Postprint: Research on the Basic Theory and Methods of Technology Convergence

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Abstract

[Purpose / Significance] Technology convergence represents an important approach to technological innovation, carries significant economic and social implications, and has gradually emerged as a crucial component of national science and technology strategies.

[Method / Process] Based on a systematic review of existing concepts of technology convergence and an elucidation of its research significance, this study delineates the research process of technology convergence and provides a comparative analysis of the methodologies employed across various stages, including dataset construction, technology domain delineation, and convergence analysis.

[Results / Conclusion] By identifying gaps in current research and proposing future research directions, this study holds significant importance for advancing technology convergence research.

Full Text

Preamble

Review on the Theory and Methods of Technology Convergence

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Abstract

[**Purpose/Significance**] Technology convergence represents a significant means of technological innovation with major economic and social implications,

gradually becoming an essential component of national science and technology strategies. [**Method/Process**] This paper reviews existing concepts of technology convergence, clarifies the significance of convergence research, identifies key research stages, and comparatively analyzes methods employed in dataset construction, technology domain identification, and convergence analysis. [**Result/Conclusion**] The study identifies current research limitations and proposes directions for future work, which holds important value for advancing technology convergence research.

Keywords: technology convergence; dataset construction; technology domain identification; convergence analysis
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2 Concepts and Research Significance

2.1 The Concept of "Technology Convergence"

Contemporary scientific and technological development worldwide exhibits a landscape of multiple breakthroughs and interdisciplinary convergence. Cross-disciplinary research is increasing globally, the degree of interdisciplinarity is intensifying overall, and industrial boundaries are becoming increasingly blurred. The current innovation trend involves rapid technological development based on broad scientific and technical fields and essential interdisciplinary research [**?**], a phenomenon known as technology convergence.

The emergence of technology convergence is not accidental. While knowledge and technology become increasingly diversified and specialized, socio-economic and technical problems are growing more complex, requiring the integration of multidisciplinary knowledge and technologies for solutions. Technology convergence serves as a critical link in transforming scientific research into practical competitiveness across various levels of integration—including science, technology, products, industries, and markets—and plays an important role in leading and controlling next-generation technological innovation.

The term "convergence" in English dates back to the 17th century, derived from the Latin "convergere" (to incline together), and is primarily defined in dictionaries as "lines intersecting at a point" or "multiple things gradually becoming similar or identical" [**?**]. In Chinese dictionaries, "融合" is explained as combining together [**?**]. Additionally, individual disciplines such as biology, meteorology, and mathematics have assigned special meanings to "convergence" within their respective fields.

In the management domain, Rosenberg [**?**] first used the term "convergence" in his study of the evolution of the U.S. machinery equipment industry, where he introduced "technological convergence" as the process by which industries

with completely unrelated product functions and characteristics develop independent, specialized mechanical tools through the adoption of general-purpose technologies. Subsequently, as technology convergence improved the technical routes of existing industries or enriched their operational content and forms, different industries began to share similar technical foundations and common technology platforms, leading to the phenomenon of technology convergence [**?**].

After reviewing existing convergence concepts, this paper defines technology convergence as the process whereby relationships between at least two identifiable technology domains gradually strengthen and eventually become unified or consistent. In abstract terms, technology convergence encompasses at least three layers of meaning:

From the observation starting point, technology convergence manifests as associations between at least two technology domains, with the initial state of related domains being discrete and identifiable (see Figure 1-a [Figure 1: see original paper]).

From the observation process, technology convergence involves gradually strengthening relationships between related technology domains, manifested as the emergence of crossovers between different technology domains (see Figure 1-b) and a process of increasing overlap (see Figure 1-c).

From the observation result, the outcome of convergence moves toward unification or consistency, where boundaries between domains partially disappear. This can involve related domains collectively forming a new domain (see Figure 1-d) or the converged area independently becoming a new domain (see Figure 1-e).

2.2 The Significance of Technology Convergence Research

Convergence can occur at various levels: science, products, services, technology, business functions [**?**], and even ideas. Currently, convergence is spreading and intensifying across all levels, receiving widespread attention worldwide. This is primarily because:

(1) **Convergence stimulates innovation.** Convergence encourages competition among existing overlapping industries and can bring tangible economic benefits or development prospects. Key developments in information technology, chemistry, and related industries over the past few decades have shortened the lifecycle of fundamental innovations and led to double-digit R&D expenditures [**?**]. The healthcare industry has generated new sectors such as digital healthcare driven by IT innovations [**?**], and the deep integration of information and communication technologies and internet platforms with traditional industries has spawned innovative "Internet Plus" business models [**?**].

(2) **Convergence creates cross-industry products adapted to new era user needs.** This is particularly evident in the ICT (information technolo-

gies, consumer electronics, and telecommunications) industry, where strict industry boundaries have largely disappeared, creating cross-boundary products such as smartphones. The cosmetics and food industries also show convergence trends, giving rise to cosmeceuticals (combining cosmetics and pharmaceuticals) and functional foods (combining nutrition and pharmaceuticals) through health-oriented features [**?**].

(3) **Convergence stimulates enterprises to develop new interaction forms.** Technology convergence provides opportunities for both new and existing market participants to build entirely new market ecosystems and break fixed value chains. Market participants leverage collective knowledge from complementary technological innovations to cultivate new industrial and technology clusters, thereby promoting industrial convergence. During this process, increased inter-enterprise interactions generate more alliances, agglomerations, and cooperation with standardization organizations, driving convergence at the standards level across different domains [**?**].

(4) **Convergence requires proactive management practices and strategic decisions.** Convergence enables R&D institutions to strategically manage factors affecting business success such as cost, quality, flexibility, and time, potentially altering related services, markets, policy provisions, industrial structures, and corporate alliances and mergers. The strategic actions, asset divestitures, and even corporate mergers of AOL and Time Warner in 2000 demonstrate that senior management has recognized the impact of technology convergence [**?**].

3 A Typical Model of Technology Convergence: Convergence Diffusion

Technology convergence exhibits a complex temporal process during technological development across science, products, services, technology, business functions, and even ideas. Using an evolutionary paradigm, the four-stage division of science, technology, market, and industrial convergence has been widely accepted by scholars. However, whether this ideal temporal process actually occurs depends on the triggers and drivers behind convergence trends. These triggers can include natural scientific discoveries, technological advances, changes in user demand, or even policy regulation and industrial standards.

In technology convergence research, scholars focus more on technology convergence diffusion models to analyze and explain current phenomena or to develop strategies and policies based on convergence impacts. Tang [**?**] argues that the process of technology convergence is essentially the result of technology diffusion across industries, noting that technology can diffuse and innovate among different types of industries and enterprises, including upstream and downstream industrial innovation, convergence, and diffusion and fusion among related industries.

Since the early 20th century, many fields have proposed different diffusion models. Diffusion models were originally used in business management to explain the diffusion of products or services, but they are now widely applied in social sciences such as anthropology and natural sciences such as biology. Diffusion models have undergone three developmental stages: the basic model era (1960-1970), the extended model era (1970-1980), and the new application era (after 1980) [**?**]. The basic model era focused primarily on mathematical model research; the extended model era developed various application models based on the Bass diffusion model; and research since 1980 has expanded to improve the scope and flexibility of previous models and further apply them to new products and services such as high-definition television and IP communication services.

Based on the Bass model, the diffusion cycle can be divided into three stages: embryonic period, growth period, and maturity period. The diffusion curve generally assumes an "S"shape, with new products, services, or technologies growing slowly during the embryonic period, developing rapidly during the growth period, and stagnating during the maturity period.

The general diffusion model can be represented by the following differential equation:

$$\frac{dN(t)}{dt} = g(t) \cdot [m - N(t)]$$

where $N(t)$ and $n(t)$ represent the cumulative and non-cumulative quantities of adopters at time t, respectively, and m is the potential final number of adopters. g is the diffusion coefficient that affects the potential adopters brought by diffusion. The cumulative number of adopters $N(t)$ gradually approaches m over time. The influence of diffusion coefficient g on diffusion effects can be expressed as either a function of time or a function of adopter numbers. $g(t)$ can be characterized in three modes: external influence diffusion model, internal influence diffusion model, and mixed influence diffusion model.

If the diffusion coefficient is constant, i.e., $g(t)$ is a constant p, the equation becomes an external influence diffusion model. If the diffusion coefficient is affected by the cumulative number of adopters, i.e., $g(t)$ is $qN(t)$, the equation becomes an internal diffusion model. The mixed influence diffusion model considers both internal and external influences, i.e., $g(t)$ is $p+qN(t)$. Among these, internal influence diffusion models include the Logistic model and Gompertz model, which are frequently used in convergence research [**?**].

4 Main Research Framework and Methods of Technology Convergence

Since the concept of technology convergence was proposed, many scholars have conducted research on this phenomenon. Technology convergence research primarily focuses on concept proposal and extension, theoretical research, domain-

specific empirical studies, macro-level empirical studies, temporal studies, and comprehensive empirical studies. Related theoretical research mainly emphasizes defining convergence concepts a priori to analyze and explain current phenomena or to develop strategies and policies based on convergence impacts.

4.1 Technology Convergence Research Framework

Due to the inherent ambiguity and complexity of convergence, it is difficult for any single convergence indicator to gain universal acceptance. Scholars have designed many different methods to measure convergence according to various research purposes. Since technology convergence is strongly associated with science convergence, market convergence, and industrial convergence, measurement methods for convergence at different levels all provide certain reference value for technology convergence identification and research.

Overall, technology convergence research requires selecting appropriate data sources to construct datasets, defining technology domain identification criteria, and selecting research methods and constructing analysis indicators based on specific research purposes. Among these, research purpose, data sources, and technology domain identification criteria form the research foundation, while research methods and analysis indicators constitute the methodological system, with all five elements being interrelated.

4.2 Dataset Construction for Technology Convergence Research

Different stages of convergence require different data for measurement (see Table 1). Papers, patents, media information, research entity information (institutions of paper authors and patent assignees), and industrial information can all be used for convergence research at different levels. Overall, publicly available data sources, especially patents, are most suitable for early signal monitoring of convergence, empirical studies of specific technology domain convergence, full-domain technology convergence status analysis, and temporal studies of technology convergence.

Existing research primarily constructs datasets for convergence studies from three dimensions: (1) starting from specific domains, obtaining datasets through topic or technology classification-limited retrieval; (2) starting from specific entities, obtaining all data of major R&D entities in a particular domain; and (3) starting from specific countries, obtaining full-domain data of a particular country. Few studies construct datasets from a global, full-domain perspective.

4.3 Technology Domain Identification

The primary standard for technology domain identification in existing research is to transform the formal or content features of analytical data into industrial domains through mapping. Specific mapping standards include journal-domain, paper-discipline, SIC (Standard Industrial Classification)-IPC (International

Patent Classification), UC (US Classification)-domain, enterprise-industry, and expert interpretation methods (see Table 1).

Table 1 Data Sources and Technology Domain Identification Standards for Convergence-Related Research

Research Type	Data Source	Technology Domain Identification Standard
Science Convergence	Papers	Journal domain classification [**?**], Paper discipline domain [**?**], ACS classification for SciFinder [**?**]
Technology Convergence	Patents	SIC-IPC mapping [**?**], WIPO technology domain-IPC mapping [**?**], Technology domain-UC mapping [**?**], Database-provided industry mapping [**?**], Patent assignee industry [**?**]
Industrial Convergence	Enterprise information	Enterprise industry [**?**], Expert knowledge [**?**]
Market Convergence	Media information	Expert knowledge [**?**]

4.4 Main Research Methods for Technology Convergence

Technology convergence research methods are mainly divided into two categories: expert-centered methods and data quantitative analysis-centered methods. Table 2 presents the classification of convergence-related research methods, representative literature, and their main advantages and disadvantages. These quantitative analysis methods each have strengths and weaknesses, which this paper compares primarily from perspectives of data availability and technology association.

Table 2 Convergence-Related Research Methods and Their Advantages and Disadvantages

Method	Advantages	Disadvantages
Expert-based Methods		
Technology Roadmapping [**?**]	Can fully extract expert tacit knowledge and help reach consensus	Standards difficult to unify
Delphi Method [**?**]	Facilitates group decision-making	Predictions lack rigorous scientific analysis
Case Study [**?**]	Can fully explore various influencing factors of convergence process with rich details	Material collection is difficult

Method	Advantages	Disadvantages
Data-based Methods		
Statistical Analysis [?]	Indicators are easy to understand	Indicator data acquisition is relatively difficult
Co-occurrence Analysis (IPC [?], UC [?], journal classification [?])	Can reflect associations between technologies; can reflect cooperation trends	Impact of different classification schemes uncertain; depends on classification accuracy; patent assignee cleaning is difficult
Clustering Analysis [?]	Flexible, can freely choose clustering angles and methods; can discover hidden associations	Clustering results difficult to interpret
Citation Analysis [?]	Patent and patent examiner citations of prior art have strong correlations, reflecting certain hidden associations	Citation data itself is relatively scarce
Input-Output Analysis [?]	Can discover quantitative effects of different influencing factors	Data collection is difficult; result interpretation is difficult
Big Data Analysis [?]	Suitable for large-scale data analysis, can discover key nodes	Dataset construction is difficult

4.4.1 Expert-Based Methods Qualitative analysis methods centered on experts mainly include technology roadmapping, Delphi method, and case study research. Technology roadmapping often incorporates the Delphi method in its application.

(1) **Technology Roadmapping**: Originally an enterprise technology management method, its application in convergence research primarily involves predicting convergence technology development paths through expert knowledge.

(2) **Delphi Method**: Also known as expert opinion method or expert consultation survey method, its original purpose was to obtain the most reliable consensus opinions from a group of experts through a series of intensive questionnaires and controlled feedback. Its application in convergence mainly involves obtaining expert consensus on convergence technology paths.

(3) **Case Study**: Also called case research method, it involves analyzing a single object in combination with literature materials to derive general and universal patterns. In convergence research, it is suitable for comprehensive analysis of multiple factors with rich details.

Expert-based quantitative analysis faces high difficulty in selecting appropriate experts and obtaining consistent expert knowledge.

4.4.2 Data-Based Methods Current convergence research primarily employs data-based quantitative analysis methods. Among these, co-occurrence and other methods require specific statistical analysis indicators in practical application.

(1) **Statistical Analysis**: Due to the complexity of convergence, Mayer [**?**] proposed correlation analysis indicators between research entity characteristics and literature types, which can be used for statistical analysis presentation and further enriched for association analysis from different perspectives.

(2) **Co-occurrence Analysis**: It is generally believed that if a common content or formal feature frequently appears simultaneously in the same document, it often indicates a relatively close connection between these two features. In technology convergence research, scholars mainly conduct co-occurrence analysis from perspectives such as classification, patent assignees, and keywords, with co-classification analysis being particularly widely applied.

(3) **Clustering Analysis**: This method uses unique clustering techniques to divide data into different subclasses according to technology domains, typically requiring combination with co-occurrence analysis, citation analysis, and text mining analysis. In convergence research, it mainly involves clustering by topic or technology classification co-occurrence matrix to discover main convergence domains.

(4) **Citation Analysis**: This involves analyzing the citation situation of target patents and the citations of target patents by others. M. Karvonen et al. [**?**] used patent citation analysis to empirically study the early stages of technology convergence discovery.

(5) **Input-Output Analysis**: Also known as inter-industry analysis, it analyzes the quantitative dependency relationship between inputs and outputs within a specific economic system. In convergence research, it can be used to discover the quantitative effects of different influencing factors.

(6) **Big Data Analysis**: Suitable for massive data analysis, it can discover key nodes and convergence trends from full-domain datasets.

Among these methods, due to difficulties in dataset construction and analysis indicator calculation, citation analysis and input-output analysis have poor

applicability in large-scale datasets and are mainly suitable for specific problems/domains or smaller datasets.

5 Future Research Directions

From the above analysis, it is evident that although considerable exploration and significant development have been achieved in technology convergence research, the following problems and deficiencies remain as directions for future research:

(1) **Systematic research on multi-technology domain associations**. Existing technology convergence research focuses more on binary relationships between technology domains, with less research on systematic structural characteristics among technology domains. However, in real technological development, technology convergence results from the comprehensive effects of multiple technologies. Future research can investigate multi-technology domain associations from a systematic perspective.

(2) **Research on predicting future development directions of convergence signals**. Current technology convergence research mainly focuses on observing the starting point and process of convergence, with relatively little research on what state reaches the critical threshold for convergence occurrence and how convergence signals will develop in the future. This can serve as an important direction for further research.

(3) **Research on reasonable dataset construction methods**. Technology convergence empirical research requires selecting appropriate data sources according to different research purposes. Existing research does not distinguish the contribution magnitude of patent literature itself to technology convergence, which can easily generate false signals of enhanced technology overlap from peripheral patents, bringing uncertainty to research results. Therefore, reasonable dataset construction methods can be studied from perspectives of comprehensiveness and denoising of patents themselves.

(4) **Research on identifying specific convergence technology directions**. The technology domain identification standards used in existing research mainly transform formal or content features of analytical data into industrial domains through mapping. Compared with the granularity of real-world domain refinement, this mapping has relatively coarse granularity and does not adequately reflect specific technology direction situations. Future research can consider more fine-grained identification of convergence technology directions.

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Author Contributions

Zhang Jing: Content review and manuscript writing;
Zhang Zhiqiang: Refined paper structure and provided revision suggestions.

Note: Figure translations are in progress. See original paper for figures.