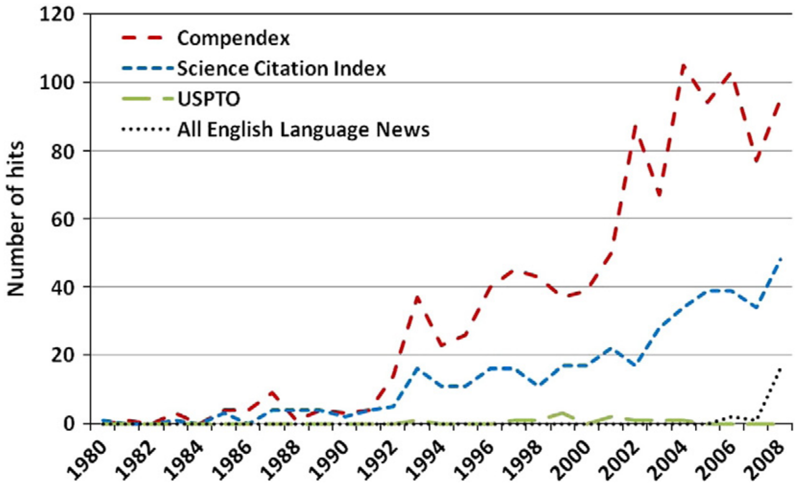

Fig. 4. The number of yearly hits mentioning laser cladding in the Technology Life Cycle indicators.

Laser cladding first appeared in the Science Citation Index in 1980, in Compendex in 1981, and in the U.S. Patents database in 1993. The first article that mentioned laser cladding in the headline appeared in All English Language News in 2006. The sequence of the laser cladding appearance in different indicators follows the order suggested by the TLC indicators.

In the case of blue LED, the first indicator was the Science Citation Index; the first published blue LED article appeared in 1975. Compendex had the first blue LED article in 1976, U.S. Patents in 1988, and English Language News in 1983. Here, the first two indicators proceed as the suggested Technology Life Cycle indicator sequence, but the News indicator presents activity five years before patent activity in the US.

5. Discussion

The reporting activity sequence in the TLC indicators appeared to go differently for each of the case technologies. The TLC indicators suggested that reporting on technologies first appear in sources such as the Science Citation Index, then proceed to sources such as Compendex, followed by U.S. Patents, and finally News sources. The results revealed that only one of the cases, laser cladding, followed the reporting sequence suggested by the TLC indicators. In the case of biodiesel, three of the four measured sources—the Science Citation Index, Compendex, and the News source—started their reporting the same year, 1992, while the reporting on blue LED started according to the TLC indicators, with the news indicator then preceding any U.S. patents mentioning blue LED in the title. Based on these results, the reporting order depends on the technology at stake as none of the three cases had a similar publishing order behavior.

As laser cladding was the only case that followed the TLC indicator order, the nature of the technology can be interpreted as having implications. Laser cladding, when compared to the other two cases, is a field that is clearly a creation of a scientific opportunity whereas in the case of biodiesel it was already seen in the case description that the initiator for biodiesel efforts is not

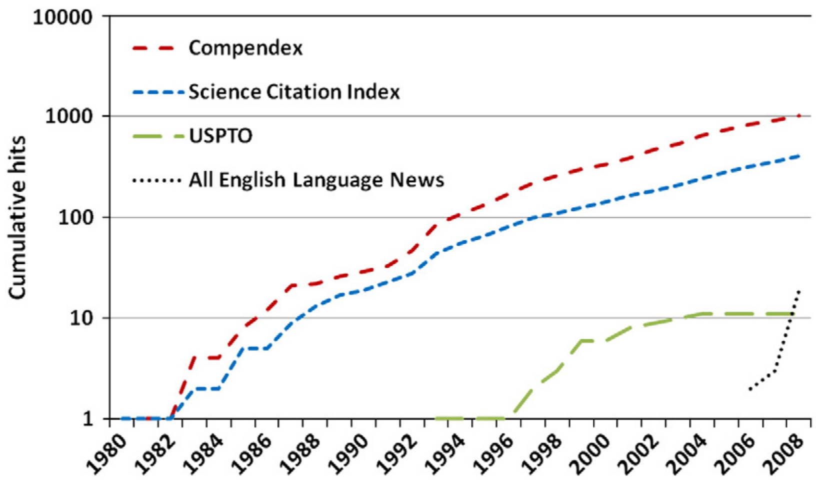

Fig. 5. The cumulative number of hits on a logarithmic scale for laser cladding in the Technology Life Cycle indicators.

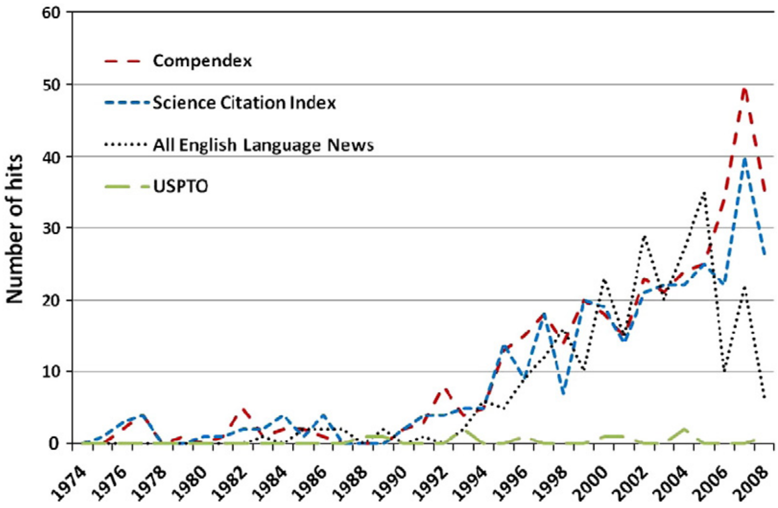

Fig. 6. The number of yearly hits mentioning blue LED in the Technology Life Cycle indicators.

science: The first-generation biofuels, which biodiesel is part of, are based on conventional technologies, whereas the second-generation biofuels originate from more science-based technologies [40]. The story of blue LED is unique in that although the blue LED is proclaimed to have been invented in 1993 the quest for blue LEDs began in the 1970s. Thus, there was an early awareness and demand from the market, but the scientific knowledge lagged behind. When the scientific solution was solved, the focus moved to applications and the process around them. Altogether, the narrative descriptions of the case technologies go well in line with what was seen in the publication activity graphs. Laser cladding was the only clear case of a science-based technology that followed the TLC indicator model that relies on the linear model of innovation. However, Balconi et al. suggested that the linear model may still be useful in science-based industries [24]. Laser cladding appears to be one such case.

In addition, the Science Citation Index and Compendex were in all three cases the first databases that included articles that reported on the technologies. These indexes were also very close to each other time wise in their beginning year of reporting, indicating that there is overlap between those two but, more importantly, that these phases might not be so easily separated from each other. Especially science originating innovation opportunities seem to have a linear type of dynamics. However, this remains a fruitful avenue for future studies to validate, since the results reported in this paper are limited to three case technologies.

The results of this study also showed that the technology that was claimed not to have a scientific origin, biodiesel, had the highest number of publications in all sources—the Science Citation Index and Compendex. For biodiesel, three of the four sources also followed a similar growth pattern, news media being one of them. Thus, the inferences from this are that non-science originated technologies can still be heavily present in scientific publications and that, at least in the case of biodiesel, the news media were very heavily present with a tenfold publication activity compared to the Science Citation Index or Compendex. This can mean that a heavy presence in the news media also has to do with the efforts in the research world. Biodiesel, in addition to being a technical or technological issue, is a heavily political topic; thus, the societal impact and political discussions have an

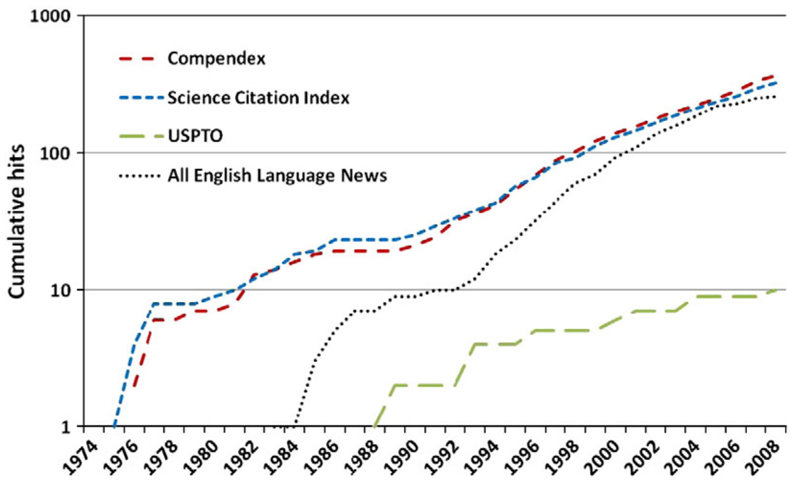

Fig. 7. The cumulative number of hits on a logarithmic scale for blue LED in the Technology Life Cycle indicators.

Table 3
The first appearance of biodiesel, laser cladding, and blue LED in each of the Technology Life Cycle indicators.

	Biodiesel		Laser cladding		Blue LED	
	Year	Order	Year	Order	Year	Order
Science Citation Index	1992	1	1980	1	1975	1
Compendex	1992	1	1981	2	1976	2
USPTO	1995	2	1993	3	1988	4
All English Language News	1992	1	2006	4	1983	3

impact on the technological development side. This underlines the interconnectivity and feedback loops stressed by the more complex models of innovation.

Naturally, there are a number of limitations in the study, including the databases used and the limitations of the bibliometric approach. Specifically, in the case of all four databases is the bias in favor of the English language [43] and the specific terminology used. Limitations related to the use of the sources specific to this study was the usage of only U.S. patents, and what appeared especially valid in the patent search was the limitation of the study in analyzing only the headline part from each of the databases. The headline part, although grasping the relevance aspect, does limit the results in terms of breadth—not all headlines are formulated to mention the name of the technology. The non-cumulative publishing activity graph on laser cladding especially demonstrates this limitation as the patenting activity remained at a very low level with only 11 patents mentioning laser cladding in the title while Dubourg and Archembeault found 580 patent records on laser cladding when searching not just headlines and using European and Japanese databases in addition to the USPTO [33]. Thus, the use of more databases than the patent database suggested by the TLC indicators (U.S. patents) could be useful in future studies. The limitation in analyzing the news database LexisNexis comes from the availability of sources: The availability and number of newspapers available when going back in time drop dramatically.

6. Conclusion

The results of this paper suggest that when science is the source of new ideas and the driver for technological development and innovations, communication can happen in the order suggested by the TLC indicators. However, this is not a general model for detecting and forecasting a technological life cycle. At the same time, the TLC indicators could be used in some cases, possibly with science-based technologies that follow the linear model of innovation, when the determination of those science-based technologies consequently becomes a crucial issue. The approach suggested in this paper can help future studies in identifying those technologies that follow the TLC indicators' progression. In addition, future studies could investigate attributes that differentiate technologies that follow the TLC indicators from those that do not.

The results of this study thus contribute to bibliometric technology forecasting, finding evidence that, first, the TLC model is not universally valid and that the order can be determined only ex post, and second, that the use of only one database as a source of bibliometric analysis only partly represents the process. If the media are actively involved early in the technology's life cycle, there may be forces other than technology push from the developers influencing the process. In the case of scattered sources of information about a technology, it is also critical to detect where the communication is happening in different phases. Recognizing the sources to use at different phases will thus help focus qualitative studies on communication about technologies. In addition, to comment on the note that bibliometric analyses are applicable only if scientific journals are a major means of communication [2], other text sources are available to be bibliometrically analyzed. Of course, the actual bibliometric methods have to differ, but using only scientific journals as a source can give a very biased picture of the phase of progression of the technology.

In addition, the results of the paper point to the possibility of studying non-linear models of innovation and contexts where this type of dynamics might take place. For example, applied research in engineering might produce new innovations that need public attention before scientific activity in order to gain funding necessary for the scientific developments in the applied research phase to materialize.

Managerially, the paper's approach can be used to monitor, to detect, and to analyze the phase of progression in technological developments in different sources. With this type of knowledge, practicing managers have clues on where the “action is happening.” With this understanding, the management of R&D can be directed to appropriate directions, whether it is basic research, applied research, or publicity about the research results, depending on the competitive situations that the developers are facing.

References

[1] R.J. Watts, A.L. Porter, Innovation forecasting, Technol. Forecasting Soc. Change 56 (1997) 25–47.
[2] A.F.J. van Raan, Measurement of central aspects of scientific research: performance, interdisciplinarity, structure, Meas. Interdiscip. Res. Perspect. 3 (2005) 1–19.
[3] Z. Griliches, R&D and Productivity: The Econometric Evidence, University of Chicago Press, 1998.
[4] A.J. Nelson, Measuring knowledge spillovers: what patents, licenses and publications reveal about innovation diffusion, Res. Policy 38 (2009) 994–1005 7.
[5] A. Kleinknecht, K. Van Montfort, E. Brouwer, The non-trivial choice between innovation indicators, Econ. Innov. New Technol. 11 (2002) 109–121.
[6] N. Rosenberg, Exploring the Black Box: Technology, Economics and History, Cambridge University Press, Cambridge, UK, 1994, p. 274.

[7] B. Godin, The Linear Model of Innovation — the historical construction of an analytical framework, Sci. Technol. Hum. Values 31 (2006) 639–667.
[8] C.L. Borgman, J. Furner, Scholarly communication and bibliometrics, Annu. Rev. Inf. Sci. Technol. 36 (2002) 2–72.
[9] M.J. Norton, Introductory Concepts in Information Science, Information Today Inc., 2000.
[10] J.P. Martino, Technological Forecasting for Decision Making, 3rd ed., McGraw-Hill, Inc., 1993, p. 462.
[11] IDC, Tackling information overload at the source, White Paper, March, 2009 vol.
[12] Y. Kajikawa, J. Yoshikawa, Y. Takeda, K. Matsushima, Tracking emerging technologies in energy research: toward a roadmap for sustainable energy, Technol. Forecasting Soc. Change 75 (2008) 771–782 7.
[13] R.N. Kostoff, D.R. Toothman, H.J. Eberhart, J.A. Humenik, Text mining using database tomography and bibliometrics: a review, Technol. Forecasting Soc. Change 68 (2001) 223–253 11.
[14] C. Chao, J. Yang, W. Jen, Determining technology trends and forecasts of RFID by a historical review and bibliometric analysis from 1991 to 2005, Technovation 27 (2007) 268–279 5.
[15] Y. Kajikawa, Y. Takeda, Citation network analysis of organic LEDs, Technol. Forecasting Soc. Change 76 (2009) 1115–1123.
[16] R.N. Kostoff, M.B. Briggs, R.L. Rushenberg, C.A. Bowles, M. Pecht, D. Johnson, S. Bhattacharya, A.S. Icenhour, K. Nikodym, R.B. Barth, S. Dodbele, Comparisons of the structure and infrastructure of Chinese and Indian Science and Technology, Technol. Forecasting Soc. Change 74 (2007) 1609–1630 11.
[17] R.N. Kostoff, J. Antonio del Río,, H.D. Cortés, C. Smith, A. Smith, C. Wagner, L. Leydesdorff, G. Karypis, G. Malpohl, R. Tshiteya, The structure and infrastructure of Mexico's science and technology, Technol. Forecasting Soc. Change 72 (2005) 798–814 9.
[18] K. Chuang, Y. Huang, Y. Ho, A bibliometric and citation analysis of stroke-related research in Taiwan, Scientometrics 72 (2007) 201–212.
[19] R.N. Kostoff, Comparison of China/USA science and technology performance, J. Informetrics 2 (2008) 354–363 10.
[20] R. Haupt, M. Kloyer, M. Lange, Patent indicators for the technology life cycle development, Res. Policy 36 (2007) 387–398.
[21] P.J. Palmer, D.J. Williams, C. Hughes, Observations and models of technology trends within the electronics industry, Eng. Sci. Educ. J. 8 (1999) 233–240.
[22] Z. Griliches, Patent statistics as economic indicators: a survey, J. Econ. Lit. 28 (1990) 1661–1707 12.
[23] P. Moser, How do patent laws influence innovation? Evidence from nineteenth-century world's fair, Am. Econ. Rev. 95 (2005) 1214–1236 09.
[24] M. Balconi, S. Brusoni, L. Orsenigo, In defence of the linear model: AN essay, Res. Policy 39 (2010) 1–13.
[25] S.J. Kline, N. Rosenberg, An Overview of Innovation, in: R. Landau, N. Rosenberg (Eds.), The Positive Sum Strategy: Harnessing Technology for Economic Growth, The National Academy of Sciences, 1986, pp. 275–305.
[26] B. Lundvall, B. Johnson, The learning economy, J. Ind. Stud. 1 (1994) 23–42.
[27] J. Caraça, B. Lundvall, S. Mendonça, The changing role of science in the innovation process: from Queen to Cinderella? Technol. Forecasting Soc. Change 76 (2009) 861–867 7.
[28] J. Shina, Y. Park, Brownian agent-based technology forecasting, Technol. Forecasting Soc. Change 76 (2009) 1078–1091.
[29] H.D. White, K.W. McCain, Bibliometrics, in: M.E. Williams (Ed.), Annual Review of Information Science and Technology, vol. 24, Elsevier Science Publishers B.V., 1989, pp. 119–186.
[30] M. Bengisu, R. Nekhili, Forecasting emerging technologies with the aid of science and technology databases, Technol. Forecasting Soc. Change 73 (2006) 835–844.
[31] B.M. Gupta, P. Sharma, C.R. Karisiddappa, Growth of research literature in scientific specialities. A modelling perspective, Scientometrics 40 (1997) 507–528.
[32] E. Abrahamson, G. Fairchild, Management fashion: lifecycles, triggers, and collective learning processes, Adm. Sci. Q. 44 (1999) 708–740.
[33] L. Dubourg, J. Archambeault, Technological and scientific landscape of laser cladding process in 2007, Surf. Coat. Technol. 202 (2008) 5863–5869 8/15.
[34] C. Watanabe, Y.S. Tsuji, C. Griffy-Brown, Patent statistics: deciphering a 'real' versus a 'pseudo' proxy of innovation, Technovation 21 (2001) 783–790.
[35] S. Mishra, S.G. Deshmukh, P. Vrat, Matching of technological forecasting technique to a technology, Technol. Forecasting Soc. Change 69 (2002) 1–27.
[36] C. Courseault Trumbach, D. Payne, A. Kongthon, Technology mining for small firms: knowledge prospecting for competitive advantage, Technol. Forecasting Soc. Change 73 (2006) 937–949 10.
[37] E. Wolvaardt, How journalism can hide the truth about science, SciDev.Net, January 5 2007.
[38] D. Deacon, Yesterday's papers and today's technology: digital newspaper archives and 'push button' content analysis, Eur. J. Commun. 22 (March 1. 2007) 5–25.
[39] National Biodiesel Board. (2009, Biodiesel definitions. 2009(12/2009)).
[40] R.A.A. Suurs, M.P. Hekkert, Competition between first and second generation technologies: lessons from the formation of a biofuels innovation system in the Netherlands, Energy 34 (2009) 669–679 5.
[41] J. Tuominen, Engineering Coatings by Laser Cladding — The Study of Wear and Corrosion Properties, 2009, p. 223.
[42] I. Akasaki, Key inventions in the history of nitride-based blue LED and LD, J. Cryst. Growth 300 (2007) 2–10 3/1.
[43] C. Palmberg, H. Dernis, C. Miguet, Nanotechnology: an overview based on indicators and statistics, Directorate for Science, Technology and Industry, OECD, Jun 26 2009.

Heini Järvenpää is a researcher at the Center for Innovation and Technology Research (CITER) at the Department of Industrial Management, Tampere University of Technology, Finland.

Saku Mäkinen, PhD, is Professor of Technology and Innovation Management and the Head of the Department of Industrial Management at the Tampere University of Technology (TUT), Finland. Prof. Mäkinen was formerly with the Department of Marketing, Faculty of Business Administration, National University of Singapore. He received a M.Sc. in Electrical Engineering and a PhD in Technology Strategy both from TUT, Finland. His research interests include technology and innovation management, strategy, and technology and industry co-evolution.