The Theoretical Evolution, Practical Landscape, and Future Pathways of Trusted Data Spaces[–]

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Abstract

[Purpose/Significance] Clarifying the current theoretical research and practical progress of trusted data spaces at home and abroad is of great theoretical and practical significance for building secure and trustworthy data circulation infrastructure, promoting the market-oriented allocation of data elements, and cultivating new quality productive forces. [Method/Process] Using the VOSviewer analytical tool, this paper systematically reviews relevant research and practical achievements from the dimensions of the connotative elements and functional characteristics, rule architecture, technical system, value objectives, practical examples, and application scenarios of trusted data spaces. [Results/Conclusion] At present, phased progress has been made in the theoretical construction, technical pathways, and scenario expansion of trusted data spaces, but some deficiencies remain. In the future, efforts should be made to promote domain-specific integration of connotative elements, localized rule construction, adaptation of technical scenarios, quantitative value assessment, refinement of practical paradigms, and application in the field of public culture, so as to advance the deep transformation of trusted data spaces from theoretical frameworks to large-scale and industrialized practice.

Full Text

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Author biographies: Fang Xiangming, associate research librarian, master' s supervisor, corresponding author: E-mail: xmfang@staff.shu.edu.cn; Wang Minran, master' s student; Tang Feng, information librarian.

Fang Xiangming[1], Wang Minran[2], Tang Feng[3]

1. Shanghai University Library, Shanghai 200444

2. School of Cultural Heritage and Information Management, Shanghai University, Shanghai 200444

3. Shanghai Polytechnic University Library, Shanghai 201209

Abstract: [**Purpose/Significance**] Clarifying the current state of theoretical research and practical progress on trusted data spaces, both in China and abroad, is of important theoretical and practical significance for building secure and trustworthy data-circulation infrastructure, promoting the market-oriented allocation of data elements, and fostering new quality productive forces. [**Methods/Process**] Using the VOSviewer analysis tool, this paper systematically reviews relevant research and practical outcomes concerning trusted data spaces across such dimensions as connotative elements and functional characteristics, governance frameworks, technical systems, value objectives, practical cases, and application scenarios. [**Results/Conclusion**] At present, phased progress has been made in the theoretical construction, technical pathways, and scenario expansion of trusted data spaces, but some shortcomings remain. Future efforts should focus on advancing the cross-domain integration of connotative elements, the construction of localized rules, the adaptation of technologies to scenarios, the quantitative evaluation of value, the refinement of practical paradigms, and applications in public cultural domains, so as to promote the deep transformation of trusted data spaces from theoretical frameworks to large-scale and industrialized practice.

Keywords: trusted data space; data governance; trusted circulation; data value release

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Fang Xiangming[1], Wang Minran[2], Tang Feng[3]

1. Shanghai University Library, Shanghai 200444

2. School of Cultural Heritage and Information Management, Shanghai University, Shanghai 200444

3. Shanghai Polytechnic University Library, Shanghai 201209

Abstract: [**Purpose/significance**] Clarifying the current state of theoretical research and practical developments on trusted data spaces—both domestically and internationally—is of significant theoretical and practical importance for building secure and trustworthy data infrastructure, facilitating the market-oriented allocation of data as a production factor, and fostering new quality productive forces. [**Methods/Process**] Using the VOSviewer bibliometric tool, this paper systematically reviews relevant research and practical outputs across six dimensions: conceptual elements and functional characteristics, governance frameworks, technical architectures, value objectives, exemplary implementations, and application scenarios. [**Results/Conclusion**] Significant progress has been made in the theoretical development, technical pathways, and scenario expansion of trusted data spaces, though certain shortcomings remain. Future efforts should focus on advancing the cross-domain integration of core elements, the construction of localized rules, the alignment of technologies with application scenarios, the quantitative assessment of value, the refinement of practical paradigms, and the application in public cultural domains. These steps will

promote the deep transformation of trusted data spaces from theoretical frameworks to large-scale, industrialized practices.

Keywords: Trusted Data Space; Data Governance; Trusted Data Circulation; Data Value Realization

With the in-depth development of the digital economy, data, as a new type of production factor, is accelerating changes in the global economic structure and promoting high-quality development. The *Recommendations of the Central Committee of the Communist Party of China for Formulating the Fifteenth Five-Year Plan for National Economic and Social Development*[1] propose to "improve the foundational institutional system for data, facilitate the large-scale circulation of data resources, and accelerate the construction of a nationally integrated data market." The Third Plenary Session of the 20th CPC Central Committee pointed out the need to deepen the development and utilization of data resources and to develop new quality productive forces in line with local conditions. The state has successively issued policy documents such as the *Opinions on Accelerating the Development and Utilization of Public Data Resources*[2] and the *Action Plan for the Development of Trusted Data Spaces (2024–2028)*[3] (hereinafter referred to as the *Action Plan*), providing an institutional framework and implementation pathway for building a secure, trustworthy, efficient, and collaborative environment for data circulation. The *Action Plan* defines a trusted data space as "a data-circulation and utilization infrastructure based on consensual rules, linking multiple parties, and enabling the sharing and common use of data resources; it is an application ecosystem for the co-creation of value from data factors and also a key vehicle supporting the construction of a nationally integrated data market."

At present, the academic community has carried out multidimensional explorations around trusted data spaces, with research topics covering policy backgrounds[4], conceptual connotations[5], construction theories[6], institutional architectures[7][8], technical solutions[9], implementation paths[5]92, and application scenarios[10], among others. However, existing achievements mostly focus on local issues or a single perspective, and a systematic integration of the theoretical lineage and practical development of trusted data spaces has not yet been formed. To this end, this study adopts bibliometric methods to systematically sort out theoretical research and practical progress concerning trusted data spaces at home and abroad, clarifying their theoretical evolution, practical landscape, and future trends. The aim is to deepen theoretical understanding of trusted data spaces as a new type of data infrastructure, while also providing theoretical reference and practical inspiration for unleashing the value of digital resources held by public cultural institutions such as libraries and for serving the national strategy of transforming data into a production factor.

1 Data Sources and Thematic Analysis

This study used "data space" as the Chinese search term. In the CNKI, Wanfang, and VIP databases, the title was specified as the search field, and the literature sources were limited to CSSCI, Peking University Core, and CSCD journals, yielding 306, 353, and 136 documents, respectively. For the English-language search, "data space"was used as the keyword, and exact-match retrieval was conducted in the title field in databases including EBSCO, ScienceDirect, Springer, Taylor & Francis, Scopus, Wiley, and WoS, yielding 181, 89, 82, 5, 965, 22, and 354 documents, respectively. Subsequently, the initially retrieved literature was screened according to the following criteria: limited to Chinese- and English-language literature; duplicate records removed; full text ensured to be obtainable; irrelevant literature excluded on the basis of titles and abstracts; and literature whose content deviated from the research topic removed. After multiple rounds of screening, 253 valid documents were ultimately obtained. In addition, through retrieval in the National Library' s bibliographic collection system, six related books were obtained (four in Chinese and two in foreign languages), bringing a total of 259 documents into the subsequent analysis. VOSviewer software was used to conduct co-occurrence clustering analysis of the keywords in the above literature. Before analysis, foreign-language keywords were uniformly translated into Chinese; meaningless words were deleted; synonyms and near-synonyms were merged; and core terms such as "data space" and "trusted data space," which highly overlapped with the topic and occurred too frequently, were removed to avoid interfering with the clustering structure. The clustering threshold was set as keyword occurrence frequency $ $2, and a keyword co-occurrence network map was ultimately generated (see Figure 1).

Figure 1 Keyword map of trusted data spaces

The figure above shows that current research themes on trusted data spaces have formed six major clusters. The first cluster (purple) focuses on the connotative elements and functional characteristics of trusted data spaces; the second cluster (cyan) develops around their rule architecture, covering institutional issues such as governance mechanisms, allocation of rights and responsibilities, and compliance frameworks; the third cluster (blue) mainly reflects the technical system, including key technologies such as data interoperability, secure computing, and identity authentication; the fourth cluster (green) points to value objectives, emphasizing value co-creation, rights protection, and the public interest in the circulation of data elements; the fifth cluster (red) focuses on systematic governance and institutionalized practical exemplars, represented by the European Health Data Space (EHDS), reflecting benchmark explorations in which law, technology, and organization are advanced in coordination; the sixth cluster (yellow) emphasizes application implementation across multiple scenarios, covering fields such as industrial manufacturing, healthcare, cultural heritage, finance, agriculture, smart cities, and tourism, and attends to concrete implementation-level issues such as platform construction, embedding in business processes, and ecological collaboration. Details on the research themes, keywords and their frequencies, number of keywords, and total word frequencies contained in each cluster are provided in Table 1.

Overall, the first four clusters place greater emphasis on theoretical construction and institutional design, responding to scholarly questions such as "what is" a trusted data space, "why build it," and "what is it useful for" ; the latter two clusters focus on practical exploration and scenario implementation, answering real-world concerns such as "how to build it" and "where to use it," thereby presenting a pattern in which theoretical deepening and practical expansion advance in parallel.

Table 1 Keyword clusters for trusted data spaces

Cluster name	Research themes	Main keywords and their frequencies	Total frequency
Connotative elements and functional characteristics	Definition of connotation, key constituent elements, and core functional characteristics	data sharing (44), data elements (17), data sovereignty (15), data management (7), decentralized storage (2), and 16 keywords in total	112
Rule architecture	Policy basis, regulatory constraints, and standard-norm system	international data space (13), Industry 4.0 (8), GAIA-X (6), European Union (3), and 12 keywords in total	47
Technical system	Technical integration solutions supporting spatial operation, security controllability, and efficient collaboration	artificial intelligence (9), big data (5), blockchain (4), federated learning (4), cloud computing (2), and 15 keywords in total	81

Cluster name	Research themes	Main keywords and their frequencies	Total frequency
Value objectives	Core value positioning and goal orientation	data governance (21), ecosystem (15), value co-creation (3), sustainability (2), and 18 keywords in total	108
Practical exemplars	Represented by EHDS, systematic gov[[unclear: row continues below page]]	European Health Data Space (13), digital health (2), [[unclear: row continues below page]]	38
	Governance architecture and institutionalized practice	Health data (2), cross-border health care (2), and other 11 keywords	
Application scenarios	Exploration of applications in multiple fields, covering scenarios such as manufacturing, culture, agriculture, and smart cities	Manufacturing (5), smart cities (3), cultural-heritage data spaces (2), agriculture (2), and other 14 keywords	33

2 The Theoretical Evolution of Trusted Data Spaces

2.1 Connotative Elements and Functional Characteristics

2.1.1 Evolution of Connotation Existing research shows that a trusted data space is a complex open system composed of multiple elements and multiple actors. Unlike traditional modes of data exchange, it embeds trust mechanisms into the process of data circulation, thereby realizing a transformation from "interconnection and interoperability" to "trusted circulation" [11]. From the perspective of systems theory, this transformation does not depend on a single factor; rather, in a multi-actor environment it must simultaneously respond to several interrelated core issues, including the compliance boundaries and delineation of rights and responsibilities in data circulation, security and controllability during circulation, value realization in applications, and the mechanism for sustained operation under cross-actor collaboration[12]. This gives rise to the logical structure of "boundaries of rights and responsibilities—security and controllability—application value—cross-actor collaboration." On this basis, this study respectively maps these four core issues onto four interrelated dimensions —institutional governance, technological implementation, social application, and ecosystem collaboration—and, accordingly, analyzes the connotation of trusted data spaces (see Figure 2).

Text in Figure 2

- **Institutional governance perspective**: Establishing a trustworthy rule system and collaborative governance mechanism
- **Technological implementation perspective**: Decentralized, standardized trusted technical framework
- **Social application perspective**: A socio-technical field that evolves dynamically with application scenarios
- **Ecosystem collaboration perspective**: A data ecosystem or value co-creation platform connecting multiple participants
- **Center**: Connotation of trusted data spaces
- **Links and directions**:
  - Trustworthy, compliant, and sustainable
  - Secure and reliable data circulation
  - Multi-actor innovation and value release
  - Ecological feedback governance framework
- **Bottom sequence**: Build a trustworthy framework → Ensure trusted security → Release data value → Shape the future landscape

Figure 2 Evolution of the Connotation of Trusted Data Spaces

(1) Institutional governance: building a trustworthy framework

From the perspective of institutional governance, a trusted data space is viewed as a systematic governance methodology[13], the core of which is to rely on a rule system to form a collaborative governance mechanism. This perspective emphasizes that data spaces need to organically integrate consensus rules, allocation of rights and responsibilities, and value co-creation mechanisms, so as to systematically resolve the "trust—security—value" ternary paradox in data circulation[11]7. Specifically, its institutional architecture covers a system of trustworthy rules throughout the entire data life cycle[6]128, and relies on "balance, accountability, security, interoperability, and controllability" (the BASIC principles) to construct an institutional supply framework[14]. The European Union and international practice generally recognize that a trusted data space is, in essence, a governance assemblage based on common policies, standards, and rules[15][16]. It can thus be seen that a trusted data space is not a purely technical product, but a composite of co-governance between technology and institutions; its institutional dimension provides guarantees of legality, compliance, and sustainability for technological applications[17].

(2) Technological implementation: ensuring security and trustworthiness

The technological implementation perspective focuses on the underlying architecture for trusted data circulation. Early studies defined a data space as a complete collection of information surrounding a specific subject (such as an enterprise or individual), aiming to break through the constraints of data formats and storage locations and improve the efficiency of access to heterogeneous data[18]. It is characterized by "on-demand integration and value orientation" [19][20]. As awareness of data sovereignty has strengthened, its technological connotation has gradually evolved into decentralized, standardized trusted technical infrastructure. Its core objective is, while retaining data control rights, to support secure cross-domain invocation through unified protocols and realize efficient and reliable data interaction among multiple actors[21]. At the same time, this frame—

The architecture must be capable of dynamically processing heterogeneous data and support the real-time integration and management of both structured and unstructured data[22]. Therefore, from the technical dimension, a trusted data space is a distributed system that integrates trusted technologies such as privacy computing, identity authentication, and interoperable interfaces, providing underlying support for the secure, controllable, and efficient circulation of data[23][24].

(3) Social application: releasing data value

From the perspective of social application, a trusted data space is understood as a "socio-technical" field rooted in industrial practice and dynamically evolving with scenarios; in essence, it is a highly contextualized practical product that cannot be fully preset[25]. This perspective emphasizes that a data space is a new type of infrastructure guided by consensus rules, centered on multiple participants, based on data resources, guaranteed by key technologies, and aimed at scenario applications[26]. Its formation has a clear demand-driven character—originating from the practical needs of enterprises, public institutions, and other diverse actors to actively build systems for integrating multi-source data and supporting data-driven decision-making[4]8. Particularly crucial is that its openness and inclusiveness enable participants of different roles, types, and scales to access it on an equal footing and carry out data exchange[27], thereby making it an open platform that empowers industrial innovation and social development.

(4) Ecosystem collaboration: shaping the future landscape

From the perspective of ecosystem collaboration, the trusted data space is elevated to the level of a data ecosystem or a value co-creation platform[28][29], with its connotation shifting from promoting data flow to supporting collaborative value creation and sustained value enhancement[30]. This perspective argues that, by building standardized resource catalogs, cross-space mutual recognition mechanisms, and frameworks for allocating rights and interests in data products, a symbiotic system of resource sharing, shared services, and collaborative innovation can be formed[31]. Some studies define it as a "collaborative alliance composed of multiple legally autonomous entities," that is, a new type of meta-organization[32]. Under this framework, the data space is not merely an exchange channel, but also an ecosystem-based operational carrier that supports the assetization, servitization, and even financialization of data, ultimately realizing value co-creation among multiple parties[33][34].

2.1.2 Key constituent elements

The key constituent elements of a trusted data space include governance elements, technical elements, trust elements, and value elements[11]3. Among them, governance elements ensure the orderly, compliant, and sustainable development of the data space and provide stable institutional expectations for data sharing. The data rights of all participating parties should be smoothly exchanged through governance mechanisms; these mechanisms need to be established on a fair, open, compliant, and lawful basis rather than on compulsory requirements[27]24. Technical elements are the concrete tools and infrastructure that put governance rules into practice, ensuring the security, controllability, and usability of data throughout its circulation and achieving the goal that "data are usable but not visible" [35]. Trust elements are the safeguard that connects all participating parties and reduces transaction costs; they are the intuitive embodiment of the "trustworthiness" of the data space. By consolidating the foundation of trust, improving trust elements, and expanding trust scenarios, a trusted data space can create a secure and controllable data ecosystem[36]. Value elements, in turn, focus on answering the question of "why participate," ensuring that the data space has sustainable internal momentum. Data value co-creation is manifested as process collaboration, subject collaboration, and value collaboration, thereby promoting cooperative innovation among different stakeholders[28]44.

2.1.3 Core functional characteristics

A trusted data space has three core capabilities: trusted governance and control, resource interaction, and value co-creation[37]. These three are mutually interconnected and mutually reinforcing, forming a dynamically collaborative system, as shown in Figure 3. First, trusted governance and control are what distinguish data spaces from traditional data-sharing models. Relying on an integrated "institution–mechanism–technology" architecture, the data space ensures the security and compliance of multiple actors in the process of data sharing and circulation by constructing a trusted execution environment[38]. Second, the trusted architecture of a data space can realize the interconnection and interoperability of data resources. Through unified release of data resources and efficient interaction models, it enables diverse actors to participate in resource sharing and obtain data services[31]82. Among these, interoperability is an important support for realizing large-scale data circulation, and is mainly achieved through such means as semantic-level unification[39], the formulation of data governance frameworks[40], and the definition of data models[41]. Finally, value co-creation capability is the sustained driving force for the development of a trusted data space. By providing all participants with a fair environment for co-creating data value, it constructs a new ecosystem for data circulation[37]16. In addition, value co-creation is not only a core function of the data space but also its development goal; it guides the data space in evolving from a simple data-exchange facility into a value ecosystem that supports multi-party collaborative innovation[28]44.

Visible labels in Figure 3: Core functions of a trusted data space; trusted management and control; resource interaction; value co-creation; institution; mechanism; technology; data; sharing; service; release; fairness; ecosystem; safety and compliance; collaborative innovation; feedback; guarantee; support; endogenous; data-product ecosystem; trusted execution environment; data circulation and utilization; multi-subject participation; reliance; orientation.

Figure 3 Core Functions of a Trusted Data Space

In summary, as a key infrastructure in the process of data factorization, the trusted data space has evolved in connotation from an early instrumental concept emphasizing technical implementation into a comprehensive system integrating institutional rules, technical architecture, application scenarios, and ecosystem collaboration. Existing studies have defined its connotation from different perspectives and explored its constituent elements and core functions. However, these studies mostly focus on single dimensions, and still lack systematic integration of the internal connections among dimensions, interaction mechanisms, and their collaborative roles in practice. In the future, it will be necessary to strengthen the integration of interdisciplinary perspectives and to conduct in-depth analysis of how institutional arrangements support technological applications, how technological capabilities adapt to scenario needs, and how scenario practices drive ecosystem evolution, so as to understand more comprehensively the operational logic and development patterns of trusted data spaces.

2.2 Rules Framework

The institutional guarantee system for trusted data spaces has gradually moved from early conceptual exploration toward systematic rule construction. Its core lies in providing institutional support for the secure, trustworthy, and efficient circulation of data through hierarchical policies and regulations as well as collaborative governance frameworks.

Internationally, Germany has a first-mover advantage in the institutional construction of trusted data spaces. Since launching the national-level "Industrial Data Space" research project in 2015, Germany established the Industrial Data Space Association (IDSA) in 2016 and released the IDS reference architecture model. In 2018, the association was upgraded into an international organization, marking its shift from a national initiative to a global standards setter. In 2022, it launched IDS 4.0, further improving the integrated "technology–governance" framework[42]. The European Union followed closely, building a personal-data-protection legal system with the *General Data Protection Regulation* (GDPR) as its cornerstone[43]. It subsequently proposed, in the *European Data Strategy*, the construction of "European common data spaces" covering nine major fields such as industry, green development, and transport[44], and established three major goals: promoting the free flow of data, upholding European values, and establishing fair and practical rules for data use. Thereafter, the *Data Governance Act*[45] and the *Data Act*[46] refined institutional arrangements for data sharing and circulation from dimensions such as public-data reuse and inter-enterprise data access rights. On this basis, the EU has focused on constructing a "legislative framework for European common data-space governance," covering key issues such as data sovereignty, security, trust, and transactions[47]. Legislation in specific sectors has also advanced in parallel: the *European Health Data Space* (EHDS) provides a paradigm for vertical industry governance[48], while horizontal legislation such as the *Artificial Intelligence Act* collaboratively strengthens the overall digital regulatory ecosystem. In addition, practice projects such as Gaia-X translate institutional requirements into operable technical standards and compliance guidelines[49], promoting the implementation of rules. Countries such as Singapore and Japan have also successively introduced relevant policies, providing regional institutional guarantees for trusted data flows[50].

Domestically, the institutional construction of trusted data spaces displays the salient characteristics of "high-level promotion, rapid iteration, and pilots first," advancing rapidly from macro-level strategy toward industry and regional practice. With the "Twenty Data Measures" as the top-level design, China has established a new model of rights attribution and benefit distribution for non-public data featuring "joint use and shared benefits"[51]. At the end of 2023, the National Data Administration, together with sixteen other departments, issued the "*Data Element ×*" *Three-Year Action Plan* (*2024–2026*), explicitly incorporating trusted data spaces into the national data-infrastructure system[52]. More landmark still, in 2024, seventeen departments including the National Data Administration released the *Action Plan*, systematically planning the development paths of five types of spaces—enterprise, industry, city, individual, and cross-border—and [[unclear: text continues after the visible character "标"]].

This marked the formal shift in the focus of data-space construction from conceptual exploration to large-scale implementation[53][50][61]. As an important lever, the National Data Administration has continued to promote a multilevel pilot layout; meanwhile, some regions have carried out differentiated explorations around specific application scenarios, gradually forming representative practical models[54].

In terms of localization research, scholars have begun to focus on the problem of adapting international experience to China, mainly along two dimensions. First is macro-level policy planning, including the domestic applicability and transformation schemes of policy frameworks such as data-governance policy and regulatory systems[4][11], data-sharing models[55], and EU data-space policies[47][85]. The aim is to form a data-ecosystem pathway that both absorbs international experience and is rooted in China' s governance logic and social needs. Second is micro-level scenario application. Existing studies have gone deep into specific fields of practice, exploring the application of and challenges for European experience in data spaces with different attributes, such as health[56], finance[57], archives[58], and culture[59], with the goal of promoting the efficient circulation of data across fields in China under the premise of trustworthiness and controllability.

Overall, existing research has provided theoretical support for the localized exploration of trusted data spaces from the two levels of macro-level policy adaptation and micro-level scenario application. However, most findings still focus mainly on interpreting policy texts and comparing international models. There remains a lack of in-depth empirical analysis and systematic discussion of issues such as the actual operational effectiveness of local practices, cross-domain coordination mechanisms, and the adaptability and sustainability of institutional rules over long-term evolution. Future research should combine the outcomes of pilot practices, strengthen tracking and evaluation of the effectiveness of rule implementation, and promote the theoretical deepening of institutional rules from "reference and transplantation" toward "endogenous innovation."

2.3 Technical System

For trusted data spaces to move from theory to practice, they must be supported by a complex and coordinated technical system. Its core mission is to realize the trusted circulation of data while safeguarding data sovereignty and privacy security. Literature analysis shows that the core technical system of data spaces can be summarized into three progressively layered and mutually coordinated levels: the infrastructure layer, the security and trust layer, and the data-understanding layer, as shown in Figure 4.

Data-understanding layer
- Semantic-level interoperability
- Collaboration of heterogeneous cross-source data

Security and trust layer
- Ensuring privacy and security
- Regulating the behavior of all parties

Infrastructure layer
- Building the connection framework
- Safeguarding data sovereignty

Right-side progression: **Laying the foundation → Secure circulation → Enabling interaction**

Figure 4. Technical system of trusted data spaces

The infrastructure layer lays the physical and logical foundation of the data space. It mainly addresses the question of "how to achieve secure connection and trusted exchange," with the core goal of building a decentralized and interoperable connection framework and safeguarding data sovereignty at the system-design level. To achieve this goal, it mainly relies on several key components and technologies. For example, the IDS connector, as a core component in the International Data Spaces architecture, is essentially a gateway that connects existing systems and data into the IDS ecosystem, and is responsible for identity authentication, access control, and secure data exchange[60]. Blockchain technology and smart contracts, by virtue of their tamper-proof and automated-execution characteristics, provide an auditable and traceable trust cornerstone for data circulation throughout the entire process[61][62]. Digital identity authentication technology enables trusted identification of participating entities, thereby precisely defining the boundaries of the rights and responsibilities of all parties[63].

On top of reliable connection, the security and trust layer focuses on safeguarding privacy and security issues during data circulation and use, and serves as the core support for constructing a trusted environment. The technologies at this layer take privacy-preserving computation as their core idea[64]: that is, they enable collaborative computation and value mining of data without disclosing raw data, ensuring that the privacy of all parties in the data space is not leaked while also regulating participant behavior. In terms of implementation pathways, federated learning supports multiple parties in collaborative modeling without sharing raw data, realizing "value sharing rather than data sharing" [65][66]. Secure multi-party computation allows joint analysis to be performed directly on data in an encrypted state, ensuring the privacy of the computation process[67]. In addition, the zero-trust model emphasizes the security concept of "trust no one by default and verify continuously," transforming traditional static perimeter defense into dynamic authentication and authorization checks for every access request[68]. Data sandboxes, by providing

an isolated computing environment, providing a practical solution of "usable but not visible" for the analysis of sensitive data[35]22.

The data-understanding layer aims to solve problems of data-semantic interoperability across subjects and systems, so as to realize semantic-level interoperability and intelligent integration of heterogeneous data. With only physical connectivity and security safeguards, but without unified semantic understanding, data remain "information islands." This layer mainly reduces the integration complexity of multi-source heterogeneous data by constructing standardized data models and unified data descriptions and interaction specifications[69]; it uses semantic models such as ontologies to endow data with explicit meanings, thereby enhancing machines' ability to understand and reason about data[70]; and it employs data-catalog technologies to catalogue and manage distributed and fragmented data assets, improving data discoverability, understandability, and usability[71].

In addition to the above layered system, technological integration is an important driver of the development of data spaces. For example, the combination of retrieval-augmented generation (RAG) and large language models uses trusted data spaces as high-quality and trustworthy external knowledge sources, improving the accuracy and reliability of content generated by large models[72][73]; the development of natural-language interfaces allows users to interact with data spaces in a more intuitive and natural manner, greatly lowering the threshold for use and improving the usability of data spaces[74].

Although existing studies have preliminarily constructed technical frameworks for trusted data spaces, most results focus on the functional realization of individual technologies, paying relatively little attention to their coordinated adaptation with laws and regulations, industry standards, organizational processes, and business needs. This has led to a separation between technical feasibility and practical feasibility. For example, although privacy computing supports "usable but not visible," its cost, efficiency, and compliance boundaries need to be adapted in light of specific industry rules; the interoperability of IDS connectors depends on governance consensus across organizations. Future research should promote the deep integration of technical systems with institutional arrangements and application scenarios, gradually form a technical reference architecture that balances security, efficiency, and operability, and provide unified interface specifications and implementation guidelines to support scaled application.

2.4 Value Objectives

Academic discussions of the value objectives of trusted data spaces can be summarized into the following three interrelated dimensions:

First is the release of data value. The *Action Plan* points out that the core mission of trusted data spaces lies in fully releasing the value of data elements. By constructing a secure, trustworthy, and clearly regulated circulation environment, they can effectively break the "data island" predicament caused in traditional models by unclear ownership, lack of trust, and technical barriers[75]. Existing studies have explored this issue across multiple domains: in the field of public culture, they focus on value activation of archival data elements[76] and trusted utilization pathways for libraries' digital special-collection resources[77]; in vertical industries, they analyze the key mechanisms for transforming data elements in the European health data space[56]3; and from the perspective of educational scenarios, they examine in detail the realization logic and institutional adaptation issues involved in the circulation of educational data elements[75]39.

Second is the co-creation of data value. Its essence is to rely on a quantifiable and verifiable governance framework to systematize and institutionalize the innovative behaviors of multiple subjects, thereby forming a sustainable positive incentive mechanism[31]83. At the national strategic level, trusted data spaces rely on institutional and technological collaborative architectures to promote deep cooperation among multiple subjects, including governments, enterprises, and research institutions, thus providing foundational support for enhancing national digital-innovation capacity and optimizing the allocation of key resources[31]83. In the field of public cultural services, this is manifested in the horizontal collaboration of libraries, archives, museums, and other institutions to integrate and activate public digital resources and improve the effectiveness of public cultural services[78]. In the field of industrial development, it is embodied in the secure and efficient exchange of data through data spaces across industrial chains such as industry and agriculture, driving process optimization and efficiency improvement[79].

Third is the construction of a data ecosystem. This dimension does not exist in isolation; rather, it is the result of the continuous deepening of data-value release and value co-creation. Data-value release enables originally scattered and closed data resources to enter a trusted circulation system, while data-value co-creation further promotes collaborative innovation among different subjects around data sharing[80]. On this basis, data spaces not only realize the interconnection and interoperability of data resources, but also promote deep coupling among data, technologies, scenarios, and services, driving the evolution of data elements from a single-resource form toward a networked ecosystem form[81]. Unlike the traditional platform-centered model of data organization, trusted data spaces place greater emphasis on building an open data network by relying on unified rules, standards systems, and trust mechanisms. By reshaping the modes of data connection and value relationships among subjects, they promote the formation of a more stable data-cooperation system among governments, enterprises, research institutions, social organizations, and other participating subjects under shared rules, and further construct an open, shared, and continuously evolving data ecosystem[82]. The formation of this ecosystem helps improve resource-allocation efficiency and data-circulation capacity, facilitates the continuous circulation of data, technologies, and application scenarios, and thereby provides sustained support for industrial collaboration, optimization of public services, and social innovation.

At present, related research has been carried out in fields such as culture, industry, and medicine, but much of it remains at the level of conceptual interpretation or ideal architectural design. There remains insufficient research on formation mechanisms, coordination of stakeholder interests, and the evolution of governance rules, and there is a lack of case-

case analyses and long-term tracking observations, making it difficult to reveal the driving forces and constraining factors in the ecological evolution of data spaces.

Overall, existing research has embedded the value objectives of trusted data spaces into diverse scenarios such as public culture, industrial development, and national strategies, achieving an initial connection between concept and practice. However, systematic empirical testing remains lacking with respect to the dynamic mechanisms of the value-realization process, the logic of interaction among actors, and its actual effects. In the future, it will be necessary to construct a value-evaluation indicator system that combines domain adaptability, measurability, and cross-scenario comparability, and to conduct continuous observations in conjunction with typical pilots, thereby providing a scientific basis for assessing the effectiveness of data-space construction.

3 Practical Prospects of Trusted Data Spaces

3.1 Practical Examples

The EU data space, through the coordinated advancement of "technical governance and legal rules," has become a benchmark paradigm for global data governance[83]. As an important component of it, the European Health Data Space (EHDS) has received extensive attention and study from the academic community. The *European Health Data Space Regulation* was first proposed by the European Commission in 2022 and was formally signed into law in March 2025. It aims to simplify the secondary use of health data, promote data access and exchange, and establish a health-data infrastructure with both technical and legal interoperability[84].

Existing research mainly focuses on the system architecture of the EHDS, which can be summarized in the following three aspects. First is the core architecture. The EHDS proposal contains 76 articles and is mainly centered on two major pillars. The first pillar focuses on regulating the use of primary health data, the design and development of electronic health registries, the interoperability of electronic health-record systems in EU Member States, and application rules; the second pillar establishes, for the first time at the EU level, a legal framework for the secondary use of health data[85]. This architecture will provide an environment integrating the storage, management, and operation of health data, so as to overcome challenges such as limited data interoperability, fragmentation of rules for accessing research data, and restricted control over personal health data[86]. Second are the key rules. Through the EHDS, the European Commission establishes a data-governance regime that, on the one hand, provides a legal basis for the collection and processing of electronic health data as an alternative to traditional individual consent. On the other hand, it clarifies requirements for interoperability and security, paving the way for the cross-border construction of health-data infrastructure[85]347. Specifically, the EHDS not only defines the scope of health data available for secondary use[86]944 and the groups of people qualified to use it[87], but also introduces health-data access bodies to facilitate the aggregation and management of access to electronic health data used for secondary purposes[84]2. Third is technical support. The operation of the EHDS relies on the coordinated support of three types of components: technologies, tools, and standards. Technological components include privacy-preserving computation and blockchain-based evidence storage; tool components include connectors and clearing centers; and standard components include EHRX standards and cross-platform data-interaction protocols. Together, these three constitute the technical foundation for EHDS operation.

Academic research on the EHDS exhibits methodological diversity and can be summarized into two categories: first, comparative-law and policy-text analysis, which systematically analyzes the *European Health Data Space Regulation*[56]3 to reveal its operating mechanisms and existing problems; second, empirical research, specifically including: using focus groups combined with thematic analysis to propose guiding health-policy strategies[88]; using semi-structured interviews to explore the risks, challenges, and gaps faced in implementing privacy-enhancing technologies in the EHDS[64]1; and case analysis, taking xR games as a use case to analyze how the purpose-limitation principle of the *General Data Protection Regulation* affects the framework for the secondary use of electronic health data[89]. Given that the EHDS involves multiple dimensions such as legal regulation, technical implementation, economic incentives, and ethical constraints, future research needs to adopt interdisciplinary mixed research methods to systematically respond to the compound governance challenges it faces in institutional design, technological implementation, and social acceptance.

Compared with international practical exploration, the construction of trusted data spaces in China is also accelerating under policy impetus. The National Data Administration has organized pilot work for three types of trusted data spaces—enterprise, industry, and city. The first batch selected 63 pilot projects, covering 13 cities including Nanjing and Ningbo, 22 industry entities including China Southern Power Grid, and 28 enterprises including China Post Group[54], forming a multi-level, multi-actor pattern of coordinated advancement. Different regions have formed differentiated development paths based on their own resources and industrial foundations. For example, city-level exploration represented by the "Jinan model" emphasizes the coordinated advancement of infrastructure construction and institutional mechanisms[90]. Relying on a "4+N" system architecture, it takes as its core supports an infrastructure base, a central control and management platform, a data-factor development and utilization system, and a system of standards, norms, rules, and mechanisms; combined with diverse application scenarios, it constructs an open, jointly built and shared regional infrastructure for data circulation and utilization. At the same time, Jinan has continuously improved mechanisms for protecting data rights and interests and distributing benefits, promoted the coordinated implementation of market-oriented allocation reform of data factors and the "Data Factors ×" initiative, and formed a data ecosystem that balances security and trustworthiness, circulation efficiency, and value release, thereby providing a representative practical pathway for the construction of urban trusted data spaces. By comparison, with "South

The pilot projects represented by the "Beijing model" place greater emphasis on government–enterprise collaboration and scenario traction. By building an integrated development model of "public data + enterprise data," they explore data-circulation pathways involving government–enterprise connectivity, enterprise collaboration, and cross-domain linkage[91]. Nanjing relies on the construction of "chain-owner" enterprises and industry-specific zones to promote deep coupling among public data, enterprise data, and application scenarios. In areas such as financial services, scientific and technological innovation, and artificial intelligence, it has formed mechanisms for co-creating data value, building a data-circulation ecosystem that has both market-oriented operational capacity and the capacity for sustainable value release, and demonstrating the development feature of using scenarios to drive the transformation of data value.

3.2 Application Scenarios

At present, trusted data spaces are moving from conceptual exploration toward large-scale practice across multiple fields and levels, showing a developmental trend of continuous evolution from pilot verification to systematic implementation. The *Data Spaces Radar (Version 4)* report released by the International Data Spaces Association (IDSA) divides the development of trusted data spaces into five stages: exploration, preparation, implementation, operation, and scaling. Judging from the industry distribution and development stages of the cases it has collected, relatively many data-space practices in the implementation and operation stages have appeared in fields such as industrial manufacturing, logistics supply chains, mobile travel, and energy, whereas related cases in fields such as agriculture and cultural heritage are relatively few, and overall they remain mainly in the exploration or preparation stages[92]. From the distribution of application scenarios, existing trusted data-space practices are mainly concentrated in data-intensive fields such as industrial manufacturing and medical health. The former focuses on industrial-chain collaboration, equipment interconnection, industrial data sharing, and digitalized production; the latter focuses on scenarios such as medical-data sharing, cross-institutional collaboration, and privacy protection. In addition, exploration in fields such as smart cities, public services, and finance is also continuing to expand, promoting trusted data spaces toward cross-domain and multi-actor collaboration. The specific scenario distribution is shown in Table 2.

Table 2 Distribution of Application Scenarios of Trusted Data Spaces

Application field	Typical scenarios
Industrial manufacturing	Automotive supply chains, semiconductor manufacturing, process industries, predictive maintenance, industrial Internet, etc.
Medical health	Clinical research, hospital data platforms, cross-border healthcare, patient privacy protection, etc.
Culture and heritage	Digitalization of cultural heritage, digital protection of cultural resources, archives management, sharing of library resources, etc.
Smart cities / government affairs	Urban governance, intelligent transportation, sharing of government-affairs data, opening of public data, public-service collaboration, etc.
Agriculture	Agricultural data sharing, new-quality productive forces in agriculture, smart agriculture, etc.
Finance	Data assetization, open banking, risk control, credit evaluation, etc.
Tourism	Optimization of visitor experience, destination management, tourism data sharing, smart tourism, etc.
Science	Scientific data sharing, etc.
Military	Military data integration, intelligence collaboration, etc.
Other	Personal data circulation, enterprise data-asset management, etc.

In the field of industrial manufacturing, relevant practices of trusted data spaces are relatively concentrated. Application scenarios already cover complex value-chain links such as automotive supply chains[32], intelligent manufacturing[93], and semiconductor manufacturing[94]. Their core objective is to achieve predictive maintenance, supply-chain transparency, and production-process optimization through secure and controllable data sharing, thereby significantly improving the efficiency and resilience of industrial collaboration. Relatively rich practical explorations have also emerged in the field of medical health. Their applications place strong emphasis on data security and compliance, focusing on key scenarios such as clinical research[68] 71, hospital data-platform construction, cross-border medical collaboration, and secondary use of health data[95]. These practices aim, under the premise of strictly safeguarding patient privacy and data sovereignty, to promote the sharing and use of medical data in scientific-research innovation, public-health governance, and precision medicine.

The field of culture and heritage emphasizes the digital governance and open sharing of public cultural resources. Related practices involve the digitalization of cultural heritage[96], innovation in archives-management mechanisms[58] 41, and cross-institutional collaborative use of library collections[97]. Such explorations are intended to build infrastructure that supports the permanent preservation, activated use, and public accessibility of cultural resources. Overall, however, they remain at an early conceptualization stage and have not yet formed scaled application models. Practices in the agricultural field focus on solving the problem of fragmented agricultural-production data[98]. By building trusted sharing mechanisms, they promote the integration of multi-source data such as agricultural conditions, production and sales, and the environment, providing data support for developing new-quality productive forces in agriculture and serving the rural-revitalization strategy[99]. The financial field is actively exploring pathways for marketizing data elements. Application scenarios are concentrated in data assetization[13] 4, open banking[100], joint risk control, and intelligent credit assessment[66] 54, seeking to release the financial value of data as a new type of production factor in a trusted environment.

In addition, in subfields such as tourism[101], scientific research[102], and the military[103], trusted data spaces demonstrate cross-subject···

the capacity for data collaboration and resource integration. By breaking down inter-institutional "data islands," it supports collaborative innovation and decision optimization, demonstrating its broad application potential as a general-purpose data infrastructure.

Although trusted data spaces have already taken shape in preliminary practice across multiple fields, most applications still remain at the level of case description or functional demonstration. Systematic assessment of actual application outcomes, governance mechanisms, and long-term operating models remains relatively insufficient. In the future, it will be necessary to establish a quantifiable and comparable benefit-evaluation system, distill common cross-domain needs and differentiated constraints, and form reusable implementation methods. At the same time, attention should be paid to the impact of institutional adaptation and organizational change on technology implementation, so as to promote the deepening of trusted data spaces from "technically usable" to "willingly used by business" and "usable within the ecosystem," thereby supporting their sustainable development and large-scale promotion.

4 Future Pathways for Trusted Data Spaces

The preceding discussion systematically reviewed trusted data spaces from two levels: theoretical evolution and practical landscapes. The theoretical-evolution part focused on connotative elements and functional characteristics, rule architecture, technical systems, and value objectives, with an emphasis on answering the fundamental theoretical question of "what they are." The practical-landscape part focused on typical practice examples and diversified application scenarios, responding to the practical concern of "how they are applied." Overall, current research shows a development trend in which theoretical construction is continuously deepening and practical exploration is steadily expanding. However, as revealed in Sections 2.1 to 3.2, existing research still has certain weaknesses: at the level of connotative dimensions, the internal connections and coordination mechanisms among various elements lack systematic integration; in terms of rule architecture, there remains a lack of empirical analysis of the operational effects of local practice and cross-domain coordination mechanisms; in the technical system, coordination and adaptation among technologies, laws and regulations, standards, and business needs are insufficient; in value objectives, the dynamic mechanisms of value realization and quantitative evaluation systems have not yet been established; in practice examples, the refinement of China' s local models and cross-national comparative research need to be strengthened; and in application scenarios, especially in the field of public cultural institutions, data circulation still faces practical obstacles and lacks systematic evaluation. Accordingly, the following section proposes prospects for subsequent research and practice from the above six dimensions.

First is the integrated deepening of connotative elements and functional characteristics. As stated in Section 2.1, existing studies mostly define trusted data spaces from a single dimension, lacking systematic integration of the interaction mechanisms and co-evolution among institutions, technologies, applications, and ecosystems. Future work should move beyond a separated perspective and explore the internal connections and dynamic logic of these four dimensions. At the same time, it is necessary to further clarify the type attribution, ownership relations, and value forms of data elements in specific fields. For example, medical clinical data, industrial equipment data, and digital collections of cultural institutions differ in sensitivity, purpose of use, and applicable rules. Future research should be grounded in specific fields and construct classification systems for data elements and pathways for value release: in the healthcare field, clarifying the boundaries for secondary use of anonymized data; in the industrial field, defining the attribution of control rights and sharing rules for equipment data; and in the cultural field, formulating tiered opening strategies for special-collection resources, so that the theoretical system better fits practical needs.

Second is the localization of rule architecture and collaborative governance. Section 2.2 points out that current research largely remains at the level of policy interpretation and international comparison of models such as the EU' s IDS and EHDS, while lacking in-depth empirical analysis of the actual operational effects of China' s local practices, cross-domain coordination mechanisms, and the adaptability of long-term institutional evolution. Future research should focus on promoting the localization of rule systems. On the one hand, it should strengthen continuous tracking of the practical construction of the 63 first-batch national pilot projects, analyzing coordination mechanisms, interest balancing, and governance obstacles in the operation of rules. On the other hand, it should explore data-circulation rule systems applicable to different levels and fields, such as enterprises, industries, and cities, gradually forming an institutional framework that both absorbs international experience and is rooted in China' s governance logic.

Third is the evaluation of technical-system effects and scenario adaptation. Section 2.3 points out that most studies focus on the functional realization of individual technologies, while paying less attention to their coordinated adaptation with laws and regulations, industry standards, organizational processes, and business needs, resulting in a separation between technical feasibility and practical feasibility. Future research should place greater emphasis on the operational performance of technologies in real business scenarios. For example, in industrial supply-chain pilots, it should evaluate the improvement effect and computational overhead of federated learning on the accuracy of predictive-maintenance models; in medical data platforms, it should test the actual impact of privacy-preserving computing solutions on clinical research efficiency; and in cultural institutions, it should verify the deployment costs and operation-and-maintenance difficulty of lightweight connectors. Through such scenario-based evaluations, technical implementation specifications that balance security, efficiency, and ease of use can gradually be formed, providing a basis for different industries to choose appropriate technical pathways.

Fourth is the quantitative evaluation of value objectives and research on mechanisms. Section 2.4 points out that existing research lacks systematic empirical testing of the dynamic mechanisms of the value-realization process, the interaction logic among subjects, and their actual effects. It is therefore necessary to build a value-evaluation indicator system that has both domain adaptability and cross-scenario comparability. Future research should comprehensively evaluate the construction effects of trusted data spaces from multiple dimensions, including the effect of data-value release, the degree of subject collaboration, innovation outputs, and public-service effectiveness. At the same time, attention should also be paid to value-allocation mechanisms and issues of ecosystem sustainability, and long-term collaborative relationships among different institutions and users should be explored, so as to support the trusted data space' s 可

provide theoretical support for sustained operation.

Fifth, empirical tracking of practical cases and methodological expansion. Section 3.1, taking EHDS as an example, presents the institutional framework of an international model and introduces preliminary experience from city-level pilot projects in China, such as Jinan and Nanjing; however, in-depth investigation of the operating mechanisms of local practice remains insufficient. Future research should be integrated with the national data-space pilot program and adopt qualitative methods such as case studies, participatory observation, and semi-structured interviews to continuously track the construction processes of data spaces in different domains and systematically identify the actual conditions and core demands of various actors. By selecting typical pilot units, collecting first-hand materials on data management, technological deployment, and willingness to collaborate, and incorporating the usage experience of end users such as physicians, researchers, and corporate managers into the analytical framework, the practical explanatory power of the research can be strengthened.

Sixth, hierarchical adaptation of application scenarios and deeper advancement in the public-cultural sector. Section 3.2 points out that most current applications still remain at the level of case description or functional demonstration, while systematic evaluation of actual application effects, governance mechanisms, and long-term operating models is relatively inadequate. In particular, although public cultural institutions such as libraries, archives, and museums possess abundant digital resources, they face real obstacles in funding, technology, and talent[104]. Different fields (such as libraries and archives) and different types of institutions within the same field (such as university libraries and public libraries) differ significantly in data scale, technical capacity, and business objectives. Future research should pay further attention to industry adaptability, and explore hierarchical and categorized construction models. In particular, it may focus on such directions as cross-institutional resource sharing, support for digital humanities research, and the open use of cultural data, so as to promote the in-depth application of trusted data spaces in the public-cultural domain and gradually remove barriers to data circulation.

It should be noted that this study also has certain limitations. First, this study is mainly based on bibliometric analysis and lacks first-hand investigation and data support regarding the construction practices of trusted data spaces; thus, it is difficult to reveal in depth the real conditions and intrinsic mechanisms of different fields in terms of rule-based operation, technological implementation, and value realization. Second, the study focuses on theoretical clarification and framework summarization at the macro level, and has not yet conducted systematic empirical testing of the operating mechanisms, actual effects, and influencing factors of trusted data spaces in different domains. In the future, specific application scenarios will be combined with case tracking, field investigation, questionnaire surveys, and quantitative evaluation, so as to strengthen in-depth examination of the first batch of 63 national pilot projects and cross-case comparison, thereby enhancing the theoretical explanatory power and practical guidance value of the research.

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Author contribution statement:

Fang Xiangming: topic selection, conceptual framework, and writing and revision of the paper;

Wang Minran: data collection and paper writing;

Tang Feng: data organization and manuscript revision.

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