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Measuring the Pace of Technological Progress: Implications for Technological Forecasting

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ABSTRACT

The pace of technological progress is a construct that has evolved from technological change theories. Although the construct is well described, it lacks a valid objective measure. Measuring the pace of technological progress is believed to be important for both technology management and technology forecasting. A newly-developed objective measure of the pace of technological progress called the Technology Cycle Time indicator (TCT) is evaluated. The TCT indicator was used in two comparison analyses: (1) assessing the pace of progress of superconductor and semiconductor technologies; and (2) assessing the position of various countries patenting in the semiconductor technology field. The TCT assessments were then analytically compared with specialist assessments found in the literature. The findings revealed that the TCT provided a valid assessment in each situation. The TCT has important implications for technology management and technology forecasting research. © 1999 Elsevier Science Inc.

Introduction

The importance of understanding the technological innovation process has long been recognized, and has given rise to academic research that stretches back to the 1950s. The result has been the recognition that it is an activity which should be managed. Practice, however, is more difficult than theory. To manage technology, as with any other activity, the variables affecting it must be controlled. But before these variables can be controlled, they must be measured. One variable related to the technological innovation process is the pace of technological progress.

WHAT IS THE PACE OF TECHNOLOGICAL PROGRESS?

Technological change theories describe how the development and progress of a technology field may go through slow and fast cycles [1–6]. This cyclical and dynamic phenomenon can be briefly described as follows. As a new technology is being developed in the laboratory and knowledge accumulation is underway, the pace of technological progress tends to be very slow due to technological obstacles (lack of adequate knowledge impeding its progress). A breakthrough (or discovery) in knowledge that removes a development obstacle will most probably be followed by a significant change in the pace of progress of this technology. The pace of progress will continue to be rapid until

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another technological obstacle or limit is reached, which will cause the next slowdown in the pace of progress of the technology.

Through technological innovations, technologies progress over time, offering better performance at lower cost. This process is based on the cumulation of small improvements, each in itself a minor advance, that push forward the state-of-the-art of knowledge [3, 5, 7].

Technological progress has also been described as not always having a smooth regular pattern. Occasionally, a technological innovation pushes forward the state-of-the-art (best cost/performance combination attainable) by an order of magnitude which results in a discontinuity (departure from existing competencies) in the progress pattern [5].

Technology Cycle Time Indicator: A Measure for the Pace of Technological Progress

Robert Ayres [2] suggested that the pace of technological progress notion may be considered as a sequence of substations of successively better combinations. Furthermore, he believed that the faster this sequence of substitutions occurs in a technology field, the faster the technology is progressing. The author has worked on modifying an objective technology indicator called the Technology Cycle Time (TCT) in a fashion that permitted its use as an objective measure of the pace of the technological progress construct, with encouraging results [8].

The TCT is defined as the median age of the patents cited on the front page of a patent document. This indicator measures the pace of technological progress in terms of the age of the "prior art" of patented inventions. The prior art term is used by the US Patent and Trademark Office to describe the cited references section in a patent document, which are usually other patented inventions. This unique feature captures the linkage between an invention and the prior knowledge that is most closely related to it, and the TCT technique utilizes this feature.

If most of the prior art for a group of technically related patents (technology) are relatively old, then this indicates that most of these patents are improving upon relatively old art, or inventions. Improving upon old inventions means that the technology has not experienced a major upgrading or replacement by a new generation of inventions. The lack of frequent upgrading is a sign of a slow progressing technology. On the other hand, if the prior art was relatively recent then this indicates that the technology is experiencing a frequent replacement of one generation of inventions by another, which is a sign of a rapidly progressing technology.

The premise made by the author was that the TCT can measure the rate of substitution to which Ayres relates technological progress. Shorter cycle times reflect faster substitutions indicating fast progress; longer cycle times reflect slower substitutions indicating slow progress.

To verify the assumption above, the TCT indicator was used in two comparison analyses: (1) assessing the pace of progress of the superconductor and semiconductor technologies; (2) assessing the position of various countries patenting in the semiconductor technology field. The TCT assessments were then analytically compared with the specialist assessments found in the literature.

Data Collection

Data collection was conducted in a two-step procedure. First, all the patents in the US Patent and Trademark Office (USPTO) relating to superconductor and semiconductor technologies were identified and gathered, in technology profile reports, by the

Technology Assessment and Forecast program (TAF), which is now part of the USPTO's Office of Information Products Development. A request was then made for a section of the reports containing all the patent numbers to be generated by this office. About 3931 patents were identified for superconductor technology, and 62,200 patents for semiconductor technology from 1969 to 1994.

The second step in the data collection procedure required the patent numbers to be sent to CHI Research Inc., which is a technology consulting company specializing in patent analyses (CHI are the original developers of the TCT). From the patent numbers identified, CHI provided all the information needed to calculate the TCT. For consistency reasons, only the patents from 1974 to 1994 were used.

Analyses

MEASURING THE PACE OF TECHNOLOGICAL PROGRESS IN THE SUPERCONDUCTOR AND SEMICONDUCTOR TECHNOLOGIES

Before using the TCT indicator in this analysis, a brief review of the actual pace of progress in the superconductor and semiconductor technologies, as described by specialists in the field, is provided.

Pace of Progress in Superconductor Technology

According to specialists, the pace of progress in superconductor technology, from its discovery in 1911, until 1986, had been gradually slowing down; but since the 1986 breakthrough discovery of high temperature superconductors, progress has rapidly accelerated [9–12]. If a technological breakthrough in superconductor technology has significantly changed the pace of its progress from slow to rapid, then any valid indicator of technological progress should identify this change.

Pace of Progress in Semiconductor Technology

During the last three decades, the pace of progress of semiconductor technology in virtually all of its performance dimensions (speed, computational capacity, memory storage capacity, compactness, etc.) has been astounding. Technological barriers have been consistently overcome almost as soon as they were recognized. As Ayres ([2], page 62) indicates, "It is probably safe to say that any truly constraining limits to semiconductor performance are still quite far away." The general view however, is that semiconductor technology is entering into a mature stage of its life cycle. This view is held by industry analysts who see the rapidly rising costs of R&D and capital equipment, the increasing entry barriers, and the increasing movement toward vertical integration, as indicators of technological maturity and, eventually, a decline in technological progress [2, 13, 14].

From the descriptions above, a general view regarding technological progress from 1974 to 1994 in each field can be obtained. Superconductor technology has experienced a significant change in its pace of progress since 1986; semiconductor technology is now a rather mature technology, although its pace of progress during the period from 1974 to 1994 has not experienced significant change, and has yet to slow down significantly.

The plots of the TCT values for the two technologies from 1974 to 1994 are shown in Figure 1. The plot for superconductor technology indicates that it has experienced significant change in its pace of progress since 1987. The plot for semiconductor technology indicates that it has experienced a slight reduction in its progress during the early 1980s, but has leveled off since 1988. The findings are in accord with specialist assessments regarding both technologies.

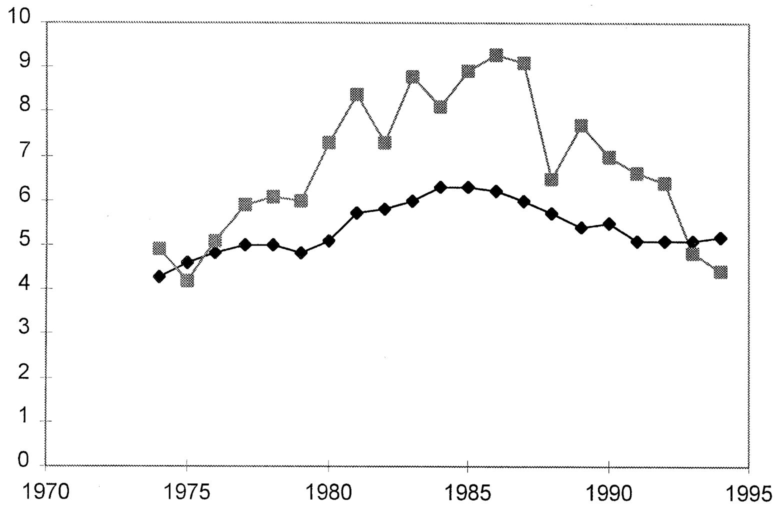

Fig. 1. Plots of the TCT values for semiconductor (*diamonds*) and superconductor (*squares*) technologies.

In comparing the two plots of Figure 1, the pace of progress for semiconductor technology was found to be faster than superconductor technology until 1993, when the latter caught up and then overtook it. The figure also shows that, in 1975 and 1976, both technologies had about the same TCT values. This observation was somewhat unexpected because, during the mid-1970s, the pace of progress of superconductor technology was expected to be much slower than semiconductor technology. One explanation for this discrepancy is that, since both technologies come from the same science field, the inventions for superconductor technology could have been drawing from its more mature, and established sister. This might explain why the patent examiners found relatively recent inventions to reference in superconductor technology patents during the early 1970s.

SUPERCONDUCTOR TECHNOLOGY SEPARATED BY HIGH-TC, LOW-TC CHARACTERISTICS

In an effort to further illustrate the sensitivity of the TCT indicator, the superconductor technology patents were separated into their two major technical characteristics, which are the high critical temperature (high-Tc), and low critical temperature (low-Tc). (Temperatures at which materials superconduct are called the critical temperature or Tc).

Technology experts have described the progress of high-Tc superconductors, since their discovery in 1986, as progressing faster than low-Tc superconductors [9–11, 15].

The USPTO Classification System enables the high-Tc patents to be separated from the low-Tc patents but only from 1988 onward. It was therefore possible to calculate the TCT for both division of the technology from 1988 to 1994.

Table 1 shows that the two superconductor technology subdivisions have been progressing at different paces from 1988 to 1994. The high-Tc pace was faster (having smaller TCT values) than the low-Tc pace. Furthermore, the high-Tc TCT values decreased over time, indicating an acceleration in pace. The low-Tc superconductors, on the other hand, roughly maintained the same pace except in 1994. The TCT drop in

TABLE 1
TCT for the Two Subdivisions of Superconductor Technology

Year	High-Tc	Low-Tc
1988	1.8	6.6
1989	10.2	6.9
1990	7.0	7.0
1991	6.2	6.9
1992	4.3	7.9
1993	3.4	7.5
1994	3.9	5.0
Average	5.27	6.83

1994 could be due to the reported belief that progress in this technology was also picking up in pace in the early 1990s [11]. These findings correspond with the specialist assessments described previously.

POSITION OF COUNTRIES DEVELOPING SEMICONDUCTOR TECHNOLOGY

This section focused on assessing the positions of various countries having US patents related to semiconductor technology. The country of origin for a US patent was identified by the USPTO. The patents of each country considered were grouped and then the TCT for each country was calculated in order to assess their positions. To show a change of position over time, two six-year periods were considered 1979–1984, and 1989–1994, as shown in Table 2. The average TCTs of each period were then compared in Figures 2, 3, and 4.

Figure 2 reveals that, during the 1979–1984 period, Canada and Japan had the fastest pace of progress, while the European countries had the slowest. In the 1989–1994 period, shown in Figure 3, South Korea and Taiwan had the fastest pace of progress, and France jumped ahead of the United States and Canada. The changes in the pace of progress between the two periods is shown in Figure 4, which indicates that the countries that experienced the most change were France and the UK.

TABLE 2
TCT Values for Various Countries Patenting in Semiconductor Technology

Year	USA	Japan	France	UK	Germany	Canada	S. Korea	Taiwan
1979	4.8	4.7	4.7	6.5	4.8	5.1		
1980	5.0	5.1	5.0	5.9	5.9	4.1		
1981	5.6	5.8	6.2	7.8	5.5	5.8		
1982	5.8	5.4	6.4	6.4	6.6	4.5		
1983	6.1	5.5	6.1	6.0	6.7	5.3		
1984	6.4	5.9	6.1	8.7	7.0	6.4		
Average	5.62	5.4	5.75	6.89	6.08	5.2	NA	NA
1989	5.7	4.8	6.2	7.6	6.9	5.6	3.9	3.2
1990	5.8	4.8	5.1	8.3	6.3	5.5	3.4	5.4
1981	5.3	4.7	4.5	4.2	5.7	5.4	3.8	4.7
1992	5.3	4.7	4.7	4.5	5.9	7.0	3.8	3.8
1993	5.3	4.7	5.2	5.0	6.3	4.6	3.9	3.9
1994	5.4	5.0	4.7	5.05	6.7	4.0	3.5	3.5
Average	5.46	4.78	5.07	5.78	6.3	5.3	3.72	4.1

Note: South Korea had only three patents in this technology prior to 1985, and Taiwan had only four.

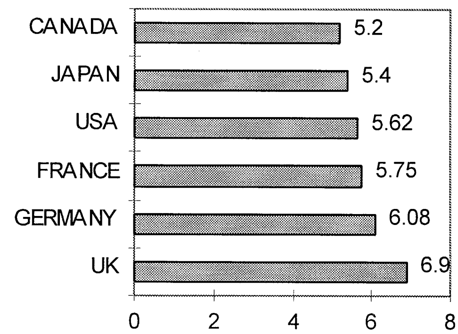

Fig. 2. Positions of countries in the first period, 1979–1984.

To check the accuracy of the TCT indicator, specialist reports describing the positions of various countries in the semiconductor technology were used. One report was generated by the Technology Administration [16], which assessed the technological status and trends of he United States, Japan, and Europe in semiconductor technology. The technological status and trend were assessed using experts' opinions, R&D investments, and new product introductions. The report showed the status of the United States as being "behind" Japan, but "ahead" of Europe. Regarding trend, it showed the United States "losing" to Japan but "holding" its position against Europe [16]. This assessment corresponds with the TCT assessment obtained from Table 2 and Figures 2 and 3.

In another report, Hobday [17] argued that, by the mid-1980s, Europe's semiconductor industry was technologically backward, fragmented, and uncompetitive, especially compared to the United States and Japan. However, this situation has been changing since the mid-1980s due to the direct intervention of European governments in an effort to make up this deficit [17]. This assessment corresponds with the findings obtained from Figure 4, which shows that the largest change in TCT value was experienced by France and the UK. However, the TCT assessment for Germany did not parallel this trend.

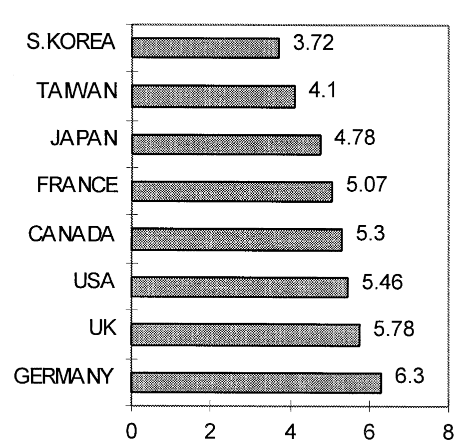

Fig. 3. Position of countries in the second period, 1989–1994.

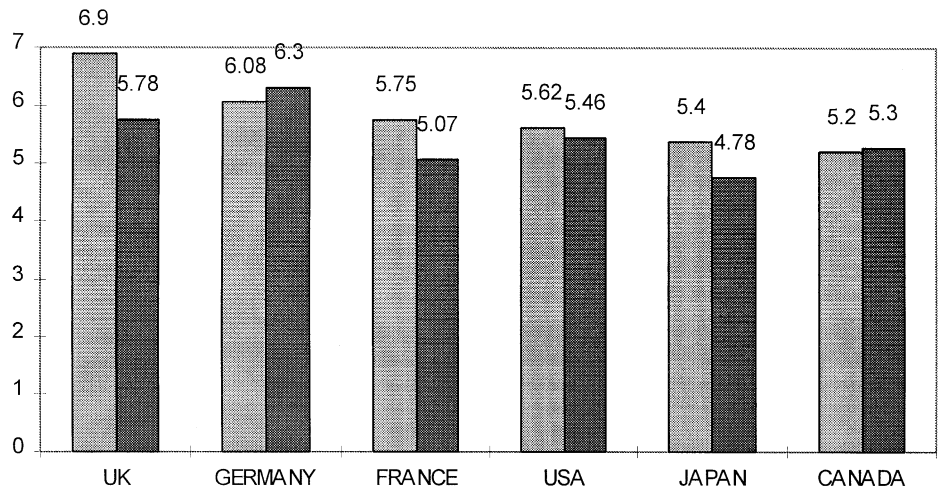

Fig. 4. Change in the average TCT value of each period: 1979–1984 (*shaded bars*) and 1989–1994 (*solid bars*).

Hobday also reported that, following Japan, Korea and Taiwan began producing leading-edge semiconductor chips, which shows that lagging economies can catch up with the leaders by leapfrogging them [17]. The situation described by Hobday can be seen in Figure 3, which shows South Korea and Taiwan in the top two positions in terms of technological progress in semiconductor technology.

Conclusions

The TCT indicator has been used to assess the pace of technological progress in superconductor and semiconductor technologies, and the positions of various countries developing semiconductor technology. In almost all cases, the TCT assessments were found to correspond with these identified by specialists in the field.

The above conclusion suggests that the TCT technique may be used in conjunction with other technology indicators to provide meaningful assessments. It is felt that this is a fruitful avenue, and particularly so with reference to an earlier study by Bierly and Chakrabarti, which found that a firm's TCT value significantly correlated with its knowledge base, R&D diversity, and size [18].

Limitations

Since patents are grouped in the USPTO Classification System by technology categorization, and not by industry or product, the approach is capable of analyzing most technological fields as long as the technology can be defined in terms of USPTO classes and subclasses. However, the broader the technology field is made, (i.e., mechanical, chemical, microelectronics), the more aggregation of classes and subclasses is needed. This would pull together a vast number of patents and make in-depth analyses very difficult. Also some of the patents included could be unrelated to the field of study. To overcome these problems it is recommended that the technology be more narrowly defined (i.e., semiconductors, liquid crystal display, jet engines) or even narrower still, such as high-temperature superconductors and low-temperature superconductors.

The underlying limitation of this study lies in the use of patents. Some of the limitations of patents have already been well recognized by practitioners. Not all inventions are patentable, and the inventions that are patented differ greatly in quality. In other words, one patent may deal with a very small product or part of a product while another may deal with entire systems. Also, the percentage of inventions that is patented can vary over time as well as among industries and firms. Since the TCT approach involves the aggregation of many patents, it is believed that the effect of the above limitations is reduced.

Implications for Technology Forecasting

Technology Management and Technology Forecasting are two fields in need of new valid objective measures. The TCT technique provides a method of measuring a hard to measure construct important to both fields, the pace of technological progress. To forecast the pace of technological progress for a specific technology, a good assessment of past and recent activities is needed before one can predict future progress. If the pace of technological progress can be accurately assessed using a valid objective measure, then this assessment could be used along with other forecasting methods to predict the pace of progress in the future.

Recommendations

The TCT is of great use to both academic theorists and industry analysts. It could be used to indicate how fast overall progress is in a certain technology field, and which country (or company) is progressing faster than its competitors. The measure could also enable researchers to study factors that influence the pace of technological progress in order to establish control over them, if possible.

Finally, the findings from this study cannot be generalized until they are supported by more evaluation studies. Hence further research is indicated in this area.

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