Comparative Analysis of Digital Twin Implementations – Identifying Cross-Disciplinary Knowledge Transfer Potentials for Space Systems Development

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Abstract

Digital twin implementation in space systems faces significant challenges despite recognized potential. This study presents the first systematic cross-domain analysis comparing implementation challenges between space systems and product development through literature review of 204 sources. Using qualitative analysis, 27 transfer connections were analysed. Results reveal that 70% of product development solutions demonstrate high-to-moderate transfer potential to space systems. The analysis supports strategic reorientation from operational toward design and verification applications, enabling space systems to leverage mature terrestrial solutions while minimizing communication constraints. This establishes a foundation for future empirical validation and cross-domain knowledge transfer.

Keywords

Digital Twin, Space Systems, Knowledge Transfer, Cross-Domain Analysis, Implementation Challenges

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1. Motivation

Early researchers conceptualized product lifecycle management with digital representations that mirror physical assets throughout its lifetime [1]. Building on this foundation, Glaessgen and Stargel articulated a digital twin paradigm for aerospace applications in 2012, defining it as "an integrated multiphysics, multiscale, probabilistic simulation of an as-built vehicle" [2]. Despite over a decade of research and development, digital twin implementation in space systems remains challenging, with significant variations in maturity and readiness [3]. Other industries have identified multiple interconnected factors including technical limitations, methodological gaps, and organizational barriers as implementation difficulties. Digital twin development has been characterized by inconsistent definitions across domains, complicating communication between researchers and industry practitioners [4]. Maturity levels vary significantly across industries, with manufacturing leveraging extensive operational data to drive Industry 4.0 digitalization initiatives [5].

Recognizing the need for clarity, industry organizations have developed domain-specific definitions. The German Scientific Society of Product Development (WiGeP) established a foundational definition for product development contexts, characterizing digital twins as "digital representations of product instances or product-service systems" [6]. Similarly, the American Institute of Aeronautics and Astronautics (AIAA) published a position paper in 2020 defining digital twins in aerospace as "a virtual representation of a connected physical asset," encompassing applications such as performance monitoring, validation, and optimization [7].

Space systems exemplify complex product development with a distinctive methodological heritage. The convergence of extreme operational environments, established standards and frameworks, unprecedented system complexity, and comprehensive technology integration across all lifecycle phases distinguishes space systems from conventional terrestrial product development approaches. The sector presents implementation challenges that amplify core digital twin issues. Limited physical access for maintenance and stringent reliability requirements create distinct barriers requiring specialized consideration. However, mature digital twin methodologies from product development domains could provide foundational approaches for space system applications, enabling knowledge transfer opportunities.

Clearly defining these implementation challenges and their relationship to space systems applications is essential for addressing the fundamental question: *What specific potential does digital twin implementation offer for space systems?* Answering this question systematically enables a comprehensive comparison of digital twin challenges across domains, particularly between space systems and the broader product development context. This comparative analysis will examine how space systems development challenges intersect with digital twin implementation requirements, while assessing the more mature terrestrial applications that offer potential solutions. The central research question guiding this investigation is: *How do the challenges of implementing digital twins in space systems development differ from those in general product development contexts?*

This research study addresses these questions through a systematic approach: Chapter 1 presented the motivation and research foundation; Chapter 2 outlines the research methodology; Chapter 3 examines challenges in space systems development and digital twin solution potential; Chapter 4 identifies challenges for digital twin implementations in space systems and product development for the analysis of knowledge transfer opportunities towards space systems; Chapter 5 discusses the current research status and identifies knowledge gaps; and Chapter 6 concludes with findings and future research directions.

2. Research Methodology

This study employs a five-stage systematic methodology to identify cross-disciplinary knowledge transfer potentials for digital twin implementation in space systems, established within the framework of this work and shown in more detail in Figure 1. The research methodology is designed to establish a comprehensive understanding of the current state-of-the-art before identifying implementation gaps and knowledge transfer opportunities.

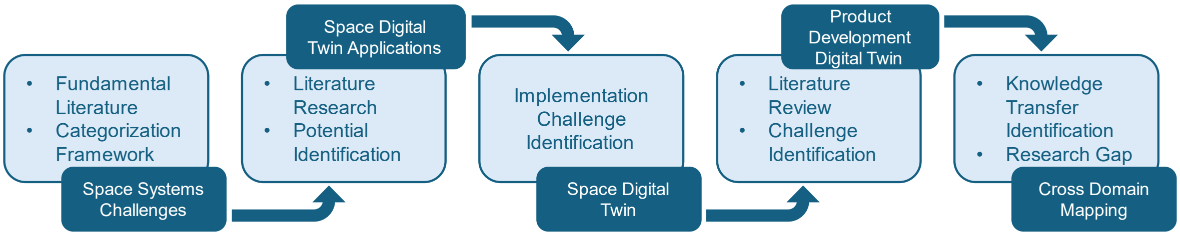

Figure 1: Five-Stage Methodological Approach for Cross-Disciplinary Knowledge Transfer Identification.

The research begins with the identification and categorization of fundamental challenges in space systems development from established literature, organizing them into technical, methodological, and organizational domains. This categorization framework provides the foundation for subsequent analysis and maintains consistency throughout the study [4].

Following this foundation, a systematic literature review examines digital twin applications in space contexts using Machi and McEvoy's six-step methodology in the Scopus database [8]. Multiple targeted keyword combinations focusing on digital twin applications and space systems terminology were employed without temporal restrictions to capture the complete research evolution. The initial search yielded 304 documents. Through abstract review focusing on concepts, frameworks, implementations, and case studies, 93 documents are identified as relevant. After accounting for document accessibility and supplementing with citation tracking and industrial whitepapers, 82 documents form the final corpus for analysis. This stage systematically extracts and categorizes digital twin potentials using qualitative content analysis, coding each potential according to the established technical-organizational-methodological framework. This analysis reveals the distribution of research focus identifying areas of concentrated research activity and preliminary gaps in literature coverage.

Building on this state-of-the-art understanding, the methodology shifts towards critical analysis of practical implementation barriers. This stage identifies specific challenges for implementing digital twins in space systems contexts, to identify realistic obstacles to achieving the potentials identified in the previous analysis.

To enable cross-domain knowledge transfer analysis, the second systematic literature review focuses on digital twin implementation in product development. This review yields 106 initial documents that expand to 122 sources after citation tracking and inclusion of relevant standards. The product development review identifies the main challenges for implementing digital twins in product development contexts, serving as the source domain for knowledge transfer analysis.

The methodology concludes with cross-domain knowledge transfer analysis, systematically mapping the challenges for implementing digital twins in space systems with the main challenges for implementing digital twins in product development. This comparative analysis enables the identification of knowledge transfer opportunities from product development to space systems applications and highlights areas requiring specialized approaches unique to space contexts.

3. Challenges for Space Systems and Digital Twin Application Potentials

Space systems development presents unique challenges that distinguish it from conventional product development contexts. These domain-specific challenges create particular requirements and constraints that must be addressed for successful mission outcomes. Understanding these challenges comprehensively enables the identification of potential digital twin applications and assessment of current research coverage in addressing these problems.

3.1. Comprehensive Challenge Space Systems Analysis

Following Kober's classification framework for digital twin implementation challenges in manufacturing, space systems challenges are categorized into technical, methodological, and organizational domains [4]. Challenge identification draws from established space systems engineering literature [9-11]. The systematic analysis identifies 61 individual challenges, with relatively balanced distribution among the different domains. The challenges can be summarized to 13 challenges as illustrated in Table 1.

Table 1: Space Systems Development Challenges by Technical, Organizational, and Methodological Domains

	Challenge	Description
Technical	Environmental Adaptation & Protection	Managing extreme space conditions including thermal extremes, radiation exposure, vacuum effects, and material degradation
	System Reliability & Fault Tolerance	Ensuring continuous operation without maintenance access, eliminating single-point failures, and achieving high mission success rates
	Long-term Operations & Maintenance	Sustaining autonomous system performance over extended mission durations without physical intervention or component replacement
	System Architecture & Design Philosophy	Reconciling conservative design approaches with performance requirements across multiple engineering disciplines and stakeholder needs
Organizational	Financial & Economic Management	Managing high development costs, budget constraints, cost overruns, and transition from cost-plus to fixed-price contracts
	Project & Program Management	Coordinating complex multi-year projects with diverse stakeholders, managing schedule delays, and bureaucratic processes
	International Cooperation & Politics	Navigating multinational partnerships, political influences on technical decisions, and coordinating across different space agencies
	Operations & Infrastructure	Establishing ground systems, communication networks, mission control facilities, and operational support infrastructure
	Team & Organizational Dynamics	Managing multidisciplinary teams, stakeholder coordination, and organizational structures for complex space projects
Methodological	Requirements Engineering & Design	Defining precise mission requirements, managing requirement changes, and translating objectives into technical specifications
	Verification, Validation & Quality Assurance	Ensuring mission success through comprehensive testing, analysis, and quality control under extreme operational conditions
	Systems Integration & Complexity Management	Integrating subsystems with limited production quantities, managing interfaces, and handling high system complexity
	Cost & Process Optimization	Optimizing development processes, reducing costs while maintaining quality, and adapting to changing requirements

The identified challenges reveal the interconnected nature of space systems development. Technical challenges primarily stem from the harsh operational environment and the impossibility of post-launch maintenance, driving requirements for extreme reliability and autonomous operation [9-11]. These technical constraints directly influence organizational complexity, as space projects require extensive stakeholder coordination, specialized project management approaches, and navigation of international partnerships with political considerations [9-11]. The resulting system complexity demands specialized methodological approaches that must balance conservative design philosophies with diverse stakeholder requirements while ensuring mission success through comprehensive verification and validation processes [9-11]. The multi-year development cycles with frequent requirement changes further compound these methodological challenges, requiring adaptive approaches for effective project execution.

3.2. Digital Twin Application Potentials in Space Systems

Having established the comprehensive challenge landscape for space systems development, this section examines the potentials that digital twin implementations offer for space systems as identified in the current literature. Based on systematic analysis of 82 documents, as described in Chapter 2, researchers claim that digital twins provide multiple opportunities to address existing problems and enhance space systems development processes.

The identified potentials have been systematically categorized using the same technical, organizational, and methodological framework established for the challenge analysis. This categorization reveals the multidimensional nature of digital twin applications and provides analytical insight into current research priorities.

The distribution of potentials across categories reveals notable patterns in current research focus. Technical potentials dominate with 12 identified capabilities, followed by 10 methodological potentials, while organizational potentials account for only 8 identified areas. This distribution suggests a potential research bias toward technical solutions, with comparatively limited attention to organizational transformation and change management aspects of digital twin implementation in space systems contexts.

The technical potentials primarily focus on operational capabilities such as real-time monitoring, predictive maintenance, and advanced simulation techniques that directly address spacecraft reliability and performance challenges [12-14]. Organizational potentials, while fewer in number, address critical aspects of collaboration, data management, and business model innovation necessary for successful digital twin adoption [15-17]. Methodological potentials emphasize systematic approaches to implementation, validation, and framework development that support structured digital twin deployment [18-20].

Many identified potentials appear to address known space systems challenges, suggesting alignment between research directions and industry needs. However, the concentration of research attention on technical aspects, combined with the relative scarcity of organizational and methodological solutions, indicates potential gaps in addressing the full spectrum of implementation requirements for digital twin technology in space systems.

This state-of-the-art analysis establishes the foundation for examining the practical challenges of implementing these literature-identified potentials in real-world space systems development contexts, which will be addressed in the following section.

4. Digital Twin Implementation Challenges: Cross-Domain Analysis

While existing literature has examined digital twin implementation challenges, most studies focus exclusively on technical aspects rather than adopting a comprehensive systems perspective. This analysis applies a holistic view that recognizes digital twins as socio-technical systems, involving complex interactions between humans, technology, and organizational contexts that must adapt to changing technological and social environments [21]. Consistent with the analytical framework established in previous sections, implementation challenges are categorized into technical, organizational, and methodological dimensions to maintain analytical consistency and enable systematic comparison.

4.1. Space Systems Implementation Barriers

Space missions face fundamental technical constraints that significantly impact digital twin implementation. Communication delays, limited bandwidth, and large volumes of sensitive mission data create synchronization challenges between physical spacecraft and ground-based digital twins, directly impacting real-time feedback and monitoring capabilities [12, 22]. The extreme space environment compounds these issues, as current uncertainty models inadequately represent space-specific conditions and sensors must withstand harsh environments where failures compromise digital twin accuracy [12].

Beyond these technical constraints, space systems face significant organizational barriers including high initial investments in specialized hardware and software, organizational resistance to change, insufficient digital skills, and departmental silos [3, 15, 23, 24]. Large-scale international projects face additional complexity from diverse processes and the absence of unified platforms, leading to integration errors and operational inefficiencies [3, 15].

Complementing these challenges, methodological barriers present equally significant obstacles. The absence of standardized architectures, data formats, and communication protocols complicates integration with existing systems while hindering scalability [3, 12, 25, 26]. Validation and verification methodologies remain underdeveloped, while synthesizing multi-source data across disciplines presents methodological complexity without established best practices [3, 27].

4.2. Product Development Implementation Challenges

Digital twin implementation in product development contexts faces challenges that provide a comparative baseline for understanding space-specific requirements. Unlike space systems, product development must harmonize diverse data sources including sensors, simulations, supply chain systems, and customer feedback within digital twin architectures [28-31]. Legacy system integration poses particular barriers for small and medium enterprises lacking connectivity infrastructure [32, 33], while overly complex models can lead to prohibitive computational costs that differ from space systems' reliability-focused constraints [5, 30, 34, 35].

Organizationally, product development emphasizes cross-functional collaboration across engineering, data science, and information technology domains, with return on investment visibility being a primary concern for smaller enterprises [4, 30, 32, 33, 36].

Methodologically, product development faces unique lifecycle integration challenges from design through manufacturing, operation, and maintenance due to inconsistent information flows across these phases [37]. Validation complexity arises from each implementation being unique with varying degrees of physical access for comparison [29, 30].

4.3. Comparative Analysis with Knowledge Transfer Assessment

The previous chapters displayed the challenges in the specific disciplines and provided insights on the status of research on these topics. These challenges form interdependent systems where technical solutions require simultaneous organizational change management and methodological framework development to achieve successful implementation. Building on this understanding, the following section focuses on the shared challenges of the domains and the connected transfer opportunities, followed by a summary of space-specific challenges which require novel approaches and further research focus.

Figure 2 presents a Sankey diagram visualizing knowledge transfer potential from digital twin implementations in product development (left) to those in space systems (right) across technical, organizational, and methodological challenge categories. The diagram illustrates both the availability of solutions in the product development domain and the degree to which these solutions can address space systems challenges, revealing interconnections between challenges and their transferability across domains.

The knowledge transfer assessment employs a systematic qualitative analysis methodology to evaluate transfer potential between domains. Each identified challenge from product development was mapped to corresponding space systems challenges based on similarity analysis conducted in sections 4.1 and 4.2. Transfer potential was assessed using a three-tier classification system: high (80-100 points), moderate (60-80 points), and low (below 60 points), where scores reflect the degree to which existing product development solutions can address space systems challenges with minimal adaptation. The Sankey diagram node sizes correspond to these transfer potential scores, with larger nodes indicating higher transferability.

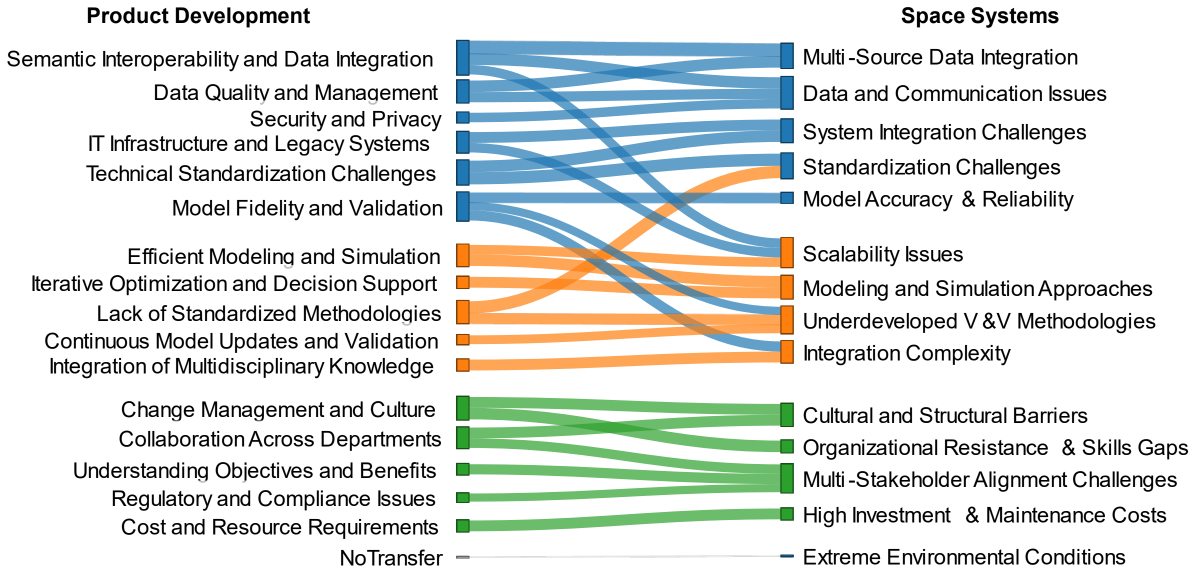

Figure 2 Sankey Diagram Showing Knowledge Transfer Potential with Technical (Blue), Methodological (Orange), and Organizational (Green) Categories.

A particularly promising example is the direct transfer of ontology-based and semantic integration approaches from product digital twins to space systems for multi-source data integration. Both domains must unify diverse data types, but space systems may require additional robustness due to mission-critical operations. This makes the transfer potential very high, with only moderate adaptation needed [13, 30].

The connection between change management approaches in product development and organizational resistance in space systems demonstrates particularly high transferability. Approaches for upskilling and managing resistance in product DTs are highly transferable to space, where similar workforce and cultural challenges exist. The literature emphasizes the need for digital and analytical literacy, as well as the importance of stakeholder engagement in both sectors [38].

However, not all challenges demonstrate equal transfer potential. Some challenges, such as those related to extreme environmental conditions, remain unique to space and have little to no transfer potential from product development. Overall, the literature indicates substantial knowledge transfer potential from product development to space systems digital twins, particularly in technical and methodological domains [13, 38].

5. Discussion and Knowledge Transfer Assessment

A critical gap emerges from the literature analysis: while 82 space systems studies claim digital twin benefits, only a small fraction report empirical validation through operational implementations, indicating a theory-practice divide that undermines adoption confidence. The limited direct industry engagement in digital twin research for space systems compounds this issue, as academic studies often proceed without sufficient input from practitioners who understand operational constraints and requirements. The aerospace industry's conservative nature and high-stakes environment further exacerbate this academic-industrial divide, creating substantial barriers to technology adoption and the collaborative development approaches necessary to integrate real-world requirements into digital twin frameworks.

Space systems present unique complexity through their stakeholder constellation, where operators, customers, and manufacturers have divergent interests, creating data sharing reluctance and maintenance challenges compounded by cost-intensive space data communication. Despite these fundamental implementation barriers, including limited real-time capability and extreme environmental conditions, the literature analysis reveals an intense focus on operational applications rather than alternative implementation strategies.

The systematic transfer assessment reveals that approximately 70% of identified product development solutions demonstrate high-to-moderate applicability to space systems challenges, with semantic interoperability and change management approaches showing the strongest cross-domain potential. Based on 27 individual transfer connections analysed in the Sankey diagram, only extreme environmental conditions demonstrate zero transfer potential, as no terrestrial product development faces comparable operational constraints including radiation exposure, vacuum effects, and thermal extremes.

This abundance of transferable solutions suggests a strategic reorientation toward design and verification applications for space systems digital twins, where communication constraints and operational risks are minimized. Given the extended development timelines characteristic of space systems, digital twin implementation during design and verification phases can influence decisions across the entire product lifecycle while avoiding the ongoing communication costs and technical constraints of operational implementations.

This study's transfer potential assessment methodology presents limitations requiring acknowledgment. The qualitative scoring system relies on literature-based similarity analysis without empirical validation through pilot implementations or expert panel review. This represents a critical gap between theoretical knowledge transfer potential and practical implementation feasibility in the aerospace industry's conservative, high-stakes environment.

These findings suggest a staged implementation pathway that first implements basic capabilities using proven product development solutions, then incrementally addresses space-specific challenges, and finally develops novel solutions for remaining gaps, with validation steps between each stage. This cross-domain transfer approach leverages existing mature solutions, enabling even small companies and new space ventures to benefit from the technology. Repositioning digital twin as a methodological solution throughout the development process, serving as the single source of truth that MBSE attempts to create, could lower adoption barriers, potentially through service-based models that address stakeholder challenges while providing manufacturers access to operational data.

6. Conclusion

This study presents the first systematic cross-domain analysis of digital twin implementation challenges between space systems and product development. Through comprehensive literature analysis of 204 sources, this research identifies that approximately 70% of product development digital twin solutions demonstrate high-to-moderate transfer potential to space systems challenges, analysed through 27 individual transfer connections.

The Sankey diagram methodology provides an innovative visualization approach for complex cross-domain transfer relationships, enabling systematic assessment of knowledge transfer opportunities. This analysis supports a strategic reorientation from operational implementations toward design and verification applications, where space systems can leverage mature product development solutions while minimizing communication constraints and operational risks.

Future research should prioritize empirical validation through pilot implementations focusing on product development phases and industry-academia collaboration frameworks. The conservative aerospace industry requires demonstrated value and careful risk management before widespread adoption, creating opportunities for research that bridges theoretical potential with practical implementation through systematically designed pilot studies and industry partnerships.

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