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Organizational Over Technology: Why Digital Twin Adoption in Oil and Gas Stalls—A Review and the Case for Mechanism Design

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ABSTRACT

A literature review of ten peer-reviewed articles published between 2018 and 2025 examines the adoption of digital twins in the oil and gas sector. According to Meza et al. [1], 68% of the implementations are digital shadows, which involve one-way data flow, 18% are digital models, and only 14% are actual digital twins with bidirectional feedback. Wanasinghe et al. [2] noted that 88% of the published work comes from the industry, with 95% related to the supply chain and 5% from operators, while 12% of the studies are from academic institutions. Furthermore, only 7% of the research involves collaboration between industry and academia (Meza et al. [1]). The lack of standardization and data silos are identified as the major obstacles in six studies each. Pandi [3] highlights a persistent "broken chain" in data transfer that has persisted for more than two decades, emphasizing that errors in 10% of engineering work can significantly impact 90% of costs. Only three papers present specific quantitative outcomes: Shen et al. [4] reported a 5.41% increase in efficiency across 35 oil wells, while LeBlanc [5] modeled a net present value of $211 million over 27 years.

These findings suggest that the main limitation is organizational rather than technological. Theoretical frameworks, especially those developed by Professor Jun Cai on incentive-compatible mechanisms for distributed systems, provide a foundational approach for tackling governance issues. Future studies should focus on applying these mechanism design concepts within the specific institutional environment of digital twins in the oil and gas industry.

Keywords: Digital twin, Oil and gas, Mechanism design, Data governance

INTRODUCTION TO THE REVIEW

Digital twin technology has been gaining significant attention in the oil and gas industry since 2017. However, the literature shows that what is typically referred to as a "digital twin" is often not a true digital twin. The obstacles to adoption are not due to technology but are more related to organizational and governance factors.

Wanasinghe et al. [2] conducted a systematic literature review of 1,099 articles and narrowed the corpus through successive screening stages. They found that the overall rate of publication was less than ten articles per year before 2017, with a notable increase in 2018 and 2019. The authors noted that prior to 2017, oil and gas-related publications did not use the term "digital twin" but instead used terms like "virtual environment," "digital model," and "virtual model." Meza et al. [1] reviewed 98 articles from 2018 to 2023 and found that only 14% of the implementations qualified as actual digital twins – defined as systems with real-time data integration and two-way feedback that impacts the physical asset. In contrast, 68% were digital shadows – systems with real-time data integration but no two-way flow – and 18% were digital models – systems without real-time data integration but using batched data.

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VII, July 2026

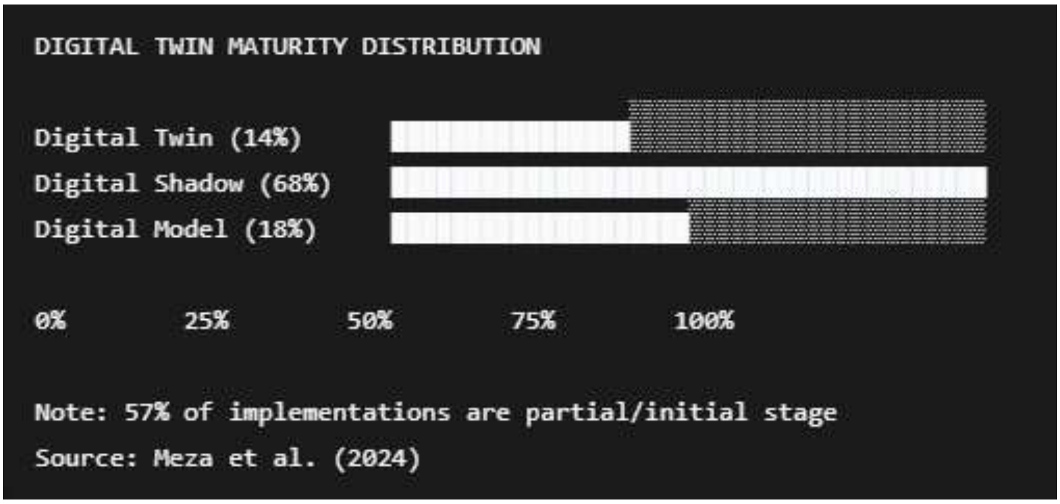

Figure 1. Digital Twin Maturity Distribution in Oil and Gas (Meza et al. [1]).

This gap in maturity exists because the term "digital twin" is used broadly without strict adherence to its defining characteristic: two-way feedback. As noted by Cameron et al. [6], "marketing and vendor communication is raising expectations about digital twins," while the actual implementations lag behind. The distinction between digital models, digital shadows, and digital twins – formalized by Kritzinger et al. [7] and cited by both Wanasinghe et al. [2] and Meza et al. [1] – is crucial. Digital models and digital shadows are already common practices in many organizations. The promise of the digital twin lies in its ability to proactively respond to information from the physical object in an automated way, thus generating positive value or avoiding negative outcomes. The fact that 86% of what is referred to as "digital twin" does not fully meet this definition shows that the industry is still in the early stages of real digital twin adoption. Because of this, the main issue is not the lack of digital tools, but the failure to connect physical assets with their digital versions. This gap in maturity helps explain why governance and incentive problems—not technical abilities—are the main obstacles to digital twin adoption.

The Stakeholder Imbalance And Industry-Academia Collaboration Gap

Digital twin research and development in the oil and gas sector is mostly led by industry players, focused on the supply chain rather than the operators, and there is very little meaningful collaboration between industry and academic institutions.

Wanasinghe et al. [2] used a four-stage filtering process (1,099 → 375 → 199 → 82 articles) and found that at the final stage, 88% of publications using the term "digital twin" came from the industry, while only 12% were from academic sources.

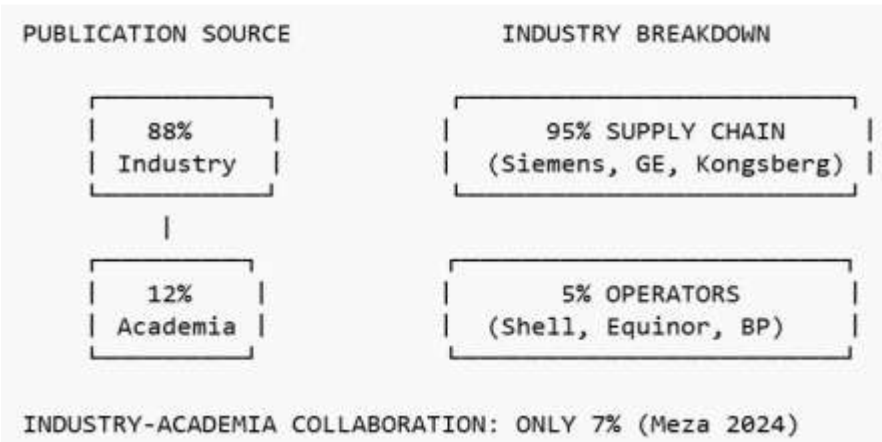

Figure 2. Stakeholder Distribution in Oil and Gas Digital Twin Research (Wanasinghe et al. [2]).

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Within industry contributions, 95% were from supply chain vendors such as Siemens, GE, Kongsberg, and Akselos, while only 5% came from operators like Shell, Equinor, BP, and Saudi Aramco. Meza et al. [1] confirmed this trend, finding that 65% of the articles were written by corporate authors alone, 28% by academic authors alone, and just 7% involved collaboration between industry and academia. The authors also noted that in their 98 articles, about 34.44% of the first authors did not have their nationality listed, and the main companies mentioned included ADNOC, Aker Solutions, Gazprom Neft, PetroChina, Siemens, Baker Hughes, and CNOOC.

This imbalance directly affects digital twin interoperability and standardization. When supply chain vendors lead innovation, they often develop their own proprietary platforms (e.g., Siemens MindSphere, GE Predix, Kongsberg Kognitwin, Akselos RB-FEA) that are not designed to work together. Operators, who own the assets and have the strongest interest in data integration, contribute only 5% of research output according to Wanasinghe et al. [2]. The 7% collaboration rate between industry and academia, as reported by Meza et al. [1], means that theoretical progress in areas like mechanism design, data governance, and semantic interoperability is not being applied in practice. As Cameron et al. [6] pointed out, semantic standards such as ISO 15926 have not lived up to their potential as tools for integration and data exchange. This is partly because of a lack of tools and because the standard development aimed to be too comprehensive, ignoring smaller, more realistic problems along the way.

Therefore, the governance issue is not just technical but structural. The stakeholders who have the most incentive to create interoperable, standardized digital twins are operators. The errors in 10% of the engineering work can significantly affect the remaining 90% of the costs.

Data silos and fragmentation are also commonly mentioned. Li et al. [8] pointed out that "data is still scattered across different systems, and the large information gap makes it difficult to effectively share data between various business units." Xue et al. [9] mentioned "multiple self-developed systems with overlapping functions" and that "data standards have not yet been established." Cameron et al. [6] observed that data is stored "in different places, in both structured and unstructured formats, not connected to a common database, takes a long time to produce, and has not been thoroughly and consistently checked for quality."

These organizational problems continue because they stem from misaligned incentives, not a lack of technical capability. The technologies needed for data integration, such as cloud platforms, APIs, and IIoT, are well-developed and available, as shown by Wanasinghe et al. [2] and Meza et al. [1]. The main obstacles are related to behavior and structure: stakeholders do not have a reason to share data in standardized formats because it does not provide a competitive edge and could reveal confidential information. Pandi [3] explains that EPC contractors are not encouraged to produce data-focused deliverables, compared to drawing-based ones, because contracts do not include data requirements. Xue et al. [9] also note that operators face the issue of "many self-built systems with overlapping functions" and "data standards have not yet been unified." Correia et al. [10] argue that "semantic interoperability is essential for a shared understanding of data," but is not addressed by current platforms. This creates a cycle: there is no demand for standardized data, so there is no supply, leading to continued fragmentation.

Therefore, the main obstacle to adopting digital twins is not a lack of technology, but the absence of governance systems that align incentives for data sharing. This conclusion, supported by studies from Li et al. [8], Wanasinghe et al. [2], Cameron et al. [6], Meza et al. [1], Correia et al. [10], and Pandi [3], strongly supports the use of mechanism design and network economics in addressing challenges related to digital twins in the oil and gas industry.

The Geographic And Application Concentration

Digital twin research in the oil and gas sector is focused on the North Sea and the Gulf of Mexico, with the United States, Norway, and the United Kingdom leading the way. The research is mainly concerned with asset monitoring and maintenance. Wanasinghe et al. [2] identified the top ten countries by the number of publications:

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VII, July 2026

the United States (leading), Norway, the United Kingdom, Canada, China, Italy, the Netherlands, Brazil, Germany, and Saudi Arabia.

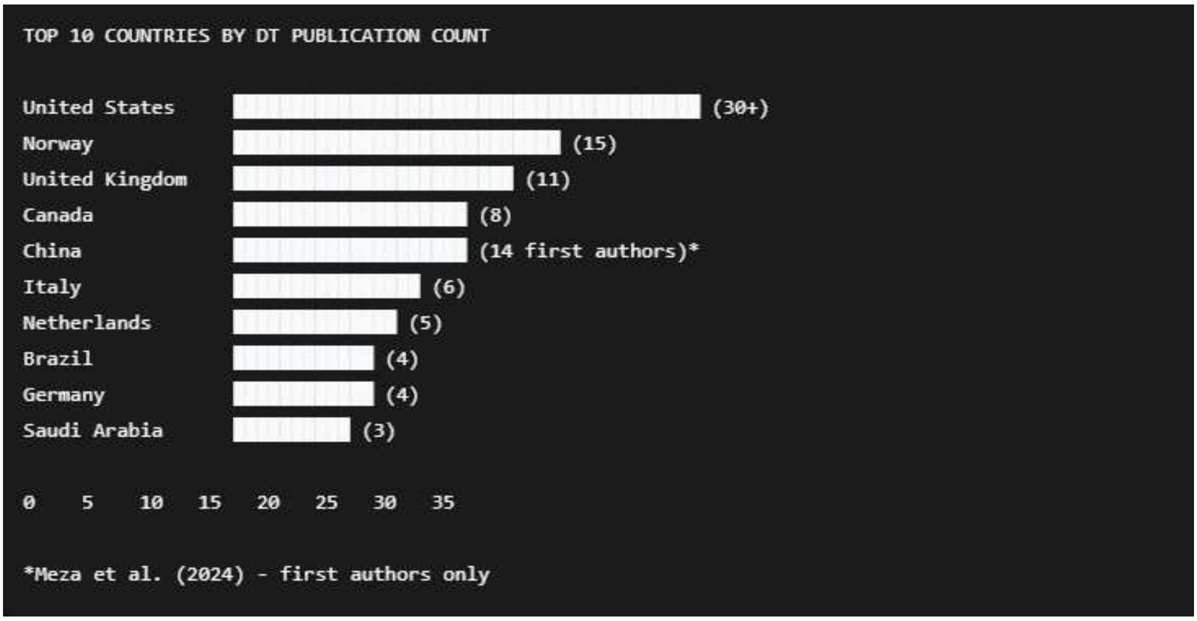

Figure 3. Top Countries by Digital Twin Publication Count (Wanasinghe et al. [2]; Meza et al. [1]).

The authors found that the top three countries (the United States, Norway, and the United Kingdom) contributed approximately 97 articles, or about 49% of the total. They noted that "given that the major oil and gas operations are in the North Sea and the Gulf of Mexico, this distribution is expected."

Meza et al. [1] found a similar pattern, with the United States contributing about 30 articles, Norway contributing 15, and the United Kingdom contributing 11. The authors also pointed out that China became a significant contributor with 14 first-author articles.

Regarding applications, both studies highlighted asset monitoring and maintenance as the primary use. Wanasinghe et al. [2] identified, in their level four sorting, asset monitoring and maintenance, project planning, and life cycle management as the top three. The authors stated that "asset monitoring and maintenance, project planning, and lifecycle management are the most anticipated areas for digital twin applications." Meza et al. [1] categorized the objectives of the 98 articles into three main types: monitoring, control, and management (featured in 9 articles); optimization of outcomes and resources (featured in 12 articles); and prediction and detection of abnormalities (featured in 10 articles). The authors concluded that "asset monitoring and maintenance, project planning, and lifecycle management continue to be the top applications of digital twin."

LeBlanc [5] confirmed this trend, noting that in the 12 case studies she evaluated, asset monitoring and maintenance were the most common applications. Her analysis using taxonomy levels, technology readiness levels, and concept levels found that "six out of the twelve case studies reviewed have passed the demonstration level and are operating in a ready state," but she also noted that "there is not yet a fully developed cognitive digital twin distinguished at any taxonomy level within the oil and gas industry."

The geographic concentration reflects the locations of major offshore oil and gas operations in the North Sea and the Gulf of Mexico, where harsh environments, deepwater challenges, and mature assets create strong economic incentives for digital innovation.

LeBlanc [5] noted that Norway has become a hub for digital twin innovation, with case studies from Aker BP's Ivar Aasen platform (a sparsely staffed, onshore control center) and Shell's Nyhamna gas plant. The dominance of asset monitoring and maintenance as the top application reflects the industry's core economic challenge: reducing unplanned downtime. LeBlanc [5] quantified this challenge, stating that "deepwater facilities, on

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VII, July 2026

average, experience up to 5% annual production losses due to unplanned downtime, costing oil and gas billions of dollars." Shen et al. [4] provided field evidence from 35 wells, showing that digital twin implementation increased system efficiency by 5.41 percentage points, directly addressing this downtime issue.

Therefore, while the literature provides strong evidence about where digital twin research is taking place (the United States, Norway, and the United Kingdom) and what it is focused on (asset monitoring), it also reveals that these applications are largely confined to one-way monitoring instead of true bidirectional digital twins.

The focus on monitoring, as documented by Wanasinghe et al. [2] and Meza et al. [1], reflects the maturity gap previously identified: the industry is good at gathering and visualizing data but has not yet established a feedback loop.

The Quantification Gap—Limited Empirical Evidence Of Value

Despite many claims about the value of digital twins, there is very little empirical data on the return on investment. Only three of the ten reviewed papers provide numerical performance data.

TABLE 1: QUANTIFIED RESULTS FROM REVIEWED PAPERS

Paper	Metric	Value
Shen et al. (2021)	System efficiency	+5.41 percentage points
	Power consumption	-48.12 kWh/day
	Number of wells	35 wells
LeBlanc (2020)	Facility availability	+3.6 percentage points
	Net Present Value	+$211 million
	Time horizon	27 years
Dmitriev et al. (2025)	Market size (2026)	$48 billion
	Cost savings (2030)	$300 billion
	Production increase	+6%
	Downtime reduction	-4%

Note: Only 3 of 10 papers (30%) provide quantified results.

Figure 4. Quantified Results from Reviewed Papers.

Among the papers reviewed, only three present quantified results. Dmitriev et al. [11] report market projections: a $48 billion digital twin market by 2026, with a projected $60 billion market by 2030, and a $300 billion cost reduction in construction and planning. A 5-year ramp-up period is anticipated, with facility availability expected to start at 5% and increase to 90% once the system reaches steady state. The author examined five digital twin scenarios (DT10 to DT90, denoting goals for average improvement of 10% to 90%) and discovered that a highly robust digital twin (DT90 case) boosts facility availability from 81.0% to 84.6% (+3.6 percentage points), resulting in an improved net present value of $211 million over 27 years. The author also explored reductions in offshore staffing from 100 personnel to zero, finding that "as the costs of offshore personnel decrease, the cost of software development and maintenance will increase sharply." Deployment costs ranged from $11 million (DT50, fully staffed, based on the Nyhamna plant reference) to $41 million (DT90, unstaffed, based on the DARPANOMARS program reference), with the total cost of ownership reaching $103 million for the most aggressive case.

The lack of quantified results is not accidental. As LeBlanc [5] points out, "realized value is often hard to quantify and explicitly link to digital twin technology." Operators regard performance data as proprietary and do not make it public. Moreover, as Cameron et al. [6] note, "explicit references to digital twins in the oil and gas industry are few and are often high-level, non-technical presentations" – typically vendor marketing rather than empirical evidence. This gap in quantification has real-world consequences: without proven return on investment (ROI), operators are unable to justify the significant investment needed for implementing true digital twins. LeBlanc [5] estimates the total cost of ownership for a single facility to be between $45 million and $103 million,

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VII, July 2026

depending on the level of automation. Pandi [3] provides a heuristic: the 90/10 cost rule – "mistakes in 10% engineering will have a huge impact in 90% cost" – which highlights the economic risk of poor data governance.

Hence, the absence of quantified evidence creates a circular problem: operators do not invest in true digital twins because ROI is unproven, yet ROI cannot be proven without investment in true digital twins.

This suggests that mechanism design could be instrumental in creating shared data ecosystems where the costs and benefits of implementing digital twins are shared among stakeholders, enabling the gathering of empirical evidence without exposing proprietary information – a gap identified by LeBlanc [5], Cameron et al. [6], and Pandi [3].

The Governance Gap As A Mechanism Design Problem

Persistent governance issues identified in the literature—lack of standardization, data silos, fragmented incentives, and the "broken chain" of data handover—constitute a classic mechanism design problem requiring incentive-compatible solutions.

Across the reviewed literature, the governance gap presents in several forms. Pandi [3] explains how EPC contractors are not contractually required to produce data-centric deliverables, resulting in drawing-based outputs that compel downstream disciplines to "re-enter the data in their design," leading to "double handling of data, inaccurate information, quality issues, rework, and collateral delays." The author notes that in a typical oil and gas project with 150 to 300 P&IDs, each containing multiple tags for equipment, pipelines, instruments, and valves, manual data handling creates "potential chances of inconsistency and rework in design."

Wanasinghe et al. [2] report that 95% of industry contributions come from supply chain vendors who benefit from proprietary lock-in, while operators, who own the assets and have the greatest incentive for integration, contribute only 5% of research output.

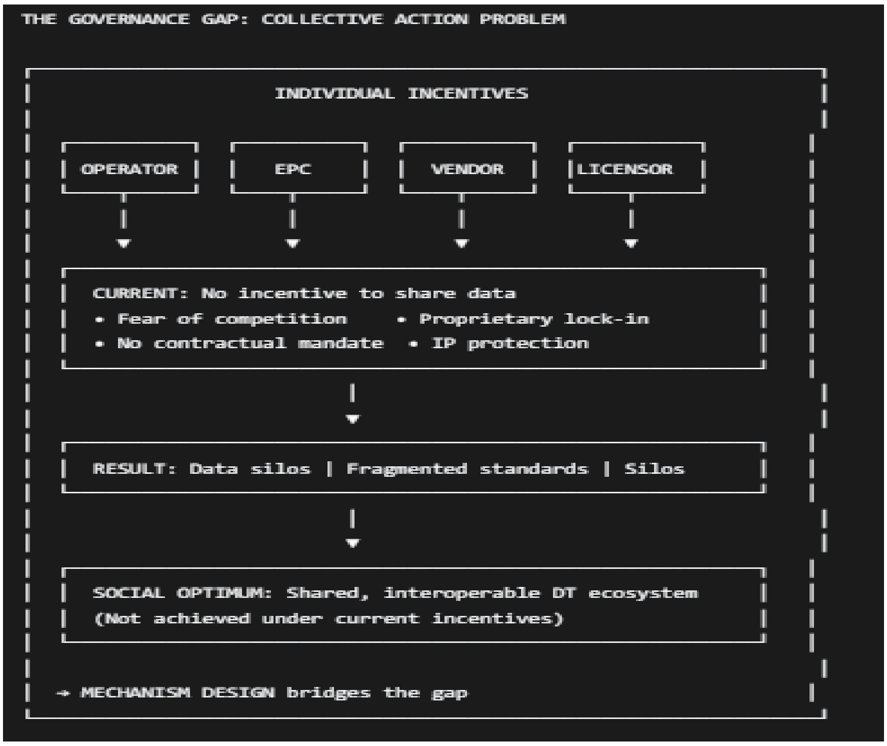

Figure 5. The Governance Gap as a Collective Action Problem.

The authors also point out that "approximately 75% of US O&G companies experienced at least one cybersecurity-related incident," illustrating the risks of data sharing without proper governance.

Cameron et al. [6] observe that semantic standards such as ISO 15926 "have not lived up to their promise as tools for integration and data exchange" because "the standard development attempted to be comprehensive at the expense of solving smaller, realistic problems along the way."

The authors also identify eight specific challenges: business models and confidentiality, work practices, scope, usability, integration, maintenance, computational overload, and uncertainty and validation. Regarding integration, they state that "a digital twin will consist of many data sources and simulation models" and ask, "how can we connect different models together without creating a 'point-to-point nightmare'?"

Correia et al. [10] evaluate the OSDU data platform and conclude that while it provides essential resources, it lacks semantic interoperability and "searches on the platform are performed at the syntactic level... limits discovery of relevant data since it requires the user to know the properties of the data beforehand."

The authors also note that the platform "does not allow for keeping track of the decisions this data generated, in which analysis and simulation models this data was used."

These patterns are not random. They reflect a classic collective action problem: each stakeholder (operator, EPC, vendor, licensor) would benefit from a shared, interoperable digital twin ecosystem, but each has individual incentives that conflict with the industry-wide social optimum. As Pandi [3] explains, operators fear exposing operational data to competitors. EPC contractors are not contractually obligated to produce data-centric deliverables. Vendors benefit from proprietary lock-in, as documented by Wanasinghe et al. [2]. Licensors protect intellectual property. The result is a suboptimal equilibrium where total industry welfare is lower than it could be, but no single stakeholder can unilaterally change the outcome.

This is closely aligned with the domain of mechanism design, a branch of economics and game theory concerned with designing rules and incentives so that self-interested participants can contribute to a desired collective outcome. Mechanism design has been effectively used to solve problems related to resource allocation, data sharing, and aligning incentives in distributed systems, such as crowdsensing, edge computing, and spectrum auctions.

The oil and gas digital twin challenge has similar characteristics: it involves multiple self-interested participants, each with private information, and a shared goal of maximizing social welfare, which is not currently being achieved through existing structures.

As a result, mechanism design presents a strong theoretical basis for tackling the governance issues in the adoption of oil and gas digital twins.

None of the studies reviewed have applied mechanism design to the governance of digital twins in this sector, suggesting a clear path for future research at the intersection of digital twins, network economics, and incentive mechanism design.

Prof. Jun Cai [12] from Concordia University has created detailed mechanism design frameworks that can be applied to digital twin systems.

These include methods for incentive-compatible data sharing, online incentive structures for distributed learning, and truth-telling mechanisms for resource allocation when information is private. These frameworks offer a solid theoretical foundation that can be adapted to address governance challenges in the oil and gas digital twin context.

Prof. Jun Cai is a professor in the Department of Electrical and Computer Engineering at Concordia University in Montreal, Canada. His research includes digital twins, distributed machine learning, mechanism design, and network economics, with applications to distributed systems, edge computing, and federated learning. He is the author of "Self-Evolving Digital Twin Over Wireless Networks - Dynamic Twin Construction and Service Interaction" [13], published by Springer in 2026, and co-author of "Human Digital Twin - Exploring Connectivity and Security Issues," published by Springer in 2024.

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VII, July 2026

Prof. Cai's work in mechanism design provides frameworks that may be relevant to governance and incentive problems in digital twin ecosystems.

One such framework, developed by Li, Cai, and Ni [14] in 2022, is titled "Truthful Deep Mechanism Design for Revenue-Maximization in Edge Computing With Budget Constraints," published in the IEEE Transactions on Vehicular Technology. This framework ensures that participants truthfully share their private information, similar to how stakeholders in oil and gas might be reluctant to share operational data. The design is incentive-compatible, meaning that rational agents benefit by being truthful.

Another framework, by Li, Cai, He, Zhang, and Chen [15] in 2024, is "Online Incentive Mechanism Designs for Asynchronous Federated Learning in Edge Computing," published in the IEEE Internet of Things Journal.

This addresses situations where stakeholders join the digital twin network at different times, which is common in the oil and gas industry. The mechanisms ensure that data contributors remain honest even when participation is asynchronous.

In 2025, Li, Cai, Lu, and Chen [16] presented "Incentive Mechanism Design for Cross-Device Federated Learning: A Reinforcement Auction Approach" in the IEEE Transactions on Mobile Computing. This paper uses reinforcement learning and auction theory to create adaptable mechanisms for distributed systems, suitable for the dynamic nature of the oil and gas industry.

Additionally, Okegbile, Cai, Chen, and Yi developed [17] "A Reputation-Enhanced Shard-Based Byzantine Fault-Tolerant Scheme for Secure Data Sharing in Zero Trust Human Digital Twin Systems," published in the IEEE Internet of Things Journal. This work uses blockchain-based reputation systems to secure data sharing in digital twin environments, addressing cybersecurity concerns raised by previous studies.

TABLE 2: PROF. JUN CAI'S MECHANISM DESIGN FRAMEWORKS

Framework	Key Feature	O&G Application
Truthful Deep Mechanism Design (Li, Cai, Ni 2022)	Truthful reporting of private info	Operators share operational data
Online Incentive for Asynchronous Federated Learning (Li, Cai 2024)	Asynchronous participation	EPCs join at different times
Reinforcement Auction Approach (Li, Cai 2025)	Adaptive, dynamic mechanisms	Changing asset conditions
Reputation-Enhanced Byzantine Fault-Tolerant (Okegbile, Cai 2024)	Blockchain-based reputation + secure sharing	Cybersecurity (75% incident rate)

Figure 6. Prof. Jun Cai's Mechanism Design Frameworks.

CONCLUSION

The potential relevance of these mechanisms to the oil and gas digital twin challenge is evident from the shared governance characteristics.

A recurring issue addressed by these mechanisms—multiple stakeholders holding private information and facing different incentives—resembles the oil and gas digital twin context, where operators, EPC contractors, vendors, and other stakeholders control different categories of data. The structure of the problem remains the same: multiple agents with private interests must be motivated to contribute to a shared goal.

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VII, July 2026

Prof. Cai's frameworks offer three key solutions for digital twin governance in oil and gas.

First, they enable incentive-compatible data sharing, ensuring participants are rewarded for truthful reporting. Second, the asynchronous participation mechanisms address the varying times of stakeholder involvement. Third, reputation systems aided by blockchain ensure secure and trustworthy data sharing, especially important in light of cybersecurity issues.

While mechanism design alone cannot resolve semantic interoperability or tacit knowledge barriers, it directly targets the core issue of misaligned incentives, which maintains data silos, fragmented standards, and the dominance of proprietary systems.

Looking forward, research should explore how Prof. Cai's frameworks can be applied to the oil and gas industry, considering its unique characteristics like long asset lifecycles, diverse stakeholders, regulatory environments, and the mix of new and existing assets.

The reviewed literature highlights specific needs for mechanism design in this context.

Pandi [3] stresses the need for data standards defined by the owner-operator, not individual EPC contractors. Correia et al. [10] emphasize the importance of ontologies for semantic interoperability. LeBlanc [5] quantifies the economic scale of digital twin adoption, while Wanasinghe et al. [2] provide insights into stakeholder distribution and the challenge of unlocking historical knowledge.

A research program combining mechanism design and oil and gas digital twin governance needs to address four main adaptations: stakeholder diversity, long time horizons, regulatory constraints, and semantic interoperability.

Each of these requires tailored mechanisms that align incentives and ensure compliance.

This literature review concludes that mechanism design, particularly the incentive-compatible frameworks developed by Prof. Jun Cai, offers a promising direction for addressing the governance issues in oil and gas digital twin adoption.

Adapting these frameworks requires addressing the unique characteristics of the industry, but the core concepts are directly applicable and have proven effective in related fields. The lack of existing research on this topic points to a significant gap and an important new direction at the intersection of digital twins, network economics, mechanism design, and industrial data governance.

Ethical Approval

Not applicable. This manuscript is a literature review and does not involve human participants or animals.

Conflict Of Interest

The authors declare that they have no conflict of interest.

Data Availability

No new dataset was generated for this literature review. Data underlying the review are contained in the cited publications.

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