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Industrialising Digital Twins: Governance of Data, Metadata, and AI in Production System Ecosystems

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Abstract. Industrial digital twins offer opportunities for cross-firm optimisation and AI-enabled decision-making, yet their deployment at enterprise scale remains limited. While many organisations have implemented pilot projects, scaling digital twins across production systems and organisational boundaries remains difficult because current approaches focus primarily on data integration and modelling, with less attention to governance. This paper aims to conceptualise industrial digital twins as distributed decision-support systems and to explain how governance of data, metadata, access rights, and AI-enabled decisions can support their industrialisation in production system ecosystems. The study adopts a conceptual research approach, drawing on digital twin research, data governance, digital servitization, data spaces, zero-trust architecture, and emerging European regulation. The paper develops a governance framework that separates data ownership from metadata governance and links lifecycle stages, ecosystem actors, policy-driven access control, zero-trust enforcement, and decision accountability. The results show that the value of digital twins is not created by data availability alone, but by the controlled, context-aware use of data in decision-making across organisational boundaries. The paper contributes by positioning metadata as a governance mechanism and by outlining a research agenda for scalable, accountable, AI-enabled digital twin ecosystems.

Keywords: Industrial Digital Twins; Digital Twin Governance; Metadata Governance; Zero-Trust Architecture; AI-Enabled Decision-Making.

1 Introduction

Industrial digital twins are increasingly recognised as a key enabler of advanced production systems, supporting lifecycle integration, cross-firm optimisation, and data-enabled decision-making. In this paper, an industrial digital twin is defined as a lifecycle-spanning digital representation of a physical asset, process, or production system that uses data, models, and contextual information to support decisions and, where appropriate,

influence actions in the physical system. Rather than serving solely as virtual representations, digital twins support decision-making throughout design, manufacturing, operation, and maintenance, thereby contributing to product-service systems and digital servitization [1-3]. As shown in Fig. 1, digital twins enable actors to formulate context-specific queries across lifecycle stages, generating insights that inform action.

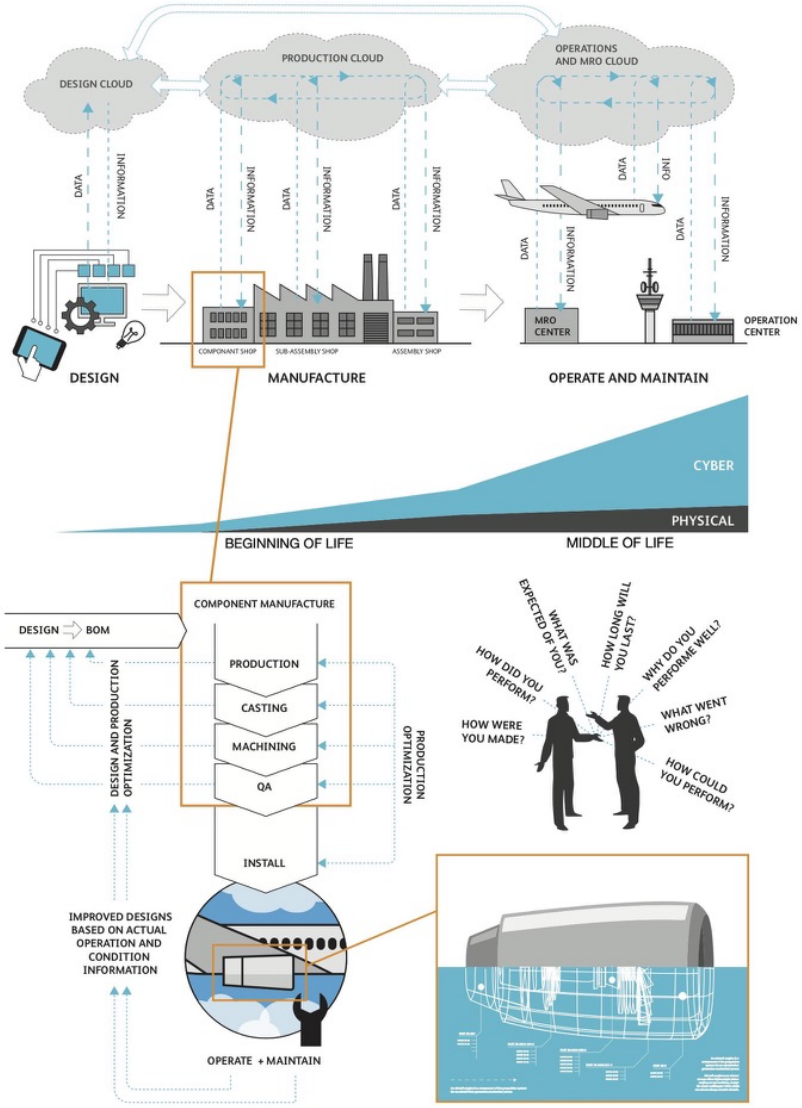

Fig. 1. Digital twins as lifecycle-spanning decision-support systems.
The figure illustrates how multiple actors interact with digital twins across lifecycle stages through context-specific queries, enabling knowledge generation and decision-making [4].

While many organisations have implemented pilot digital twin applications, scaling them across production systems and organisational boundaries remains difficult. Digital twins may work in isolated pilots but become harder to scale when multiple organisations must share data, interpret results, assign decision rights, and remain accountable for AI-enabled recommendations and actions. Existing research has mainly focused on modelling, simulation, and system integration [5, 6] while paying less attention to governance in multi-actor ecosystems [7]. Standardisation initiatives, including the Asset Administration Shell (IDTA) and data space architectures, provide a foundation for interoperability and controlled data exchange [8, 9]. However, they do not fully address how metadata, access rights, and AI-enabled decision accountability should be governed across organisational boundaries.

A key limitation of current approaches is the assumption that managing data alone suffices. In reality, inter-organisational digital twins serve as distributed decision-support systems in which multiple actors require context-specific insights across lifecycle stages [10]. This shifts attention from treating data as a uniformly exchangeable resource to the conditions under which it is accessed, interpreted, and used. Metadata that captures semantics, context, and usage conditions becomes essential for coordination and interoperability among collaborating partners [11, 12]. The increasing integration of AI, which uses shared data for operational optimisation, introduces challenges related to access, control, and accountability in organisational decision-making [13, 14]. Therefore, the industrialisation of digital twins requires a shift from data-focused approaches to the governance of collaborative decision-making, metadata, access rights, and accountability across lifecycle stages and organisational boundaries. Without such governance, digital twins remain isolated applications and cannot scale across production-system ecosystems. To close this gap, this paper proposes a governance framework that connects data ownership, metadata management, lifecycle decision processes, and accountability mechanisms among collaborating actors.

This paper adopts a conceptual research approach and is presented as a position paper. It integrates insights from digital twin research, digital servitization, data governance, metadata governance, data spaces, zero-trust architecture, and AI accountability. The framework was developed through a conceptual synthesis: limitations in existing digital twin approaches were identified, translated into governance requirements, and organised into framework elements covering data ownership, metadata governance, policy-driven control, zero-trust enforcement, and AI-enabled decision accountability. The paper, therefore, reconceptualises digital twins as lifecycle-spanning decision systems and identifies future research directions for their industrialisation within production-system ecosystems.

Accordingly, the paper addresses the following research question: "*How can industrial digital twins be governed as distributed, metadata-driven decision systems?*". The findings are used to outline a research agenda for their industrialisation within production-system ecosystems.

The remainder of this paper is organised as follows. Section 2 examines digital twins as decision-support systems across the product lifecycle. Section 3 addresses governance challenges in multi-actor production-system ecosystems. Section 4 presents the proposed

governance framework. Section 5 outlines the research agenda. Section 6 discusses theoretical contributions and managerial implications. Section 7 concludes the paper.

2 Conceptual Foundations: Digital Twins as Decision Systems

To address the research question, it is important to clarify the conceptual role of digital twins within the wider ecosystem of collaborating production systems. While digital twins are often viewed in terms of modelling, simulation, and data integration, these perspectives do not fully capture how they facilitate value realisation and scaling across organisational boundaries [1, 5, 6]. In practice, digital twins operate across the lifecycle phases of product design, manufacturing, operation, and maintenance, supporting interactions among multiple actors who depend on shared system representations to inform decisions [7, 14].

A key source of ambiguity in digital twin research is the inconsistent use of the term 'digital twin' across different types of digital representations. Kritzinger [15] distinguishes between a digital model, a digital shadow, and a digital twin based on the direction of data exchange. A digital model has no automated data exchange with the physical system. A digital shadow allows one-way data flow from the physical system to the digital representation. A digital twin facilitates bidirectional data exchange, where the digital system can influence the physical system. This distinction is important because it affects how digital representations are implemented, governed, and utilised throughout the lifecycle stages [11]. Effectively, this means that the existence of a digital twin requires active governance. Governance requirements can be complex, and a digital model primarily raises issues of version control, provenance, and model validity. A digital shadow raises concerns about data quality, timeliness, and observation rights. A digital twin expands these challenges further to include write-back authority, decision rights, explainability, and liability. As digital twins scale across organisational boundaries, governance must extend beyond data integration to encompass how data, metadata, and decisions are controlled and accounted for by different actors.

Complementing the digital twin is the concept of the digital thread, which represents the continuous flow of information across lifecycle stages, connecting design, manufacturing, operation, and maintenance [16]. The digital thread provides traceability and continuity of information, forming the foundation of the data infrastructure, while the digital twin uses this data to generate insights and support decision-making [2, 5]. This distinction emphasises that value is not inherent in data itself but arises through its application in context, a central tenet of the service-dominant logic perspective [10, 17].

Instead of serving merely as data repositories or simulation tools, digital twins enable actors to pose context-specific queries and generate insights that guide actions across different stages [2, 10, 7]. This shifts the emphasis from viewing data as a static resource to recognising decision-making as the primary means of creating value, aligning with emerging research on digital twin-enabled services and ecosystems [3, 14].

The effectiveness of such systems relies on their capacity to convert heterogeneous data into actionable knowledge. While data in digital twins is often intended to represent aspects of physical systems, its significance depends on how it is interpreted within a

specific decision context, a process that requires integrating data, models, and contextual information [5, 11, 12]. In distributed environments, this challenge is heightened by the need to align meaning across different actors and systems [7, 12].

Consequently, digital twins can be viewed as socio-technical infrastructures that coordinate interactions between data, models, and actors to support distributed decision-making. This perspective demonstrates that the main challenge is not only data integration but also actors' access to, interpretation of, and use of data; shared governance structures influence all activities. It further suggests that governance must go beyond simply managing data to encompass the control of decision rights, usage conditions, and accountability in multi-actor ecosystems [13, 18].

3 Governance Challenges in Digital Twin Ecosystems

Building on the idea of digital twins as distributed, lifecycle-spanning decision systems, the main challenge shifts from technical implementation to governance. While digital twins facilitate the integration of data, models, and analytics throughout the lifecycle, their industrialisation depends on how interactions among actors, data, and decisions are coordinated in multi-organisational settings. Existing research has mostly focused on modelling, simulation, and system integration [5], offering limited guidance on managing access, usage, and decision rights among actors with differing objectives [7]. As digital twins operate across organisational boundaries, coordination becomes a key obstacle to scaling.

Digital twin ecosystems are inherently multi-actor, involving operators, OEMs, service providers, and platform providers who contribute different data, capabilities, and objectives. These actors engage with digital twins across lifecycle stages, leading to distributed decision-making that must be coordinated across organisational and functional boundaries [1, 7]. While interoperability approaches support data exchange and system integration [5], they do not address how actors interpret and act on shared data in context, which limits their effectiveness in enabling coordinated decision-making.

A key limitation of current approaches is the dominance of data-centric views, which assume that managing data and ownership alone is enough to create value. However, in digital twin ecosystems, value comes from how data is utilised in decision-making processes rather than from the data itself [10, 17]. In multi-actor settings, restricting data to protect ownership can impede value creation, but increasing data availability does not resolve differences in interpretation or usage [12]. Consequently, data-centric approaches fail to address how data is employed in distributed decision-making.

The governance challenge, therefore, shifts from managing data to governing how data is accessed, interpreted, and used. Metadata plays a central role by linking data to its context, semantics, and usage conditions, enabling coordinated interpretation across actors [11, 12]. However, current approaches often treat metadata as a technical artefact rather than as a governance mechanism. In distributed environments, metadata must also encode access rights and usage constraints to enable controlled, context-aware data use [18].

Existing approaches provide important building blocks for the industrialisation of digital twins, but they address different parts of the governance challenge. AAS-based approaches support structured asset representation and metadata governance [8, 19], while data space architectures enable sovereign, controlled data exchange across organisations [9, 20, 21]. Interoperability frameworks support technical and semantic integration [22, 23], and AI governance addresses transparency, oversight, and accountability for AI-enabled systems [24, 25, 26]. Although these approaches support interoperability, controlled data exchange, and collaboration, they do not fully resolve how data is governed during use across different actors [27]. They therefore remain fragmented and do not fully explain how metadata, access rights, usage conditions, decision authority, and accountability can be combined into an ecosystem-level governance framework for industrial digital twins.

The integration of AI introduces additional governance challenges as digital twins increasingly generate predictions, recommendations, and automated actions, raising questions about transparency, control, and accountability in distributed settings [13, 14]. This requires governance not only of operational data but also of AI artefacts throughout their lifecycle, drawing on MLOps and AI asset management practices, including models, datasets, versions, deployment environments, monitoring outputs, and decision logs [28]. As digital twins incorporate more operational data, they may provide richer inputs for AI-enabled, real-time decision-making, but also increase risks related to interpretation, misuse, decision authority, and accountability. Governance must therefore include mechanisms for model provenance, performance monitoring, and accountability for AI-supported decisions.

4 A Governance Framework for Industrial Digital Twins

Building on the governance challenges outlined in Section 3, the framework is developed as a conceptual response to the limitations of current approaches to digital-twin industrialisation. While existing approaches provide important foundations for modelling, interoperability, and system integration [5], they offer limited guidance on how interactions among actors, data, metadata, and decisions should be governed in distributed environments [7]. As digital twins expand across organisational boundaries and lifecycle stages, these coordination challenges become more significant, especially when AI-enabled decision-making is involved [13]. The framework, therefore, translates these limitations into governance requirements concerning metadata, access rights, usage conditions, policy enforcement, and accountability. These requirements provide the basis for the proposed framework elements: data ownership, metadata governance, policy-driven control, zero-trust enforcement, and AI-enabled decision accountability.

Existing governance approaches centred on data ownership, interoperability, and technical exchange are insufficient in this context. While these approaches help digital twin infrastructures operate, they offer limited guidance on governing strategic, cross-organisational decisions, in which multiple actors interpret shared data, make distributed decisions, and create emergent ecosystem-level outcomes. Digital twin ecosystems depend on distributed decision-making, in which value arises from the utilisation of data rather

than from the data itself [10, 17]. Governance must therefore shift from managing data as an asset to regulating how data is accessed, interpreted, and utilised across different actors.

This shift is reflected in emerging regulatory frameworks that emphasise controlled data sharing and accountability. The European Data Act establishes rights to access and use data without transferring ownership [29]. At the same time, the EU AI Act introduces requirements for transparency, human oversight, and accountability in AI-enabled systems [25]. Together, these developments reinforce the need for governance approaches that regulate not only data access but also the conditions under which data and decisions are used [26].

In response, digital twin ecosystems require governance frameworks that are lifecycle-oriented, multi-actor, and decision-centric. Governance must ensure the continuity of context and traceability of decisions throughout lifecycle stages [1], while facilitating coordination among actors with different objectives [7, 23]. Interoperability alone is inadequate, as it does not address how data is interpreted and applied in context [22], and it also requires governance to oversee the meaning, context, and usage shared among actors.

A central implication is the separation of data ownership from access and usage rights. In digital twin ecosystems, data remains closely linked to assets and organisational responsibilities, making a complete transfer of control impractical [12]. At the same time, lifecycle decision-making requires data to be accessed and utilised across organisational boundaries, which calls for dynamic, context-dependent access control mechanisms [7, 22].

Within this framework, metadata plays a central role by providing the contextual, semantic, provenance, quality, and usage-related information required to interpret data and apply it in decision-making processes [11, 12]. These metadata elements inform policies that define who may access data, under which conditions, for which purpose, and with which decision rights. While interoperability approaches support data exchange, they do not ensure consistent interpretation or controlled use across actors [23]. Metadata addresses this gap by linking data to its context, meaning, and permissible use, enabling coordinated and controlled interaction across organisational boundaries [18].

Governance is operationalised through policy-driven mechanisms that manage access, use, and decision-making. Unlike role-based approaches, policy-driven governance offers detailed, context-aware control by defining conditions for data use and decision-making [22]. These policies must be dynamically linked to metadata, enabling governance rules to adjust throughout lifecycle stages and in response to actor relationships, while ensuring that usage conditions remain enforceable across systems [12].

Zero-trust architecture provides the enforcement mechanism for this governance approach. It assumes that no actor or system is implicitly trusted and requires all access requests and actions to be continuously verified against defined policies [30]. In digital twin ecosystems, this ensures that metadata-defined access and usage conditions are consistently enforced across actors and systems, even in distributed environments [13].

Based on these principles, the framework presented here integrates data ownership, metadata governance, policy-driven control, and decision-making within a layered structure. Data remains under the control of its producer, reflecting data sovereignty principles

[12, 29], while metadata provides the structures necessary for interpretation and coordination [18]. In this way, the framework complements AAS and data space approaches by adding governance mechanisms for decision rights, accountability, and enforcement across organisational boundaries. Policies define and enforce access rights, usage conditions, and trust levels [22]. At the decision layer, value is created through actions taken by human and AI agents with clearly defined accountability [24, 25].

Fig. 2 illustrates the proposed governance framework for industrial digital twins across organisational boundaries. The framework distinguishes governance layers that support interactions among ecosystem actors, including data governance, metadata governance, and lifecycle decision processes. The lower part of the framework represents the focal organisational environment in which operational data, metadata, policies, and decision accountability are managed. The upper layer represents collaborating actors that interact with the focal organisation through governed access, usage conditions, and decision rights. By making the organisational boundary explicit, the figure highlights that industrialising digital twins requires governance mechanisms that operate not only within organisations but also across partner interfaces.

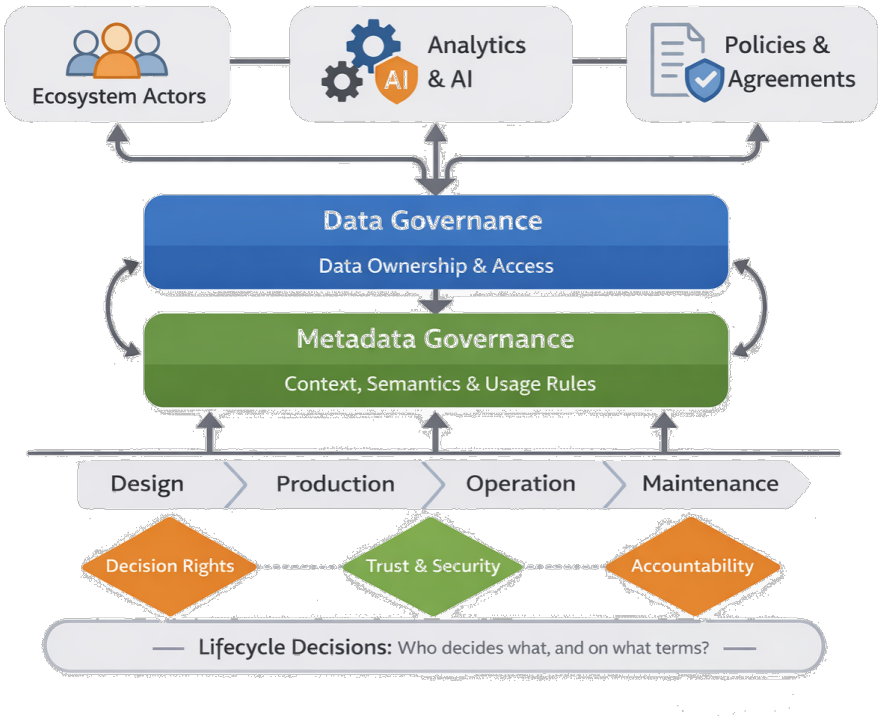

Fig. 2. Governance framework for distributed digital twins.
Distinguishing data governance and metadata governance, the framework links lifecycle stages, ecosystem actors, and AI-enabled decision-making, emphasising decision rights, trust, and accountability for scalable deployment.

To illustrate its application, consider a predictive maintenance scenario for an industrial pump. Operational data remains under the operator's control, while metadata describes the asset, operating context, data quality, provenance, and permitted uses. A service provider may access selected condition-monitoring data only if the applicable policy allows this purpose, such as fault prediction or maintenance planning. The AI model may generate a maintenance recommendation, but the right to approve or execute the intervention remains defined by the governance policy. A zero-trust mechanism verifies access, model use, and action rights before the recommendation is acted upon. Decision logs record which data, model version, actor, and approval rule were involved, supporting traceability and accountability across the operator, OEM, platform provider, and service provider.

5 Research Agenda

Building on the governance framework introduced in Section 4 and illustrated in Fig. 2, this section outlines a research agenda that shifts the focus of digital twin research from data integration towards the governance of distributed, multi-actor decision ecosystems. The research agenda is derived from the governance challenges identified in the preceding sections and from the core framework elements: metadata governance, data ownership and access, AI-enabled decision accountability, zero-trust enforcement, and scaling from pilot applications to industrial deployment. Table 1 summarises the resulting research areas, their focus, and guiding research questions. In particular, these research areas highlight the central role of metadata, policy-driven control, and decision accountability in digital twin governance.

At the same time, the separation of data control from access and usage rights raises important questions regarding value creation, especially in light of regulatory developments such as the European Data Act discussed in Section 4. The increasing integration of AI further complicates these challenges by introducing issues of decision authority, responsibility, and accountability in environments that are partially or fully automated. As digital twins scale from pilot applications to industrial deployment, future research must focus on governance mechanisms that operationalise metadata management, access control, and AI accountability in a policy-driven, context-aware manner, enabling scalable, coordinated operations across lifecycle stages and organisational boundaries.

Table 1. Research agenda for digital twin governance

Research Area	Key Focus	Research Questions
Governing Metadata and Context	Metadata as coordination layer linking context, semantics, and usage	— How can metadata represent context dynamically across lifecycle stages? — How can semantics and usage rights be integrated into metadata models? — How can metadata governance be implemented and standardized across multi-actor ecosystems?
Data Ownership, Access, and Value Realisation	Separation of data control and access rights under regulatory constraints	— How can access rights be designed to enable value creation while preserving data sovereignty? — What business models support controlled data sharing in digital twin ecosystems? — How can regulatory requirements (e.g. EU Data Act) be operationalized in access governance mechanisms?
AI and Decision Accountability	Governance of AI-enabled decisions and automated actions	— How can decision authority be defined across human and AI actors in digital twin systems? — How can responsibility and liability be assigned for AI-driven decisions and actions? — How can traceability and explainability be ensured in distributed, AI-enabled decision processes?
Zero-Trust Digital Twin Ecosystems	Policy-driven governance under limited trust conditions	— How can zero-trust principles be operationalized in digital twin ecosystems? — How can different levels of trust be represented and enforced in access and usage policies? — How can policy-driven governance be implemented across organizational and technical boundaries?
Scaling from Pilot to Industrial Deployment	Transition from pilots to scalable, enterprise-wide systems	— How can governance frameworks evolve as digital twins scale across lifecycle stages and organizations? — What organizational and technical capabilities are required for large-scale deployment? — How can governance mechanisms support interoperability and coordination at ecosystem scale?

6 Discussion

This paper examines how governance can enable scalable, cross-organisational deployment and the value realisation of digital twins within production system ecosystems. The analysis shows that the central challenge is not only technical integration but also how data is accessed, interpreted, and used in distributed decision-making. This extends prior work on digital twin architectures, modelling, and interoperability [5] by foregrounding coordination among actors with different objectives, responsibilities, and decision contexts [7].

The proposed framework addresses this challenge by separating data ownership from access and usage rights, aligning with emerging approaches to data access and sovereignty [29]. It also positions metadata as a coordination mechanism for context, meaning, and usage conditions [18]. It employs policy-driven control to support accountable decision-making across organisational boundaries [22]. This implies that industrialising digital twins requires governance of interaction, not only governance of data. In other words, the key issue is not only whether data can be exchanged, but also under what conditions it is interpreted, used, acted upon, and made accountable.

Although the paper focuses on digital twins, the governance issues identified apply more broadly to distributed, data-enabled systems. Similar challenges arise in data spaces and cross-organisational service systems, where value depends on coordinated decisions amid limited trust [12]. This aligns with service-dominant logic, which holds that value is created through the use of resources in context rather than through resources alone [17]. The framework, therefore, provides a basis for understanding digital twins not only as technical infrastructures but also as socio-technical decision infrastructures that require governance mechanisms for metadata, access rights, policy enforcement, and accountability.

6.1 Theoretical Contributions

This paper makes three theoretical contributions. First, it reconceptualises industrial digital twins as governed decision systems rather than only as technical representations, simulations, or integration infrastructures. This shifts attention from the availability of data to the governance of how data is interpreted and used to support decisions across organisational boundaries. In doing so, the paper extends service-dominant logic by showing that value co-creation in digital twin ecosystems depends on governing the resource use of resources in context [10, 17].

Second, the paper positions metadata as a governance mechanism rather than merely as a technical artefact that supports interoperability. Prior research has addressed semantic interoperability, ontologies, and ecosystem coordination [22, 23], but has paid less attention to how metadata can govern the interpretation and use of data. By linking metadata to context, semantics, usage rights, policy-driven access, and decision accountability, the paper contributes to emerging research on governing distributed, data-enabled ecosystems [12].

Third, the paper contributes to digital twin governance by integrating policy-driven control, zero-trust enforcement, and AI-enabled decision accountability into a single conceptual framework. This extends existing work on interoperability and controlled data exchange by showing how access rights, usage conditions, decision authority, and accountability can be coordinated across multiple actors. The framework, therefore, provides a conceptual basis for future research on the governance of industrial digital twins as cross-organisational decision infrastructures.

6.2 Managerial Implications

The findings have direct implications for the design and governance of production systems within digital transformation contexts. They indicate that successful adoption of digital twins relies not only on technical capabilities but also on governance mechanisms that facilitate controlled data sharing and coordinated decision-making throughout the lifecycle stages. This corroborates earlier findings that organisational and ecosystem-level challenges often hinder adoption despite technical viability [1, 7].

For practitioners, this suggests that digital twin initiatives should be designed with governance in mind from the outset. OEMs need to retain control over operational data while allowing controlled access for partners and customers, aligning with emerging data-sharing practices [18]. Operators should develop skills in data governance, AI oversight, and accountability as digital twins advance toward decision support and automation systems [13]. Platform providers are required to support policy-driven governance and interoperability, facilitating secure and scalable interactions across various actors [22]. More broadly, managers should understand that the value of digital twins is realised not simply through data ownership but through the use of data in decision-making, aligning with service-oriented views of value creation [17]. This necessitates developing organisational capabilities to manage access rights, metadata, and accountability in increasingly regulated and AI-enabled environments [26].

7 Conclusion

This paper explored how industrial digital twins can be governed to enable scalable, cross-organisational deployment and value creation within production-system ecosystems. The analysis shows that the main challenge is not data integration but governance, through a collective agreement on how data is accessed, interpreted, and utilised in distributed decision-making processes. By conceptualising digital twins as decision systems that span their lifecycle, the paper shifts focus from data-centric architectures to governance mechanisms that coordinate metadata, access rights, and AI-enabled decisions across actors and stages of the lifecycle.

While the analysis focuses on digital twins, the results are applicable beyond this specific domain. Digital twins are just one example of a broader category of distributed, data-driven systems in which multiple actors must coordinate decisions based on shared data under conditions of limited trust. Therefore, the main contribution of this paper is to enhance the understanding of how data, metadata, and AI-enabled decisions can be managed within multi-actor ecosystems, including data spaces and other cross-organisational service systems.

The paper's three contributions are: a reconceptualisation of digital twins as governed decision systems; the positioning of metadata as a governance mechanism connecting context, semantics, and usage rights across multi-actor ecosystems; and a policy-driven, zero-trust framework integrating data access, metadata management, and decision accountability, aligned with emerging regulatory developments such as the European Data Act and the AI Act.

The findings highlight that the industrialisation of digital twins and, more broadly, distributed data-driven systems, depends on governance mechanisms that enable controlled interaction without requiring full data sharing or a centralised authority. At the same time, the study stresses the need for further research to develop and assess these mechanisms in real-world settings. Future research should explore how metadata-oriented governance, policy-based access control, and AI accountability can be implemented across lifecycle stages and organisational boundaries, and how these mechanisms can support value creation within practical limits.

Overall, this paper improves the understanding of digital twins as governed socio-technical systems and broadens the perspective on managing distributed, data-driven decision-making systems. By shifting the focus from data integration to governance, this approach provides a foundation for the scalable implementation of digital twins and related systems as AI-enabled decision-making infrastructures.

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