Standards Digitalization Governance Strategy: Opportunities, Challenges, and Countermeasures Postprint

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Abstract

[Purpose/Significance] Standard digitalization can deeply mine the latent knowledge within standards and unleash their potential value. The strategy for standard digitalization governance is directly critical to the development of China' s digital economy and the enhancement of international competitiveness. [Method/Process] Based on global transformation trends in standard digitalization, this study investigates from four aspects: new technologies, development policies, development patterns, and governance concepts. [Results/Conclusions] The findings indicate that: (1) Standard digitalization governance needs to seize four opportunities. First, new technologies for standard digitalization facilitate the full-chain development of standard and industrial chains. Second, standardization development policies encourage and guide the advancement of standard digitalization. Third, traditional standardization development patterns are undergoing transformation. Fourth, concepts of standard data governance have changed. (2) Standard digitalization governance faces three challenges. First, basic theories, key technologies, implementation pathways, and application scenarios have yet to form a complete system. Second, mature products and excellent pilot cases are scarce. Third, institutional systems and management mechanisms require improvement and perfection. (3) Standard digitalization governance should consider four countermeasures. First, vigorously develop basic conceptual systems and fundamental common key technologies. Second, strengthen relevant policy safeguards. Third, promote the integration of relevant theories with diverse business scenarios and foster innovative applications. Fourth, proactively plan for future international markets.

Full Text

Standard Digital Governance Strategy: Opportunities, Challenges, and Countermeasures

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Abstract:
[Purpose/Significance] Standard digitalization can deeply explore the latent knowledge within standards and unlock their potential value. The strategy for standard digital governance is directly related to the development of China' s digital economy and the enhancement of its international competitive discourse power. [Method/Process] Based on global trends in standard digital transformation, this study examines four key dimensions: new technologies, development policies, development patterns, and governance concepts. [Result/Conclusion] The findings indicate that: (1) Standard digital governance must seize four opportunities: first, new digital technologies for standards promote full-chain development of the standards and industrial chains; second, standardization development policies encourage and guide the advancement of standard digitalization; third, traditional standardization development patterns are undergoing transformation; and fourth, the philosophy of standard data governance is evolving. (2) Standard digital governance faces three major challenges: first, the basic theories, key technologies, implementation paths, and application scenarios have not yet formed a complete system; second, there are few mature products and exemplary pilot cases; and third, the institutional system and management mechanisms require improvement and refinement. (3) Four countermeasures should be considered for standard digital governance: first, vigorously develop basic conceptual systems and foundational common key technologies; second, strengthen relevant policy safeguards; third, promote the integration and innovative application of relevant theories with various business scenarios; and fourth, proactively plan for future international markets.

Keywords: Standard digitization; Development of Standardization in China; Machine-readable standards; Standardization development strategy

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In October 2021, the "National Standardization Development Outline" issued by the Central Committee of the Communist Party of China and the State Council explicitly called for developing machine-readable standards and open-source standards, and promoting the transformation of standardization work toward digitalization, networking, and intelligence [**?**]. As a crucial element of high-quality development in quality infrastructure, standards serve as the cornerstone of national economic and social development, a banner guiding the digital economy, and vital support for enhancing China' s international competitiveness [**?**]. With the deepening of national digital transformation, the digital transformation of the standards field has attracted considerable atten-

tion from experts and scholars. Standard digital governance refers to the new concept of using digital technologies such as big data, cloud computing, the Internet of Things, and artificial intelligence to transform standard document formats and application processes. Unlike traditional modes of manually reading paper standards, it emphasizes innovative changes in machine governance of standard knowledge (e.g., machines intelligently reading, understanding, executing, and interpreting relevant standard data), focusing not only on breaking through existing AI technologies to achieve machine readability, executability, and interpretability of standard data, but also on the series of transformations in management mechanisms, governance models, products, scenarios, and industrial forms triggered by changes in standard formats. Therefore, deeply understanding the relationship between the digital economy, international competition, and standard digital transformation (including changes in standard formats themselves, digital transformation applications of standard data, standard data security, and standard copyright protection) is an inevitable choice for promoting high-quality national standardization development and rapidly integrating into the broader trend of standard digital transformation.

Currently, many experts and scholars in the industry have conducted extensive research on the basic concepts and connotations of standard digitalization and machine-readable standards, domestic and international developments in standard digitalization, and typical application cases across different industries. These studies can be broadly categorized into three types:

First, research on domestic and international development trends and the essential characteristics of standard digitalization. For instance, Wu Hequan [**?**] argues that standard digitalization includes both the digitalization of standard presentation formats and the digitalization of standardization methods. Yu Xinli [**?**] defines standard digitalization as the use of AI technologies or tools to process, parse, annotate, and correlate standards and related data to enable human or machine reading, understanding, invocation, and access to standards. Wang Shuo et al. [**?**] consider machine-readable standards as the core content of standard digitalization. Liu Xize et al. [**?**] view standard digitalization as the process of using digital technologies to empower standards themselves and their entire lifecycle, enabling the rules carried by standards to be read, transmitted, and used by digital equipment.

Second, practical explorations of standard digitalization in different industries. For example, in the aviation sector, Li Xiangyu et al. [**?**] emphasize that standard digitalization should focus on intelligent standard applications, specifically how to use digital technologies to solve the two major problems of "which standards to use" and "how to use standards" throughout the entire lifecycle of aviation equipment. In industrial automation, Wang Chunxi et al. [**?**] propose applications of machine-readable standards encompassing public data dictionary construction, equipment information models, and digital factory models. In the electric power sector, Ma Chao et al. [**?**] propose digital application scenarios for power standards covering "full-text retrieval, index retrieval, dynamic standard

updates, display of standard-related content, intelligent standard recommendation, intelligent standard Q&A, and intelligent standard decision-making." In information resource management, Gan Keqin et al. [**?**] propose technical routes for building a national digital standards library, highlighting the need to advance the construction of standard digital resource databases, standard literature digital service platforms, and standard digital experience centers.

Third, forward-looking theoretical research on standard digitalization-related technologies. Cheng Yun et al. [**?**] propose a key technology path for standard digitalization from an AI perspective, including "standard bibliographic attribute extraction, clause (paragraph) extraction, keyword generation, FAQ generation based on clauses for standard literature Q&A, and result review annotation." Wang Yihe et al. [**?**] believe that standard digitalization technologies involve big data, knowledge graphs, natural language understanding, and user profiling. Bai Dianyi [**?**] argues that standardization principles provide a solid foundation for standard digitalization, not only guiding the establishment of conceptual and classification systems for standard digitalization but also providing guidance for its application.

In summary, existing research tends to focus on international frontier developments, industry status, and technological innovation achievements, with relatively less research on how to promote China' s standard digital transformation. The research lacks foresight, specificity, and systematicity, and has not yet proposed a complete, systematic development 思路 and countermeasures for standard digitalization. As a major country in standardization construction and the digital economy, deepening research on China' s standard digital transformation development holds significant practical importance. Therefore, this paper focuses on China' s actual situation, analyzing how China can currently carry out standard digital transformation, including its development opportunities, problems, challenges, and countermeasures, thereby providing references for China' s digital economy development and industrial digital transformation.

1 Global Trends in Standard Digital Transformation

Standards are technical supports for economic activities and social development, and important aspects of national foundational systems [**?**]. Standards not only influence market dominance but also profoundly affect China' s discourse power in international competition [**?**]. The core of standard digitalization is to promote the integration of digital technologies and standardization work, breaking through paper-based standard formats and emphasizing the transformation of standards into knowledge formats (algorithms, formulas, models, codes, modules, tools, systems, platforms, etc.) [**?**]. Therefore, to adapt to the general trend of digital development, standards urgently need to undergo digital transformation.

The connotation of standard digitalization comprises two aspects: first, the digitalization of standards themselves, and second, the digitalization of standard-

ization processes. (1) The digitalization of standards themselves, also called machine-readable standards, refers to new types of standards in portable digital formats that can be directly parsed and used by machines, software, or automation systems to meet user applications [**?**]. Machine-readable standards are divided into five levels: 0, 1, 2, 3, and 4. Level 0 is paper text, Level 1 is traditional digital format standards, Level 2 is machine-readable documents [**?**], Level 3 is standards with machine-readable and executable content [**?**], and Level 4 is standards with machine-interpretable content [**?**]. (2) The digitalization of standardization processes, also called the digitalization of standardization methods, refers to using digital technologies to manage the entire lifecycle of standardization work [**?**]. For example: digital standard development refers to using software for online standard writing with multi-person collaborative editing; digital standard inquiry refers to using digital technologies to achieve full-text retrieval, display of standard relationships, and dynamic update notifications; digital standard application refers to using digital technologies for standard index comparison and parameter analysis [**?**], as well as achieving full lifecycle management and standard data profiling [**?**].

1.1 International Developments in Standard Digitalization

Standard digitalization upgrades the traditional process of manual reading, understanding, and using standards, thereby enhancing the speed, efficiency, and effectiveness of standard writing, inquiry, and application. Unlike digital transformation in traditional industries, standard digital transformation has a broader radiation scope. Due to the foundational and guiding characteristics of the standards field itself, once standard text formats change, the usage processes of standards across all industries will undergo major transformations, with far more profound impacts than digital transformation in any single field. This will generate massive amounts of data knowledge and data value, rapidly leading the development pattern of high-quality global economic transformation [**?**]. International standard digitalization development trends are mainly reflected in two aspects:

(1) International standardization research institutions have elevated standard digitalization to a strategic development level. Taking the International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC) as examples: first, ISO has incorporated "digital technology" into its "ISO 2030 Strategy" [**?**]; second, ISO has proposed the concept of SMART standards (i.e., Level 3 machine-readable and executable content standards and Level 4 machine-interpretable content standards), and established a Machine Readable Standards Working Group (MRS) and a Strategic Advisory Group on Machine Readable Standards (SAGMRS); third, IEC has established the Digital Transformation and Systems Approach Strategic Group (SMB/SG12), proposing important foundational concepts such as standardization architecture models, minimum information units, standard information models, and standard man-

agement shells [**?**], and developed an intelligent standards roadmap. Additionally, the European Committee for Standardization/European Committee for Electrotechnical Standardization (CEN/CENELEC) has proposed vigorously exploring potential open-source and innovative technologies in the field of standard digitalization [**?**].

(2) European and American countries focus more on integrating standard digitalization technologies with industrial applications [**?**]. Taking the United States, Germany, and the United Kingdom as examples: first, the U.S. has conducted "SMART standards" research in defense technology hotspots such as 5G, drones, advanced materials, and aerospace [**?**]; second, the American National Standards Institute (ANSI) and U.S. industry organizations [**?**] have jointly promoted "ISO SMART"standards, which represent a new intelligent standard format required for user-standard interaction (including new standard formats, new standardization processes, and new standardization tools); third, the U.S. has listed "standard digitalization" as an emerging frontier technology [**?**]; fourth, Germany has conducted full-chain research on the "standard-industry-application" model [**?**] based on achievements from the Industry 4.0 platform [**?**] and industrial asset administration shells [**?**]; fifth, the UK has proposed BSI Flex standards [**?**].

In summary, standard digitalization is becoming a key element leading digital economic development. International standardization organizations and developed countries are advancing from Level 3 to Level 4 standard formats, with their development strategies almost all closely linked to standard digitalization. Standard digitalization development has become an international hotspot (see Table 1).

Table 1 International Standard Digitalization: Key Directions, Development Status, Typical Scenarios, and Development Overview

International Standardization Organizations and Selected Countries	Development Stage	Key Directions	Development Status and Typical Scenarios
ISO/IEC	Levels 3-4	SMART standards technology roadmap, online collaborative standard development platform	In 2017, the IEC Development Plan proposed using new machine-readable digital standards; in 2018, IEC established the Digital Transformation Strategic Group (SG12); in 2019, ISO/IEC proposed the SMART standards concept; in 2021, ISO and IEC jointly established the SMART Steering Working Group; in 2022, ISO and IEC jointly developed the Online Standard Development (OSD) platform

International Standardization Organizations and Selected Countries	Development Stage	Key Directions	Development Status and Typical Scenarios
CEN/CENELEC	Levels 3-4	SMART standards, online collaborative standard development, machine-readable standard supporting software, online collaborative standard development platform	In 2020, began exploring potential open-source and innovative technologies in standard digitalization
USA	Levels 3-4	Standard reference databases, standardization information systems	In 2019, the U.S. AI R&D Strategic Plan promoted establishing and improving digital standards in relevant fields; in 2020, ANSI' s annual report listed ISO SMART standards as an emerging frontier technology

International Standardization Organizations and Selected Countries	Development Stage	Key Directions	Development Status and Typical Scenarios
Germany	Levels 3-4	Machine-readable standard supporting software, standard integration models, Industry 4.0 platform, industrial asset administration shells	Smart manufacturing, digital factories
UK	Levels 3-4	BSI Flex standards	COVID-19, connected vehicles

1.2 Domestic Developments in Standard Digitalization

The key to standard digital transformation lies not only in breaking through specific technical challenges but also in systematically studying and addressing transformation requirements, overall objectives, technology roadmaps, implementation pathways, management processes and mechanisms, supporting software tools and platforms, and typical pilot cases. Following international standardization developments, China has also begun exploring standard digitalization.

First, the Chinese government has elevated standard digitalization to a strategic development level. The government has conducted research from multiple perspectives including "top-level strategic planning, expert teams, and project

support" : in 2021, it released the "National Standardization Development Outline" [?], proposing to vigorously develop machine-readable standards and open-source standards, and promote the digitalization, networking, and intelligentization of standardization work [?]; the Standardization Administration of China has established professional teams such as the "Machine-Readable Standards Working Group," "Machine-Readable Standards Special Task Group," and "Machine-Readable Standards International Cooperation Group" to conduct research on international development strategies and key theories for machine-readable standards; and it has launched major special projects under the National Key R&D Program for National Quality Infrastructure (NQI) and MIIT intelligent manufacturing special projects to support theoretical and technical research on machine-readable standards.

Second, various industries have explored standard digitalization applications based on their industrial advantages. Taking industrial automation, aviation, and electric power as examples: the industrial automation sector focuses on integrating standard digitalization theory with intelligent manufacturing systems, actively researching key technologies and application scenarios for machine-readable standards such as public data dictionary construction and digital factory models [?, ?, ?]; the aviation sector emphasizes applying standard digitalization theory to aircraft product development, production, and operation, actively researching key technologies and application scenarios such as aviation standard information service cloud platforms, aviation standard digital knowledge graphs, and aviation standard digital semantic knowledge networks [?]; in the electric power sector, the State Grid Corporation of China has conducted research on power standard digitalization concepts, technical paths, core technologies, and application scenarios, actively studying power standard knowledge graph construction methods and application scenarios [?]. The Southern Power Grid Company focuses more on integrating standard digitalization theory with digital platform infrastructure, developing digital ecosystems covering "standard management, standard inquiry, standard application, and standard writing" [?].

In summary, standard digitalization is becoming a new force driving digital transformation across domestic industries. China is advancing from Level 2 to Level 3 standard formats, with national standardization development strategies clearly indicating that standard digitalization represents the general trend. New demands such as machine recognition and automatic processing of standard indicators, automatic inspection and testing, and embedding standard databases in industrial R&D software applications are rapidly developing domestically, making standard digitalization a hot direction (see Table 2).

Table 2 Domestic Core Standard Digitalization Requirements, Representative Fields, Typical Scenarios, and Pilot Cases

Core Standard Digitalization Requirements	Development Stage	Urgency Level	Typical Scenarios and Pilot Cases
Machine recognition and automatic processing of standard indicators	Levels 2-3	High	Machine processing equipment automatically recognizes length, width, and height parameters from screw and nut-related standards for automatic production
Machine recognition and automatic inspection/testing of standard indicators	Levels 2-3	High	Inspection and testing equipment automatically recognizes resistivity parameters from electronic chip-related standards for automatic inspection and testing
Embedding standard databases in industrial R&D software applications	Levels 2-3	High	In aircraft component structural selection and design, standard indicators in data format are embedded in 2D and 3D modeling and simulation software
Dynamic tracking of standard status and content	Levels 2-3	High	During power line inspection, machines automatically provide inspection personnel with feedback on standard publication, withdrawal, and update status, as well as specific content changes

Core Standard Digitalization Requirements	Development Stage	Urgency Level	Typical Scenarios and Pilot Cases
Online standard writing and standard data statistics/analysis	Levels 2-3	High	Using computers to enable multi-person online standard writing and achieve standard indicator data analysis and visual graphics display

2 Opportunities for Standard Digital Governance

2.1 New Standard Digitalization Technologies Promoting Full-Chain Development

New standard digitalization technologies play crucial roles in improving standard writing efficiency, expanding standard retrieval resources, and 挖掘 ing potential value in standard data. First, improving standard writing efficiency. Standard writing is a critical component of standardization work, and the application of standard digitalization will trigger transformations in both writing methods and content [**?**]. Big data analytics and AI technologies have broken through temporal and spatial limitations in standard content writing, enabling multi-person online collaborative writing of the same standard document, computer-assisted text formatting and layout, computer-assisted image text recognition, and achieving a leap from standard text writing to standard data writing. Second, expanding standard retrieval resources [**?**]. The audience for standard retrieval is extremely broad, covering not only standardization practitioners but also countless ordinary people seeking standard knowledge. Standard digitalization applications will transform society from retrieving full standard texts to retrieving standard knowledge [**?**]. People no longer 满足于 obtaining full standards through standard names or numbers but expect to directly access corresponding key indicator and parameter values through standard index or parameter names [**?**]. Furthermore, computers automatically display series information resources such as references and cited documents related to search terms, while big data analytics and AI technologies have broken through human brain storage and computational analysis limitations [**?**], achieving precise retrieval and rapid knowledge analysis by computers, representing a stepwise leap from full-text retrieval to knowledge retrieval. Third, 挖掘 ing potential value in standard data. Standard data value 挖掘 ing is important work, and standard digitalization applications will trigger transformations from manual data collation to computer-automated analysis and 挖掘 ing for standardization top-level designers. Big data analytics and AI technologies have broken through human brain logical analysis and relational reasoning limitations [**?**], enabling rapid analysis of data correlation relationships and visual image display by com-

puters, representing a stepwise jump from manual standard data collation to computer-automated standard data value 挖掘 ing.

2.2 Standardization Development Policies Encouraging and Guiding Standard Digitalization

To 顺应 the wave of global standard digital transformation, China has established a policy system adapted to standard digital transformation and social needs through national standard system reform, robot standard system construction, new-generation AI standard system construction, and machine-readable standards (see Table 3). In 2015, the State Council issued the "Plan for Deepening Standardization Work Reform," followed by policy documents such as the "National Robot Standard System Construction Guide" and "National New-Generation Artificial Intelligence Standard System Construction Guide," which strengthened the development of frontier technologies like robotics and AI. In 2021, the "14th Five-Year Plan for National Economic and Social Development and Long-Range Objectives Through 2035" was officially released, followed by a series of policy plans including the "National Standardization Development Outline," "14th Five-Year Plan for High-Quality Development National Standard System Construction," and "Action Plan for Implementing the National Standardization Development Outline," initially constructing a policy guarantee system for standard digital transformation.

Table 3 China' s Main Policy Documents for Standard Digital Transformation

Policy Document	Background	Content
"Plan for Deepening Standardization Work Reform" (2015)	The current standard system and standardization management system were established in the 1980s, with misaligned roles between government and market, insufficient market vitality, hindering effective standardization work and affecting its role	Transform the government-single-supply standard system into a new system jointly constituted by government-led and market-autonomous standards, integrating government-led standards from 6 categories to 4

Policy Document	Background	Content
"National Robot Standard System Construction Guide" (2017)	People gradually realized robots play important roles in supporting intelligent manufacturing, improving production efficiency, and enhancing public welfare	Develop robot collaboration standards, including human-robot, robot-robot, and robot-production environment standards
"National New-Generation AI Standard System Construction Guide" (2020)	AI technology plays important roles in promoting healthy and sustainable industrial development	Establish a national new-generation AI standard system, promote continuous self-optimization in open-source, open industrial ecosystems, and fully leverage its leading role in basic sharing, ethics, and security privacy standards
"2021 National Standardization Work Priorities" (2021)	Accelerate building a high-quality development standard system to provide support for a good start to the 14th Five-Year Plan	Conduct machine-readable standards and database standards pilots, explore new forms and mechanisms for national standard management under digital conditions

Policy Document	Background	Content
"National Standardization Development Outline" (2021)	New era high-quality development and building a modern socialist country urgently require further strengthening standardization work	Develop machine-readable standards and open-source standards, promote digitalization, networking, and intelligentization of standardization work
"14th Five-Year Plan for High-Quality Development National Standard System Construction" (2021)	Implement the National Standardization Development Outline, guide national standard formulation and implementation, accelerate building a high-quality development national standard system	Advance national standard digitalization pilots, explore increasing new forms of national standard supply such as machine-readable, open-source, and database standards
"2022 National Standardization Work Priorities" (2022)	Implement the National Standardization Development Outline, further build a high-quality development standard system	Strengthen standard digitalization technology research, grasp frontier technology development trends, increase basic theoretical reserves for standardization

Policy Document	Background	Content
"Action Plan for Implementing the National Standardization Development Outline" (2022)	Implement the National Standardization Development Outline, clarify key tasks before end of 2023	Provide standard support for building a modern socialist country; strengthen digital technology standard formulation, promote digital industrialization and industrial digitalization; formulate data security and data transaction standards to promote data factor market development; build a national digital standards library, promote development of standards libraries at all levels; improve the national standard information public service platform function to achieve cross-department, cross-industry, cross-regional standard information exchange and sharing

Policy Document	Background	Content
"2023 National Standardization Work Priorities" (2023)	Deeply implement various key tasks of the National Standardization Development Outline, strengthen quality support	Promote standard digitalization, strengthen standard digitalization system construction, formulate digital basic standards; conduct standard digitalization roadmap research, carry out standard digitalization pilots in key fields
"2024 National Standardization Work Priorities" (2024)	Further advance implementation of various key tasks of the National Standardization Development Outline	Actively promote standard digitalization research, conduct standard digitalization pilots

2.3 Traditional Standardization Development Patterns Undergoing Major Transformation

First, the dependency between traditional libraries, archives, standards institutions, publishing houses, and Internet platforms is becoming increasingly close. Standard digital transformation will change the current development pattern dominated by traditional libraries, archives, standards institutions, and publishing houses [**?**], introducing new Internet enterprise competitors and likely changing current market scales and dominant market positions. Various Internet platforms will no longer merely be recipients and storage service providers for PDF-format standard documents but will deeply participate in all aspects of the entire standard lifecycle management (including standard development, project initiation and publication, inquiry, review, and application), such as establishing standard data formats, defining data interfaces, managing data resources, and building databases. This deep participation will, on one hand, accelerate the digital transformation pace of traditional libraries, archives, standards institutions, and publishing houses [**?**], promoting innovative integration of digital technologies and standardization; on the other hand, it may intro-

duce Internet-era traffic-centric values into the standardization field, potentially causing Internet platforms to over-compete for traffic value while neglecting the importance of 挖掘 ing potential value and knowledge behind standards, which requires focused attention.

Second, the digital governance difficulty of standard information resource service platforms has substantially increased. The governance level of standard information resource service platforms is mainly reflected in the openness of standard database sharing and the smoothness of standard data format interconnectivity. However, China' s current standard information resource service platform development is relatively lagging, with no established management mechanisms suitable for emerging standard digitalization information resources, resulting in isolated standard index databases and resource libraries across industries. This not only leads to redundant construction but also leaves industries and enterprises without clear plans for how to better interface with national standard resource service platforms or how to embed themselves into future national standard resource databases and information service platforms. Although national standard management departments have undertaken digital construction of standard information resource service platforms [**?**], they have not yet implemented nationwide networked and intelligent management of standard resource library sharing across industries and fields, failing to fundamentally conduct data governance and standard data value sharing in the standardization field. Although developing open-source standards, machine-readable standards, and public data standards has become a government priority, significant obstacles remain in standard database interconnectivity and sharing. The reasons are: on one hand, numerous industry institutions have invested substantial costs and resources in establishing and maintaining standard resource libraries; on the other hand, standard databases may involve large amounts of core technologies and confidential enterprise data [**?**], making simple "one-size-fits-all" database approaches difficult.

2.4 Profound Changes in Standard Data Governance Concepts

The deep integration of digital technologies and standardization has caused tremendous changes in standard writing methods, management models, and application scenarios, triggering profound changes in standard data governance concepts (see Table 4).

Table 4 Characteristics of Standard Data Governance Concept Transformation

Standard Digital Transformation Process	Governance Concept Transformation Characteristics
From Level 0 paper text to Level 1 PDF digital format standards	From manual reading of paper standards to machine automatic reading, understanding, execution, and interpretation of data-format standards

Standard Digital Transformation Process	Governance Concept Transformation Characteristics
To Level 2 machine-readable document standards	To online collaborative standard writing, standard index extraction and comparison, intelligent standard recommendation, and standard data embedding in software applications
To Level 3 machine-readable and executable content standards	From manual use of full standard texts to computer 挖掘 ing of standard potential knowledge and value
To Level 4 machine-interpretable content standards	From paper-based formats to data-based formats
From ordinary full-text retrieval	From offline standard institutions, libraries, and bookstores to online digital resources like software tools, systems, and platforms
To online collaborative standard writing, standard index extraction and comparison, intelligent standard recommendation, and standard data embedding in software applications	From manual reading and processing of standards to computer-assisted manual processing achieving human-machine collaborative interaction, to computer and other system equipment collaborative processing achieving machine-machine collaborative interaction
From manual use of full standard texts to computer 挖掘 ing of standard potential knowledge and value	From paper-based management to data governance
From paper-based formats to data-based formats	From binary dominant structure to four-quadrant collaborative development
From offline standard institutions, libraries, and bookstores to online digital resources	From manual processing of standard texts to human-machine and machine-machine collaborative governance of standard knowledge

Based on the basic concepts and development level models of machine-readable standards, standard data governance concepts can be analyzed from five dimensions: standard format, business requirements, carrier forms, acquisition methods, and governance objects. In terms of standard format, the evolution is from ordinary paper text and PDF formats to more advanced machine-readable, executable, and interpretable formats. At the business requirements level, the shift is from full-text retrieval to standard data 挖掘 ing and value sharing. Regarding carrier forms, the transition is from paper-based formats to knowledge formats such as formulas, algorithms, codes, models, and software systems. In acquisition methods, the change is from offline physical institutions to online standard

information platforms. For governance objects, the transformation is from manual standard reading to human-machine and machine-machine collaborative governance of standard knowledge. The standard digital governance model exhibits diversified and complex characteristics, forming a "government-market demand-industry institutions-publishing houses" four-quadrant structure on the basis of the original "government-standards publishing house" binary model. This structure reflects both top-down national strategic demands and bottom-up market economic demands, showing trends toward transparent regulatory mechanisms, diversified participants, and market-oriented economic development.

3 Challenges in China' s Standard Digital Transformation Development

Currently, China' s exploration of standard digital transformation is still in an emerging development stage. It is evident that China' s standard digital transformation will certainly take data-format standards as the breakthrough point, inevitably evolving toward more advanced machine-readable, executable, and interpretable standards. The future development focus lies in the quantity and quality of machine-readable standards and the 挖掘 ing of application scenario requirements [**?**]. China' s standard digital transformation needs to focus on foundational common key technologies such as standardized data management, unified data model management, and data governance, as well as specialized technologies containing domain knowledge like public data dictionaries, natural language understanding, and knowledge graphs. Meanwhile, China' s standard digital transformation still lacks theoretical depth and innovative applications at the macro level of standard system research, the deep analysis level of standard index databases, the analysis and management level of standard data, and the optimization and application level of standard models, facing numerous problems and challenges. Therefore, China urgently needs to conduct relevant scientific research and exploration with problem-solving as the orientation, particularly focusing on the impact of frontier technologies such as ChatGPT-like large models, AI, data governance, cybersecurity, privacy protection, and copyright protection on standard digital transformation [**?**], and how to embed these frontier technologies into standard digital transformation for innovative application, in order to promote the transformation of standardization work toward digitalization, networking, and intelligence.

First, the basic theories, key technologies, implementation paths, and application scenarios of standard digital transformation have not yet formed a complete system. Currently, China has limited opportunities and discourse power in participating in the formulation of important international standards such as "ISO SMART," resulting in low participation and contribution to relevant international standards. Additionally, there is a lack of basic forward-looking concepts such as standard information units, standardization architecture models, standard information models, and other machine-readable standard conceptual models and use case methods. The construction 思路 and discourse power

for these extremely important basic conceptual systems and theoretical models are held by developed countries [**?**], greatly limiting the long-term development of China' s standard digital transformation-related international standards and frontier key technologies.

Second, there are few mature products and excellent pilot cases related to standard digital transformation. The standardization field has high barriers, and most enterprises lack mature professional standardization research teams and experience [**?**]. Therefore, in the process of standard digitalization development, many enterprises remain at the theoretical level, without clearly defining standard digital transformation requirements closely related to their own business, nor proposing core technology products and business scenarios suitable for their transformation needs. While many professional standardization institutions and research institutes have conducted pilot demonstration cases, most are limited to specific professional scenarios or partial explorations around their own business needs [**?**], with extremely high R&D investment and costs, making it difficult for other enterprises to learn from and replicate [**?**]. This dampens the enthusiasm of relevant enterprises for standard digital transformation research, making it difficult to derive ecosystems and industrial clusters related to standard digitalization, and preventing a flourishing development landscape.

Third, the institutional system and management mechanisms supporting standard digitalization construction and development need improvement and refinement. Standard digitalization is an emerging concept from recent years and represents the major trend for future standardization development, thus possessing forward-looking and frontier attributes. Many existing standardization systems and management mechanisms are no longer suitable for new-era development requirements [**?**]. In 2021, the Central Committee and State Council released the "National Standardization Development Outline," explicitly proposing to vigorously develop "digital standards and machine-readable standards" [**?**]. In 2022, the "Action Plan for Implementing the National Standardization Development Outline" clearly stated "strengthen digital technology standard formulation, promote digital industrialization and industrial digitalization" [**?**]. However, how to high-quality and scientifically promote the integration of digital standards with industrial digitalization and digital industrialization remains to be further improved [**?**].

4 Countermeasures for China' s Standard Digital Transformation Development

China' s standard digital transformation development should explore countermeasures from immediate to long-term and macro to micro perspectives, while balancing international and domestic considerations, theory and practice, and technology and management.

First, vigorously develop basic conceptual systems and foundational common key technologies for standard digitalization. Aim at world advanced technology

development directions and trends [?], benchmark against international and regional standardization organizations, track and analyze digital standards released by ISO, IEC, and other international standardization organizations and countries [?], closely monitor technical standard development directions represented by machine-readable standards, accelerate research on foundational common technologies such as standard information unit construction methods, standard information models, standard tag sets, and public data dictionaries, and accelerate research on key application technologies such as natural language understanding and knowledge graphs [?].

Second, strengthen policy guarantees for standard digitalization. Take the "National Standardization Development Outline" as the fundamental guide and the "Action Plan for Implementing the National Standardization Development Outline" as the action program to establish a policy guarantee system adapted to standard digital transformation development, strengthening top-level design for standard digital transformation. Establish a national-level standard digitalization strategic planning expert committee to conduct strategic research and deployment, planning technology roadmaps and implementation pathways from the top level. Establish mechanisms for phased digital transformation of existing standards and stepwise digital transformation of incremental standards, exploring new demands, technologies, applications, models, scenarios, and business forms combining standard digitalization technology with standardization work. Use digital means to evaluate, supervise, and manage standard formulation/revision, publication, and implementation [?]. Regularly conduct implementation effect evaluations and application effect assessments for machine-readable and digital standards.

Third, promote the integration and innovative application of standard digitalization theories with various business scenarios, accelerate the establishment of a unified-interface national standard digitalization resource service platform to ensure the uniqueness and authority of standard data sources. Strengthen the sharing of standard index databases and resource databases across industries to reduce redundant construction of similar standard data resources and index databases [?]. Enhance research on knowledge graph semantic networks and structured index databases to improve capabilities in intelligent standard retrieval, intelligent recommendation, data value 挖掘 ing, and data visualization processing. Promote innovative integration of standard digitalization achievements across different industries and fields, achieving interconnectivity and sharing of standard data resources in aviation, industrial automation, electronic communications, power grids, and other fields, improving the extraction, classification, and verification capabilities of standard technical elements and core indicators, and strengthening dynamic association and real-time update capabilities of standards. Promote ecological integration of standards with industrial digitalization, improving the efficiency and management capabilities of standards in pre-research, project initiation, formulation/revision, review, application, implementation, and service, enhancing support capabilities for digital project design, development, maintenance, and assurance, and promoting inte-

grated development of standard chains and industrial chains [?].

Fourth, proactively plan for future international markets for standard digitalization, vigorously promoting international exchanges and cooperation on machine-readable and digital standards. Leverage the "Belt and Road" development opportunities to accelerate cross-border business cooperation with countries along the route in standard digitalization-related scientific and technological projects and engineering projects, promoting mutual recognition and exchange of international standards, and strategically seizing development opportunities for machine-readable standards. Encourage industry-academia-research alliances, research institutes, social organizations, and enterprises to actively participate in international exchanges [?], leading and participating in the formulation of "ISO SMART" related international standards. Build international cooperation and exchange platforms to attract overseas high-end talents to China for strategic cooperation and high-end think tank research, continuously enhancing China' s international influence in standard construction.

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