applied sciences

MDPI

Review

Data Spaces in Manufacturing and Supply Chains: A Review and Insights from European Initiatives

Matteo Gabellini *, Lorenzo Civolani, Michele Ronchi, Ludovica Diletta Naldi and Alberto Regattieri

Department of Industrial Engineering, University of Bologna, Viale del Risorgimento 4, 61121 Bologna, Italy;
lorenzo.civolani@unibo.it (L.C.); michele.ronchi8@unibo.it (M.R.); ludovica.naldi2@unibo.it (L.D.N.);
alberto.regattieri@unibo.it (A.R.)
* Correspondence: matteo.gabellini5@unibo.it

Abstract: Data spaces are increasingly recognized as a key enabler of secure, sovereign, and interoperable data exchange across manufacturing and supply chain networks. Despite growing institutional interest in Europe, academic research on this topic lacks a consolidated perspective. This study addresses this gap by combining a systematic literature review with an analysis of early insights from European initiatives to explore how data spaces are being conceptualized and implemented in industrial contexts. The review covers bibliometric trends and thematic content in the scientific literature, while also examining the structure and maturity of ongoing European projects. Results show a recent surge in scholarly interest, with early applications focusing primarily on resilience and sustainability. Practical initiatives are progressing toward implementation, supported by reference architectures like International Data Space and Gaia-X. The study concludes by outlining future research priorities, including the need for standardized design approaches and greater support for cross-sector collaboration.

Keywords: data spaces; manufacturing; supply chains

check for updates

Academic Editor: Arkadiusz Gola

Received: 16 April 2025
Revised: 12 May 2025
Accepted: 19 May 2025
Published: 22 May 2025

Citation: Gabellini, M.; Civolani, L.; Ronchi, M.; Naldi, L.D.; Regattieri, A. Data Spaces in Manufacturing and Supply Chains: A Review and Insights from European Initiatives. *Appl. Sci.* **2025**, *15*, 5802. https://doi.org/10.3390/app15115802

1. Introduction

Nowadays, manufacturing and supply chains have become globally distributed and highly interconnected, involving a wide range of autonomous actors [1–3]. However, despite advancements in digital technologies, a fundamental challenge persists: the fragmentation of data across organizational and technological boundaries [4,5]. Manufacturers often lack visibility into upstream constraints or downstream demand changes, while suppliers remain unaware of production schedules or quality issues further along the chain. This lack of integrated data exchange undermines coordination, reduces responsiveness, and limits innovation potential across the value chain. Poor data integration can lead to overproduction, inventory imbalances, delayed deliveries, and reactive decision-making [6,7], undermining strategic sustainability and operational initiatives in small- and medium-sized manufacturers [8] and affecting sustainable performance through supply chain visibility [9]. This challenge also intersects with broader sustainability goals, as transparent and integrated data flows have been shown to shape stakeholder perceptions of sustainable development, mediate green behavior and corporate social responsibility interactions, and enhance environmental performance through operational transparency in manufacturing contexts [10–12]. Moreover, the absence of real-time, standardized, and contextualized data can become particularly dangerous in regulated or complex industries, where delayed recalls or compliance failures can result in substantial financial and reputational damage. Lastly, in an increasingly AI-driven environment [13–18], limited access to high-quality, cross-organizational data hinders the performance of manufacturing and supply chain predictive models, impeding opportunities for automation, optimization, and intelligent decision support.

Given the increasing complexity and volatility of global supply chains, the ability to share and utilize data across organizational boundaries has become critical for industrial competitiveness and systemic resilience. However, achieving seamless and secure data exchange remains a significant challenge due to a combination of technical, organizational, legal, and trust-related barriers [19–21]. A major obstacle is the heterogeneity of systems and data models across different organizations [22]. Manufacturing stakeholders typically use diverse platforms with incompatible formats and terminologies. This lack of interoperability leads to costly, fragile, and often manual integration efforts that are difficult to scale and maintain. The distributed and hierarchical structure of supply chains further complicates matters [23]. Limited data sharing between these tiers impedes end-to-end visibility and delays the detection of disruptions or quality issues. Trust is another critical barrier [24]. Companies are often reluctant to share sensitive data due to concerns over misuse, competitive risks, and lack of control. The absence of standardized frameworks for data usage rights, consent management, and access control across organizational boundaries exacerbates these concerns. Legal and regulatory constraints—such as data privacy laws and cross-border compliance requirements—further complicate data exchange, especially when ownership, responsibility, and liability remain ambiguous [25]. Finally, existing solutions based on bilateral integration or centralized platforms do not scale effectively in large, dynamic ecosystems. As each new partnership requires a custom integration effort, complexity and cost increase exponentially. As a result, even firms with well-integrated internal data systems often struggle to extend those capabilities to external partners.

Over the past two decades, various technological solutions have thus been proposed to address data fragmentation in manufacturing and supply chains, including centralized platforms, EDI systems, blockchain, and industrial cloud solutions [26]. While each has contributed to improving data exchange, none has fully resolved the systemic interoperability, scalability, governance, and trust challenges [27]. Centralized platforms often concentrate control in the hands of dominant actors, limiting participation by smaller firms [28]. EDI systems remain rigid and lack semantic depth [29], while cloud-based solutions typically reinforce enterprise-centric models and fall short of supporting decentralized, sovereign data sharing [30].

Fortunately, the concept of data spaces has recently emerged as a novel approach grounded in decentralization, semantic interoperability, and data sovereignty. Data spaces allow organizations to retain control over their data while sharing it under clearly defined usage policies [31]. Enabled by federated infrastructure and standardized governance frameworks, data spaces emphasize trust-by-design and enforce usage conditions through technical and contractual mechanisms. The European Union has recognized the strategic potential of data spaces, embedding them within its broader digital and industrial policy agendas [32,33].

However, despite these developments, the academic literature on data spaces in manufacturing and supply chains remains sparse and fragmented. Moreover, unlike earlier solutions, which have been the subject of extensive scholarly analysis, data spaces lack a comprehensive consolidated review as reported in Table 1.

Table 1. Summary of key literature review studies on technologies enabling data sharing and integration in manufacturing and supply chains.

Study	Technology
[34]	Digital Platform
[35]	Digital twin
[36]	Industry 4.0 related
[37]	Electronic Data Interchange
[38]	Cloud
[39]	Blockchain
This study	**Data Spaces**

The review of existing studies reveals three primary gaps: (1) fragmented theoretical perspectives with no unified framework for understanding data spaces; (2) limited empirical evidence on real-world implementations, particularly within European initiatives; and (3) few studies that bridge bibliometric trends, thematic analysis, and practical outcomes. To address these gaps, this study makes three contributions: a comprehensive mapping of academic research through a systematic literature review; practical insights from European initiatives by analyzing the structure and maturity of ongoing EU-funded data space projects; and an integrated agenda for future work by synthesizing theoretical and practical findings to propose standardized design approaches and areas for cross-sector collaboration. These contributions are operationalized via three Research Questions (RQs):

1. *What are the bibliometric trends and patterns in the academic literature concerning data spaces in the context of manufacturing and supply chains?*
2. *What are the main thematic contributions and conceptual perspectives in the existing scientific literature on data spaces in this context?*
3. *What initial evidence and practical insights can be drawn from ongoing European initiatives developing and implementing data spaces in manufacturing and supply chains?*

The remainder of this article is organized as follows: Section 2 presents the methodology used to conduct the literature review and collect data from European initiatives. Section 3 reports the answer to each RQ. Section 4 interprets the results to define potential future research areas and Section 5 concludes by summarizing key insights and outlining limitations.

2. Materials and Methods

A multi-level research design was adopted in this study to address the three RQs identified in Section 1 related to the evolution of scientific literature and real-world initiatives on data spaces in manufacturing and supply chains. Specifically, the research approach combines bibliometric analysis, qualitative content analysis, and a document-based review of real-world projects. This triangulation allows for both a broad and deep understanding of the topic, grounded in peer-reviewed sources and institutional documentation. Despite this rigorous design, several limitations should be acknowledged. The exclusive reliance on the Scopus database may have led to the omission of relevant studies indexed elsewhere or published in languages other than English, and the April 2025 cutoff means that the very latest advances in data spaces might not be captured. Although manual screening and qualitative coding were guided by clear criteria and supplemented by co-citation checks, they remain subject to interpretive bias. The analysis of European initiatives draws solely on publicly available documentation, which may overlook proprietary or in-progress project details. Finally, the process of mapping academic publications to real-world initiatives depends on explicit references in the literature, so initiatives not directly cited or using alternative terminology could have been missed.

2.1. Literature Search and Selection

The academic literature was retrieved through a systematic search of the Scopus databases. The Scopus database was selected due to its comprehensive indexing of engineering, information systems, and industrial management research. The search was designed to capture studies focusing on data spaces within manufacturing and supply chain contexts using the following Boolean expression:

("data space") AND ("manufacturing" OR "supply chain*")*

The query was restricted to English-language documents published up to April 2025, including journal articles, conference proceedings, review articles, and book chapters. After deduplication, the remaining publications were screened manually based on their titles and abstracts to ensure relevance. Studies focusing solely on non-industrial sectors were excluded. Moreover, to enhance the completeness of the review and capture relevant but less explicitly labeled publications, citation and co-citation analyses were performed using reference lists from core papers. This allowed the identification of additional studies that were thematically aligned with the topic but may not have matched the initial search string. The overall workflow adopted for the review process is illustrated in Figure 1, which summarizes the steps of data retrieval, filtering, and analysis.

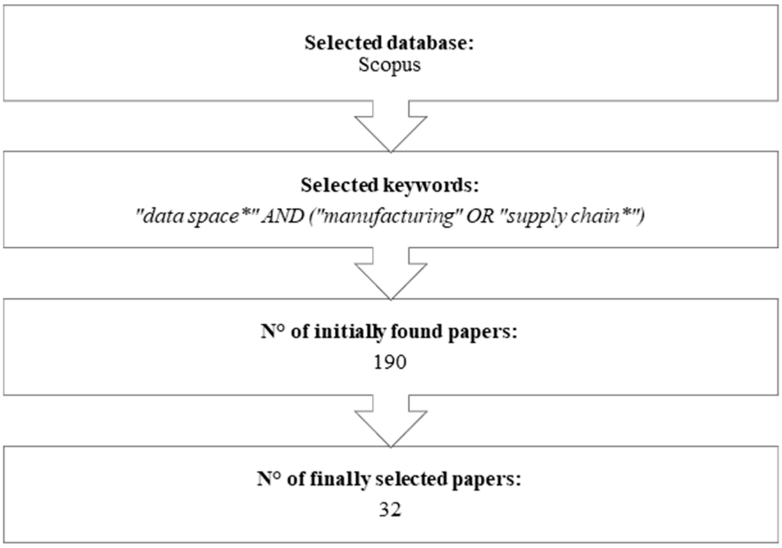


Figure 1. Overview of the literature review workflow adopted in the study.

The resulting set of publications served as the basis for both quantitative and qualitative analyses.

2.2. Bibliometric Analysis

A bibliometric analysis was conducted to explore the evolution and distribution of scholarly attention to data spaces in manufacturing and supply chains. Key indicators included the following:

- **Yearly publication trends**: to track the growth and timing of scholarly interest in the topic.
- **Distribution by document type:** to assess the maturity of the field based on the balance between exploratory (conference) and consolidated (journal/review) outputs.
- **Publishing sources**: to identify core journals and conferences and understand the disciplinary orientation of the research.
- **Geographic and institutional affiliations**: to map regional and institutional research activity and highlight key academic and industrial contributors.

- **Most prolific authors**: to recognize leading researchers shaping the field and influencing ongoing developments.
- **Keyword co-occurrence analysis**: to explore the thematic structure of the literature, identify dominant research clusters, and reveal how key concepts interconnect across publications.

2.3. Content Analysis of Scientific Contributions

A qualitative content analysis was performed on the selected publications to assess the conceptual development of data spaces in manufacturing and supply chains. Each study was systematically reviewed and categorized according to several analytical dimensions, including the following:

- **Industrial domain:** to identify which sectors (e.g., automotive, energy, food) are leading or emerging in the adoption of data spaces and to assess cross-sectoral applicability.
- **Operational objectives:** to determine the operational focus of data space use (e.g., cost efficiency, sustainability, resilience).
- **Type of integration:** to distinguish between vertical integration (across supply chain tiers) and horizontal integration (among peer organizations), which reflect different collaboration models and data-sharing structures.
- **Integrated technologies:** to capture the technological ecosystems (e.g., IoT, digital twins, AI) that integrate with data space functionality and enable data-driven applications.
- **Types of shared data:** to analyze what categories of data (e.g., production metrics, maintenance logs, environmental indicators) are most commonly exchanged, indicating the functional scope of data spaces.
- **Use of standards and architectures:** to examine adherence to recognized frameworks (e.g., International Data Space (IDS), Gaia-X), which is essential for interoperability, scalability, and compliance with governance models.

To execute this analysis, the lead author conducted a full-text reading of each publication, annotating passages that matched the predefined dimensions and recording analytical memos to refine category definitions. Periodic discussions with co-authors ensured coding decisions were transparent and consistent, resolving any ambiguities by consensus. This structured yet adaptable procedure yielded a systematic, reproducible classification of the literature, which underpins the thematic synthesis presented in Section 3.2. The goal was to identify dominant application patterns, variations in technical implementation, and recurring gaps in documentation.

2.4. Analysis of European Data Space Initiatives

In parallel with the literature review, a document-based analysis was conducted to examine major European initiatives' structure, maturity, and strategic orientation related to data spaces in manufacturing and supply chains. To identify and select relevant projects, we first retrieved the complete list of European data space initiatives from the International Data Spaces Association (IDSA) Data Spaces Radar repository. Each initiative entry and its official project website were screened to confirm that the project explicitly addressed data space challenges in manufacturing or supply chains. In addition, we performed targeted Scopus searches using project names (e.g., "Catena-X", "Gaia-X") to collect peer-reviewed publications describing their data space implementations. Any documents or studies that mentioned a project but did not explicitly describe its data space features or use cases were excluded. This dual-track approach—combining repository screening with bibliographic validation—ensures that our analysis focuses solely on initiatives with a clear, documented commitment to data space development. The analysis then examined the following:

- **Maturity levels:** the five-stage model (Exploratory, Preparatory, Implementation, Operational, Scaling) captures the lifecycle progression of initiatives, indicating their readiness and deployment status.
- **Architectural foundations:** Identifying the use of frameworks like IDS or Gaia-X allows assessment of technical alignment with recognized standards and interoperability models.
- **Design principles:** core principles such as data sovereignty, interoperability, and trust reflect the governance philosophy and foundational values shaping each initiative.
- **Funding sources:** analyzing the role of EU, national, and private funding highlights the degree of public investment and institutional prioritization of data spaces.
- **Business models:** classification into patterns like joint innovation or marketplace structures provides insight into the economic rationale and collaboration modes behind the initiatives.
- **Geographic distribution:** mapping projects by country enables the identification of regional leadership, policy alignment, and cross-country engagement in data space development.

Finally, cross-mapping was conducted to connect academic publications with the real-world initiatives they referenced or studied. This provided insight into the degree of alignment between theory and practice and identified which initiatives are most embedded in scholarly discourse. This enabled the synthesis of content presented in Section 3.3.

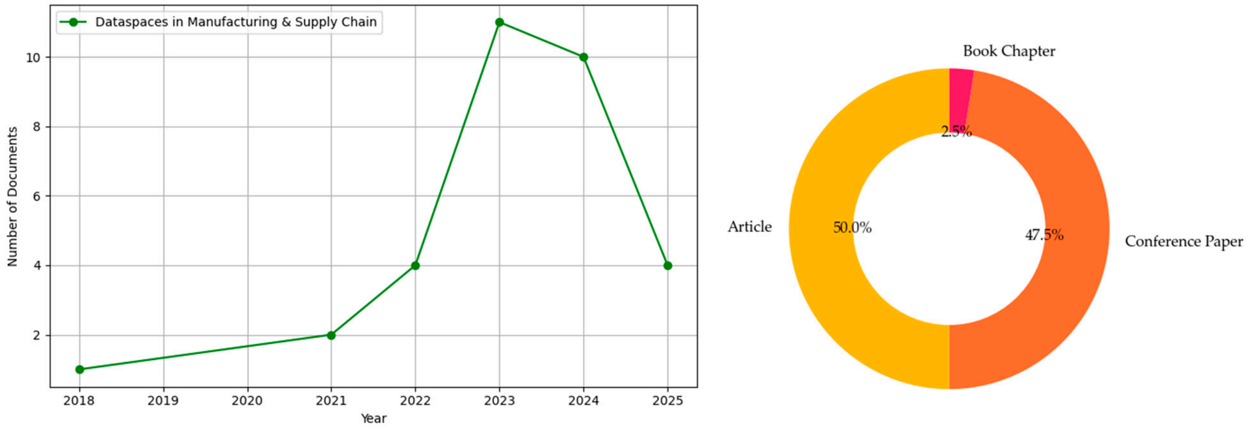
3. Results

The following Section presents the results of the study, structured to address the three RQs outlined in Section 1. Section 3.1 explores the bibliometric evolution of research on data spaces in manufacturing and supply chains. Section 3.2 focuses on the content of the scientific literature. Finally, Section 3.3 examines the main European initiatives and industrial projects in advancing data space adoption.

3.1. What Are the Bibliometric Trends and Patterns in the Academic Literature Concerning Data Spaces in the Context of Manufacturing and Supply Chains?

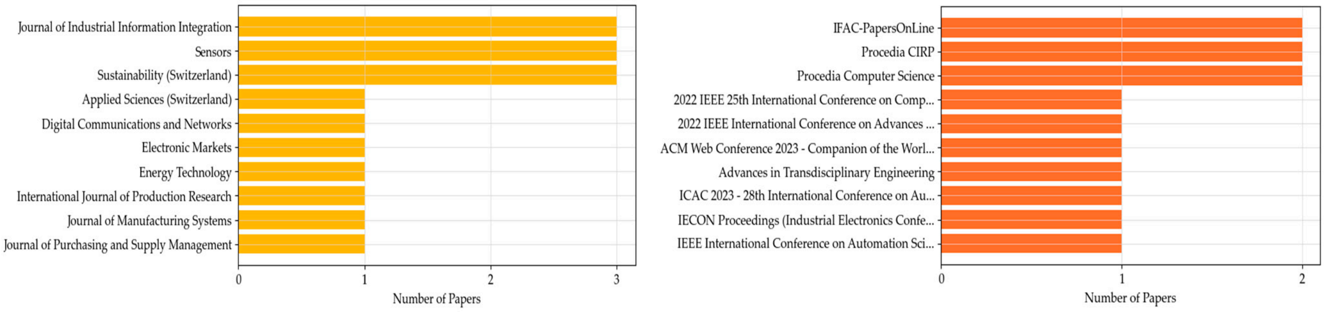
Figure 2 presents an overview of publication activity related to data spaces in manufacturing and supply chain contexts. Panel (a) illustrates the number of publications per year between 2018 and early 2025. Panel (b) displays the distribution of document types among the retrieved records, including journal articles, conference papers, and book chapters for the manufacturing and supply chain subset.

Figure 2a shows that publications on data spaces in manufacturing and supply chains have climbed steadily—from just one document in 2018 to two in 2021, four in 2022, and then a dramatic jump to eleven in 2023. Although the count dips to ten in 2024 and currently sits at four for 2025, that latest figure almost certainly underestimates the true output because of indexing lags. Figure 2b breaks down those contributions by document type: exactly half are journal articles (50%), conference papers account for 47.5%, and book chapters make up only 2.5%. This distribution suggests a maturing field—anchored now by peer-reviewed articles—while still actively exchanging new ideas at conferences, even as full-length, integrative volumes remain rare. Together, these patterns imply that research on data spaces in manufacturing and supply chains is rapidly solidifying its scholarly foundations, even as more comprehensive treatments are just beginning to appear. Figure 3 illustrates the distribution of scientific publications on data spaces in manufacturing and supply chains, categorized by main publication source. Panel (a) presents the count of research articles across main academic journals, while panel (b) displays the distribution of conference papers across main proceedings.



(**a**) (**b**)

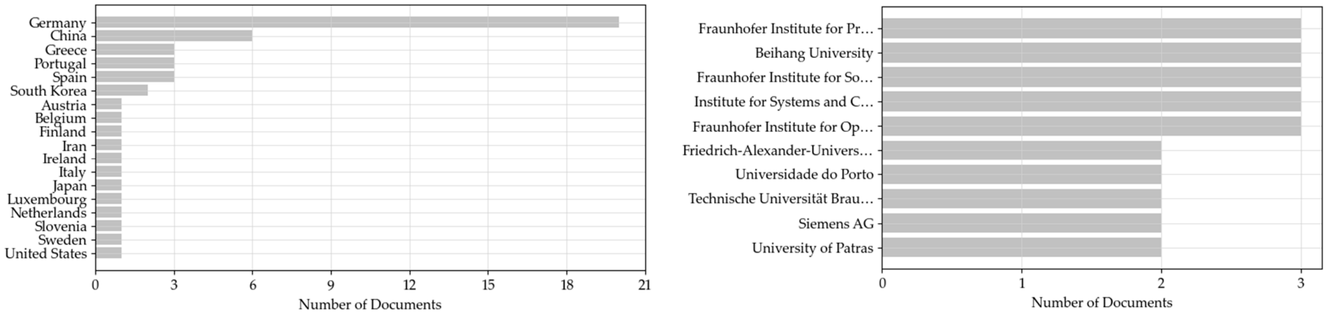
Figure 2. Scholarly attention to data spaces in manufacturing and supply chains: (**a**) annual publication trends; (**b**) distribution by document type.



(**a**) (**b**)

Figure 3. Distribution of publications on data spaces in manufacturing and supply chains by outlet: (**a**) main journal sources for research articles; (**b**) main conference proceedings for conference papers.

Figure 3a shows that four journals—Journal of Industrial Information Integration, Sensors, Sustainability (Switzerland), and Applied Sciences (Switzerland)—are tied as the most prolific outlets, each publishing three papers on data spaces. A second tier of sources—including Digital Communications and Networks, Electronic Markets, Energy Technology, International Journal of Production Research, Journal of Manufacturing Systems, and Journal of Purchasing and Supply Management—each contributed one paper. This distribution underscores a strong research focus within industrial informatics, digital manufacturing, and sustainability-oriented publications. Figure 3b reveals that Procedia Computer Science, IFAC-PapersOnLine, and Procedia CIRP lead the conference scene with two papers apiece. Beyond these, a wide array of other conferences—from IEEE's automation and electronics symposia to ACM workshops and transdisciplinary engineering forums—each hosted one contribution. Together, the journal and conference breakdown highlights a balanced, multidisciplinary engagement with data spaces, marrying rigorous peer-reviewed studies in established journals with vibrant, industry-focused debates at conferences. Figure 4 illustrates the geographical and institutional distribution of scientific publications related to data spaces in manufacturing and supply chains. Panel (a) shows the number of publications by country, while panel (b) presents the top contributing institutions based on their publication count.



(**a**) (**b**)

Figure 4. Distribution of publications on data spaces in manufacturing and supply chains by affiliation: (**a**) contributing countries based on author affiliation; (**b**) contributing institutions based on publication output.

Figure 4a shows that Germany dominates with 20 documents—nearly three times the 7 produced by China—while Greece follows with 3. Portugal, Spain, and South Korea each contributed 2 papers, and a long tail of single-document entries comes from Austria, Belgium, Finland, Iran, Ireland, Italy, Japan, Luxembourg, the Netherlands, Slovenia, Sweden, and the United States. This distribution underlines Germany's leading role—driven by its strong academic–industrial ecosystem and European data-space initiatives—alongside emerging activity in China and a broad international base. Figure 4b reveals a five-way tie at the top: Fraunhofer IPK, Beihang University, Fraunhofer ISST, INESC TEC (Institute for Systems and Computer Engineering), and Fraunhofer IOSB each published three documents. A secondary group—including Friedrich-Alexander-Universität Erlangen-Nürnberg, Universidade do Porto, Technische Universität Braunschweig, Siemens AG, and the University of Patras—contributed two apiece. Together, these patterns highlight both the centrality of key German and Chinese centers and a widening network of institutional expertise across Europe and beyond.

Figure 5 displays the most prolific authors in the scholarly literature on data spaces applied to manufacturing and supply chains, ranked by the number of published documents.

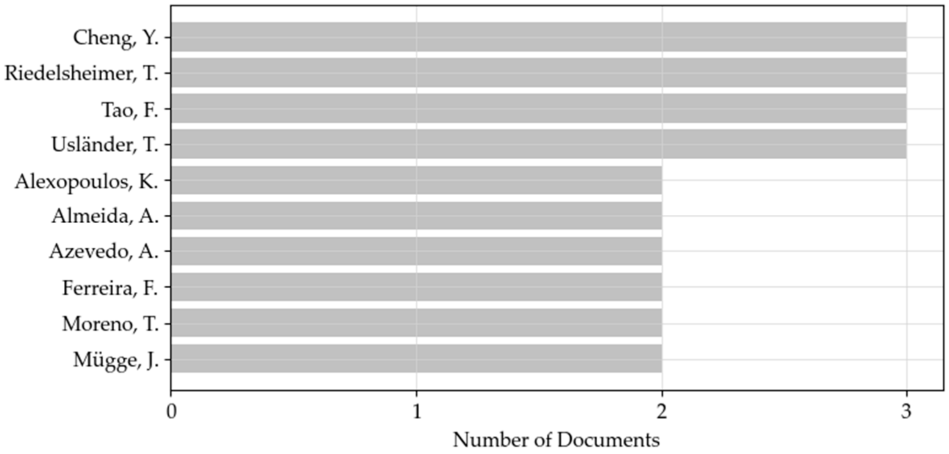


Figure 5. Most prolific authors in the field of data spaces for manufacturing and supply chain management based on the number of publications.

According to Figure 5, four authors—Cheng, Y., Riedelsheimer, T., Tao, F., and Usländer, T.—each contributed three documents, marking them as the core drivers of the discourse. They are followed by a second tier of six researchers—Alexopoulos, K., Almeida, A., Azevedo, A., Ferreira, F., Moreno, T., and Mügge, J.—each with two papers. Many of these prolific authors map directly onto the institutional hubs identified in Figure 4 (e.g., Beihang University and the Fraunhofer Institutes), while contributors like Alexopoulos (University of Patras) highlight the broader European engagement. Overall, this author-level profile reveals a tight-knit group of repeat scholars shaping both the theoretical frameworks and practical case studies in industrial data spaces, against a backdrop of growing international collaboration. Lastly, Figure 6 visualizes the keyword co-occurrence network extracted from the reviewed literature. Each node represents a keyword, and links indicate the frequency of co-occurrence within the same publication. Colors correspond to clusters of semantically related terms, identified using the Louvain community detection algorithm. These clusters highlight the main thematic areas currently structuring academic discourse on data spaces in manufacturing and supply chains.

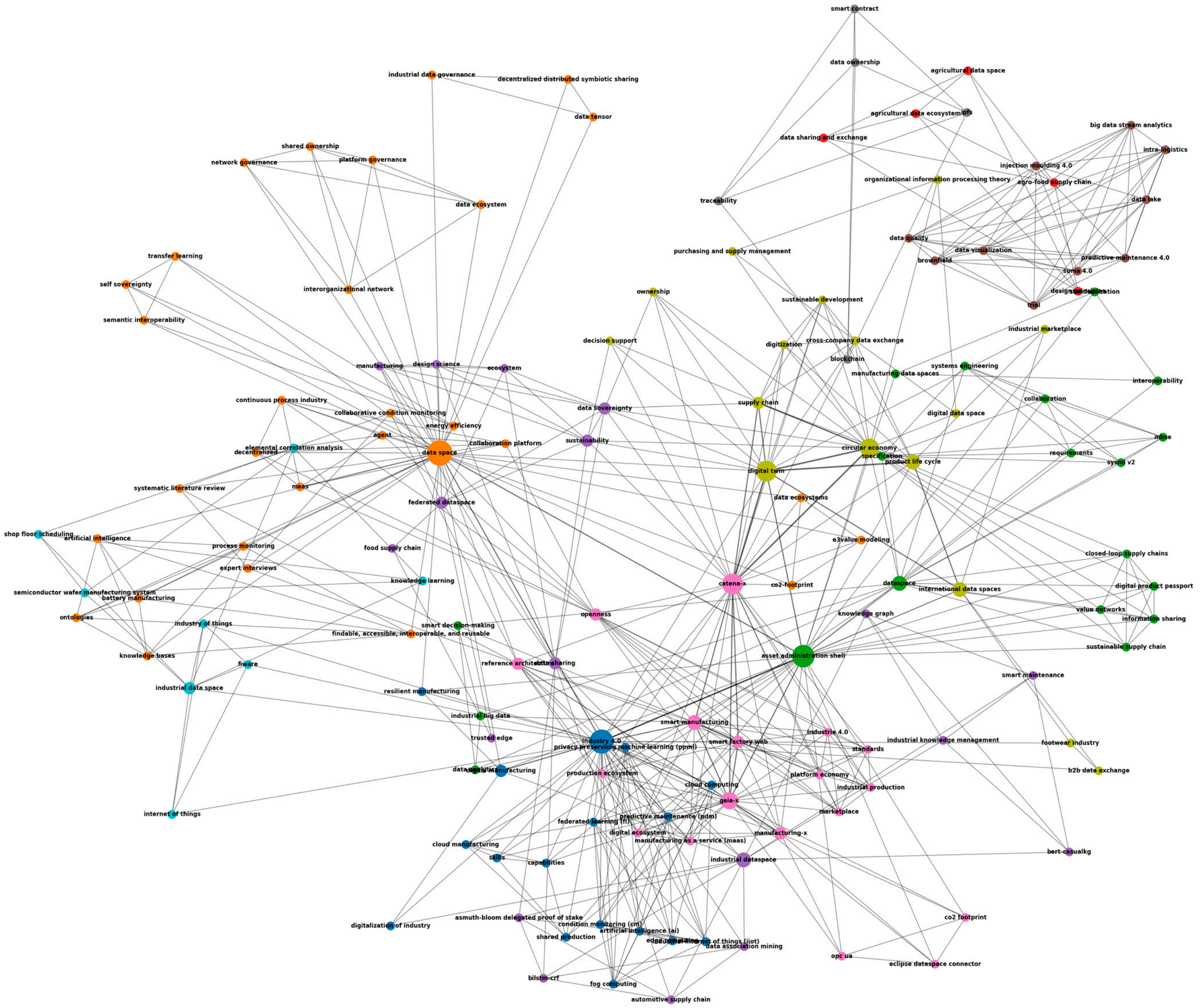


Figure 6. Keyword co-occurrence network for publications on data spaces in manufacturing and supply chains, highlighting thematic clusters and their interrelations.

In reviewing the literature, ten thematic clusters emerge—each distinguished by its color in the network map—and together they sketch the evolving contours of industrial data space research.

Advanced Data Space Intelligence and Edge Computing (Blue): this cluster examines how data space architectures embed intelligence at the edge. Terms like artificial intelligence, federated learning, and privacy-preserving machine learning illustrate distributed model training within the industrial Internet of Things. Edge and fog computing extend the data space to shop-floor devices, while cloud computing and cloud manufacturing provide scalable off-site processing. Operational use-cases—condition monitoring, predictive maintenance, and resilient manufacturing—show how data space platforms enable real-time analytics and adaptive control. "Shared production" and "digitalization of industry" capture how data spaces reshape manufacturing workflows and requisite skills.

Socio-Technical Governance of Industrial Data Spaces (Orange): at the conceptual core of data space research, this cluster articulates frameworks for collective stewardship and policy. Central concepts—data space, data ecosystem(s), decentralized distributed symbiotic sharing—merge with governance models like platform governance, network governance, self-sovereignty, and shared ownership. Methodologies (e3value modeling, systematic literature review, expert interviews) validate these socio-technical designs. FAIR principles (findable, accessible, interoperable, reusable) and "openness" ensure data space services remain transparent and equitable, while domain tags (battery manufacturing, continuous-process industry) demonstrate how governance adapts to sectoral needs.

Formal Modeling and Standards for Data Spaces (Green): interoperability in data spaces hinges on rigorous architectures and engineering methods. The Asset Administration Shell and SysML v2, along with MBSE practices, define meta-models for data space components. Ontologies, requirements, and specifications translate these models into implementable standards, while "manufacturing data spaces" and "digital product passport" ensure traceability across the product lifecycle. Collaboration patterns and "value networks" bind diverse stakeholders into coherent data space ecosystems, enabling closed-loop supply chains and sustainable practices.

Agro-Food Design Frameworks in Data Spaces (Red): this cluster tailors data space principles to agriculture and food systems. "Agricultural data space" and "agricultural data ecosystem" describe domain-specific instances, while "agro-food supply chain" highlights end-to-end data flows. Core design principles and "data sharing and exchange" protocols ensure interoperability among sensors, platforms, and regulatory databases. By embedding farming and logistics into data-space infrastructures, this cluster addresses food-safety, traceability, and efficiency imperatives.

Provenance and Knowledge Management in Data Spaces (Purple): trust in a federated data space arises from tamper-proof provenance and semantic integration. Blockchain constructs—Asmuth–Bloom delegated proof of stake, smart contract, IPFS—securely anchor transaction history. Knowledge graphs, data-association mining and "industrial knowledge management" enable the fusion of heterogeneous datasets. Anchored in use cases like the automotive and food supply chains, "trusted edge" and "semantic interoperability" ensure data space participants can verify, query, and leverage shared intelligence without sacrificing sovereignty.

Brownfield Integration and Real-Time Data Spaces (Brown): legacy facilities pose unique challenges for data space adoption. This cluster spotlights "brownfield" scenarios where big-data stream analytics, data lakes, and data-quality tools retrofit existing lines. Applications such as injection molding 4.0, predictive maintenance 4.0, intra-logistics optimization, and SUMA 4.0 trials demonstrate how data spaces can overlay non-disruptively, providing continuous monitoring, scheduling, and iterative experimentation.

Federated Data Space Architectures and Marketplaces (Pink): underpinning industrial data spaces are shared infrastructures and trading venues. Initiatives like Gaia-X and Catena-X, connectors such as the Eclipse Dataspace Connector, and platforms like FIWARE define reference architectures for secure interoperability. "Marketplace" and "platform economy" concepts translate data space connectivity into commercial exchanges, while "design science" and "standards" ensure these federated environments scale. Embedding CO_2 footprint metrics further aligns data space marketplaces with sustainability goals.

Blockchain-Enabled Trust Mechanisms in Data Spaces (Gray): a focused look at distributed-ledger tools within data spaces. Blockchain, smart contracts, and IPFS provide immutable registries that enforce provenance, while "traceability" and "data ownership" frameworks ensure participants can audit and control data flows. This trust layer is indispensable for high-assurance applications—where data space collaborations cross company and regulatory boundaries.

Circular-Economy and Cross-Company Data Spaces (Olive): this cluster explores how data spaces drive circularity and inter-firm exchange. B2B data exchange and cross-company data exchange models enable collaborative recycling, remanufacturing, and resource sharing. Digital twins and product-lifecycle management tools integrate into data space workflows, while purchasing and supply management functions leverage international data space standards. Sectoral examples—such as the footwear industry—illustrate how industrial marketplaces foster co-innovation and sustainable development.

Shop-Floor IoT and Learning in Data Spaces (Cyan): at the operational frontier, this cluster fuses IoT sensing with data space analytics. FIWARE-based platforms, elemental correlation analysis, and knowledge-learning algorithms transform raw sensor feeds into actionable patterns. Case studies in semiconductor wafer manufacturing systems and shop-floor scheduling exemplify how data spaces enable continuous learning loops—turning each production trial into an insight generator within the "Industry of Things".

Together, these ten color-coded clusters map a rich tapestry of governance, infrastructure, analytics and application domains—illustrating how industrial data spaces have evolved into a multidimensional research frontier.

3.2. What Are the Main Thematic Contributions and Conceptual Perspectives in the Existing Scientific Literature on Data Spaces in This Context?

To address RQ2, the reviewed literature was systematically classified based on several key dimensions relevant to the implementation of data spaces in manufacturing and supply chains. The classification framework considers the industrial domains addressed, the operational objectives pursued, the type of integration implemented, the technologies integrated, the nature of shared data, and the use of data-sharing standards or architectures. These dimensions, summarized in Table A1, provide the basis for the following analysis.

Automotive dominates sectoral coverage in the literature: as shown in Appendix A Table A1, the automotive sector is the most frequently examined, with five purely automotive cases [40–44] plus one cross-sector study with electronics [45]. Beyond this, food (three studies [46–48]), machining (three studies [49–51]), and battery manufacturing (two studies [52,53]) also appear. Niche domains—such as aerospace [54], footwear [55], nuclear energy [56,57], semiconductor processing [58], home appliances [59], and heavy equipment [60]—round out the landscape.

Resilience is the most common operational objective driving data space adoption: resilience leads as the primary objective, addressed in half the sample. Efficiency follows in 13 studies [45,50,51,54–56,58,59,61–65], and sustainability in 10 studies [40,42,43,46,47,52,65–68]. Multi-objective approaches include resilience + sustainability (four studies [40,42,66,68]), efficiency + resilience (two studies [51,59]), and efficiency + sustainability (one study [65]).

Vertical integration is the predominant form of data sharing, while horizontal and sector-level integration are rare: Two-thirds of the works focus on cross-enterprise (within-supply-chain) integration. Company-level implementations appear in 11 studies [45,50,53,56–58,60,62,65,69,70], only one study adopts a sector-wide scope [54], and one bridges both scopes [60].

IoT, digital twins, and machine learning are the most frequently integrated technologies: Internet of Things is the most integrated technology, followed by machine learning in 10 studies [45,46,48,49,53,56,57,62,70,71], digital twins in 7 [40,42,52,58,63,70,71], big-data analytics in 4 [45,48,50,56], and blockchain in 3 [44,47,64]. Notably, 11 studies report no specific technology integration [41,43,51,54,59–61,65–67,69].

Shared data types primarily relate to production, quality, and product lifecycle: production metrics are the most exchanged data type, with product status next in 11 studies [40,43,46,47,49,51,52,54,56,61,68]. Maintenance records appear in seven studies [42,43,45,48,50,56,57], quality measures in four [44,45,50,65], sustainability metrics in two [52,66], demand data in one [66], inventory in one [44], and energy in two [44,62].

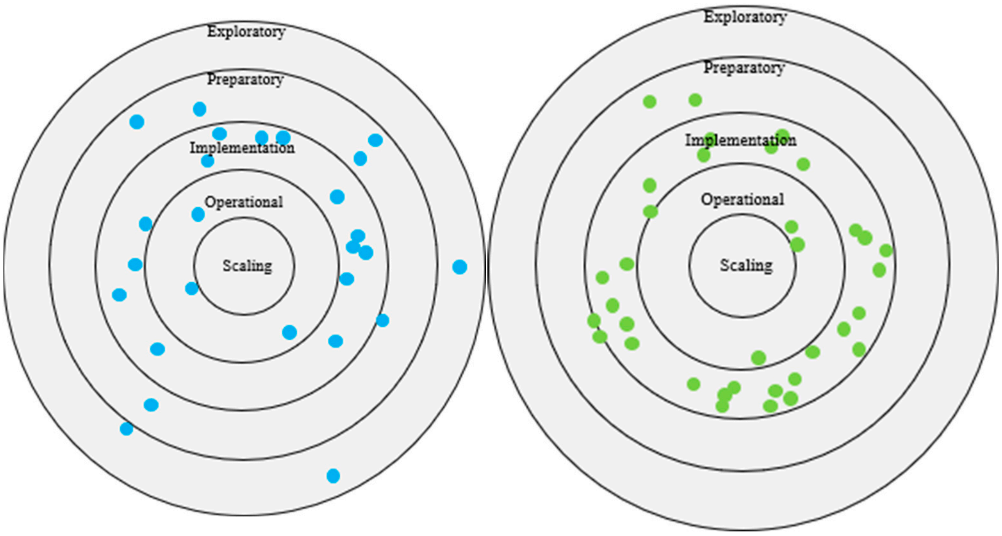
International Data Spaces (IDS) is the most cited reference architecture, but standard adoption remains fragmented: The IDS architecture leads standardization, followed by the Asset Administration Shell in 11 studies [40,44,49,51–53,59,66,67,70,71] and Gaia-X in 10 [40,41,46,48,51,54,67,68,70,71]. Other standards—OPC UA, EDC, FIWARE, Catena-X, IDS-RAM—appear only once or twice, and 10 studies cite no formal interoperability framework [43,47,56–58,60–62,65,69].

Reporting practices vary, limiting cross-study comparability and synthesis: While general patterns emerge across sectors, technologies, and operational goals, significant inconsistencies in reporting persist. Many studies lack detail regarding integration types, data semantics, or technical implementation frameworks, making it difficult to compare approaches or replicate findings. Several studies omit reference architectures entirely, while others do not clearly define shared data types or technological components. These gaps underscore the need for consistent taxonomies, standardized descriptors, and transparent reporting practices to enable robust cross-study learning and methodological clarity in future research on industrial data spaces.

3.3. What Initial Evidence and Practical Insights Can Be Drawn from Ongoing European Initiatives That Are Developing and Implementing Data Spaces in Manufacturing and Supply Chains?

In order to assess RQ3, the evolution and current state of real-world initiatives related to data spaces in the European context from the IDSA platform were analyzed. Figure 7 presents two radar plots illustrating the distribution of identified initiatives across five maturity stages—Exploratory, Preparatory, Implementation, Operational, and Scaling—indicating their progression along the data space development lifecycle.

According to Figure 7a, the documented data spaces are most heavily concentrated in the Preparatory and Implementation stages. Figure 7b, which maps the use cases associated with these data spaces, similarly shows a predominance in the Implementation and Operational phases. This juxtaposition suggests that, although a considerable number of projects remain in preparatory planning, a substantial share has already moved into implementation and practical deployment. The presence of several data spaces in the Exploratory stage reflects an ecosystem in which foundational infrastructure and governance arrangements are still taking shape. Concurrently, the clustering of use cases toward the Operational phase indicates that many applications have progressed beyond pilot testing into live environments. Collectively, these patterns illustrate a clear shift from theoretical exploration to real-world execution in European data space development, demonstrating that reference architectures such as IDS and Gaia-X have evolved from abstract concepts into active, functioning systems. This progression underscores a deepening institutional and industrial commitment to data-driven collaboration, interoperability, and sovereignty—cornerstones of modern manufacturing and supply chain digitalization.



(**a**) (**b**)

Figure 7. Maturity levels of data spaces and associated use cases documented by the IDSA (source by https://www.dataspaces-radar.org/radar [accessed 11 May 2025]): (**a**) distribution of data spaces across five maturity levels; (**b**) distribution of documented use cases within the same maturity framework.

Building on the previous analysis of the evolution of European data space initiatives, Figure 8 offers a deeper look into these projects' structural and strategic characteristics, focusing on their foundational building blocks, architectural frameworks, funding models, business case patterns, and geographical distribution.

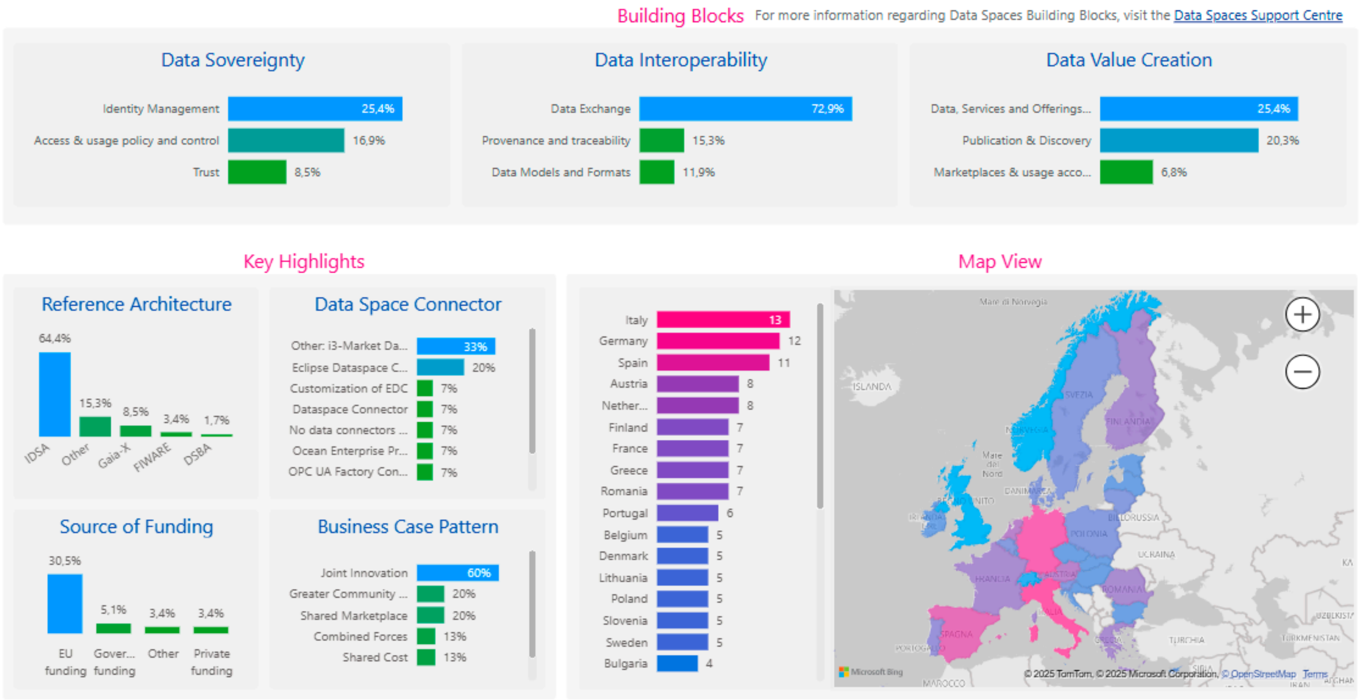


Figure 8. Overview of key characteristics of European data spaces initiatives (source by https://www.dataspaces-radar.org/radar [accessed 11 May 2025]).

In the top section of the figure, the foundational pillars of data space design are highlighted through three thematic blocks: data sovereignty, data interoperability, and data value creation. The emphasis on data exchange under the interoperability block

(72.9%) underscores the central role of ensuring seamless data flow between stakeholders. However, comparatively lower shares for provenance and traceability (15.3%) and data models and formats (11.9%) suggest that while exchange mechanisms are being prioritized, standardization and lineage tracking may still be in earlier phases of implementation. Under data sovereignty, identity management (25.4%) and access and usage policy control (16.9%) emerge as key enablers, aligned with the broader goal of ensuring secure and rule-based access to data. Trust, however, remains the least addressed aspect (8.5%), indicating a potential gap in ecosystem-wide mechanisms for establishing and verifying trust—possibly reflecting the early maturity of some ecosystems or the reliance on pre-existing business relationships. The data value creation segment shows the leading role of data services and offerings (25.4%) and publication and discovery (20.3%) in driving economic utility from data. Nonetheless, marketplace and usage accounting (6.8%) remain underrepresented, suggesting that monetization models and governance for transactional data economies are still emerging while technical sharing is advancing.

In terms of reference architecture, the dominance of IDSA (64.4%) confirms its status as the de facto standard for many European data space projects. Alternative frameworks like Gaia-X (8.5%) and FIWARE (3.4%) are also in use but to a lesser extent, reinforcing the strong institutional backing for IDS as the structural blueprint of data sovereignty. On the technical implementation side, the most widely adopted data space connector, the Eclipse Data-space Connector (EDC), holds significant traction (20%), especially among projects aligning with open-source and federated architecture principles.

Source of funding data highlight the critical role of EU funding (30.5%) in enabling the development of these data spaces, followed by minor contributions from governmental and private funding sources. This reliance on public investment emphasizes the strategic role of data spaces in Europe's digital agenda and industrial policy. From a business perspective, joint innovation (60%) dominates as the leading business case pattern, indicating the strong emphasis on collaboration over direct monetization. Other patterns such as shared marketplace and greater community engagement (each 20%) suggest that data spaces foster shared innovation ecosystems and public–private partnerships beyond value creation. Finally, the geographical distribution reveals that Italy, Germany, and Spain are leading in terms of the number of documented data spaces.

Lastly, to further integrate insights from both academic research and real-world initiatives, Table 2 presents an overview of scientific publications that directly reference or align with specific European data space projects.

Table 2. Studies related to the most-discussed data spaces projects in the scientific literature.

Data Spaces	Related Studies
Catena-X	[40,41,43,72–74]
COOPERANTS	[54]
Boost 4.0	[45]

The most frequently discussed project is Catena-X, a flagship initiative in the automotive industry, referenced in seven publications [40,41,43,72–74]. These studies confirm Catena-X's role as a testbed for decentralized, cross-enterprise data sharing grounded in IDS and Gaia-X principles. They explore various aspects, including platform governance models in networked ecosystems [72], circular economy use cases via digital twins and end-of-life vehicle data [40,73], CO_2 tracking and sustainable business models [74], federated marketplaces and Manufacturing-as-a-Service (MaaS) infrastructures [41], data management across the asset lifecycle [42], and informational capabilities for purchasing and supply management in the context of data-driven sustainability [43]. Together, these contributions illustrate how Catena-X enables multi-stakeholder data exchange, supports sustainability goals, and operationalizes key principles such as data sovereignty and federated control. The diversity of research perspectives reflects the richness and complexity of the ecosystem being developed.

In addition to Catena-X, other European initiatives have begun to receive academic attention. The COOPERANTS project, which focuses on advanced smart services in the space industry, is highlighted in [54] for its pioneering work in the continuous exchange of functional digital twins between component suppliers and system integrators. The study outlines how Gaia-X-compliant architectures are used to improve software integration and model sharing in safety-critical aerospace systems—demonstrating the flexibility of data space concepts beyond traditional manufacturing. Finally, the Boost 4.0 initiative is examined in [45] for its contribution to cross-factory data spaces in digital manufacturing. The study presents three real-world implementations that leverage big data and sovereign sharing frameworks to enhance interoperability and analytics on highly automated shop-floors.

These examples collectively illustrate a growing convergence between academic research and industrial deployment of data spaces in Europe. While much of the literature still focuses on conceptual frameworks or single-use applications, projects like Catena-X in scientific studies and implementation roadmaps reflect the practical maturity and strategic relevance of data spaces in manufacturing and supply chains. Continued integration of academic and applied perspectives will be essential for standardizing practices, scaling infrastructures, and refining governance models across sectors.

4. Discussion

The evolving landscape of data spaces in manufacturing and supply chains has been examined in this paper by addressing three research questions: *(1) what are the bibliometric trends and patterns in scholarly publications on data spaces within these contexts; (2) which thematic contributions and conceptual perspectives emerge from that literature; and (3) what practical insights can be drawn from ongoing European initiatives deploying data spaces in industry?* To answer these questions, a comprehensive bibliometric analysis has been conducted—tracking publication volumes, authorship and outlet distributions, geographic and institutional affiliations, and keyword co-occurrence networks—alongside a structured content classification of thematic and technological contributions and a targeted review of European data-space projects.

Findings indicate a sharply increasing scholarly interest since 2020, characterized by both peer-reviewed journal articles and conference proceedings. Thematic clustering reveals a progression from foundational governance and federated-sharing principles through trust mechanisms and core platform infrastructures (e.g., Gaia-X, Catena-X) to application domains such as sustainability, circular-economy frameworks, and AI-enhanced factory operations. The automotive and electronics sectors lead real-world implementations, while Internet of Things, digital twins, and machine-learning techniques emerge as the predominant associated technologies. International Data Spaces remains the principal reference architecture, although complementary standards (AAS, OPC UA, Eclipse Data-space Connector) show varied uptake. European initiatives predominantly occupy implementation stages, supported mainly by EU funding and joint-innovation business models, yet inconsistencies in reporting and fragmented standard adoption highlight the need for greater harmonization.

The analysis of the current academic and practical landscape of data spaces in manufacturing and supply chains thus highlights promising developments. However, several critical opportunities for further research can be identified:

Developing standardized design taxonomies for data spaces: future research should aim to establish a unified and widely accepted taxonomy that classifies the fundamental components of data space architectures. This includes roles, system components, governance models, and data categories. A shared design vocabulary would enhance comparability across projects, facilitate replication of successful configurations, and support the transfer of best practice across sectors.

Expanding the use of advanced empirical research methodologies: with a growing number of real-world data space projects entering the operational phase, researchers are encouraged to adopt empirical methods such as longitudinal case studies, field experiments, and benchmarking analyses. These methodologies would enable a deeper understanding of performance outcomes, implementation challenges, and long-term impacts.

Operationalizing federated learning and decentralized AI within data spaces: there is strong alignment between data spaces' principles—such as data sovereignty and distributed governance—and techniques in federated and privacy-preserving AI. Future research should focus on developing and validating AI models that can operate in decentralized environments, respecting data usage constraints while enabling advanced analytics across organizational boundaries.

Integrating unstructured and textual data into data-sharing ecosystems: as manufacturing and supply chain operations generate increasing volumes of unstructured data—such as service logs, technical documentation, and communication records—research should explore how such data can be effectively shared and utilized within data spaces. This includes defining metadata standards, secure exchange protocols, and use cases for training large language models or enhancing semantic interoperability.

Enabling horizontal and cross-domain data integration: new research is needed to conceptualize and pilot frameworks that promote horizontal data exchange (among peer organizations) and cross-sector interoperability (e.g., between manufacturing, logistics, and energy). This includes designing incentive mechanisms, legal templates, and technical standards that facilitate data collaboration beyond traditional vertical supply chain structures.

These directions collectively call for interdisciplinary collaboration and deeper engagement between research and industry to shape the next generation of industrial data ecosystems.

5. Conclusions

This study addressed the growing relevance of data spaces in the context of manufacturing and supply chains, where fragmented data exchange continues to hinder interoperability, responsiveness, and innovation across organizational boundaries. Although digital integration tools have long been the subject of academic inquiry, the existing literature has not adequately captured the emerging paradigm of decentralized and federated data sharing enabled by data spaces. This gap is particularly striking given the increasing policy and industry attention to establishing secure and sovereign data ecosystems in Europe.

To fill this gap, the study conducted a systematic literature review combined with a document-based analysis of ongoing European initiatives. The goal was twofold: to synthesize scholarly knowledge on data spaces in manufacturing and supply chains, and to contextualize it through observation of real-world implementations. Three research questions guided the investigation, examining bibliometric patterns, thematic trends in the academic discourse, and practical insights from European projects.

The results show that academic interest in data spaces has accelerated since 2022, with increasing contributions from journals and conferences, particularly in industrial informatics and digital manufacturing. Germany and China emerged as the most active countries in terms of scholarly output, reflecting their institutional and industrial engagement with the topic. Content-wise, the literature remains concentrated on production and product lifecycle activities within vertically integrated value chains, with limited coverage of horizontal collaboration models. While IoT, digital twins, and machine learning are frequently discussed, the explicit adoption of data-sharing standards and architectures such as IDS or Gaia-X is inconsistent. Moreover, reporting practices vary significantly across studies, hindering comparability and knowledge transfer. On the other hand, the European data space initiatives review revealed a maturing ecosystem, with most projects situated in the implementation or operational phase. These initiatives strongly reflect the design principles of interoperability, sovereignty, and shared innovation. Catena-X, in particular, stands out as both a technical and governance benchmark, having influenced a significant portion of the academic literature through use cases involving circular economy, platform governance, and Manufacturing-as-a-Service. Other projects, such as COOPERANTS and Boost 4.0, highlight the applicability of data spaces beyond traditional manufacturing, including aerospace and advanced smart services.

Despite these advances, several limitations were identified. First, the academic literature still lacks a standardized design taxonomy, which would facilitate replication and cross-domain learning. Second, empirical validation remains limited, with few studies leveraging real-world performance data or advanced evaluation methodologies. Third, opportunities to integrate decentralized AI techniques, manage unstructured data, or promote horizontal and cross-sector data sharing remain largely untapped. Additionally, our methodological choices—namely, the focused keyword string, exclusive reliance on the Scopus database, and concentration on projects catalogued by the International Data Spaces Association—may have constrained the scope of our review and excluded relevant work documented elsewhere.

Future research should focus on consolidating design frameworks, expanding empirical inquiry, and exploring technical enablers that align with the federated nature of data spaces. Addressing these gaps will be critical for realizing the full potential of data-driven collaboration in industrial value networks. Future studies should also extend the scope beyond Europe to emerging regions, notably China, where data space activities are rapidly evolving but currently dispersed across multiple government programs, industry consortia, and corporate alliances; a dedicated, comparative mapping of these initiatives, once more consolidated data become available, will be essential for developing truly global design and governance models.

Author Contributions: Conceptualization, M.R., L.C., M.G., L.D.N. and A.R.; data curation, L.C. and M.G.; Formal analysis, L.C. and M.G.; funding acquisition, A.R.; investigation, L.C. and M.G.; methodology, L.C. and M.G.; project administration, A.R.; resources, A.R.; software, L.C. and M.G.; supervision, A.R.; validation, L.C. and M.G.; visualization, M.G.; writing—original draft, M.R., L.C., M.G., A.R. and L.D.N.; writing—review and editing, M.R., L.C., M.G., A.R. and L.D.N. All authors have read and agreed to the published version of the manuscript.

Funding: This study was carried out within the MICS (Made in Italy—Circular and Sustainable) Extended Partnership and received funding from the European Union Next-Generation EU (PIANO NAZIONALE DI RIPRESA E RESILIENZA (PNRR)—MISSIONE 4 COMPONENTE 2, INVESTIMENTO 1.3—D.D. 1551.11-10-2022, PE00000004). This manuscript reflects only the authors' views and opinions; neither the European Union nor the European Commission can be considered responsible for them.

Data Availability Statement: No new data were created or analyzed in this study.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Classification of reviewed papers on manufacturing and supply chain applications for data spaces.

Paper	Examined Sector	Operational Objective	Integration Type	Integrated Technologies	Shared Data	Standards Architecture
[40]	Automotive	S, R	Within supply chain	DT	Product	Gaia-X, AAS, IDS, Catena-X
[41]	Automotive	R	Within supply chain	None	Production	Gaia-X
[42]	Automotive	R, S	Within supply chain	DT	Maintenance	IDS-RAM
[43]	Automotive	S	Within supply chain	None	Product, Maintenance	None
[44]	Automotive	R	Within supply chain	BC	Production, Quality, Inventory, Energy	AAS
[45]	Electronic, Automotive	E	Within company	IoT, ML, BDA	Quality, Maintenance	IDS
[46]	Food	S	Within supply chain	ML, IoT	Product	Gaia-X
[47]	Food	S	Within supply chain	BC	Product	None
[48]	Food	R	Within supply chain	IoT, BDA, ML	Maintenance	Gaia-X, IDS
[49]	Machining	R	Within supply chain	ML	Product, Production	AAS, IDS
[50]	Machining	E	Within company	IoT, BDA	Quality, Maintenance	IDS, FIWARE
[51]	Machining	E, R	Within supply chain	None	Product, Production	Gaia-X, AAS
[52]	Battery	S	Within supply chain	DT	Product, Sustainability	IDS, AAS
[53]	Battery	R	Within company	ML	Product	AAS
[54]	Aerospace	E	Within sector	None	Product	Gaia-X
[55]	Footwear	E	Within supply chain	IoT	Supply, Production	IDS
[56]	Nuclear	E	Within company	IoT, BDA, ML	Product, Production, Maintenance	None
[57]	Nuclear	R	Within company	IoT, ML	Maintenance	None
[58]	Semiconductor	E	Within company	IoT, DT	Production	None
[59]	Home Appliance	E, R	Within supply chain	None	Production	AAS
[60]	Heavy Equipment	R	Within company, within supply chain	None	Production	None
[61]	PrecisionEngineering	E	Within supply chain	None	Product	None
[62]	None	E	Within company	ML	Energy	None

Table A1. *Cont.*

Paper	Examined Sector	Operational Objective	Integration Type	Integrated Technologies	Shared Data	Standards Architecture
[63]	Plastic/Metal	E	Within supply chain	DT, IoT	None	IDS
[64]	Steel casting/Oil refining	E	Within supply chain	BC	None	IDS
[65]	Not Specified	E, S	Within company	None	Quality	None
[66]	Not Specified	S, R	Within supply chain	None	Production, Demand, Sustainability	AAS, OPC UA, EDC
[67]	Not Specified	S	Within supply chain	None	Production	IDS, Gaia-X, AAS
[68]	Simulated	S, R	Within supply chain	IoT	Production, Product	IDS, Gaia-X
[69]	Electronic	R	Within company	None	Production	None
[70]	Steel	R	Within company	DT, ML, IoT	Production	AAS, IDS, Gaia-X
[71]	Simulated	R	Within supply chain	DT, ML, IoT	Production	IDS, Gaia-X, AAS

R: Resilience, S: Sustainability, E: Efficiency, DT: Digital Twin, ML: Machine Learning, IoT: Internet of Things, BDA: Big Data Analytics, BC: Blockchain.

References

1. Omar, A.; Davis-Sramek, B.; Myers, M.B.; Mentzer, J.T. A global analysis of orientation, coordination, and flexibility in supply chains. *J. Bus. Logist.* **2012**, *33*, 128–144. [CrossRef]
2. Mattsson, L.G. Reorganization of distribution in globalization of markets: The dynamic context of supply chain management. *Supply Chain Manag. Int. J.* **2003**, *8*, 416–426. [CrossRef]
3. Erfurth, T.; Bendul, J. Integration of global manufacturing networks and supply chains: A cross case comparison of six global automotive manufacturers. *Int. J. Prod. Res.* **2018**, *56*, 7008–7030. [CrossRef]
4. Bianchini, D.; Fapanni, T.; Garda, M.; Leotta, F.; Mecella, M.; Rula, A.; Sardini, E. Digital Thread for Smart Products: A Survey on Technologies, Challenges and Opportunities in Service-Oriented Supply Chains. *IEEE Access* **2024**, *12*, 125284–125305. [CrossRef]
5. Spanaki, K.; Gürgüç, Z.; Adams, R.; Mulligan, C. Data supply chain (DSC): Research synthesis and future directions. *Int. J. Prod. Res.* **2018**, *56*, 4447–4466. [CrossRef]
6. Chatfield, D.C.; Kim, J.G.; Harrison, T.P.; Hayya, J.C. The Bullwhip Effect-Impact of Stochastic Lead Time, Information Quality, and Information Sharing: A Simulation Study. *Prod. Oper. Manag.* **2004**, *13*, 340–353. [CrossRef]
7. Leuschner, R.; Rogers, D.S.; Charvet, F.F. A meta-analysis of supply chain integration and firm performance. *J. Supply Chain Manag.* **2013**, *49*, 34–57. [CrossRef]
8. Saqib, Z.A.; Qin, L.; Menhas, R.; Lei, G. Strategic Sustainability and Operational Initiatives in Small- and Medium-Sized Manufacturers: An Empirical Analysis. *Sustainability* **2023**, *15*, 6330. [CrossRef]
9. Saqib, Z.A.; Zhang, Q. Impact of sustainable practices on sustainable performance: The moderating role of supply chain vis-ibility. *J. Manuf. Technol. Manag.* **2021**, *32*, 1421–1443. [CrossRef]
10. Saqib, Z.A.; Zhang, Q.; Ou, J.; Saqib, K.A.; Majeed, S.; Razzaq, A. Education for sustainable development in Pakistani higher education institutions: An exploratory study of students' and teachers' perceptions. *Int. J. Sustain. High. Educ.* **2020**, *21*, 1249–1267. [CrossRef]
11. Saqib, Z.A.; Ikram, M.; Qin, L. Mediating role of eWOM's in green behavior interaction and corporate social responsibility: A stakeholder theory perspective. *Int. J. Ethics Syst.* **2025**. *ahead of print*. [CrossRef]
12. Saqib, Z.A.; Xu, G.; Luo, Q. Green Manufacturing for a Green Environment from Manufacturing Sector in Guangdong Prov-ince: Mediating Role of Sustainable Operations and Operational Transparency. *Appl. Sci.* **2024**, *14*, 10637. [CrossRef]

13. Gabellini, M.; Calabrese, F.; Regattieri, A.; Ferrari, E. Multivariate Multi-Output LSTM for Time Series Forecasting with Intermittent Demand Patterns. In Proceedings of the 27th Summer School Francesco Turco, Sanremo, Italy, 7–9 September 2022; 2022; pp. 1–7.
14. Gabellini, M.; Civolani, L.; Regattieri, A.; Calabrese, F. A Data Model for Predictive Supply Chain Risk Management. In Proceedings of the CARV 2023, Bologna, Italy, 20–23 June 2023; Lecture Notes in Mechanical Engineering. pp. 365–372. [CrossRef]
15. Gabellini, M.; Civolani, L.; Calabrese, F.; Bortolini, M. A Deep Learning Approach to Predict Supply Chain Delivery Delay Risk Based on Macroeconomic Indicators: A Case Study in the Automotive Sector. *Appl. Sci.* **2024**, *14*, 4688. [CrossRef]
16. Gabellini, M.; Calabrese, F.; Civolani, L.; Regattieri, A.; Mora, C. A Data-Driven Approach to Predict Supply Chain Risk Due to Suppliers' Partial Shipments. In *Smart Innovation, Systems and Technologies*; Scholz, S.G., Howlett, R.J., Setchi, R., Eds.; Springer Science and Business Media Deutschland GmbH: Berlin/Heidelberg, Germany, 2024; Volume 377, pp. 227–237. [CrossRef]
17. Gabellini, M.; Mak, S.; Schoepf, S.; Brintrup, A.; Regattieri, A. A continuous training approach for risk informed supplier selection and order allocation. *Prod. Manuf. Res.* **2025**, *13*, 2447035. [CrossRef]
18. Regattieri, A.; Gabellini, M.; Calabrese, F.; Civolani, L.; Galizia, F.G. Balancing Data Acquisition Benefits and Ordering Costs for Predictive Supplier Selection and Order Allocation. *Appl. Sci.* **2024**, *14*, 4306. [CrossRef]
19. Mahmud, P.; Paul, S.K.; Azeem, A.; Chowdhury, P. Evaluating supply chain collaboration barriers in smalland medium-sized enterprises. *Sustainability* **2021**, *13*, 7449. [CrossRef]
20. Shukla, R.K.; Garg, D.; Agarwal, A. Modeling barriers in supply chain coordination. *Int. J. Manag. Sci. Eng. Manag.* **2012**, *7*, 69–80. [CrossRef]
21. Kembro, J.; Selviaridis, K. Exploring information sharing in the extended supply chain: An interdependence perspective. *Supply Chain Manag.* **2015**, *20*, 455–470. [CrossRef]
22. Steinfield, C.; Markus, M.L.; Wigand, R.T. Through a glass clearly: Standards, architecture, and process transparency in global supply chains. *J. Manag. Inf. Syst.* **2011**, *28*, 75–108. [CrossRef]
23. Yoon, J.; Talluri, S.; Rosales, C. Procurement decisions and information sharing under multi-tier disruption risk in a supply chain. *Int. J. Prod. Res.* **2020**, *58*, 1362–1383. [CrossRef]
24. Wang, Z.; Ye, F.; Tan, K.H. Effects of managerial ties and trust on supply chain information sharing and supplier opportunism. *Int. J. Prod. Res.* **2014**, *52*, 7046–7061. [CrossRef]
25. Coche, E.; Kolk, A.; Ocelík, V. Unravelling cross-country regulatory intricacies of data governance: The relevance of legal insights for digitalization and international business. *J. Int. Bus. Policy* **2024**, *7*, 112–127. [CrossRef]
26. Surucu-Balci, E.; Iris, Ç.; Balci, G. Digital information in maritime supply chains with blockchain and cloud platforms: Supply chain capabilities, barriers, and research opportunities. *Technol. Forecast. Soc. Change* **2024**, *198*, 122978. [CrossRef]
27. Smith, K.; Seligman, L.; Swarup, V. Everybody Share: The Challenge of Data-Sharing Systems. *Computer* **2008**, *41*, 54–61. [CrossRef]
28. Nylund, P.A.; Brem, A. Standardization in innovation ecosystems: The promise and peril of dominant platforms. *Technol. Forecast. Soc. Change* **2023**, *194*, 122714. [CrossRef]
29. Damsgaard, J.; Truex, D. Binary trading relations and the limits of EDI standards: The Procrustean bed of standards. *Eur. J. Inf. Syst.* **2000**, *9*, 173–188. [CrossRef]
30. Chandra, A.; Weissman, J.; Heintz, B. Decentralized edge clouds. *IEEE Internet Comput.* **2013**, *17*, 70–73. [CrossRef]
31. Alsamhi, S.H.; Hawbani, A.; Kumar, S.; Timilsina, M.; Al-Qatf, M.; Haque, R.; Nashwan, F.; Zhao, L.; Curry, E. Empowering Dataspace 4.0: Unveiling Promise of Decentralized Data-Sharing. *IEEE Access* **2024**, *12*, 112637–112658. [CrossRef]
32. Csernatoni, R. The EU's hegemonic imaginaries: From European strategic autonomy in defence to technological sovereignty. *Eur. Secur.* **2022**, *31*, 395–414. [CrossRef]
33. König, P.D. Fortress Europe 4.0? An analysis of EU data governance through the lens of the resource regime concept. *Eur. Policy Anal.* **2022**, *8*, 484–504. [CrossRef]
34. Culotta, C.; Blome, C.; Henke, M. Theories of digital platforms for supply chain management: A systematic literature review. *Int. J. Phys. Distrib. Logist. Manag.* **2024**, *54*, 449–475. [CrossRef]
35. Chen, Z.; Huang, L. Digital twins for information-sharing in remanufacturing supply chain: A review. *Energy* **2021**, *220*, 119712. [CrossRef]
36. Tiwari, S. Supply chain integration and Industry 4.0: A systematic literature review. *Benchmarking* **2021**, *28*, 990–1030. [CrossRef]
37. Narayanan, S.; Marucheck, A.S.; Handfield, R.B. Electronic data interchange: Research review and future directions. *Decis. Sci.* **2009**, *40*, 121–163. [CrossRef]
38. Cao, Q.; Schniederjans, D.G.; Schniederjans, M. Establishing the use of cloud computing in supply chain management. *Oper. Manag. Res.* **2017**, *10*, 47–63. [CrossRef]
39. Wan, P.K.; Huang, L.; Holtskog, H. Blockchain-Enabled Information Sharing within a Supply Chain: A Systematic Literature Review. *IEEE Access* **2020**, *8*, 49645–49656. [CrossRef]

40. Mügge, J.; Grosse Erdmann, J.; Riedelsheimer, T.; Manoury, M.M.; Smolka, S.O.; Wichmann, S.; Lindow, K. Empowering End-of-Life Vehicle Decision Making with Cross-Company Data Exchange and Data Sovereignty via Catena-X. *Sustainability* **2023**, *15*, 7187. [CrossRef]
41. Schöppenthau, F.; Patzer, F.; Schnebel, B.; Watson, K.; Baryschnikov, N.; Obst, B.; Chauhan, Y.; Kaever, D.; Usländer, T.; Kulkarni, P. Building a Digital Manufacturing as a Service Ecosystem for Catena-X. *Sensors* **2023**, *23*, 7396. [CrossRef]
42. Manoury, M.; Riedelsheimer, T.; Hellmeier, M.; Meyer, T. Supporting Changes in Digital Ownership and Data Sovereignty Across the Automotive Value Chain with Catena-X. *Procedia Comput. Sci.* **2025**, *253*, 374–383. [CrossRef]
43. Steiner, B.; Münch, C. Leveraging digital data spaces in purchasing and supply management: Paving the way to the circular economy exemplified by Catena-X. *J. Purch. Supply Manag.* **2024**, *30*, 100951. [CrossRef]
44. Liao, Y.; Kong, X.; Yin, L.; Gao, Y.; Dong, X. An industrial dataspace for automotive supply chain: Secure data sharing based on data association relationship. *J. Ind. Inf. Integr.* **2025**, *44*, 100778. [CrossRef]
45. Lázaro, O.; Alonso, J.; Ohlsson, P.; Tijsma, B.; Lekse, D.; Volckaert, B.; Kerkhove, S.; Nielandt, J.; Masera, D.; Patrimia, G.; et al. Next-Generation Big Data-Driven Factory 4.0 Operations and Optimization: The Boost 4.0 Experience. In *Technologies and Applications for Big Data Value*; Springer: Berlin/Heidelberg, Germany, 2022; pp. 345–371.
46. Tessmer, A.; Mast, J.; Loer, P.; Brunner, M.; Lippert, F.; Aschenbruck, N. An Open Source Trusted Edge Architecture of Federated Dataspaces for the Food Supply Chain. In Proceedings of the 7th IFIPIoT 2024 International IFIP WG 5.5 Work-shops, Nice, France, 6–8 November 2024; Springer: Berlin/Heidelberg, Germany, 2024; pp. 3–11.
47. Abbasi, A.G.; Rydberg, A.; Altmann, P. Towards a verifiable and secure data sharing platform for livestock supply chain. In Proceedings of the 2022 IEEE Intl Conf on Dependable, Autonomic and Secure Computing, Intl Conf on Pervasive Intelligence and Computing, Intl Conf on Cloud and Big Data Computing, Intl Conf on Cyber Science and Technology Congress (DASC/PiCom/CBDCom/CyberSciTech), Falerna, Italy, 12–15 September 2022; IEEE: Piscataway, NJ, USA, 2022; pp. 1–6.
48. Farahani, B.; Monsefi, A.K. Smart and collaborative industrial IoT: A federated learning and data space approach. *Digit. Commun. Netw.* **2023**, *9*, 436–447. [CrossRef]
49. Usländer, T.; Schöppenthau, F.; Schnebel, B.; Heymann, S.; Stojanovic, L.; Watson, K.; Nam, S.; Morinaga, S. Smart factory web—A blueprint architecture for open marketplaces for industrial production. *Appl. Sci.* **2021**, *11*, 3585. [CrossRef]
50. Alonso, Á.; Pozo, A.; Cantera, J.M.; de la Vega, F.; Hierro, J.J. Industrial data space architecture implementation using fiware. *Sensors* **2018**, *18*, 2226. [CrossRef]
51. Volkmann, M.; Wagner, A.; Hermann, J.; Ruskowski, M. Asset Administration Shells and GAIA-X Enabled Shared Pro-duction Scenario. In *Flexible Automation and Intelligent Manufacturing: Establishing Bridges for More Sustainable Manufacturing Systems*; Lecture Notes in Mechanical Engineering; Springer: Berlin/Heidelberg, Germany, 2024. [CrossRef]
52. Volz, F.; Sutschet, G.; Stojanovic, L.; Usländer, T. On the Role of Digital Twins in Data Spaces. *Sensors* **2023**, *23*, 7601. [CrossRef]
53. Stier, S.P.; Xu, X.; Gold, L.; Möckel, M. Ontology-Based Battery Production Dataspace and Its Interweaving with Artificial Intelligence-Empowered Data Analytics. *Energy Technol.* **2024**, *12*, 2301305. [CrossRef]
54. Theil, S.; Holtmann, M.; Reuter, N.; Reuter, M. Enabling Seamless Collaboration in AOCS/GNC Engineering: COOPERANTS Project's Approach to Continuous Integration and Verification of Component Models. In Proceedings of the IAF Space Sys-tems Symposium, Milan, Italy, 14–18 October 2024.
55. Pinto, P.; Sousa, C.; Cardeiro, C. Data spaces based approach for B2B data exchange: A footwear industry case. *Procedia Comput. Sci.* **2023**, *219*, 933–940. [CrossRef]
56. Wang, Y.; Cheng, Y.; Zhu, Y.; Tao, F. Exploration on industrial system-aware dataspace towards smart manufacturing. In Proceedings of the 2022 IEEE 18th International Conference on Automation Science and Engineering (CASE), Mexico City, Mexico, 20–24 August 2022; IEEE Computer Society: Washington, DC, USA, 2022; pp. 1883–1889. [CrossRef]
57. 57 Wang, Y.; Cheng, Y.; Qi, Q.; Tao, F. IDS-KG: An industrial dataspace-based knowledge graph construction approach for smart maintenance. *J. Ind. Inf. Integr.* **2024**, *38*, 100566. [CrossRef]
58. Chen, D.; Zhang, J.; Wu, L.; Zhang, P.; Wang, M. Industrial data space application framework for semiconductor wafer manufacturing system scheduling. *J. Manuf. Syst.* **2024**, *77*, 464–482. [CrossRef]
59. Inigo, M.A.; Legaristi, J.; Larrinaga, F.; Perez, A.; Cuenca, J.; Kremer, B.; Montejo, E.; Porto, A. Towards Standardized Manufacturing as a Service through Asset Administration Shell and International Data Spaces Connectors. In Proceedings of the IECON 2022—48th Annual Conference of the IEEE Industrial Electronics Society, Brussels, Belgium, 17–20 October 2022. [CrossRef]
60. Chen, G.; Zhao, K.; Wang, M.; Wang, X.; Shen, Y. Towards Industry Data Governance: Construction of An Industrial Data Decentralized Distributed Symbiotic Sharing Space Based on Tensor. In Proceedings of the ICAC 2023—28th International Conference on Automation and Computing, Birmingham, UK, 30 August–1 September 2023; Institute of Electrical and Elec-tronics Engineers Inc.: Piscataway, NJ, USA, 2023. [CrossRef]
61. Li, Z.; Faheem, F.; Husung, S. Collaborative Model-Based Systems Engineering Using Dataspaces and SysML v2. *Systems* **2024**, *12*, 18. [CrossRef]

62. Ranathunga, T.; McGibney, A.; Bharti, S. Enabling secure and self-sovereign machine learning model exchange in manu-facturing data spaces. *J. Ind. Inf. Integr.* **2024**, *42*, 100733. [CrossRef]
63. Moreno, T.; Almeida, A.; Ferreira, F.; Caldas, N.; Toscano, C.; Azevedo, A. Digital twin for manufacturing equipment in industry 4.0. *Adv. Transdiscipl. Eng.* **2021**, *15*, 362–367. [CrossRef]
64. Shin, M. Development of Collaboration Model for Data Space-Based Open Collaboration Platform in Continuous Process Industries. *Sustainability* **2025**, *17*, 126. [CrossRef]
65. Hagenhoff, P.; Biehs, S.; Möller, F.; Otto, B. Designing a Reference Architecture for Collaborative Condition Monitoring Data Spaces: Design Requirements and Views. In *Design Science Research for a Resilient Future*; Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics); Springer: Berlin/Heidelberg, Germany, 2024. [CrossRef]
66. Neubauer, M.; Steinle, L.; Reiff, C.; Ajdinović, S.; Klingel, L.; Lechler, A.; Verl, A. Architecture for manufacturing-X: Bringing asset administration shell, eclipse dataspace connector and OPC UA together. *Manuf. Lett.* **2023**, *37*, 1–6. [CrossRef]
67. Jurmu, M.; Niskanen, I.; Kinnula, A.; Kääriäinen, J.; Ylikerälä, M.; Räsänen, P.; Tuikka, T. Exploring the Role of Federated Data Spaces in Implementing Twin Transition within Manufacturing Ecosystems. *Sensors* **2023**, *23*, 4315. [CrossRef] [PubMed]
68. Kunz, L.; Reif, M.; Petzsche, T.; Schmallenbach, A.; Plociennik, C.; Ruskowski, M. Realizing Closed-Loop Supply Chain Networks based on Dataspaces and Manufacturing Marketplaces. *IFAC-PapersOnLine* **2024**, *58*, 235–240. [CrossRef]
69. Guo, J.; Cheng, Y.; Wang, D.; Tao, F.; Pickl, S. Industrial Dataspace for smart manufacturing: Connotation, key technolo-gies, and framework. *Int. J. Prod. Res.* **2023**, *61*, 3868–3883. [CrossRef]
70. Bakopoulos, E.; Sipsas, K.; Nikolakis, N.; Alexopoulos, K. A Digital Twin and Data Spaces framework towards Resilient Manufacturing Value Chains. *IFAC-PapersOnLine* **2024**, *58*, 163–168. [CrossRef]
71. Alexopoulos, K.; Weber, M.; Trautner, T.; Manns, M.; Nikolakis, N.; Weigold, M.; Engel, B. An industrial data-spaces framework for resilient manufacturing value chains. *Procedia CIRP* **2023**, *116*, 299–304. [CrossRef]
72. Kari, A.; Bellin, P.; Matzner, M.; Gersch, M. Governing the emergence of network-driven platform ecosystems. *Electron. Mark.* **2025**, *35*, 4. [CrossRef]
73. Mügge, J.; Hahn, I.R.; Riedelsheimer, T.; Chatzis, J.; Boes, J. End-of-life decision support to enable circular economy in the automotive industry based on digital twin data. *Procedia CIRP* **2023**, *119*, 1071–1077. [CrossRef]
74. Gieß, A.; Neumann, J.; Jussen, I.; Schweihoff, J. Green data, green future? How data spaces enable the product carbon foot-print calculation for the automotive industry: A case study on Catena-X. In Proceedings of the INFORMATIK 2024, Wiesba-den, Germany, 26 September 2024; Lecture Notes in Informatics (LNI), Proceedings—Series of the Gesellschaft fur Informatik (GI). Gesellschaft fur Informatik (GI): Bonn, Germany, 2024; Volume 352, pp. 1799–1812. [CrossRef]