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Review Article

Multi-Physics Digital Twin Architecture for Smart Manufacturing

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Abstract: Digital twin technology has attracted substantial interest in smart manufacturing, yet the integration of multi-physics coupling, reliability prediction, and organizational standardization into a unified architecture remains underexplored. This review synthesizes advances across these domains, examining how thermo-mechano-electromagnetic coupling analysis, physics-informed neural operators, and enterprise informatization standards collectively contribute to digital twin implementation. The analysis reveals persistent challenges—trade-offs between model fidelity and computational efficiency, difficulties in transferring coupling assumptions across contexts, and organizational barriers to standardizing digital workflows. Evidence suggests successful implementations emerge through iterative calibration rather than a priori design, with closed-loop compensation critical for maintaining predictive accuracy. Methodological limitations include reliance on deterministic assumptions and insufficient attention to data provenance. Future research should prioritize empirical validation across diverse industrial settings and human-in-the-loop approaches that combine algorithmic recommendations with expert judgment. The review concludes that a hybrid methodology—neither purely data-driven nor purely physics-based, offers the most promising pathway forward, acknowledging the irreducible uncertainty inherent in complex manufacturing systems.

Keywords: Digital twin; Smart manufacturing; Multi-physics coupling; Reliability prediction; Standardization;

1. Introduction

The contemporary manufacturing landscape is undergoing a transformation that is as much conceptual as it is technological. Central to this shift is the digital twin—a construct that, in its most ambitious formulation, promises to create a persistent, dynamic, and bidirectional link between physical assets and their digital representations. Initially conceived within the aerospace and automotive sectors as a means of improving product design and maintenance planning, the digital twin has since expanded into a broader vision of manufacturing intelligence: one in which real-time sensor data, physics-based models, and machine learning algorithms converge to enable predictive optimization across product lifecycles. Yet the transition from this vision to practical implementation has proven more challenging than early proponents anticipated. Manufacturing environments are characterized by multi-physics interactions—thermal, mechanical, electromagnetic—that unfold across multiple spatial and temporal scales; by components whose degradation trajectories are shaped by operational histories that are only partially observable; and by organizational contexts in which new digital capabilities must coexist with legacy systems and established workflows. These intersecting complexities suggest that the development of effective digital twin architectures cannot proceed within disciplinary silos.

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A substantial body of research has addressed individual facets of this challenge. In the domain of multi-physics modeling, Jiang (2026) [1][3]developed comprehensive analysis frameworks for integrated automotive laminated glass, demonstrating the feasibility of integrating disparate physical domains within a unified analytical structure. The methodological sophistication of these works, particularly their attention to unified-datum tolerance coordination, multi-point geometric curvature inspection, region-aware adaptive NSGA-II layout optimization, and full-lifecycle experimental verification, establishes a benchmark for how cross-domain coupling can be systematically addressed. Yet the frameworks' focus on a specific product class raises questions about their generalizability to other manufacturing contexts, a limitation that the authors would likely acknowledge as a natural consequence of the trade-off between domain-specific fidelity and broad applicability. The integration of optimization algorithms with quality control processes is particularly noteworthy, yet the computational demands of these approaches may constrain their deployment in real-time production environments. The practical challenges of maintaining product quality under variable production conditions are further underscored by Yan (2026) [10], whose investigation into the performance evaluation and weathering resistance of high UV-blocking coatings for automotive glass highlights the critical role of long-term durability assessment in quality assurance protocols. Yan's findings suggest that environmental factors—particularly UV exposure and thermal cycling, can significantly influence the functional performance of coated components, a consideration that has direct implications for the life prediction models discussed in subsequent sections.

Parallel to these developments in physical modeling, significant progress has been made in reliability analysis and life prediction for manufacturing components. Wang [2][5][6][7]provided foundational investigations into smart manufacturing and quality assurance for new energy vehicle components, establishing how manufacturing variability propagates through product lifecycles and influences long-term performance. Wang (2025) extended this work through reliability analysis and life prediction models that incorporate operational stress profiles, offering frameworks for anticipating component failure under diverse conditions. Wang (2025) further demonstrated how advanced material applications can enhance component performance, while Wang (2026) introduced a hierarchical physics-informed neural operator for real-time electromagnetic-thermal field coupling in electric vehicle powertrains. Collectively, these contributions represent a sustained effort to advance the methodological toolkit for reliability engineering. Yet the translation of these physics-informed approaches to broader manufacturing contexts presents challenges, the neural operator's training requirements may be prohibitive for applications with limited data, and the models' performance under conditions that differ substantially from training distributions remains a subject of ongoing investigation.

The organizational dimension of digital twin implementation has received comparatively less attention, yet it may be equally consequential for successful deployment. Feng (2026) [4][8][9] investigated the construction and practice of full-domain architecture systems for enterprise management informatization under the digital economy, providing a macro-level perspective on how institutional frameworks can support or impede the adoption of intelligent systems. Feng (2026) proposed a "standard+ system" dual-drive model that offers a specific operational framework for aligning technical systems with organizational standards. Feng (2026) further examined the transformation mechanism of informatization technical achievements from the perspective of industry-university-research-user integration, highlighting the importance of stakeholder engagement in technology adoption. These contributions, though situated within the context of enterprise management rather than engineering per se, offer valuable analogies for how digital twin frameworks might be embedded within existing institutional structures. The recognition that technical systems are co-produced with organizational contexts—a theme that runs throughout Feng's work—suggests that the development of digital twin architectures must proceed in tandem with the development of institutional protocols that govern how generated insights are interpreted and acted upon.

The environmental and sustainability dimensions of manufacturing operations, while often treated as separate from core digital twin concerns, are increasingly recognized as integral to comprehensive manufacturing intelligence. This recognition is informed by Lin (2026) [11], whose environmental assessment of intelligent logistics automation provides a structured framework

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for evaluating the ecological footprint of automated manufacturing and logistics systems. Lin's analysis demonstrates that the deployment of intelligent systems in manufacturing contexts carries both efficiency benefits and environmental implications—energy consumption, material utilization, and waste generation that must be systematically accounted for in any comprehensive digital twin architecture. This perspective, while focused on logistics rather than manufacturing per se, extends the scope of digital twin considerations beyond production efficiency to encompass broader sustainability metrics, a direction that is likely to gain increasing importance as manufacturing enterprises face growing pressure to demonstrate environmental responsibility. These considerations, when viewed alongside the technical capabilities reviewed above, suggest that an integrated digital twin architecture for smart manufacturing must accommodate not only physical modeling, reliability prediction, and organizational standards, but also environmental performance assessment as a cross-cutting concern.

This leads us to further thinking about the integration of these four pillars—multi-physics modeling, reliability prediction, informatization standards, and environmental assessment—within a coherent digital twin architecture. The present paper undertakes a critical review and conceptual synthesis of these domains, with the aim of articulating design principles that can guide future research and development. The review is organized as follows: Section 2 examines the methodological foundations of multi-physics coupling analysis and geometric inspection. Section 3 reviews advances in reliability-informed life prediction and physics-informed machine learning. Section 4 analyzes the organizational and standards dimensions of digital twin implementation. Section 5 synthesizes these perspectives and articulates design principles for integrated architectures, along with persistent challenges and future research directions.

2. Multi-Physics Coupling Analysis and Geometric Inspection in Smart Manufacturing

The modeling of manufacturing processes that involve multiple interacting physical domains presents challenges that are both computational and conceptual. Thermal, mechanical, and electromagnetic phenomena rarely operate independently in advanced manufacturing contexts; rather, they interact in ways that can produce emergent behaviors not predictable from single-domain analysis. This section reviews the methodological foundations of multi-physics coupling analysis and geometric inspection, with particular attention to the contributions of Jiang (2026) [1][3]and the broader research landscape in which these contributions are situated.

2.1 Thermo-Mechano-Electromagnetic Coupling: Methodological Considerations

The integration of thermal, mechanical, and electromagnetic analyses within a unified framework requires careful attention to the coupling mechanisms through which these domains interact. Jiang (2026) [1] addressed this challenge through the development of a comprehensive analysis framework for triple-functional integrated automotive laminated glass, a product that exemplifies the multi-physics complexities inherent in advanced manufacturing. The thermo-mechano-electromagnetic coupling in this context arises from the interaction between the glass's thermal expansion characteristics, its mechanical response to forming stresses, and the electromagnetic properties of functional coatings or embedded components. Jiang's framework approaches this coupling through a sequential iterative strategy, where thermal analysis informs mechanical boundary conditions, which in turn affect electromagnetic properties through temperature-dependent material parameters. This approach, while computationally manageable, introduces approximations—the assumption of quasi-static coupling may not hold for processes with rapid thermal transients, and the convergence of the iterative scheme may be sensitive to initial conditions.

A notable contribution of Jiang's work is the attention to unified-datum tolerance coordination across the coupled analyses. In manufacturing contexts, the geometric reference frames used for thermal, mechanical, and electromagnetic analyses are often defined independently, leading to inconsistencies that can propagate through the analysis chain and compromise prediction accuracy. Jiang's framework establishes a common geometric datum that serves as the reference for all three analyses, ensuring

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that the spatial correspondence between domains is maintained. This may seem a straightforward design choice, yet its implementation requires careful attention to the measurement and representation of geometric features, particularly when dealing with laminated structures where layer interfaces introduce discontinuities. The experimental verification component of Jiang's (2026) study, which spans the full lifecycle from material characterization to final product testing, provides empirical grounding for the framework's predictions, yet the generalizability of these validation results to other product classes warrants further investigation.

The durability assessment of coated components under environmental stress represents an additional dimension of multi-physics analysis that extends beyond conventional manufacturing considerations. Yan (2026) [10]investigated the performance evaluation and weathering resistance of high UV-blocking coatings for automotive glass, revealing that the long-term functional performance of such coatings depends critically on their resistance to UV-induced degradation and thermal cycling. This finding has implications for multi-physics modeling frameworks, as it suggests that environmental factors—particularly those associated with outdoor exposure—must be incorporated into life prediction models to achieve realistic assessments of component durability. Yan's experimental methodology, which combines accelerated weathering tests with performance characterization, offers a methodological precedent for how such environmental factors can be systematically evaluated and integrated into broader assessment frameworks. The insights from this work complement the multi-physics coupling approaches discussed above, extending the temporal horizon of analysis from manufacturing processes to in-service performance.

2.2 Geometric Curvature Inspection and Quality Control Integration

The inspection of geometric features in mass-produced components presents challenges that extend beyond the technical capabilities of measurement instruments. When dealing with large-size laminated automotive windshield glass, geometric curvature must be controlled within tight tolerances to ensure optical quality, structural integrity, and compatibility with subsequent assembly processes. Jiang (2026) [3]addressed this challenge through a multi-point geometric curvature inspection framework that incorporates three innovative elements: unified-datum decoupling, region-aware adaptive NSGA-II layout optimization, and closed-loop mold compensation.

The unified-datum decoupling component addresses the challenge of establishing a consistent reference frame for curvature measurement across multiple inspection points. In conventional inspection approaches, the choice of reference datum can influence the interpretation of curvature measurements, leading to inconsistencies that complicate quality assessment. Jiang's approach decouples the datum definition from the measurement points, enabling the reference frame to be optimized based on the specific geometric characteristics of each component. This flexibility comes at a computational cost, the optimization of the reference frame must be performed for each component, which may be prohibitive for high-volume production environments.

The region-aware adaptive NSGA-II layout optimization component applies a multi-objective evolutionary algorithm to the placement of inspection points. Rather than using a fixed inspection pattern, the algorithm adapts the layout based on the geometric features of each component, allocating more measurement points to regions of high curvature variability and fewer to regions that are relatively stable. This region-aware adaptation represents a departure from conventional fixed-pattern inspection, and the use of NSGA-II enables the simultaneous optimization of multiple objectives—measurement accuracy, inspection time, and computational cost. The trade-off between these objectives, however, may not have a single optimal solution; rather, the algorithm generates a Pareto front of alternative layouts, leaving the selection of a specific layout to the manufacturer's judgment based on their quality requirements and production constraints.

The closed-loop mold compensation component closes the quality control loop by feeding inspection results back to the mold design and adjustment process. When curvature deviations are detected, the framework provides recommendations for mold modifications that would bring subsequent components into tolerance. This feedback mechanism represents a significant departure from traditional quality control approaches, which typically identify defects without providing actionable guidance for process

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correction. Yet the effectiveness of the compensation recommendations depends on the accuracy of the underlying process model, if the model does not capture the relationship between mold geometry and final curvature with sufficient fidelity, the recommended compensations may be ineffective or even counterproductive. Jiang's framework addresses this through an iterative refinement process, where compensation recommendations are evaluated against subsequent inspection results and the process model is updated accordingly. This learning capability is promising, yet its convergence properties and sensitivity to measurement noise merit further investigation.

2.3 Assessment and Limitations

The contributions of Jiang (2026) [1][3] represent significant advances in the integration of multi-physics analysis and geometric inspection within manufacturing contexts. The attention to coupling mechanisms, the establishment of unified datums, and the incorporation of adaptive optimization and closed-loop compensation demonstrate a sophisticated understanding of the challenges inherent in advanced manufacturing. Yet several limitations warrant acknowledgment. The computational demands of the framework, particularly the NSGA-II optimization and the iterative multi-physics coupling, may render real-time deployment challenging for high-volume production environments. The generalizability of the framework to product classes beyond automotive glass,such as other laminated structures, composite materials, or components with different geometric characteristics, remains to be demonstrated. The reliance on accurate process models for the closed-loop compensation component introduces a dependency that may limit the framework's effectiveness in contexts where process models are uncertain or unavailable. The weathering resistance considerations raised by Yan (2026)[10] further suggest that the temporal dimension of product performance, particularly under environmental stress—deserves greater attention in multi-physics modeling frameworks. These limitations suggest that future research should explore approximation techniques that trade some accuracy for computational efficiency, investigate the transferability of the framework to other product classes, develop methods for model updating that accommodate model uncertainty, and incorporate long-term environmental performance assessment into multi-physics modeling paradigms.

3. Reliability-Informed Life Prediction and Physics-Informed Machine Learning

The prediction of component reliability and remaining useful life is a central concern in manufacturing, where unexpected failures can lead to production downtime, safety hazards, and substantial economic losses. This section reviews advances in reliability-informed life prediction, with particular attention to the integration of physics-based understanding with machine learning approaches. The contributions of Wang [2][5][6][7]provide a focal point for this review.

3.1 Foundational Contributions to Reliability Analysis and Quality Assurance

Wang (2024) [5]investigation into smart manufacturing and quality assurance for new energy vehicle components established a foundation for understanding how manufacturing variability propagates through product lifecycles. The study examined the relationships between processing parameters, component quality characteristics, and long-term performance, revealing that variability in manufacturing processes can have disproportionate effects on component reliability. This finding underscores the importance of quality assurance not merely as a final inspection step, but as an integrated component of the manufacturing system. Wang's analysis of how manufacturing variability interacts with operational stress profiles to influence degradation trajectories provides a basis for reliability-informed process control, where process adjustments are made not only to satisfy quality specifications but also to enhance long-term reliability.

Wang (2025) [6] extended this work through the development of reliability analysis and life prediction models that incorporate operational stress profiles. The approach is grounded in the understanding that component degradation is driven by the cumulative effect of operational stresses—thermal cycles, mechanical loads, environmental exposure—and that the prediction of remaining

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useful life requires accurate characterization of these stress profiles. Wang's models use a combination of physics-based damage accumulation rules and statistical analysis of failure data to generate life predictions that account for both the mean behavior and the variability inherent in degradation processes. The inclusion of statistical uncertainty quantification represents a significant strength of this work, as it enables the communication of prediction confidence and supports risk-informed decision-making. Yet the models' performance depends on the availability of failure data for calibration, which may be limited for new components or processes. The transferability of reliability models across different operational contexts also remains a challenge, as the relationship between stress profiles and degradation may vary with environmental conditions, usage patterns, and manufacturing history.

Wang (2025) [7]further explored the role of advanced material applications in enhancing component performance, examining how material innovations, such as high-performance alloys, composite materials, and functional coatings—can extend component life and enable operation under more demanding conditions. The study highlights the importance of understanding the material properties that govern degradation mechanisms, and of incorporating this understanding into life prediction models. Yet the introduction of new materials also introduces new sources of uncertainty, as the long-term behavior of novel materials may not be fully characterized by accelerated testing or short-term performance data. This suggests that life prediction models for components incorporating advanced materials must account for epistemic uncertainty arising from incomplete knowledge of material behavior. The weathering resistance findings of Yan (2026) [10], which demonstrate that UV exposure and thermal cycling can significantly affect the performance of coated automotive glass, underscore the importance of incorporating environmental degradation mechanisms into life prediction models. Yan's experimental evidence suggests that the environmental service conditions, particularly those involving prolonged UV exposure and temperature fluctuations—can accelerate material degradation in ways that are not captured by conventional stress-based models. This observation points toward the need for life prediction frameworks that explicitly incorporate environmental factors alongside operational stresses.

3.2 Physics-Informed Neural Operators and Real-Time Field Coupling

Wang (2026) [2] introduced a hierarchical physics-informed neural operator for real-time electromagnetic-thermal field coupling in electric vehicle powertrains, representing a significant methodological advance. The physics-informed neural operator framework integrates physical constraints, in this case, the governing equations of electromagnetics and heat transfer, into the training of neural networks, enabling the network to learn the mapping from input conditions to field solutions while respecting physical laws. This integration addresses a key limitation of purely data-driven approaches, which may produce physically implausible predictions when extrapolating beyond training data. The hierarchical architecture further enables the decomposition of the field coupling problem into subproblems at different scales, enhancing computational efficiency and enabling the solution of problems that would be challenging for monolithic approaches.

The real-time field coupling capability is particularly relevant for manufacturing applications, where thermal and electromagnetic fields must be predicted quickly to enable process control and quality assessment. The computational efficiency of the neural operator, once trained, enables predictions that are orders of magnitude faster than full-scale numerical simulations, making it feasible for deployment in real-time or near-real-time manufacturing contexts. Yet the training of the physics-informed neural operator requires substantial computational resources and a comprehensive dataset of field solutions, which may be generated through high-fidelity simulations or experimental measurements. The quality of the training data and the representation of boundary conditions and material properties in the training process may influence the network's accuracy in deployment scenarios that differ from training conditions. The ability of the network to generalize to conditions not represented in the training data is a subject of ongoing investigation, and the performance under distributional shift warrants careful evaluation.

3.3 Assessment and Limitations

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Wang's contributions represent a sustained and intellectually coherent effort to advance the methodological toolkit for reliability analysis and life prediction in manufacturing contexts. The integration of physics-based understanding with machine learning approaches, the attention to uncertainty quantification, and the development of computationally efficient surrogate models are all significant advances. Yet several limitations and open questions remain. The reliance on accurate physics models for generating training data introduces a potential source of systematic bias, as the accuracy of the physics-informed neural operator cannot exceed the accuracy of the underlying physics models. The transferability of reliability models across different operational contexts and component classes remains a challenge, and methods for transferring or updating models with limited data are needed. The incorporation of environmental degradation mechanisms—such as those identified by Yan (2026)[10] in the context of UV-blocking coatings—into life prediction models represents an important direction for future research. The integration of reliability prediction with manufacturing process control, such that predictions inform process adjustments in real time, also represents an opportunity for future research. Finally, the communication of prediction uncertainty to decision-makers, and the development of decision-support frameworks that accommodate uncertainty, are important areas for continued investigation.

4. Enterprise Informatization Architecture, Standard Systems, and Environmental Assessment

The implementation of digital twin architectures in manufacturing environments is not solely a technical challenge; it is also an organizational one. This section reviews contributions to enterprise informatization architecture and standard systems, with particular attention to the work of Feng (2026) [4][8][9]and its implications for digital twin deployment. The section also considers the environmental assessment dimension introduced by Lin (2026) [11], which extends the scope of manufacturing intelligence to encompass sustainability considerations.

4.1 Full-Domain Architecture Systems and Digital Economy Integration

Feng (2026) [8]investigation into the construction and practice of full-domain architecture systems for enterprise management informatization provides a macro-level perspective on how institutional frameworks can support or impede the adoption of intelligent systems. The concept of a "full-domain architecture" reflects the understanding that informatization cannot be confined to individual functions or departments, but must encompass the entire organization and its interactions with external stakeholders. This architectural perspective is relevant to digital twin implementation, where the integration of physical modeling, data analytics, and decision-support functions requires coordination across organizational boundaries. Feng's analysis identifies key design principles for enterprise informatization architectures: modularity to accommodate evolving requirements, interoperability to enable data exchange across systems, and scalability to support growth and adaptation.

The context of the digital economy, in which data and information are recognized as strategic assets, adds urgency to the development of such architectures. Manufacturing enterprises are increasingly operating in digital ecosystems where data flows between suppliers, manufacturers, customers, and service providers. Digital twins, in this context, cannot be isolated technical artifacts; they must be designed as components of broader information systems that enable data sharing, collaboration, and value creation across organizational boundaries. This ecosystem perspective raises questions about data governance, intellectual property, and the distribution of benefits from digital twin deployment, questions that extend beyond the technical domain and require engagement with legal, economic, and social considerations. Feng's research, while focused on enterprise management, provides a framework for understanding these broader dimensions of digital twin implementation.

4.2 Dual-Drive Models and Process Standardization

Feng (2026)[4]analysis of the "standard+ system" dual-drive model offers a specific operational framework for aligning technical systems with organizational standards. The dual-drive model recognizes that the adoption of digital technologies

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depends on both the technical capabilities of the systems being introduced and the organizational standards that govern their use. These two dimensions are not independent; rather, they interact in ways that can either facilitate or impede successful adoption. When technical systems are aligned with existing organizational standards, adoption proceeds more smoothly; when they diverge significantly, organizational friction may arise, leading to resistance, underutilization, or misuse of the technology.

The "standard+ system" formulation emphasizes the role of standards not merely as constraints on technical design, but as enablers of integration and interoperability. By establishing common data formats, communication protocols, and quality metrics, standards enable the integration of digital twin capabilities with existing enterprise systems, reducing the effort required for implementation and maintenance. The adoption of standards also facilitates the sharing of digital twin insights across organizational functions, enabling the benefits of predictive modeling to be realized not only in engineering departments but also in supply chain management, production planning, and strategic decision-making. Yet the development and adoption of standards is itself a challenging process, requiring negotiation among diverse stakeholders, accommodation of legacy systems, and ongoing updating to reflect evolving technical capabilities. The integration of environmental assessment metrics into these standardization frameworks, as suggested by Lin (2026) [11], adds an additional layer of complexity. Lin's environmental assessment framework for intelligent logistics automation demonstrates that sustainability metrics—such as energy consumption, material utilization efficiency, and waste generation—can be systematically evaluated and incorporated into the performance assessment of automated systems. This approach offers a methodological precedent for extending digital twin architectures to include environmental performance indicators alongside traditional manufacturing metrics. However, the integration of such indicators into existing enterprise standards requires careful attention to measurement protocols, data collection methodologies, and reporting frameworks, all of which must be aligned with organizational capabilities and regulatory requirements.

4.3 Technology Transfer and Stakeholder Engagement

Feng (2026) 【9】 investigation into the transformation mechanism of informatization technical achievements from the perspective of industry-university-research-user integration addresses the challenge of translating research advances into practical manufacturing capabilities. This translational challenge is particularly relevant to digital twin implementation, where the gap between research prototypes and industrial deployment is often substantial. The industry-university-research-user integration perspective recognizes that successful technology transfer requires engagement with multiple stakeholder groups: researchers who generate new knowledge and methods, industry practitioners who translate methods into practical applications, and end-users who ultimately adopt and use the resulting capabilities.

The integration of these stakeholder perspectives is particularly important for digital twin architectures, where the design choices made by researchers, the selection of modeling techniques, the assumptions about data availability, the specification of interfaces and output formats, can have significant implications for the usability and value of the system in practice. End-user engagement in the design process can surface requirements that might not be apparent from a purely technical perspective, such as the need for interfaces that are intuitive to operators, the need for output formats that align with existing decision-making processes, and the need for training and support mechanisms that enable effective use. The environmental assessment framework proposed by Lin (2026) [11] similarly requires stakeholder engagement, as the selection of environmental metrics and the interpretation of assessment results must accommodate the diverse perspectives of different stakeholder groups, including environmental compliance officers, operations managers, and sustainability reporting specialists. This parallel suggests that the stakeholder engagement principles articulated by Feng may be applicable not only to technology transfer but also to the development of integrated assessment frameworks that span technical, organizational, and environmental domains.

4.4 Assessment and Implications

Feng's contributions highlight the organizational dimensions of digital twin implementation, which are often overlooked in technical research. The recognition that the successful deployment of digital twin architectures depends on alignment with

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organizational standards, integration with existing systems, and engagement with diverse stakeholders suggests that research on digital twins must extend beyond technical modeling to encompass these organizational considerations. The environmental assessment perspective introduced by Lin (2026) [11]extends this scope further, suggesting that digital twin architectures must also accommodate sustainability metrics and environmental performance assessment. This integration of environmental considerations represents both an opportunity and a challenge: it offers the prospect of digital twins that support not only manufacturing efficiency but also environmental responsibility, yet it also requires the development of new assessment methodologies, the integration of new data sources, and the alignment of digital twin capabilities with environmental reporting requirements.

Several questions warrant further investigation. The relationship between enterprise informatization architectures and the specific requirements of multi-physics digital twins—which may have data requirements and computational demands that differ from conventional enterprise systems—merits examination. The interaction between standardization and innovation, particularly in contexts where standards may constrain design choices, is a topic for continued research. The mechanisms through which organizational learning occurs following digital twin deployment, and the conditions under which the insights generated by digital twins lead to sustained improvements in manufacturing performance, are important areas for further investigation. The integration of environmental performance assessment into digital twin architectures, as suggested by Lin's work, represents a particularly promising direction for future research, as it addresses the growing demand for sustainable manufacturing practices while extending the value proposition of digital twin technology.

5. Conclusion

The preceding review of multi-physics coupling, reliability-informed life prediction, enterprise informatization standards, and environmental assessment reveals a landscape of substantial achievement within each domain, yet also exposes the considerable gap that remains between domain-specific advances and the integrated digital twin architectures that manufacturing practice increasingly demands. The contributions of Jiang (2026) in multi-physics analysis and geometric inspection, Wang (2024, 2025, 2026) in reliability modeling and physics-informed machine learning, Feng (2026) in enterprise architecture and standardization, Yan (2026) in coating performance and weathering resistance assessment, and Lin (2026) in environmental assessment of intelligent systems collectively provide a foundation upon which integrated architectures might be constructed, yet the interfaces between these domains remain under-specified and the organizational mechanisms for integrating them remain under-developed. The principal lesson that emerges from this synthesis is that the value of digital twin architectures in manufacturing lies not in maximizing the sophistication of any single component, whether the fidelity of multi-physics simulations, the accuracy of life predictions, the comprehensiveness of enterprise standards, or the scope of environmental assessments, but rather in achieving a functional integration that enables the right information to reach the right decision-maker at the right time. This functional integration requires, at minimum, the establishment of common data models that span physical, organizational, and environmental domains; the development of uncertainty propagation methods that preserve the integrity of predictions across the analysis chain; the incorporation of long-term environmental performance considerations into life prediction and quality assessment frameworks; and the design of governance mechanisms that accommodate the distributed expertise and diverse incentives that characterize manufacturing organizations. Looking forward, three complementary research directions appear particularly promising. The first is the development of adaptive standardization frameworks that can accommodate local manufacturing particularities while maintaining sufficient interoperability to enable cross-site learning and benchmark comparison, with explicit provision for environmental performance metrics. The second is the exploration of human-in-the-loop approaches that recognize the irreplaceable role of human judgment in contexts where algorithmic predictions are necessarily uncertain and where decisions have significant consequences for both production outcomes and environmental impact. The third is the

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integration of environmental life cycle assessment methodologies into digital twin architectures, enabling manufacturers to evaluate not only the immediate efficiency of production processes but also the long-term environmental implications of design choices, material selections, and operational decisions. These directions, while demanding substantial research effort, offer the prospect of digital twin architectures that are not only technically capable and organizationally sustainable but also environmentally responsible, ultimately delivering on the long-standing promise of digital twins to transform manufacturing practice in a manner that serves both economic and ecological objectives.

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Conflicts of Interest

The author(s) declare no conflicts of interest.

Ethical Approval and Consent to Participate

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