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The idiosyncrasy and dynamism of technological innovation across industries: patent citation analysis

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Abstract

In general, the structural and behavioral patterns of technological innovation are idiosyncratic across industrial sectors and dynamic over time. Yet, despite voluminous amounts of previous research, patterns of innovation are hard to standardize or theorize. The objectives of this article are two-fold. One is to investigate distinctive and changing patterns of technological innovation across industries and observe dynamic trends over time. The other is to identify patterns of relationships among industries and examine the roles of respective industries. To this end, the U.S. Patent and Trademark Office (PTO) patent database was used and patent citation analysis applied. The idiosyncratic differences among industrial sectors are highlighted, especially between conventional manufacturing sectors and science-based sectors. We also found changing trends in technological knowledge flows across industries.

Keywords: Pattern of innovation; Patent citation analysis; Industrial sector; Idiosyncrasy; Dynamism; Innovation; Technological innovation

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1. Introduction

Although the amount of previous research on technological innovation is voluminous, the behavioral patterns of technological innovation are difficult to standardize or theorize. The difficulty may be attributable to the following factors:

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- The innovation pattern is idiosyncratic across industrial sectors. Since technological regimes and market conditions differ among sectors, the nature and effect of innovation are also differentiated [1–6].
- The innovation pattern is never stable and static but unstable and dynamic. It goes through an evolutionary process of change over time [7–9].
- The innovation process is pervasive and interactive between industrial sectors. Technological knowledge not only accumulates as stock within a specific industry but also flows among related industries. Therefore, the linkages and interdependencies among sectors are emphasized as the industrial structure becomes more diverse and complex [10,11].

This article investigates the idiosyncratic patterns of technological innovation across industries and examines dynamic trends over time. Specifically, three inquiries form the principal research themes of the current study.

(a) If the patterns of technological innovation are dissimilar among industries, what are the main differences in terms of industry and/or technology characteristics?
(b) If the patterns of innovation are unstable and dynamic, what are the differences or changing trends over time?
(c) If industrial sectors are interconnected in a technological network, what is the overall shape of the network, and what are the roles of industries in the network?

This study uses patent data and applies patent citation analysis as the primary methodological approach. For a long time, the research arena of technological innovation has suffered from a lack of appropriate data; therefore most earlier studies utilized conceptual and/or qualitative approaches. Patents seem to be the one important exception. There are three primary reasons for using patent data:

(a) Patents possess both technical and market attributes since they meet explicit criteria for originality, technical feasibility, and commercial worth [12].
(b) Patents have advantages in terms of the availability of a database and variety of information.
(c) Patents cover virtually every field of innovation in most developed countries and over long periods of time. In fact, a number of past studies employed patent analysis to examine the pattern or effect of technological innovation [13–18].

The remainder of this article is organized as follows. In Section 2, the theoretical background and operational methods of patent citation analysis are presented. In Section 3, the contents of the database and the process of manipulating the raw data are described. In Section 4, the scheme for classifying industrial sectors is discussed. In Section 5, proposed research themes are analyzed and related implications are provided. Here indexes are operationally defined to facilitate the analysis. We finish with concluding remarks and future research issues.

2. Patent citation analysis

Patent documents are an ample source of technical and commercial knowledge about technical progress and innovative activity. Recently, the strategic importance of patent analysis has become apparent as the process of innovation becomes more complex, the cycle of innovation becomes shorter, and market demand becomes more volatile.

Patent analysis utilizes diverse and complex bibliometric data, and thus requires special techniques to manipulate and analyze patent statistics, and patent citation analysis is frequently used. Patent citations are defined as the number of citations of a patent in subsequent patents; citations per patent reflect the impact of technological innovation and the pervasiveness of technological information [19,20]. The number of citations per patent represents both quantitative frequency and qualitative importance of that particular patent. Therefore, in addition to simple frequency counts, such indices as citing-cited intensity and linkage, coverage of technology, and citation cycle time may be developed. By measuring these indexes within and/or between industries, patterns of technological innovation and knowledge flows can be identified and investigated [21–24].

3. Database

The database used for this research is the National Bureau of Economic Research (NBER) patent database, the most comprehensive and well-structured source for patent analysis. It provides detailed information about all patents granted by the U.S. Patent and Trademark Office (PTO) from 1975 to 1999—a total of 1,828,598 patents. The data set includes citation information about 12,541,698 citation transactions.

Since the patent documents are expressed in text format, they need to be transformed into a structured format. The manipulation of raw data is a time-consuming but indispensable prerequisite for data processing and the ensuing analysis. As summarized in Table 1, there are two categories of information for each patent: general information and citation information. General information is composed of the patent number, year granted,

Table 1
Diverse features of patent information

Category of patent information		Input type (scale)
Super level	Sub level	
General information	Patent number	Nominal
	Year granted	Nominal
	Technology category	Nominal
	Assignee number	Nominal
	Number of claims	Ratio
	Assignee code	Nominal
Citation information	Number of cited patents	Ratio
	Technology category	Nominal
	Assignee code	Nominal
	Assignee number	Nominal

assignee code, assignee number, number of claims, and the technology category. Citation information includes number of cited patents, cited patent numbers, their technology categories, their assignee codes, and assignee numbers.

4. Industrial sector classifications

Before examining the idiosyncratic pattern and inter-industrial linkage of innovation across industrial sectors, the industry classification scheme should be understood. The formal and conventional taxonomy is the international standard industry classification (ISIC). Although ISIC is readily applicable and widely accepted in policy-making practice, it has drawbacks when used for research purposes. For example, the classification scheme includes too many detailed categories, and the classification criteria are based largely on non-technical factors. Some attempts have been made to surmount these drawbacks. For instance, Malerba [9] separates firms into *basic component industry* and *system application industry* according to each industry's competitive edge, organizational strategy, and government policy.

Perhaps the most well-known classification scheme is one devised by Pavitt [1]. He proposed a taxonomy in which industries are clustered in terms of sources of technology, types of user, means of appropriation, and firm size. The scheme has distinct categories such as supplier-dominated, scale-intensive, specialized-suppliers and science-based industries. The supplier-dominated sector includes agricultural producers and traditional manufacturers. This sector represents conventional industries in which R & D intensity is low and innovations are largely developed by suppliers. The scale- intensive sector is comprised of bulk materials and assembly manufacturers. It is production-intensive but characterized by large volumes that lower production cost or standardize material processes. The specialized-supplier sector is also production-intensive but contains small and specialized firms that produce equipment and instrumentation. The science-based sector is characterized by a high degree of R & D intensity and rapid development of underlying sciences.

In this research, we have adopted Pavitt's scheme but modified it somewhat to accommodate recent trends in technological development and to incorporate the strategic implications of emerging technologies. The proposed taxonomy consists of six categories, instead of four, by breaking the science-based sector into sub-categories for chemical science-based, bioscience-based, and information science-based sectors. The entire pool of industrial sectors is separated into two distinct categories: a manufacturing-based sector and a science-based sector. Also note that supplier-dominated, scale-intensive, and chemical science-based sectors may represent conventional industries whereas specialized suppliers, bioscience-based, and information science-based sectors (represented by nano technology (NT), biotechnology (BT), and information technology (IT), respectively), may embrace contemporary or emerging industries.

Patents that were originally classified according to the PTO scheme have been reassigned into the corresponding categories in our taxonomy. Table 2 provides detailed information about the modified taxonomy of the industrial sectors.

Table 2
Modified taxonomy of industrial sectors

Major categories		Corresponding sectors in ISIC	Number of patents
Supplier dominated		Agriculture, Food, Textiles, Coating, Apparel, Furniture, House Fixtures	187,140
Production intensive	Scale intensive	Gas, Power systems, Materials Processing and Handling, Metal Working, Engines and Parts, Optics, Transportation, Motors, Miscellaneous-Mechanical, Heating, Receptacles	578,215
	Specialized supplier	Surgery and Medical Instruments, Measuring and Testing, Pipes and Joints	169,054
Science based	Chemical science based	Organic Compounds, Resins, Miscellaneous-Chemical	334,746
	Bioscience based	Drugs, Biotechnology, Miscellaneous-Drugs and Medical	101,122
	Information science based	Electrical Lighting, Nuclear and X-rays, Semiconductor Devices, Miscellaneous-Electronics, Computer Peripherals, Communications, Information Storage, Computer Hardware and Software	458,321

5. Analysis and interpretation

Innovation patterns can be investigated from various perspectives. The dimensions of analysis can be categorized hierarchically into four levels: country, industry, firm and technology.

- In the *country level*, a national innovation system (NIS) is utilized in order to analyze the interactions among major innovation players, such as private firms, universities, and government agencies [25].
- In the *firm level*, the difference of innovation patterns among firms is observed in terms of firm size, firm age, or business domain. However, only industry level and technology level are analyzed in this study because the patent database provides only limited information on country-level and firm-level attributes.
- For the *industry level* and *technology level*, there is no single standard in the literature with respect to analytical dimensions and operational indexes.

Based on the possibility of patent analysis, the current research suggests two major dimensions of analysis: characteristics of the industry, and characteristics of the technology (see Table 3 for a summary). For each major dimension several detailed indices are defined. For industry characteristics, two indices are proposed: innovativeness of industry and concentration of industry. For technology characteristics, three indices are proposed: scope of technology, cycle of technology, and flow of technology. The sections below discuss each of these indexes in more detail.

Table 3
Major dimensions of analysis

Major dimension	Index	Operational definition
Characteristics of industry	Innovativeness of industry	Mean value of number of patents held by all the firms in a particular sector
	Concentration of industry	Patent citation frequency divided by the number of linked firms in a particular sector
Characteristics of technology	Scope of technology	Number of claims on the front page of each patent
	Cycle of technology	Mean value of differences between earlier patents cited in new patents and new patents citing earlier patents
	Flow of technology	Percentage of citations contributed by other sectors

5.1. Index: innovativeness of industry

One principal point of interest is to compare the relative degree and dynamic trend of innovativeness across industrial sectors. In terms of patents, a firm's innovativeness can be measured by the number of patents held by that firm. Likewise, on an aggregate level, an industrial sector's innovativeness can be defined as the mean value of the number of patents held by all firms in that sector. Two plausible hypotheses are: (1) innovativeness tends to increase over time; and (2) variations of innovativeness exist across sectors.

Fig. 1 shows a graph of innovativeness among industrial sectors. Our research identified four findings:

- Surprisingly, we found no evidence that overall innovativeness has been increasing. Yes, the absolute volume of innovations and total number of patents has increased for all industries. However, the relative degree of innovativeness—average number of patents per firm—has been stable except of some sector-specific variations.

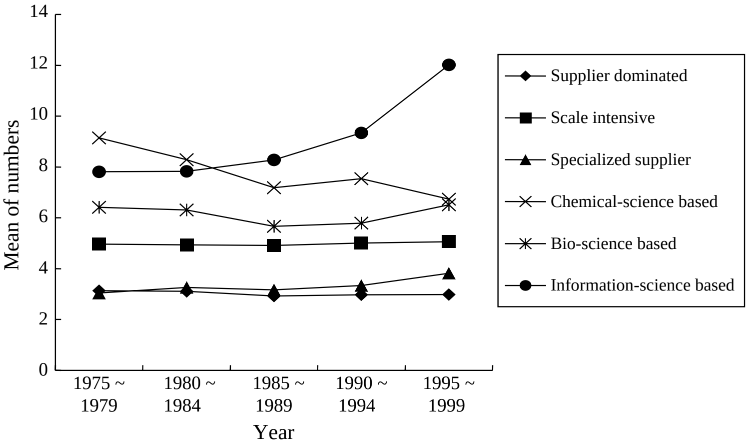

Fig. 1. Innovativeness of industry.

- Regardless of periods in time, the science-based sectors exhibit a higher degree of innovativeness as compared to conventional manufacturing sectors. In particular, the supplier-dominated sector (representing traditional agricultural or light industries) consistently shows the lowest degree of innovativeness. The reason seems quite straightforward: the industries in science-based sectors are characterized by a relatively higher degree of R & D intensity and responsiveness to market changes, which in turn leads to a higher degree of innovativeness.
- Among conventional sectors, the scale-intensive sector tends to be more innovative vis-à-vis the supplier-dominated and specialized-supplier sectors. This implies that patent-based innovations may be affected by firm size, which supports Schumpeter's famous hypothesis [26], that is, the larger is the firm size, the more innovations are produced.
- Emerging NT, BT, and IT industries have exhibited a growth trend since the mid-1980 s. This trend is more apparent in the science-based sector. While the IT and BT industries have emerged in recent years as they become more knowledge-based, the chemical science industry is declining as it becomes more production-based. Even in the conventional sector, the specialized-supplier sector has shown an increasing pattern of innovativeness, while the supplier-dominated sector has declined.

5.2. Index: concentration of firms

The next inquiry is an investigation of the concentration of firms. For a given industrial sector, the notion of concentration permits a quick and accurate assessment of the degree of dominance among participating firms. The concentration index is defined as the citation frequency divided by the number of linked firms. For example, if the citation frequency of a particular patent is 10 and the number of firms related to the citation is 5, the value becomes 2.0. In a similar vein, the concentration index of an industry is computed as the aggregated average of all the patents in that industry. If this value is high, the sector is considered concentrated because a few dominant firms are closely interconnected to form a closed link but many other firms are isolated from the link. On the contrary, if the value is low, the sector is considered dispersed in that many firms are linked to share innovative knowledge.

We found that the dynamic trend of concentration turned out to be independent of or even opposite to the innovativeness of firms. As shown in Fig. 2, it was found that, irrespective of industrial sectors, the concentration ratio has steadily gone down over time. Also note that the gap across sectors becomes narrower. It seems evident that for all industrial sectors the innovation link among firms has changed from closed link to open link. This finding implies that more and more firms have actively participated in knowledge exchange and technology diffusion.

However, we found idiosyncratic differences among sectors. As a whole, conventional sectors exhibit a relatively higher degree of concentration compared to science-based sectors. In particular, supplier-dominated and specialized-supplier industries have maintained a narrow, closed link in terms of innovation activity. In industries such as agriculture or traditional manufacturing, innovations are developed on the basis of specific

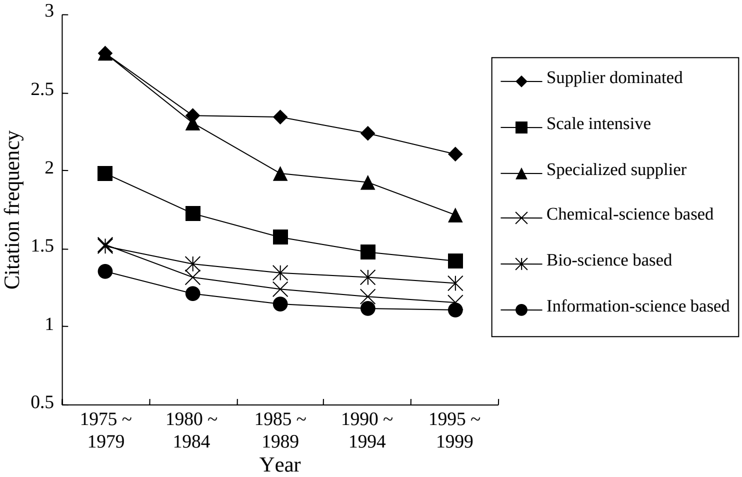

Fig. 2. Concentration of industry.

knowledge of some leading firms that constitute a closed group. Likewise, firms in specialized-supplier industries maintain close relations between supplier and customer. However, science-based firms tend to form more open and interconnected link. The reason may be attributable to two factors. First, the nature of science-based technologies is more diverse and intensive in terms of input knowledge vis-à-vis the nature of manufacturing-based technologies. Second, the shape of the industrial organization of science-based sectors is relatively flexible and decentralized compared to that of conventional sectors. Therefore, firms in science-based sectors tend to emphasize more active consultation with various knowledge sources.

5.3. Index: scope of technology

The scope of a given technology provides some valuable information about the coverage or variety of technical connectivity and commercial application. The scope is measured based on the number of claims of each patent. The claims specify in detail the building block of the patented technology, and the number of claims may be indicative of the width of the technology [27].

As exhibited in Fig. 3, the scope of technology has been extended and diversified over time across all the industrial sectors, for two reasons. One is the characteristics of technology itself. Recent technologies become more diverse and synthetic in nature, hence the scope of patents is widened. The other is attributable to the patent strategy of firms. As the strategic importance of intellectual property is recognized, the patenting policy of firms becomes more aggressive and preemptive by increasing the number of claims to as many as possible.

In terms of sectoral difference, science-based sectors exhibit a relatively broader spectrum of technology as compared to conventional manufacturing sectors. It should be pointed out that the so-called '3-T' technologies—IT, BT, NT—have shown a sharp

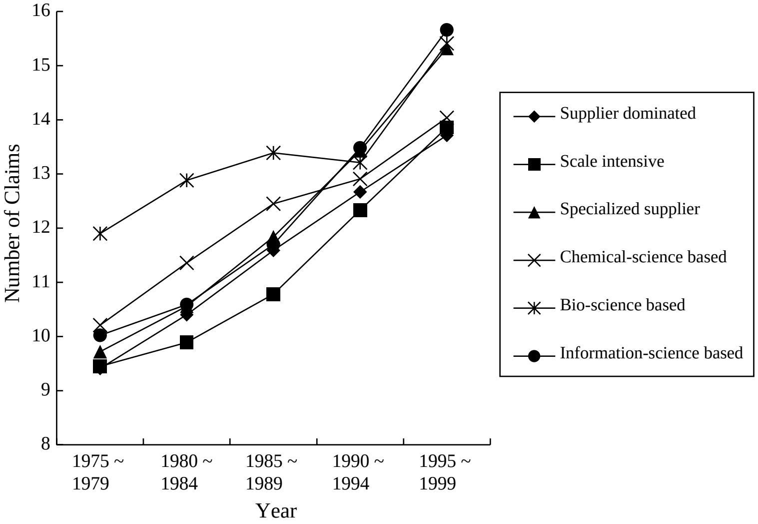

Fig. 3. Scope of technology.

increase during the late 1990 s. As a whole, the gap between emerging sectors and conventional sectors has become wider in recent years.

5.4. Index: cycle of technology

The cycle of technology is another meaningful index since it represents the changing speed of technical advances. As an operational measure, we employ the notion of technology cycle time (TCT) which is defined as the mean value of differences, in years, between earlier patents cited in new patents and new patents citing earlier patents. The interpretation of the index is clear and simple. If the cycle time is shorter, it means that more recent patents are cited because technical progress is more active and rapid.

The overall trend displayed in Fig. 4 illustrates an interesting phenomenon. Contrary to expectations, it was found that the cycle time becomes longer over time for all industrial sectors. This apparently strange finding is due to remarkable improvements in data-mining technology. The enhancement of information technology—especially Web-based systems—results in easier, faster, and wider access to old patents. Thus, it is natural that the time difference between earlier patents cited in new patents and new patents citing earlier patents gets longer over time.

As anticipated, the pace of technical progress exhibits dynamic change in time and idiosyncratic variation among sectors. First, the differences in technical progress between sectors has become conspicuous in recent years. Note that the sectoral difference is not unusual around one year before 1980; but becomes more noticeable at five years and thereafter. Second, the rate of technical progress is lower for science-based sectors, especially IT and BT, as compared to conventional manufacturing sectors.

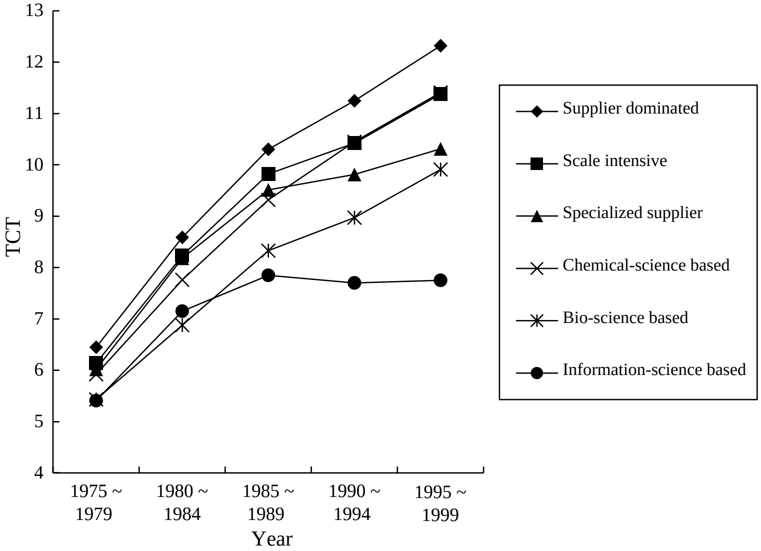

Fig. 4. Cycle of technology.

5.5. Index: flow of technology

As the industrial network becomes more technology-intensive, technological knowledge is more actively and widely disseminated among sectors. The inter-industry flow constitutes a network in which respective industries release, absorb, or intermediate technological knowledge. In that regard, the flow of technology across industries is a crucial factor in analyzing technological innovation.

Table 4
Technological knowledge flow matrix

	SD	SI	SS	CS	BS	IS
SD	71.3	12.1	2.9	9.3	1.4	3.1
	73.1	4.0	2.7	5.1	3.1	1.1
SI	3.6	81.3	2.9	5.3	0.3	6.6
	11.0	80.3	7.8	8.7	1.8	7.5
SS	2.5	8.5	76.1	3.0	2.0	8.0
	2.8	3.1	76.5	1.8	5.0	3.4
CS	4.4	8.7	1.9	78.5	3.8	2.7
	7.9	5.0	3.1	75.4	15.1	1.8
BS	4.3	2.3	4.9	22.3	65.5	0.7
	2.2	0.4	2.2	6.1	74.4	0.1
IS	1.1	8.2	3.2	1.9	0.1	85.5
	2.9	7.2	7.8	2.8	0.6	86.1

Note: SD = supplier-dominated, SI = scale-intensive, SS = specialized-suppliers, CS = chemical-science based, BS = bio-science based, IS = information-science based.

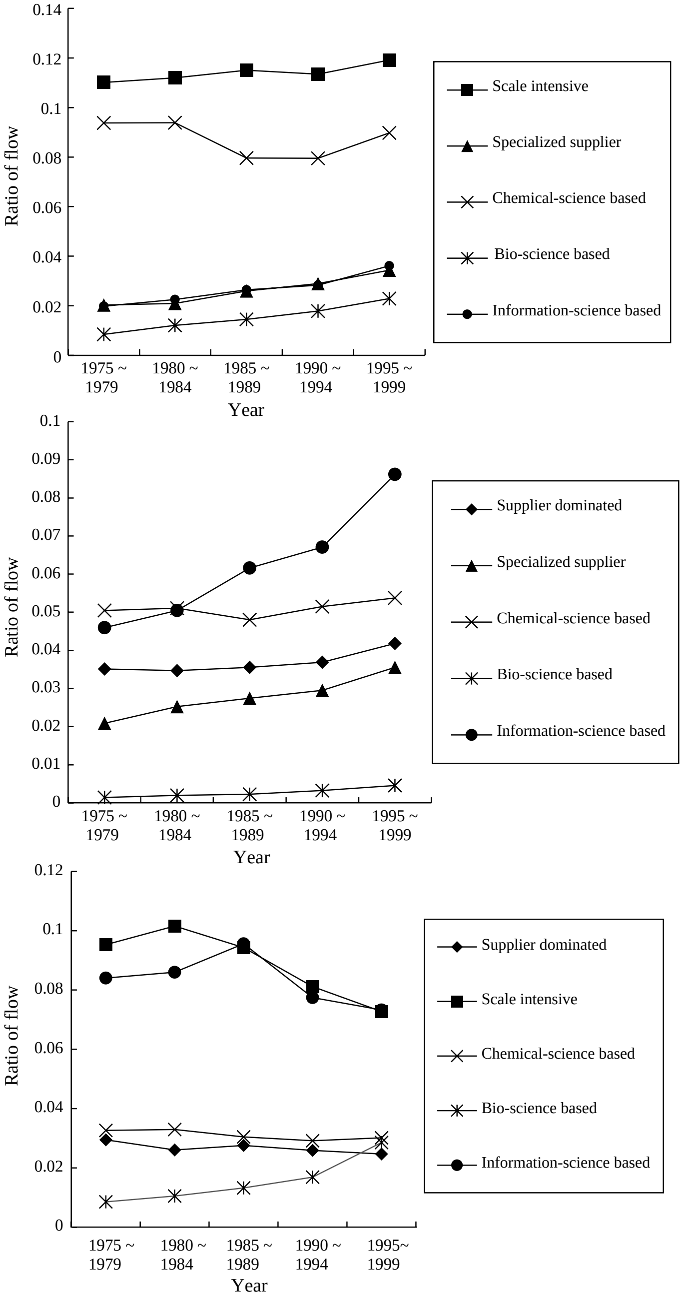

Fig. 5. (1) Flow of technology: Supplier dominated. (2) Flow of technology: Scale intensive. (3) Flow of technology: Specialized supplier. (4) Flow of technology: Chemical-science based. (5) Flow of technology: Bio-science based. (6) Flow of technology: Information-science based.

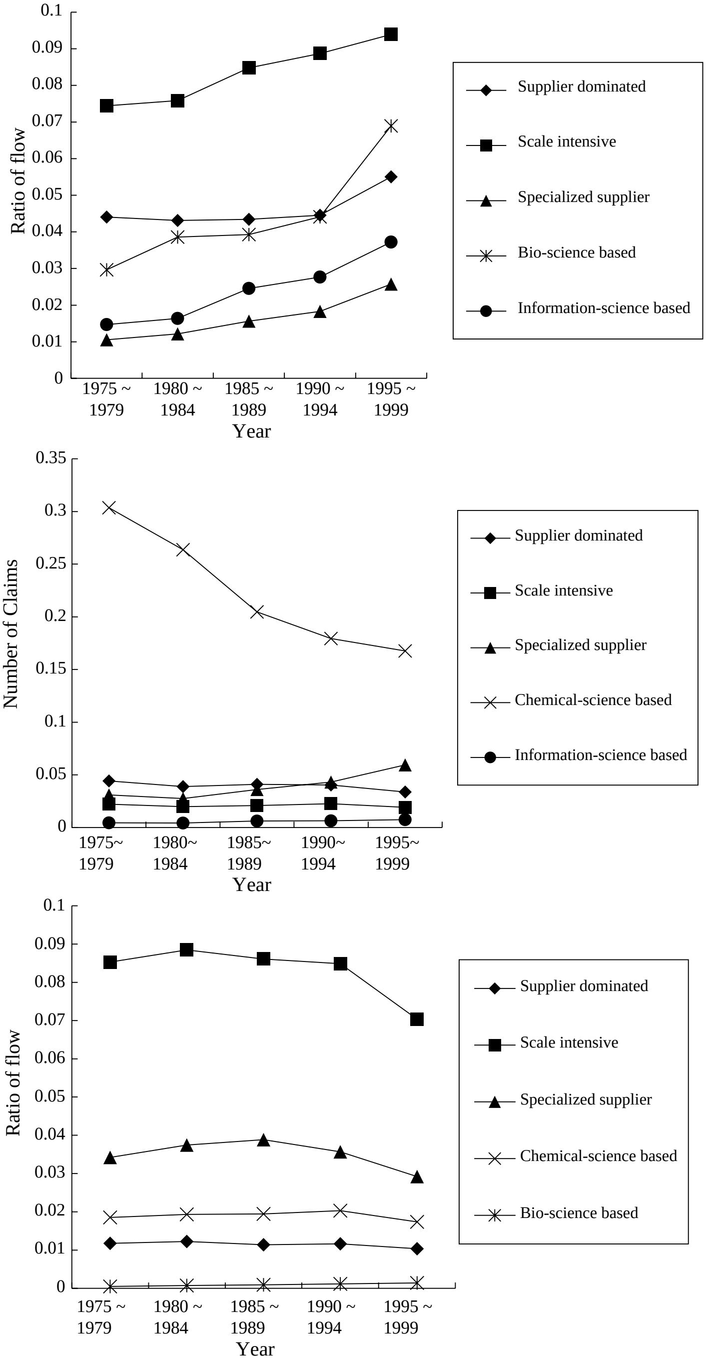

Fig. 5 (*continued*)

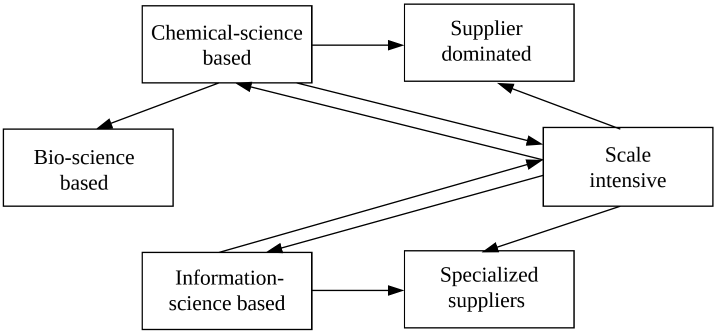

Fig. 6. Overall pattern of technological flow among sectors.

In an operational sense, knowledge flow between two different sectors is defined as the percentage of citations contributed by each sector. For instance, for sector A, if the total number of citations is 200 and 30 citations out of 200 are attributable to sector B, the flow value is 15%. In this way a knowledge flow matrix can be constructed among the sectors, as summarized in Table 4. In the flow matrix, the upper half of each cell denotes the inflow (citing) percentage while the lower half indicates the outflow (cited) percentage. Those cells on the diagonal show the self-citation percentage within each sector. In the similar vein, Fig. 5(1)–(6) show sector-wise dynamic flows in an aggregate way.

As a whole, the linkage between traditional manufacturing sectors and science-based sectors is complementary due to the user-supplier relationship. The role of respective sectors may be idiosyncratic and the paired linkages may be differentiated across industries. The overall linkage can be depicted as an inter-sectoral flow diagram, as illustrated in Fig. 6.

Among conventional industries, the scale-intensive sector and the chemical science-based sector seem to be the principal agents in the network, implying that these two sectors are the major users of technology. Interestingly, two representative science-based sectors, IT and BT, exhibit rather peculiar characteristics in common. First, against general expectation, inter-industry flows of these two sectors have decreased over time whereas within-industry flows have increased. Also note that inter-industry links between these two sectors are concentrated on a particular sector. In the case of BT, as would be expected, the majority of links are attached to the chemical science-based sector, but links with other sectors are almost missing.

IT is strongly connected with the scale-intensive sector. This is because these two sectors actively exchange technologies based on user-supplier relationships. At the same time, however, these two sectors have differentiated features as well. First, it is surprising that paired connectivity is weakest between these two sectors. IT has virtually no linkage with BT and vice versa. Second, the self-citation ratio is highest in IT but lowest in BT (see Table 4). That is, IT is an open sector whereas BT is a closed sector, isolated from other sectors.

6. Conclusions and future research

Since the advent of the techno-economic paradigm, technological innovation has driven the rate of economic growth and anchored the direction of social transition. However, the behavioral pattern of technological innovation has an industry-specific nature and thus the notion of sectoral patterns of innovation has been recognized as an important theme in innovation study.

This article proposed a taxonomy of industries and then applied patent analysis to investigate the differences across industrial sectors in terms of structural and dynamic patterns of innovation. To that end, a set of operational indices were developed to gauge the amount of technological stock and flow.

Overall, idiosyncratic differences among industrial sectors are obvious, especially between conventional manufacturing sectors and science-based sectors. Some findings were expected but others went against general expectations. By conducting this kind of analysis, it is possible to identify the sector-specific characteristics of respective industries. It is also useful for observing the changing trend of technological knowledge flows across industries. The structural natures and dynamic changes can then be addressed in industrial policy-making processes.

Despite some substantial contributions, this article has some limitations. First, the proposed taxonomy of industries needs to be extended and/or modified to reflect new trends of emerging technology and to accommodate new policy agendas. Second, if possible, more operational indexes should be developed, both static and dynamic, to explain the characteristics of technological innovation. Finally, this study is merely descriptive in nature and needs additional work before attempting to derive policy implications. Such tasks require more work and thus are reserved for future research.

Acknowledgements

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