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Measurement of depreciation rate of technological knowledge: Technology cycle time approach

Gwangman Park[1], Juneseuk Shin[2] and Yongtae Park[2,*]
[1]Electronics and Telecommunications Research Institute, 161 Gajong-dong, Yuseong-gu, Daejon, 305-700, Korea
[2]Department of Industrial Engineering, Seoul National University, San 56-1, Shillim-Dong, Kwanak-Gu, Seoul, 151-742, Korea

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In this paper, a new method is proposed for estimating the depreciation rate of technological knowledge based on the analysis of technology cycle time (TCT). Patent citation data are used in an empirical analysis. The following features characterize the proposed TCT-based method: i) Estimation of the depreciation rate is measured by using the entire set of patents; and ii) The current approach generates the sector-specific depreciation rates for individual industrial sectors. Overall, the results of empirical analysis are in accordance with expectation. The average depreciation rate (13.3 %) is rather higher than other estimates of previous research. At the same time, consistent upward trends are found over time. Regarding the sectoral variation among industries, emerging and high-tech sectors show faster pace of technical progress but at the same time higher rate of technical obsolescence, vis-à-vis traditional manufacturing sectors or light industries.

Keywords: Depreciation rate, Patent, TCT (Technology cycle time)

Introduction

With the advent of knowledge-based economy, technological knowledge (TK) has been recognized as key factor of strategic competitiveness and innovation capability of an industry and/or a country. The inherent difficulty of measurement may be attributable to the following factors: i) TK encompasses heterogeneous components that are hard to standardize[1]; ii) TK embraces embodied/tacit knowledge that is hard to separate or quantify[2]; iii) TK is subject to idiosyncratic differences across industrial sectors[3] and thus is difficult to generalize; and iv) TK changes over time and hence is hard to measure at a certain point of time.

TK is accumulated and thus increased through R&D and innovation efforts but it depreciates and becomes obsolete over time. The depreciation rate (DR) depends on changes in external circumstances, development of superior technologies, and decline in the appropriability as it diffuses[4]. Therefore, like the growth and diffusion analysis[5], the estimation of DR accounts for a major research theme in technology forecasting. Furthermore, since DR may substantially differ across industries, it is related to the notion of sectoral pattern of innovation[3].

*Author for correspondence
Tel: +82-2-880-8358; Fax: +82-2-889-8560
E-mail: parkyt@cybernet.snu.ac.kr

In spite of the importance of DR, little effort has been made to measure the DRs of TK, except for some conventional studies[4,6,8,11]. Consequently, it is not uncommon that the applied work has assumed an arbitrary DR (0.04-0.15) to construct the stock of R&D[9]. These studies used the perpetual inventory method, which was originally developed for the calculation of physical capital stock[10].

This paper proposes a new method for estimating DR of TK. The proposed method, technology cycle time (TCT), which is based on the analysis of patent citation data, is used to measure DR. TCT was also applied to conduct a comparative analysis of DRs of TK across industrial sectors.

Previous Approaches for Estimating Depreciation Rate

Previous approaches[4,6,8,11] for estimating DR are classified into four basic approaches, as follows:

Survey Approach

The expected lifespan of technology or patents were gathered directly from the private industrial sectors or firms using survey questionnaires[4,8]. This lifespan is not the length of time a patent is renewed, but rather is the length of time their patents generated royalty revenues, and/or the average length of time their products embodying the patented technologies generated profits. Assuming that R&D capital stock depreciates and become obsolete over time, they should be able to obtain DR of R&D stock by simply taking the inverse of the average lifespan of patents. It could be possible to estimate the sector-specific DRs of TK for different industrial sectors in this approach[4].

Renewal Data Approach

It is rather simple and direct method, and the first theoretical approach for estimating DR[6]. In this approach, DR of TK was measured directly using patent renewal data. Once granted, a patent obtains the proprietary right automatically for the first some years of its life. After the predetermined year, however, continued protection requires that the owner take the appropriate steps to renew the patent and typically pay patent renewal fee. Renewal generally takes place annually thereafter, at the owner's discretion, until it becomes unprofitable to do so or until the end of patent right, at which the patent is automatically expired. Thus, it is possible to trace the decay pattern or renewal pattern for each set of patents made in a particular year. Assuming the constant exponential decay rate of TK, the DR of TK is estimated for each set of patents made in a particular year by adopting simple linear regression analysis.

Renewal Theory Approach

It is based on a theoretical model of patent renewal and it would lead to a procedure for estimating DR from patent renewal data[11]. Allowing differences in the initial appropriable revenues among patents, it is assumed that the distribution of initial returns was specific distribution and it decayed deterministically thereafter. Patent holders were assumed to choose a lifespan for their patents to maximize the expected discounted value of the net returns (current returns minus renewal fees). In this probabilistic renewal model, the curvature of the percentage of patents renewed in each year would depend on the distribution of the values of the innovations patented. This renewal model would be used to obtain estimates of DR of appropriable revenue. In the following studies, Pakes & Schankerman and their inheritors have elaborated initial patent renewal model such that both the initial distribution and the decay rates would be allowed to vary over time[11,12]. The focus of the more recent studies lay in calculating the value of patent rights. But, DRs of TK were estimated as by-product additionally.

Econometric Approach

It was for estimating DR of both physical and R&D capital jointly with the other model parameters. The model was estimated for the US total manufacturing sector. Only gross investment data are needed to estimate the model parameters and DRs, and to generate consistent series for the stocks of physical and R&D capital.

Analysis of Previous Approaches

The main strand for estimating DR of TK has used patent renewal data[6,11]. Several problems, however, exist in this approach. The renewal history data of a patent by the end of patent right are needed for the analysis using patent renewal. Conventionally, the legal protection period of patent right is 17-20 years, which depends on the country-wise patent system. Thus, the analysis using patent renewal data could not capture the more recent trends. That is why most studies using patent renewal data only covered until the end of 1970s. Second, only a very small fraction of renewal data was used in the analysis. Although the number of granted patents was tens of thousands per cohort, at most tens or hundreds of renewal data were used in the analysis covering tens of study periods. This may be due to the problem of data availability. But, if the renewal data used in analysis could not appropriately represent population set of patents, the analysis results might be biased due to the problem of sample selection. Furthermore, patent renewal data is not available in some countries. In case of US, there is no patent renewal fee until 1982. Third, a patent holder tries to maximize the net profit of patent over time. However, it is not easy to access the profit potential of a patent. This requires a lot of information gathering and analysis, which is costly and time-consuming. Moreover, because patent renewal fee is relatively small in some countries, patent holders tend to renew and keep their patents even though they may no longer represent valuable TK[4]. Fourth, DR of patented innovations may differ from that of all innovations. So the estimates of DR calculated by using patent renewal data may reflect some sample selection bias. The direction of the bias is indeterminate since it depends on the correlation between the patent selection process and DR in the universe of all innovations. But, the estimates of DR might be biased downward since the innovator would actually take out a patent only if patenting lowered DR.

The survey approaches taken by Schott[8], and Goto & Suzuki[4] are also subject to some problems inherent to questionnaire-based methods. First, in these approaches, survey questionnaires were mailed to the research managers of major firms in UK and Japan to get information. But, there is some room of arbitrary interpretation in answering the questions. For example, what is 'the average lifespan of your company's patents'? In answering this question, there exists possibility of arbitrary interpretation in both 'average' and 'lifespan'. Second, the calculation of DR is based on the firm data. Thus, DR obtained is that of the firms in each industry. This must be higher than DR of the industry R&D stock as a whole because competition between the firms in the same industry erodes each firm's R&D stock[4].

For the factor demand model adopted in the study of Nadiri & Prucha[7], several issues are not yet addressed. First, they imposed certain restrictions on the model such as the assumption of constant return to scale and constancy of DRs for the two types of capital, physical and R&D capitals. Clearly, the assumption of, in particular, a constant DR is restrictive, given the aggregate nature of their investment data. Also, they do not incorporate at this stage demand equations for investment in R&D and physical capital as part of their estimating model. Furthermore, the robustness of the results needs to be checked against alternative functional forms for the restricted cost function.

TCT-based Method

The proposed method, TCT, is based on the analysis of technology cycle time by using the patent citation data. The depreciation or obsolescence of TK is closely related with the notion of pace of technological progress or technological development, which is a construct that has evolved from technological change theories. Technological change theories describe how the development and progress of a technology field may go through slow and fast cycles[13]. Along this line of research, the concept of technology life cycle (TLC), much like product life cycle (PLC), has been introduced in the more recent studies[14]. The concept of PLC is well-defined and operationalized[15] both empirically and theoretically. However, the notion of TLC has been suggested at conceptual level but yet lacks objective and quantitative measures.

Over last decade, use of patent data has been enhanced by computerization of patent system. A number of patent-based technology indicators have been developed for measuring technological strength of companies and countries. These new technology indicators are more advanced, vis-à-vis conventional indicators, in terms of information obtained from the patent document. They have drawn from a widely used bibliometric technique called "science indicators" which used the cited references in scientific papers to indicate scientific activity[16].

In this paper, possibility of using patent data in developing TLC indicator is explored. The original idea of TCT, proposed by a private consulting company[18], is defined as the 'median' age of patents cited on the front page of a patent document. The rationale is due to the assumption that the references cited in a patent, called 'prior art', provide a unique feature, which captures linkage between an invention and the prior knowledge most closely related to it. The measure also assumes that the more recent the age of cited patents, the more quickly one generation of inventions is replacing another. Since then, TCT-based indicators have been used in accessing pace of progress for different technologies or different nations in same technology[17].

In the current research, TCT is defined as 'mean', rather than median, age of the patents cited. Thus, TCT is the average lag between application year of the citing patent and that of the cited patents. The mean value is adopted because value of TK is declining with constant exponential decay rate and lifetime distribution of TK can be represented as that of the citation lag. Mean lag is computed by taking lag of each citation to be an observation and calculating the mean for all of the citations. Then, DR of TK in a particular industrial sector is calculated by simply taking the inverse of TCT. The same method cannot be employed if median value is used.

For industry level of analysis, concordance between the patent classification system and industrial classification system is necessary. Calculating TCT of each industry, DR of TK of each industrial sector can be estimated separately. And applying it into different cohort, one could estimate the time-variant DR of TK. So, the dynamic analysis of DR would be possible.

Application of Proposed Method

Data

In order to estimate TCT, the NBER patent-citations data files are used[18]. Such files comprise detailed information on 2,923,922 US patents granted between 1963 and 1999, all citations made to these patents between 1975 and 1999, totaling 16,522,438 citations. The estimation requires data on patent number, application year and main US patent class (3-digit technology class) of both citing and cited patents.

Table 1—Depreciation rates over time at different intervals

Interval	Year	Depreciation rate	Interval	Year	Depreciation rate
3 years	1985-87	0.123559	5 years	1985-89	0.124916
	1988-91	0.127786		1990-94	0.134183
	1991-93	0.134109		1995-99	0.137463
	1994-96	0.138995	10 years	1983-90	0.126228
				1991-99	0.136303

To examine the difference across industries, the US patent 3-digit technology classes are aggregated in accordance with the international standard industrial classifications (ISIC) rev. 3.1 (Appendix A). Specifically, the 4-digit classes of ISIC are referred for matching. Some classes are overlapped over a couple of industries. Such cases are excluded since they adulterate the technological homogeneity within an industry. Based on same rationale, the scope of analysis is confined to the manufacturing industry.

The application year, instead of grant year, is adopted as a measure of TCT since the actual timing of patented innovations is closer to the application year than to the grant year. Inventors have a strong incentive to apply for a patent as soon as possible following the completion of the innovation, whereas the grant date depends upon the review process at the Patent Office, which takes on average about 2 years, with a significant variance[18]. In practice, it is not rare to come up with some missing elements in application year.

Before calculating TCT, some preprocessing job is applied to these data. Keeping the homogeneity of technologies within an industry, the inter-industry citations are removed by comparing the industry code between citing and cited patent. Then, avoiding the overvaluation of TCT, the cases whose TCT are over 20 years are deleted. The criterion, 20 years, which is derived from US Patent law, is the maximal term of a patent before expiration. It is assumed that a citation over 20 years has little meaning since the cited patent had already expired.

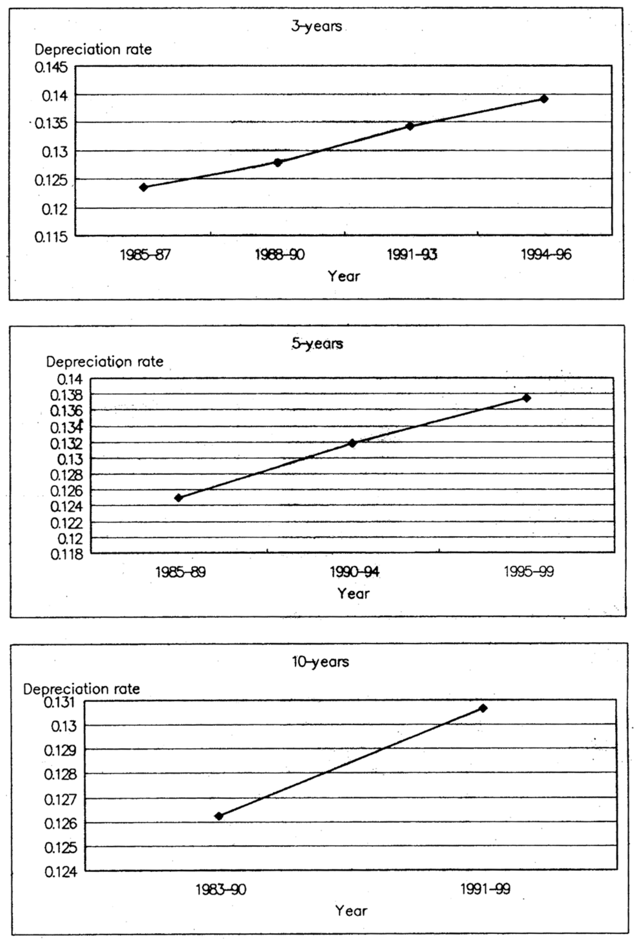

Fig. 1—Patterns of depreciation rates among time intervals

Depreciation Rate over Time

The backward citation lags are adopted as TCT i.e., the time differences between the application year of the citing patent and that of the cited patents are gauged. The patent data set extends from 1963 through 1999. Though citation data are available from 1975, the data from 1975 to 1982 was excluded since the entire distribution range of backward citation lags was confined to 20 years previously. By doing so, one could control for truncation and undervaluation due to forward citation lags and varying range of distribution.

Overall, the average DR turned out to be 13.3 percent. In other words, it is estimated that technologies have become obsolete at the rate of 13.5 percent per year. The estimate is rather higher, as compared to some other estimates (Schott's estimate, 10 %; Nadri & Prucha's estimate, 12 %). To grasp the variation of DRs over time, the average values were measured at 3 (short-term)-, 5 (mid-term)- and 10-year (long-term) intervals and analyzed (Table 1, Fig. 1).

Table 2—Aggregation of ISC rev.3.1 into new categories

ISIC code	New code	Industry	ISIC code	New code	Industry
15	1	Food & beverage	27	8	Basic metal
16			28	9	Fabricated metal
17	2	Textile	29	10	Machinery
18			30	11	Electrical, computing & communication
19			31		
20	3	Wood product	32		
21	4	Paper, printing & publishing	33	12	Precision
22			34	13	Transport equipment
23	5	Chemicals	35		
24			36	14	Other manufacturing
25	6	Rubber & plastic	37		
26	7	Non-metallic mineral		15	Unclassified

Table 3—Depreciation rates of some selective industries

Industry	Depreciation rate %	Industry	Depreciation rate %
Food & beverage	11.87	Machinery	12.75
Textile	13.09	Computer	16.79
Papers	12.02	Electrical	14.39
Chemicals	13.10	Electronics	16.08
Non-metallic mineral	12.84	Precision	13.92
Basic metal	12.62	Transport equipment	13.71

Apparently, consistent upward trends are found regardless of intervals. In order to assure the validity of intuitive finding, the means from different periods are statistically tested for 3-years interval. The null hypothesis is that no significant difference exists among means of different periods. It was tested based on the one-way ANOVA. The F-statistics is 29725 and thus the null hypothesis was rejected with a 1 % significance level.

In fact, the results are in accordance with anticipation. One of the most distinctive characteristics of modern technology is fast advancement and rapid obsolescence. It is never surprising that this phenomenon is reflected in patent citation statistics.

Depreciation Rate Across Industries

In general, it is premised that both TK accumulation and knowledge DRs vary among industrial sectors. Therefore, another theme of inquiry is whether there exist idiosyncratic differences across industries and, if so, what are estimates of depreciation for respective industries. Before examining the idiosyncratic pattern, the industry classification scheme needs to be determined. Basically, the formal and conventional taxonomy international standard industry classification (ISIC) is adopted since ISIC is readily applicable and widely accepted in policy-making practice. However, for the

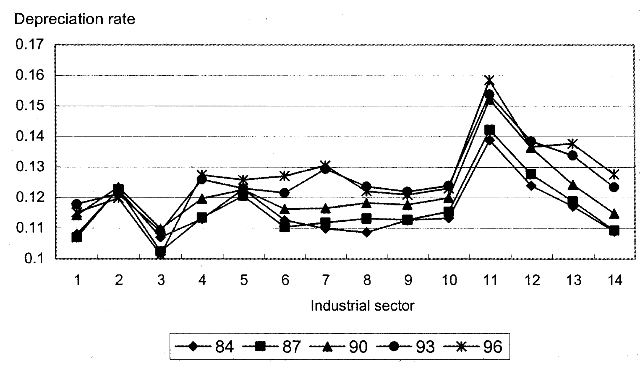

Fig. 2—Changing patterns of depreciation rates across industries: 3-years interval

convenience of analysis and comparison, ISIC is aggregated into 15 categories (Table 2). Irrespective of industrial fields, a similar upward trend was found over time. However, DRs are seemingly different across industries (Table 3, Fig. 2).

The sectoral variation among industries is noticeable between conventional sectors and high-tech sectors. Emerging sectors (computers, electronics) are characterized by the fast pace of technical progress but at the same time by the higher rate of technical obsolescence (> 16 %). On the contrary, traditional manufacturing sectors or light industries show rather incremental technical improvement and gradual rate of technical depreciation (12 %). In fact, the gap (4 %) may be tremendous as it is amplified over time.

Table 4—Cluster membership by changing rates of depreciation

Cluster	Membership	Changing pattern
1	Electrical, computing, communication, precision and transport equipment	Consistently increasing
2	Rubber & plastic, basic metal, fabricated metal, machinery	Increasing mainly from 1982 to 1994
3	Chemical	Increasing mainly from 1988 to 1998
4	Food & beverage, textile	No pattern observable

In addition, from dynamic perspective, a number of distinctive groups are found in terms of changing pattern of depreciation. Relatively high-tech industries (electrical, computing, communication, precision and transport equipment) show a consistently increasing rate of depreciation (Table 4). Manufacturing sectors such as metal and machinery exhibited increasing rate from 1982 to 1994 but have shown stable rate since then. Chemical industry is similar in that DR was increasing from 1988 to 1998 but has become almost constant since then.

Conclusions

A new method (TCT) has been proposed for estimating the depreciation rate (DR) of technological knowledge (TK) based on the analysis of technology cycle time. In TCT-based method, estimation of DR is measured by using the entire set of patents. Compared with previous methods that used only a small fraction of patent renewal data, the proposed method is built on a firm foundation. The current approach generates the sector-specific DRs for individual industrial sectors. There may be idiosyncratic differences among industrial fields but existing methods have not addressed this topic in depth. Dynamic analysis of the change of DR is possible in the proposed method. Although patent renewal data may be used for dynamic analysis, the possibility is restricted due to the limited availability of patent renewal data. Overall, the average DR (13.3 %) is rather higher than previous estimates. At the same time, consistent upward trends are found over time. Regarding the sectoral variation among industries, as anticipated, emerging, high-tech sectors show faster pace of technical progress but at the same time higher rate of technical obsolescence, vis-à-vis traditional manufacturing sectors or light industries.

Although the proposed method made some noteworthy contributions in the estimation of DR, it has limitations. Patent represents only a part of all possible innovations. Thus, DR obtained by the proposed method may be a reasonably good estimate but not a perfect and faultless estimate. Different industries may display different propensities in terms of patenting strategy. Thus, the patent-based DR may be biased across industries. These potential problems need to be solved in the future research.

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Appendix A—Aggregation of U.S. patent 3-digit technology classes into ISIC rev.3.1

ISIC code	ISIC rev. 3.1	US patent 3-digit technology class
15	Food products & beverage	99, 127, 426, 452, 460
16	Tobacco products	131
17	Textiles	2, 8, 19, 26, 28, 38, 57, 66, 68, 87,139, 442
18	Wearing apparel; dressing & dyeing of fur	112, 450
19	Tanning & dressing of leather; manufacture of luggage, handbags, saddlery, harness & footwear	12, 24, 36, 54, 69, 150
20	Wood & of products of wood & cork, except furniture; articles of straw & plaiting materials	142, 144, 212, 217
21	Paper & paper products	162, 229, 281, 493
22	Publishing, printing & reproduction of recorded media	84, 101, 276, 283, 462
23	Coke, refined petroleum products & nuclear fuel	44, 184, 208, 376, 507, 508
24	Chemicals & chemical products	23, 48, 55, 71, 95, 96, 102, 134, 137, 149,201, 203, 204, 205, 239, 250, 401, 416, 422, 423, 424, 427, 429, 430, 435, 436, 501, 502, 504, 510, 512, 514, 516, 518, 520, 521, 522, 523, 524, 525, 526, 527, 528, 530, 534, 536, 540, 544, 546, 548, 549, 552, 554, 556, 558, 560, 562, 564, 568, 570, 585, 800
25	Rubber & plastic products	106, 152, 264, 383
26	Other non-metallic mineral products	65, 125, 451
27	Basic metals	29, 72, 75, 82, 83, 141, 148, 164, 168, 199, 216, 228, 241, 242, 249, 260, 270, 420
28	Fabricated metal products, except machinery & equipment	30, 51, 59, 70, 76, 81, 117, 118, 122, 138, 140, 163, 165, 173, 175, 182, 211, 221, 222, 225, 227, 234, 237, 245, 254, 256, 267, 289, 407, 408, 413, 414, 419, 432, 470
29	Machinery & equipment n.e.c.	7, 42, 56, 62, 74, 86, 89, 100, 110, 124, 126, 132, 156, 159, 166, 169, 171, 172, 177, 187, 193, 194, 196, 198, 202, 210, 223, 224, 236, 251, 261, 266, 269, 271, 291, 294, 373, 384, 402, 406, 409, 411, 412, 417, 431, 453, 454, 474, 475, 476, 482, 483, 492
30	Office, accounting & computing machinery	235, 341, 345, 347, 360, 365, 369, 380, 382, 395, 400, 700, 701, 702, 704, 706, 707, 708, 709, 710, 711, 712, 713
31	Electrical machinery & apparatus n.e.c.	60, 116, 123, 136, 174, 191, 200, 218, 219, 257, 279, 290, 310, 313, 314, 315, 318, 322, 323, 327, 330, 331, 333, 335, 336, 337, 346, 361, 362, 363, 366, 372, 377, 388, 445
32	Radio, TV & communication equipment & apparatus	178, 181, 307, 320, 326, 329, 332, 334, 338, 340, 342, 343, 348, 349, 358, 367, 370, 375, 379, 381, 385, 386, 392, 438, 439, 455, 505, 714
33	Medical, precision and optical instruments, watches & clocks	33, 73, 128, 324, 351, 352, 353, 355, 356, 359, 368, 374, 378, 396, 399, 433, 494, 503, 600, 601, 602, 604, 606, 607, 623
34	Motor vehicles, trailers & semi-trailers	91, 180, 185, 188, 192, 293, 298, 301, 303, 415, 418, 464, 477
35	Other transport equipment	104, 105, 114, 157, 213, 238, 246, 278, 280, 295, 296, 305, 410, 440, 441
36	Furniture; manufacturing n.e.c.	4, 5, 15, 49, 63, 79, 135, 160, 273, 297, 300, 312, 446, 463, 472, 473
37	Recycling	588
	Unclassified	1, 14, 16, 27, 34, 37, 40, 43, 47, 52, 53, 92, 108, 109, 111, 119, 147, 186, 190, 206, 209, 220, 226, 231, 232, 244, 248, 252, 258, 277, 285, 292, 299, 403, 404, 405, 425, 428, 434, 449,705