Enterprise Data Governance Models in Digital Twin Environments: Postprint

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Abstract

[Purpose/Significance] To provide reference models for data governance to enterprises employing digital twin systems, thereby facilitating the realization of data value and digital-intelligent transformation and upgrading. [Method/Process] With enterprise data governance models as the investigation object, this study analyzes the underlying logic of data governance within digital twin systems through a fusion approach, and explores the construction of enterprise data governance frameworks. [Results/Conclusion] Grounded in the principles of data full lifecycle, data value chain, data security and compliance, and business processes and requirements, four distinct data governance models are identified. The core philosophy, operational mechanisms, and implementation strategies for each model are subsequently analyzed, with elaboration through specific enterprise data governance cases, ultimately offering references for both research and practice in enterprise data governance.

Full Text

Research on Enterprise Data Governance Models in Digital Twin Environments

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Abstract:
[Purpose/Significance] This study aims to provide data governance model references for enterprises utilizing digital twin systems, thereby promoting the realization of data value and facilitating digital-intelligent transformation and upgrading. [Method/Process] Taking enterprise data governance models as the research object, this paper conducts a comprehensive analysis of the inherent

logic of data governance within digital twin systems and investigates the construction of enterprise data governance frameworks. [Result/Conclusion] Four distinct data governance models are summarized based on the data lifecycle, data value chain, data security and compliance, and business processes and demand-driven requirements. Each model is analyzed in terms of its core concept, operational mechanism, and implementation strategy, with concrete enterprise cases illustrating their application. The findings ultimately provide valuable references for both research and practice in enterprise data governance.

Keywords: Digital twin; Enterprise data governance; Data governance model

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In April 2020, the Central Committee of the Communist Party of China and the State Council released the "Opinions on Constructing a More Perfect Market-oriented Allocation System and Mechanism for Production Factors," officially incorporating "data" into the ranks of production factors [1]. In December 2022, they further issued the "Opinions on Constructing a Data Basic System to Better Leverage the Role of Data Elements," providing crucial guidance for enabling data elements to lead social production [2]. In today' s rapidly evolving digital landscape, data has emerged as a new production factor and a critical driver for industrial transformation and the cultivation of new economic development models. Data element security governance, as one of the four core components of the data basic system, serves as an essential safeguard for ensuring the effective functioning of data elements [3]. In April 2020, the National Development and Reform Commission and the Cyberspace Administration of China jointly issued the "Notice on Promoting the 'Cloud Computing, Data Utilization, and Intelligent Empowerment' Action to Cultivate New Economic Development Implementation Plans," proposing the launch of a digital twin innovation initiative [4]. The application of digital twin technology not only brings new operational and business models to enterprises but also imposes new requirements on enterprise data governance. However, traditional data governance models often fail to meet the complexity and dynamism of data governance in digital twin environments. Against this backdrop, there is an urgent need to explore application models of enterprise data governance that integrate digital twin technology to respond to national digital economy development strategic requirements.

Building upon this context, this study examines enterprise data governance from an integrated perspective, focusing on the inherent logic of enterprise data governance within digital twin environments. It constructs a data governance framework and proposes data governance models for digital twin contexts, aiming to unlock the potential of data elements to drive enterprise development and ultimately provide theoretical and practical references for enterprise digital transformation.

1.1 Development of Enterprise Data Governance

As early as 2005, foreign scholars pioneered research in the field of enterprise data governance [5]. Since then, researchers both domestically and internationally have focused on specific business scenarios in enterprise management, conducting extensive in-depth discussions and studies on data governance. At the theoretical level, scholars have primarily concentrated on constructing data governance frameworks, institutional designs, architectural planning, model development, and effectiveness evaluation systems for enterprises as a whole or for specific business domains [6], or have developed data governance models composed of data quality roles, decision-making domains, and responsibilities [7]. Zorrilla et al. [8] proposed a specific framework design for enterprise data governance tailored to the Industry 4.0 context. Jiang Guoyin et al. [9] collected relevant data governance information to construct an optimization framework for data governance policies in the sharing economy platform. At the practical level, scholars have paid greater attention to the application of data governance technologies, data mining techniques, and data management tools in actual enterprise operations, striving to solve technical challenges in the data governance process to enhance governance effectiveness [6]. Fang Qian et al. [10] explored key technologies for realizing data value in intelligent coal mine construction. Hou Peng et al. [11] investigated the intelligent development of financial data security governance as a central issue. Kevin [12] conducted research on governance services related to data governance tools for internet enterprises.

1.2 Application of Digital Twin Technology

The conceptual model of "digital twin" can be traced back to 2003. In the years following its introduction, academic discussions in this field focused primarily on defining digital twins and exploring derivative model concepts, implementation technologies, and framework structures derived from these definitions. Overall, digital twin refers to the construction of virtual digital mirror copies of physical entities, systems, or processes through various digital technologies, enabling dynamic mapping and collaborative optimization between the physical and digital worlds based on real-time data interaction, model simulation, and analysis.

Beginning in 2010, digital twin technology entered the manufacturing domain. National agencies such as NASA and industrial giants including General Electric (GE), Siemens, and Dassault joined the research ranks of digital twin technology. Schleich et al. [13] focused on the evolution and application progress of digital twins, discussing new conceptual representations and implementations of models and their applications in the industrial product lifecycle. Siemens and Bentley launched PlantSight based on digital twin technology as a more effective digital solution for plant operations. Bilberg et al. [14] proposed a new human-robot collaboration model supported by digital twin technology for framework and operation. With the rapid development of artificial intelligence, digital twin technology has shown a trend of integration with Artificial Intelligence Generated Content (AIGC).

Domestic scholars' research on digital twins began in 2017. Tao Fei et al. [15] proposed the concept of "digital twin workshop," interpreted its meaning, and thoroughly discussed workshop production systems, services, operational mechanisms, and characteristics. Subsequently, Guo Dongsheng et al. [16] conducted modeling research specifically for aerospace structural component manufacturing workshops. This was followed by new interpretations under the integration of technology and new domains: Xu Hui [17] extended digital twin technology to urban development applications, innovatively proposing its positive role in urban development. In recent years, research on this technology has broken through traditional conceptual barriers, introducing it into libraries, publishing, smart homes, smart healthcare, and other fields to explore its potential. The development history of digital twin is shown in Figure 1 [Figure 1: see original paper].

1.3 Research Status of Data Governance in Digital Twin Scenarios

Since the beginning of the 21st century, the exploration of integrating digital twin technology and data governance has gradually become a global research hotspot. Representative studies include: Omrany et al. [18] investigated the implementation of digital twins in the construction industry, analyzed data governance challenges hindering digital twin technology adoption, and proposed industry standard collaboration pathways, though their research was limited to specific industries and failed to meet the data governance needs of different types of enterprises. Kalaboukas et al. [19] proposed an integrated governance framework for cognitive digital twins that combines business and sustainability governance, data governance, and cognitive model governance, but this approach lacks systematic construction of a collaborative mechanism across the three dimensions of "technology, management, and value." Ren et al. [20] innovatively applied ontology technology to the digital twin domain, proposing an ontology-reasoning-based data governance method grounded in product lifecycle management theory. Tao Fei et al. [21] established a theoretical foundation for workshop digital twin applications through a four-dimensional integration theory of physical fusion, model fusion, data fusion, and service fusion, but failed to extend it to enterprise-wide governance scenarios. Wang Jing et al. [22] introduced complex adaptive systems theory to conduct in-depth research on data governance for smart services in university libraries, constructing a five-dimensional model for library smart service data management based on digital twin technology, though the governance granularity leaned toward the service level rather than underlying data. Wang Feng [23] constructed a data governance framework relying on City Information Modeling (CIM) platforms for the specific scope and content of digital twin data governance, and explored workflow-based data governance and hierarchical multi-source data visualization technologies.

A comprehensive review of existing representative achievements reveals that scholars' research focus on data governance in digital twin environments has

primarily concentrated on constructing data governance frameworks, models, or proposing new governance methods. However, there remains a certain gap in governance methods specifically targeting enterprise data domains, particularly data governance models that integrate digital twin environments. Therefore, this study addresses the issue of enterprise data governance models in digital twin environments. Distinguishing itself from static governance in traditional framework research, this study combines classical management theories, focuses on data utilization characteristics of different types of enterprises, summarizes data governance operational mechanisms, and aims to facilitate enterprise digital-intelligent transformation.

2 Inherent Logic of Enterprise Data Governance in Digital Twin Environments

In the context of digital-intelligent transformation, maximizing the unique advantages of digital twin technology to achieve data empowerment and make it an internal driving force for enterprise innovation holds significant importance for enterprises. This study conducts a systematic analysis of the inherent logic of enterprise data governance in digital twin environments and constructs a corresponding framework. This inherent logic manifests in three aspects: the digital twin environment serves as the logical cornerstone of data governance, data quality management constitutes the core link of the governance process, and data value realization represents the ultimate goal of data governance (Figure 2 [Figure 2: see original paper]).

2.1 Digital Twin Environment as the Logical Cornerstone of Data Governance

Constructing a complete and efficient digital twin system is not only a prerequisite for enterprises to implement data management in digital twin contexts but also its theoretical foundation and core pillar. The robustness of this system directly impacts the effectiveness of data governance and the enterprise' s sustainable development path. As an emerging technology trend, digital twin technology is comprehensively reshaping the fundamental concepts, architecture, and tools of enterprise management. It profoundly transforms the mindset of enterprise managers, helps elevate data governance levels, and endows managers with enhanced real-time insights. Through virtual "twins" constructed with digital twin technology, enterprise governance entities can efficiently conduct data collection, transmission, and storage, aggregating them into comprehensive and accurate datasets [24]. These valuable data resources not only enhance enterprises' capabilities for reliable simulation and foresight in operations but also improve decision-making accuracy and data processing efficiency, empowering enterprise business to advance into deeper levels and more diverse domains.

2.2 Data Quality Management as the Core Link of Governance Process

In the digital economy era, data has ascended to become a core production factor for economic progress, and enterprises' data governance capabilities are key to shaping their market competitive advantages [25]. Data quality directly impacts the accuracy of enterprise decision-making, the smoothness of business operations, and the release of innovation potential. Enhancing enterprises' data governance capabilities and achieving high-quality data management constitute essential points in the enterprise data governance process. This process covers a wide range, including data management of the physical world reflected through digital twin technology, governance of corresponding virtual entity data, and various data management involved throughout the entire enterprise operation chain. This means that data generated from all operational links—including raw material procurement, manufacturing, marketing, and financial control—are regarded as valuable foundational resources for enterprise operations. Efficient governance of these data resources enables enterprises to precisely control production chains, sensitively respond to market changes, and consequently promote improvements in market competitiveness and industry status.

2.3 Data Value Realization as the Ultimate Goal of Data Governance

A critical link in the inherent logic of data governance in digital twin environments lies in its purpose. This purpose transcends merely ensuring enterprise data security and operational stability, manifesting more prominently in promoting leaps in enterprise service quality and efficiency and maximizing the 挖掘 of hidden data value. In fact, maximizing data value realization constitutes the fundamental goal and deep pursuit of enterprise data governance.

As market competition intensifies, deeply exploring and utilizing data value has become a key strategy for enterprises to gain an edge in fierce competition. Moreover, data value realization is not only the driving force for enterprise innovation and opening new business territories but also injects fresh growth momentum into enterprise profit models. From a societal perspective, data value realization serves as a catalyst for industrial upgrading and a powerful lever for stimulating economic growth, continuously driving social productivity to higher levels. By promoting data sharing and openness, cross-industry and cross-domain collaboration and innovation are activated, accelerating the pace of digital transformation and intelligent upgrading across society.

3 Framework for Enterprise Data Governance System in Digital Twin Environments

Constructing a framework for data governance systems in digital twin environments provides the theoretical and practical foundation for enterprises to address data governance-related issues encountered during development. Currently, the widely adopted methodology for constructing data governance sys-

tems is proposed based on the five-element integration theory, which is applicable to big data governance analysis [26]. In light of this, this paper takes the digital twin environment as the context for data governance and constructs an enterprise data governance framework from five dimensions—data governance subjects and objects, data governance activities, data governance characteristics, key data governance technologies, and data governance models—based on the five-element integration theory (Figure 3 [Figure 3: see original paper]).

3.1 Data Governance Subjects and Objects

Clearly defining governance subjects and objects constitutes an important step in constructing a governance system. A clear definition of subjects provides clear guidance on data ownership for implementing data governance activities, while precise identification of objects enables enterprises to quickly lock onto governance targets when facing complex and changing data governance scenarios. Enterprise data governance subjects should include government departments, data owners, enterprise management, and data managers [27]. This paper focuses on the primary responsibilities of the latter two: enterprise management is mainly responsible for formulating governance strategies and setting governance plans from the top level, while data managers conduct activities related to specific data governance aspects and perform data operations. In terms of types, enterprise data governance objects mainly refer to various internal data generated during the operation of "virtual and physical dual entities" and external market data generated during business activities, covering production, R&D, management, and operation and maintenance.

3.2 Data Governance Activities

Data governance, as a fundamental element of data and data system management, represents a collection of activities that exercise authority and control over data asset management [28]. Enterprises conducting data governance activities in the digital twin context encompass various types of data throughout the entire enterprise activity process, including master data management, metadata management, data standard management, data security management, data quality management, and other multi-dimensional content [29]. The goal of enterprise data governance is to ensure data security, availability, and compliance to support enterprise decision-making, data service innovation, and other processes, ultimately achieving enhancement of data element value. Therefore, conducting efficient and reliable data governance activities is crucial for business management and value creation.

3.3 Data Governance Characteristics

In digital twin scenarios, enterprise data governance exhibits several notable features that evolve with the governance environment. In this highly simulated digital twin environment, data breaks free from the limitations of isolation and static states, demonstrating a new appearance of interconnectivity and dynamic

evolution. Consequently, achieving fusion processing of multi-source heterogeneous data becomes a unique characteristic of enterprise data governance. Additionally, as an emerging production factor, data transforms into a driving force for enterprise continuous growth. From an integrated perspective, the characteristics of data governance are reflected in its comprehensive and optimized integration with all aspects of enterprise management. Data governance constitutes the cornerstone for the interaction and fusion of physical and virtual entities in digital twin systems [25], while digital twin technology brings broader application scenarios and higher execution standards to enterprise data governance.

3.4 Key Data Governance Technologies

In the information age, enterprise data governance not only welcomes the expansion of new application scenarios but also accompanies the emergence of a series of new technologies that build the technical foundation for governance activities. Key technologies for enterprise data governance cover multiple aspects: data collection and transmission technologies can adopt sensor network technology and communication technology; data processing and storage technologies can adopt distributed storage and cloud computing; digital twin modeling and simulation technology involves 3D modeling and physical simulation; data security requires network security and privacy protection technologies to ensure system operation; additionally, data-driven technologies including machine learning, data mining, and deep learning, as well as edge computing technology, constitute technical elements for achieving enterprise data governance.

3.5 Data Governance Models

Data governance models refer to a series of data governance strategies and practical methods adopted by enterprises based on their specific data governance goals, combined with current organizational structures, system architectures, and data application situations. Data governance solutions vary according to enterprise characteristics, with different requirements for data management maturity and internal collaboration efficiency. Within the overall data governance system, the application status of models directly affects the actual effectiveness of governance work. Enterprise data governance is a complex and enduring process. At different stages, enterprises often select the most suitable data governance model based on actual data environments and application needs, weighing governance goals against current conditions to ensure effective advancement of governance work.

4 Enterprise Data Governance Models in Digital Twin Environments

The novel characteristics of data elements and data governance in digital twin environments pose challenges to traditional data element governance architec-

tures, urgently requiring research and exploration of adaptive data governance models. This study systematically classifies enterprise groups based on differences in specific focuses and purposes of data utilization among different enterprises, integrates data management theories from the management discipline, and explores and constructs applicable enterprise data governance models under different business and operational scenarios. Therefore, "data governance models" in this study refer to specific methods or frameworks adopted by enterprises for data governance in digital twin technology environments. They include not only the core concept of the model but also the operational mechanism reflecting the model' s management processes and applicable scenarios for value realization that match the model. They represent a systematic solution set for maximizing data value through specific management mechanisms, with specific models shown in Figure 4 [Figure 4: see original paper]. Overall, the data lifecycle-based governance model can serve as the foundation for enterprise data governance models because it considers the entire data lifecycle and covers all aspects of governance. The other three governance models each have specific focuses, representing optimizations and extensions of the data lifecycle governance model across different dimensions.

4.1 Data Lifecycle-Based Governance Model

4.1.1 Core Concept and Operational Mechanism The concept of lifecycle originally stems from biology, referring to the objective evolutionary laws of birth, aging, illness, and death. Today, this concept has transcended disciplinary boundaries and is widely applied in social science research to describe the different development stages experienced by things or social phenomena over time [30]. With the development of big data, the data lifecycle, as a theory revealing the inherent development laws of data, has gradually become an important means for studying data management and preservation [31]. Unlike the unidirectional linear process of life in the biological world, the data lifecycle demonstrates a dynamic cyclic characteristic that contains the possibility of repeated utilization [32]. The core concept of the enterprise data governance model based on data lifecycle theory lies in treating data as an important enterprise asset and managing it throughout its entire lifecycle. The focus of this model is to grasp data governance from a comprehensive and process-oriented perspective, emphasizing the flow and management of data at various lifecycle stages to ensure effective control at each link.

Its operational mechanism focuses on four key aspects: identification and planning of the data lifecycle, data quality management and control, data authority and privacy protection, and data archiving and disposal. After constructing the digital twin system, enterprises must first clarify the full lifecycle stages of data assets collected and produced by the system, including data transmission and utilization directions, and formulate corresponding data governance goals based on data characteristics. Second, enterprises should strictly manage and control data quality. Given the real-time and complex characteristics of data produced

by twin systems, enterprises should strengthen quality supervision measures to promote rational data utilization. Third, the diversity of business processes and the privacy of customer information require enterprises to pay special attention to data protection, strictly abide by laws and regulations in data transmission between physical and virtual entities, and ensure legal data use and privacy protection. Finally, enterprises should regularly archive data and reasonably destroy unnecessary data to prevent data leakage.

4.1.2 Implementation Strategies (1) Construct a Unified Data Governance Platform
Within the scope of digital twin systems, data collection activities are primarily dominated by automated mechanical procedures with minimal manual intervention. Empowered by cutting-edge technologies such as digital twin, big data processing, and cloud computing, enterprises can build an integrated data governance system. This system fully incorporates full-cycle management mechanisms for data, ensuring transparent display of every step from data generation to application and final disposal. This enables enterprises to gain deep insights into the sources and applications of each data detail, thereby efficiently regulating data resources at all lifecycle stages. In the initial system establishment phase, enterprises can establish strict data lifecycle evaluation criteria to determine whether data should be preserved, analyzed, or discarded. Subsequently, they should refine specific norms and processes for data elimination, storage, analysis, and application to ensure precise implementation of each step. In practice, relevant personnel should continuously optimize data lifecycle management processes based on actual data conditions to maximize the 挖掘 of data potential value.

(2) Conduct Data Governance Assessment and Improvement
Given that this model is rooted in data lifecycle theory, data governance practices and their outcomes in early stages profoundly impact the performance of subsequent stages. Therefore, the effectiveness and internal coordination of data governance at each time point play a decisive role in the smooth operation of the entire model. To achieve significant data governance results and enhance process efficiency, enterprises must integrate systematic evaluation of governance outcomes when deploying measures. This requires establishing regular in-depth governance effectiveness evaluation mechanisms for key stages of data management. Based on evaluation feedback, enterprises should adopt precise improvement measures for identified problems, continuously refining governance methods and strategies, accelerating data processing and analysis workflows, reducing operational expenses, and thereby supporting more accurate and efficient data-driven decision-making.

4.1.3 Specific Case Under the Industry 4.0 framework and in today's increasingly digital and intelligent business environment, the manufacturing industry is accelerating its transformation into data-driven enterprises [33]. Data flow permeates every link of various business processes, forming the cornerstone for

decision-making, production efficiency upgrades, product quality control, and accelerated market feedback. Therefore, data quality and flow direction are directly related to enterprise production efficiency and market competitiveness. For data-driven enterprises, deeply understanding and grasping the laws of the data lifecycle is key to establishing a sound data governance system.

For example, a cabinet manufacturing enterprise' s industrial real-time data exhibits characteristics of massive volume, time-series nature, strong correlation, and high coupling, accompanied by issues such as data redundancy, inconsistency, heterogeneity, as well as information lag, incoordination, and incompleteness between management and shop floors. To address these problems, the enterprise implemented a data lifecycle-based governance strategy using a cloud box product launched by an information technology company. Starting from real-time data collection, the cloud box performed efficient architectural processing to ensure effective management from data generation. During data storage and utilization, the enterprise' s digital twin system defined a set of cross-platform, multi-device and multi-system compatible data collection and processing specifications, enabling full tracking of data collection, storage, and utilization. Additionally, the cloud box provided powerful data cleaning functions—including missing value processing, denoising, and redundancy reduction —to comprehensively control data quality throughout the lifecycle. These measures not only optimized each link of the data lifecycle but also ensured that the digital twin system could efficiently and accurately collect, store, process, and apply data from all elements of industrial site operations, including equipment, processes, and environments.

4.2 Data Value Chain-Based Governance Model

4.2.1 Core Concept and Operational Mechanism Value chain theory posits that the task of enterprises is to create value, with value and value activities forming the analytical foundation of the value chain. The value chain is a system composed of all production activities and related auxiliary activities required to deliver products or services to users, including design, production, sales, and other stages [34]. The data value chain is a new phenomenon emerging in enterprise value creation activities in the digital economy era, representing a development of value chain theory. It describes the process where data flow and value creation move together along the enterprise production chain. As the production process progresses from R&D to production, from sales to service and usage, data continuously flows and economic value is created. The core concept of the enterprise data governance model based on data value chain theory lies in maximizing the release of data' s potential value by comprehensively optimizing every link in the data value chain, emphasizing effective collaboration among all stakeholders in the data value creation process.

The operational mechanism of this model focuses on three aspects: data resource-based production, data service-oriented development, and data value-based utilization. First, at the initial stage of data governance, enterprises should es-

tablish the concept of data as an important resource. Second, during raw data recording, datasets with product attributes should be formed to provide a foundation for subsequent data service development and value utilization. Third, based on the results of data resource-based production and combined with the characteristics of digital twin systems, data services should be developed to meet business department needs, promoting the release of data resource value. Finally, enterprises should deeply analyze and 挖掘 data to reveal its hidden value, providing support and basis for enterprise decision-making.

4.2.2 Implementation Strategies (1) Establish a Comprehensive Data Governance System

To ensure effective application of value chain theory in data governance models, enterprises' primary task is to build a sound data governance system. The implementation of this system should be accompanied by continuous exploration and improvement, ultimately tending toward perfection. Based on data value chain theory, enterprises need to conduct top-level planning for their data governance systems. Given the complex nature of enterprise data governance processes involving numerous stakeholders that may cover multiple enterprises across the industrial chain, enterprises should adopt a holistic approach from the outset, leading data governance work to permeate from top to bottom. In constructing the governance system, the first step is to establish the purpose and strategic direction of data governance, ensuring they are closely aligned with the overall business strategy. Subsequently, enterprises should refine the rule system and operational processes of data governance, comprehensively promoting and implementing the data governance system with the core orientation of 挖掘 data value to deepen the practice of enterprise data governance.

(2) Promote Data Sharing and Collaboration

When enterprises construct business systems using digital twin technology, the "virtual and physical dual entities" characteristic achieves seamless docking and communication between the physical and virtual layers. On this architectural foundation, data sharing and collaboration become core elements for the stable operation of digital twin systems. This requires that various types of data in digital twin systems can flow freely, dock seamlessly, and achieve efficient collaborative operations across different levels and modules. Promoting data sharing and collaboration not only deepens enterprises' comprehensive understanding of system data but also allows them to explore potential connections between data based on the value chain structure, thereby maximizing data potential and value. Simultaneously, strengthening data sharing and collaboration can promote data communication and cooperation among enterprises in the supply chain, effectively breaking down information silos and barriers, and jointly exploring the deep value of data. This drive for data sharing and collaboration positively enhances data management effectiveness and provides support for enterprises to gain competitive advantages in the digital era.

4.2.3 Specific Case For data innovation enterprises that highly rely on data for business decision-making, product development, and service optimization, the data value chain theory provides a clear framework to guide how enterprises can extract maximum value at each data link. A certain group, as a data innovation enterprise, upholds the concepts that "high-quality data is the foundation of enterprise innovation" and "data is the key to competing for quality customers." Integrating data value chain theory, the group has established a standardized process for enterprise data governance. This process covers the entire journey from data generation to integration, analysis, and consumption. Through continuous quality monitoring and improvement, it ensures data accuracy, completeness, and timeliness, using value-added activities such as data analysis, mining, and forecasting to support business innovation. Additionally, the group has established a unified data classification management framework to provide references for data management practices in various related fields, thereby creating quality enterprise governance soil for data value realization [35].

4.3 Data Security and Compliance-Based Governance Model

4.3.1 Core Concept and Operational Mechanism Data compliance involves a series of established standards and practices aimed at protecting data from threats such as loss, theft, damage, and misuse. Data security governance, on the other hand, focuses on promoting cross-departmental collaboration within organizations to implement plans and activities based on comprehensive data security strategies, ensuring data security and effective utilization [36]. In the process of digital innovation for Chinese enterprises, the key goal of structural governance is to achieve a pattern that balances development and security, while security governance is a necessary path to realizing enterprise data compliance. The governance model for enterprise data governance development in digital twin environments focuses on ensuring data security, integrity, and compliance, emphasizing "security first, compliance-based," meaning achieving effective data governance and utilization under the premise of guaranteeing data security and complying with relevant laws and regulations.

Constructing an enterprise data security and compliance governance system is a complex systematic project whose design should be rooted in relevant legal provisions, industry standards, and legal responsibility frameworks. Applying this system for data management within digital twin system environments requires addressing four key aspects: first, thoroughly analyzing business sectors that operate relying on the system; second, defining the scope of data security protection and compliance operations while continuously focusing on critical data assets; third, using technical means to identify potential data security and compliance risk points to provide an empirical basis for planning risk mitigation measures and strategies; and finally, enterprises should fully utilize preset data security risk prevention and control mechanisms to actively practice in daily operations, commodity and service procurement, and other links to strengthen

actual data protection effectiveness.

4.3.2 Implementation Strategies (1) Construct a Security and Compliance Organizational Structure
In data governance practice, data security and compliance are regarded as core elements. The deployment of enterprise management systems must prioritize establishing a sound data security protection system. Given the complex characteristics inherent in digital twin systems, such as multi-type and heterogeneous data sources and diverse data management subjects, challenges to data protection and compliance are particularly significant and intensive. This mechanism must integrate multiple strategies including data encryption technology, access control, and security audits to ensure security without vulnerabilities at all stages of data storage, transmission, and processing. Simultaneously, enterprises should closely follow national laws, policies, and industry standards to refine data management policies and implementation processes, ensuring that enterprise data management practices strictly comply with legal and regulatory frameworks. Based on this, establishing compliance monitoring and early warning systems to timely identify and effectively respond to potential risks can lay a solid foundation for maintaining the robustness of enterprise data management. Additionally, defining a clear data management organizational structure and responsibility allocation is equally indispensable.

(2) Strengthen Technical Support for Data Security and Compliance
In the digital economy era, enterprises create economic value relying on data resources, and data quality directly impacts enterprise performance generation. To achieve sustainable development, enterprises need to value data resources, with data security being the core guarantee of these resources. The continuous evolution of information technology prompts enterprises to ensure data security and legal compliance from a technical strategic height. To this end, enterprises need to construct a three-dimensional, comprehensively covered data security compliance management system and use information technology tools to promote efficient collaboration between this system and digital twin systems. Specific measures include: adopting advanced data encryption technology to maintain data privacy during storage and transmission processes to prevent data leakage or illegal theft; implementing sophisticated access control mechanisms to refine management granularity of data access and use, effectively curbing unauthorized access and operations to consolidate data protection walls; leveraging big data analysis and artificial intelligence to strengthen data compliance supervision and using AI to automate processing of massive data volumes to accelerate data processing efficiency; considering the unique advantages of blockchain and other technologies for decentralized management and ensuring data authenticity, enterprises can integrate these technologies to enhance data security levels.

4.3.3 Specific Case Data-intensive enterprises accumulate large amounts of valuable data information during their operations, and this data constitutes core

enterprise assets. The financial industry is a representative of data-intensive industries, capable of accumulating massive data resources during production and operation, making data security governance critically important for financial enterprises. A certain bank has focused on data security issues, continuously advancing data security governance practices from three aspects: data security governance system, data security control mechanism, and data security management technology platform. The bank has formulated comprehensive data security policies and strategies, clarified data security management principles, and conducted comprehensive and prudent management of data and data ownership systems; established a basically complete data security organizational structure system and, based on the fintech organization committee established by the enterprise, carried out data security management work along both technology and business lines; in terms of data security institutional norms, it started from both business management and technology management lines to release management system frameworks, continuously consolidating and improving data security business management institutional guarantee capabilities [37].

4.4 Business Process and Demand-Based Governance Model

4.4.1 Core Concept and Operational Mechanism When enterprises execute data acquisition, processing, transmission, and value creation, their purpose is to facilitate the smooth implementation of various business projects. In this process, the data governance system ensures that the data foundation on which enterprises depend is both stable and efficient by establishing data source legitimacy, maintaining data quality, and guiding data application, thereby building a solid platform for promoting continuous business evolution and innovation. Conversely, the massive amount of data accumulated in enterprises' daily operations provides rich material for the data governance system. This data derived from business practices comprehensively reflects the actual situation of enterprise operations, market dynamics, and customer needs across multiple dimensions, providing strong support for exploring new market opportunities and optimizing business strategies. In view of this, constructing a data governance system centered on business processes and actual needs has become one of the enterprise data governance models. This system emphasizes deep integration of data governance mechanisms with specific business processes and actual needs, aiming to promote synergy between data management and business progress. This model focuses on the business orientation and practicality of data governance work, concentrating on meeting actual business demands, refining business processes, enhancing business value, and ensuring that data governance practices can substantially empower enterprises.

Data governance unfolds around enterprise business activities. The primary step is to comprehensively sort out existing business processes, identify key business processes and data needs in enterprise operations, and formulate data governance directions and plans accordingly. On this basis, enterprises should deeply analyze the specific data needs of various business processes to provide

clear goals and basis for subsequent data governance work. Subsequently, enterprises should formulate corresponding data governance solutions for different businesses and extend them to enterprise business activities. As business dynamics evolve and data conditions change, enterprises should continuously adjust and improve data governance strategies and processes to ensure the timeliness and effectiveness of data governance work.

4.4.2 Implementation Strategies (1) Establish Cross-Departmental Data Governance Teams

Facing enterprises, especially large-scale ones, whose businesses exhibit highly diversified characteristics resulting in complex internal departmental structures, data transmission and circulation among different departments and systems face challenges. These challenges stem from heterogeneous personnel composition, dispersed responsibilities, and inconsistent norms, which may negatively impact data management effectiveness. In view of this, when implementing the business process and demand-based governance model, enterprises need to select personnel with data governance experience and professional skills from various departments to form a cross-departmental professional data governance team. This team needs to fully participate in all enterprise data governance activities, which places relatively high requirements on team members' data knowledge levels and professional qualities. Enterprises should enhance investment in data management talent selection and training to ensure the team can operate continuously and efficiently, providing solid organizational guarantees for enterprise data governance work.

(2) Strengthen Integration of Business Processes and Data Governance

Deepening the tight integration of business processes and data governance systems is not only a key element of internal governance innovation but also a forward-looking strategy for enterprises to achieve continuous growth when facing the wave of digital transformation, aiming to achieve seamless docking between business processes and data governance. In implementing this strategic initiative, the initial step is to conduct thorough and profound analysis of core businesses and key processes. This requires enterprises not only to meticulously decompose each business link and accurately grasp its operational mechanisms and characteristics but also to clarify the specific data requirements of these processes in daily operations. In the data governance domain, enterprises should implement precise and purposeful improvement measures based on the unique attributes and needs of business processes. This includes deeply integrating data governance strategies with business processes to ensure archival management practices can precisely address business needs and strongly enhance business processing efficiency and quality. Additionally, enterprises need to actively explore new strategies for promoting business development through data governance, using data governance to catalyze and lead new opportunities for future business expansion.

4.4.3 Specific Case Data-driven enterprises optimize their internal operational processes and drive continuous business growth by leveraging data, thereby promoting digital transformation. The business process and demand-based data governance model can closely align with enterprise business needs and optimize data flow within business processes. A certain company actively promotes digital transformation strategies in multiple fields including human resources, project management, and financial management. To achieve effective data integration and sharing, the company successfully connected core office systems such as human resources, finance, and projects, and preliminarily constructed a small data warehouse for storing and managing various business data. On this basis, the company further clarified data governance responsibilities by subdividing data management tasks to various business departments to ensure continuous improvement of data quality. Additionally, it innovatively subdivided data sources to various system modules, treating data as a natural extension of business processes and achieving refined data management. By tightly integrating data application with actual enterprise business scenarios, the company not only promoted seamless docking and efficient circulation of business data but also significantly improved data usage efficiency and greatly enhanced the enthusiasm of various departments to participate in data governance [38].

Data governance, as a core component of enterprise digital transformation and upgrading, aims to effectively manage and utilize data resources to enhance enterprise competitiveness and innovation capabilities. The emergence of digital twin technology has opened new perspectives and scenarios for enterprise data governance. Through a comprehensive literature review, this paper first analyzes the concepts of data governance and digital twins and systematically explains their development trends. Second, it explores the inherent logic of enterprise data governance in digital twin environments. Then, based on the five-element integration theory, it constructs a system framework integrating five dimensions: governance subjects and objects, governance activities, governance characteristics, key governance technologies, and governance models. Finally, facing digital twin systems, it proposes enterprise data governance models based on data lifecycle, data value chain theory, data security and compliance, and business processes and demands, illustrating model applications with specific enterprise governance cases.

In summary, the research results provide ideas and model frameworks for enterprise data governance in digital twin systems. However, this study focuses on theoretical and case analysis, with limitations in the depth of empirical analysis and model validation. Subsequent research will deepen exploration by strengthening the systematic nature of empirical research and dynamic validation of model applicability.

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