

BEYOND COMMON DATA ENVIRONMENTS: A FRAMEWORK FOR INTEGRATED INFORMATION ENVIRONMENTS IN THE BUILT ASSET INDUSTRY

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ABSTRACT: The built asset industry faces critical challenges in managing information across complex project deliveries, operations, and maintenance lifecycles. While Common Data Environments (CDEs) have provided centralized approaches for project-centric information management in construction and asset maintenance, they fall short in supporting true lifecycle integration and cross-organizational collaboration essential for modern built environment management. As the industry evolves toward Digital Twin (DT) implementations that require sophisticated data integrations, real-time synchronizations, and advanced semantic capabilities, these CDE limitations become increasingly problematic. This paper presents a conceptual foundation for Integrated Information Environments (IIEs) that transcends traditional CDE limitations by applying System-of-Systems (SoS) principles and interoperability approaches to the built asset information management. Through systematic analysis of current CDE capabilities mapped against established digital twin maturity dimensions (data integration, synchronization, semantic modeling, intelligence, and system autonomy), this paper identifies critical gaps and establishes requirements for an advanced information management approach. The research provides a structured framework for evaluating and addressing the interoperability challenges inherent in transitioning from conventional CDEs to information environments capable of supporting mature digital twin implementations. This conceptual foundation provides the built asset sector a pathway beyond CDEs toward truly integrated lifecycle information management, supporting the industry's digital transformation while maintaining alignment with established standards and practices.

1. INTRODUCTION

Information fragmentation persists as a significant challenge in the built asset industry (Kloosterman et al. 2024), where traditional information management approaches fail to support integrated value chains and comprehensive lifecycle thinking (Bucher & Hall 2020). Organizations managing complex built assets such as buildings, infrastructure, and industrial facilities have historically maintained or are still maintaining information in disconnected repositories, creating informational silos that impede effective collaboration, restrict visibility across asset lifecycles, and prevent the emergence of holistic insights (Jaskula et al. 2024). This fragmentation manifests in multiple dimensions; Technical fragmentation: Incompatible Building Information Modeling (BIM) data formats, diverse software systems with limited integration capabilities (Jaskula et al. 2024), inconsistent asset information structures between project delivery and operations, and disconnected IoT and sensor data platforms in smart building implementations (Ruiz-Zafra et al. 2022). Organizational fragmentation: Information divided across departments, companies, and stakeholders with limited sharing mechanisms, and siloed knowledge between design, construction, and maintenance stakeholders. Procedural fragmentation: Disconnected workflows, inconsistent processes, and handover

discontinuities between project and asset lifecycle phases (Motamedi et al. 2019). The resulting information landscape consists of independent systems that, while individually effective, collectively fail to provide the integrated perspective necessary for optimized asset lifecycle management. These disconnected repositories lead to redundant data collection, inconsistent decision-making, and missed opportunities for value creation, particularly during transitions between project delivery and operational phases in the built asset industry.

1.1 Research Methodology

This research follows a Design Science Research (DSR) methodology (Hevner 2007) to develop the conceptual foundations for Integrated Information Environments within the built asset industry. Following established DSR principles, the focus is placed on problem identification through industry stakeholder engagement, solution design informed by current built environment practices, and theoretical contribution addressing sector-specific challenges. The research synthesizes findings from built asset information management, digital engineering, and systems integration domains to iteratively develop and refine conceptual requirements for addressing integration challenges. This design-oriented approach enables systematic identification of industry needs while maintaining scientific rigor through continuous evaluation against established industry frameworks and standards including ISO 19650 (Organization and digitization of information about buildings and civil engineering works), ISO 16739 (Industry Foundation Classes - IFC), ISO 19157 (Geographic information - Data quality), and emerging digital twin guidelines. The methodology prioritized theoretical development aligned with industry requirements and practical implementation considerations.

1.2 Research Objective

This research aims to establish the conceptual foundation and requirements for Integrated Information Environments (IIEs) that transcend the limitations of Common Data Environments (CDEs) in the built asset industry. By systematically mapping CDE capabilities against digital twin maturity dimensions and applying Systems-of-Information Systems principles, this study identifies appropriate interoperability approaches needed to enable seamless information flows across organizational boundaries and lifecycle phases while preserving system autonomy and diversity. The research utilizes digital twin maturity dimensions as an analytical framework to evaluate current CDE limitations and define requirements for advanced information environments. This structured approach addresses the critical gap between project-centric information management and true lifecycle integration, providing the built asset industry with a conceptual model toward advanced digital twin implementations and optimized asset management while maintaining alignment with established standards and practices.

2. BACKGROUND

2.1 The Evolution of Common Data Environments

The recognition of aforementioned challenges led to the development of Common Data Environments (CDEs), defined in ISO 19650-1:2018 as "agreed sources of information for any given project or asset, for collecting, managing, and disseminating each information container through a managed process (ISO, 2018)." CDEs establish centralized repositories with standardized processes for information exchange, enabling more structured collaboration during project delivery phases (Preidel et al. 2018).

The current state of CDEs reflect several important capabilities but also significant limitations. Based on analysis of current literature (Bedoiseau et al. 2022; Bucher & Hall 2020; Jaskula et al. 2023, 2024; Kloosterman et al. 2024; Losev 2020; Poinet et al. 2021; Preidel et al. 2018), contemporary CDEs typically provide centralized information storage with controlled access and standardized file management with version control systems. They implement defined workflows for information approval and distribution along with basic collaboration tools for project teams. CDEs also feature structured classification of information states (work in progress, shared, published, archived) as defined in ISO 19650. Despite these

advancements, current CDEs remain predominantly project-centric with a focus on document-based information management during design and construction phases. Their integration capabilities are generally limited to file-based exchanges with basic API connectivity, while offering restricted cross-organizational access that typically terminates at project boundaries. Most CDEs provide limited real-time synchronization capabilities, relying instead on manual updates and batch processing. They typically support only basic semantic integration with simple metadata models and limited relationship management. Their analytics capabilities are generally restricted to descriptive reporting rather than predictive or prescriptive insights, while visualization is typically limited to basic model viewers rather than immersive experiences. Most concerning is their limited support for true lifecycle integration, creating significant discontinuities between project delivery and operational phases.

Recent research has attempted to address some of these limitations through enhanced CDEs that integrate specialized capabilities. For example, a study by Santos et al. (2019) has explored integrating CDEs with Life Cycle Assessment (LCA) tools to support sustainability analysis throughout building lifecycles. Similarly, other researchers (Dave et al. 2018; Tang et al. 2019) have incorporated real-time data streams from IoT devices and building management systems to enhance operational monitoring. While these enhanced CDEs represent important advancements, they typically implement point-to-point integrations between specific systems rather than comprehensive information environments. These approaches still face challenges in supporting true cross-domain semantic integration and real-time synchronization across organizational boundaries, despite notable progress in establishing integration frameworks (Dave et al. 2018).

These limitations become increasingly problematic as organizations within the built asset industry attempt to implement more sophisticated digital engineering approaches that require seamless information flows across organizational boundaries and throughout the entire asset lifecycle.

2.2 Digital Twins and Their Maturity Dimensions as an Analytical Framework

Digital twins have emerged as a powerful paradigm for integrated and well-structured information management across the asset lifecycle (Moretti et al. 2022). As defined by the Digital Twin Consortium, digital twins are "virtual representations of real-world entities and processes, synchronized at a specified frequency and fidelity." The implementation of digital twins in the built asset industry introduces a multi-dimensional framework for maturity assessment, as identified by Vieira et al. (2023). These dimensions—including data integration, synchronization, geometric modeling, semantic data representation, intelligence, user interface, and system autonomy—provide a comprehensive analytical framework to evaluate information management systems in the built environment.

This paper proposes using these digital twin maturity dimensions as a structured framework to evaluate advancement from basic digital models toward sophisticated, autonomous digital counterparts that can effectively support asset lifecycle management. This approach is particularly valuable as digital twins represent the evolution of built asset information management, with CDEs serving as crucial precursors that establish the initial data foundation during the product creation phase (Bucher & Hall 2020). By systematically analyzing CDE capabilities against these maturity dimensions, specific gaps that must be addressed to enable more sophisticated integration platforms can be identified. Table 1 illustrates the maturity dimensions defined by Vieira et al. (2023), to which we have contributed an original mapping of current CDE capabilities against advanced Digital Twin requirements, along with a gap analysis. This structured mapping provides an objective method to evaluate information management approaches and reveals the systematic limitations of existing CDEs when measured against the requirements for mature digital twin implementations in the built asset domain.

Through this dimensional analysis (see Table 1), significant disparities between CDE capabilities and the requirements for advanced digital twins' support have been revealed. This systematic evaluation using established maturity dimensions provides an objective method to identify specific capability gaps. Traditional CDEs typically support only basic to medium maturity levels across most dimensions (though occasionally reaching level 4 or 5 in specific areas (Jaskula et al. 2023, 2024; Poinet et al. 2021), which restricts their ability to enable truly integrated information management. The maturity dimensions framework

reveals that progressing to the highest maturity levels across all dimensions necessitates information environments that transcend conventional CDE capabilities. Specifically, the analysis identifies critical gaps in supporting real-time data flows (Data Integration dimension), semantic integration (Semantic Data dimension), and cross-organizational collaboration (System Autonomy dimension). These identified gaps form the basis for establishing requirements for Integrated Information Environments, providing a structured pathway from current CDE capabilities toward environments capable of supporting mature digital twins.

Table 1: Digital Twin Maturity Spectrum with CDE Capabilities

Dimension	Current CDE Capabilities	Transition Requirements	Digital Twin Target State	Specific Gaps to Address
DATA INTEGRATION	<ul style="list-style-type: none"> - File-based storage with basic API connectivity. - Manual data synchronization. - Limited real-time capabilities. 	<ul style="list-style-type: none"> - Implementation of middleware solutions. - Enhanced API development. - Data standardization protocols. 	<ul style="list-style-type: none"> - Fully automated bidirectional data flow. - IoT integration. - Real-time data processing. - Event-driven architecture. 	<ul style="list-style-type: none"> - Lack of automated validation systems. - Missing real-time processing capabilities. - Limited event handling.
SYNCHRONIZATION	<ul style="list-style-type: none"> - Scheduled updates with manual verification. - Batch processing of changes. - Version control systems. 	<ul style="list-style-type: none"> - Development of automated validation rules. - Implementation of change detection systems. - Enhanced error handling. 	<ul style="list-style-type: none"> - Real-time synchronization with automated consistency checks. - Continuous data validation. - Automated error correction. 	<ul style="list-style-type: none"> - Insufficient real-time processing. - Limited automated validation. - Poor error handling.
GEOMETRIC MODELLING	<ul style="list-style-type: none"> - BIM models with manual updates. - Basic reality capture integration. - Standard model management. 	<ul style="list-style-type: none"> - Integration of automated scanning systems. - Enhanced point cloud processing. - Improved change detection. 	<ul style="list-style-type: none"> - Continuous as-built verification. - Automated geometry updates. - Real-time model synchronization. 	<ul style="list-style-type: none"> - Limited automation in scanning. - Basic point cloud processing. - Manual change verification.
SEMANTIC DATA	<ul style="list-style-type: none"> - Basic metadata with manual relationship mapping. - Simple data classification. - Limited ontology. 	<ul style="list-style-type: none"> - Development of semantic frameworks. - Enhanced relationship mapping. - Automated classification systems. 	<ul style="list-style-type: none"> - Rich semantic web with automated relationships. - Dynamic ontologies management. - Intelligent data classification. 	<ul style="list-style-type: none"> - Lack of comprehensive ontologies. - Limited relationship automation. - Basic classification systems.
INTELLIGENCE	<ul style="list-style-type: none"> - Historical analysis with basic trend identification. - Simple predictive capabilities. - Manual optimization. 	<ul style="list-style-type: none"> - Implementation of ML infrastructure. - Development of training datasets. - Enhancement of analytical capabilities. 	<ul style="list-style-type: none"> - AI-driven insights with autonomous optimization. - Self-learning systems. - Automated decision support. 	<ul style="list-style-type: none"> - Limited AI/ML capabilities. - Insufficient training data. - Basic analytical tools.
USER INTERFACE	<ul style="list-style-type: none"> - Desktop/web access with basic mobile support. - Standard visualization tools. - Limited interaction modes. 	<ul style="list-style-type: none"> - Development of multi-device support. - Implementation of AR capabilities. - Enhanced users experience design. 	<ul style="list-style-type: none"> - Context-aware interfaces with natural interaction. - Multi-modal interaction support. - Adaptive user experiences. 	<ul style="list-style-type: none"> - Basic interface options. - Limited device support. - Poor context awareness.
SYSTEM AUTONOMY	<ul style="list-style-type: none"> - Manual processes with basic automation rules. 	<ul style="list-style-type: none"> - Implementation of advanced automation. 	<ul style="list-style-type: none"> - Self-optimizing systems with bounded autonomy. 	<ul style="list-style-type: none"> - Limited process automation. - Basic decision support.

- Human-dependent workflows. - Limited decision support.	- Development of decision engines. - Enhanced safety protocols.	- Automated decision-making. - Intelligent process control.	- Manual safety checks.
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3. SYSTEMS-OF-INFORMATION SYSTEMS AND INTEROPERABILITY APPROACHES

The limitations of CDEs and the requirements for digital twin maturity in the built asset management point toward the need for more sophisticated approaches to information integration. One particularly relevant paradigm is the Systems-of-Information Systems (SoIS) concept, which applies Systems-of-Systems principles to information management challenges (Fernandes et al. 2022). The authors define a SoIS as "an arrangement of independent information systems that work collaboratively to achieve goals beyond the capabilities of any individual system", which exhibits distinct characteristics to which we have added examples for the built asset context.

- **Autonomy:** Each constituent information system operates independently for its purposes while contributing to collective goals (e.g., BIM platforms, CMMS, BMS, ERP with asset management goals within the built asset industry).
- **Belonging:** Systems choose to participate based on cost-benefit considerations.
- **Connectivity:** Mechanisms enable communication and information sharing across boundaries (e.g., design tools, construction systems, and operational platforms).
- **Diversity:** Constituent systems are heterogeneous in technologies, purposes, and governance (e.g., CAD, BIM, IoT, CMMS).
- **Dynamicity:** The structure can change as systems join or leave the arrangement (e.g., smart building technologies).
- **Emergent Behavior:** Collaboration produces capabilities beyond what individual systems provide (e.g., predictive maintenance).
- **Evolutionary Development:** Both individual systems and the overall arrangement evolve over time.
- **Interdependence:** Systems rely on one another while maintaining operational independence.

The establishment of interoperability links between constituent information systems represents critical challenges (Poirier et al. 2014) in forming a SoIS. According to ISO 14258, three primary interoperability approaches can be employed, each with distinct characteristics and applications that impact SoIS differently (Fernandes et al. 2022):

The **Integrated Approach** establishes standardized interfaces and common templates for all constituent systems. While this enhances connectivity and interdependence among systems, it can threaten autonomy, evolutionary development, diversity, and dynamicity of individual components (Fernandes et al. 2022). In the built asset context, this approach is most appropriate for core infrastructure services, baseline security controls, fundamental data structures, and technical standards implementation where consistency is paramount. For example, standardized authentication protocols might be implemented across all systems to ensure reliable security operations.

The **Unified Approach** creates common meta-models that establish semantic equivalence while preserving internal structures of constituent systems. This approach moderately preserves most SoIS characteristics while potentially constraining some aspects of evolutionary development and diversity (Fernandes et al. 2022). It is particularly valuable for semantic models and ontologies, data schemas and structures, process definitions and models, and governance principles where shared understanding is essential without forcing homogeneity. In practice, this might include standardized ontologies like ifcOWL that map diverse BIM implementations to common concepts without requiring systems to change their internal representations.

The **Federated Approach** enables runtime adaptation without imposing existing models, languages, or methods on constituent systems. This maximally preserves autonomy, evolutionary development, diversity,

and dynamicity, though it may present challenges for connectivity and interdependence (Fernandes et al. 2022). This approach works well for user interfaces and experiences, business process execution, service discovery and composition, and cross-organizational access control where flexibility and stakeholder independence are crucial. For instance, this enables different organizations to maintain their preferred visualization tools while accessing the same underlying information. The selection of appropriate interoperability approaches represents a critical decision in built asset SoIS design, as it directly impacts the preservation of essential characteristics across the asset lifecycle. A balanced implementation that strategically applies different approaches based on specific requirements can optimize the benefits of integration while preserving system independence. This strategic combination enables organizations to balance standardization needs with flexibility requirements while maintaining the essential system characteristics that support effective built asset management.

3.1 Interoperability Requirements for Integrated Information Environments

Building on the dimensional framework for digital twin maturity, the concept of Systems-of-Information Systems (SoIS), and established interoperability paradigms, we have contextualized and extended the eight fundamental interoperability requirements originally identified by Sadeghi et al. (2024). Our analysis adapts these requirements specifically for integrated information environments within the built asset domain, mapping each requirement to current CDE limitations, relevant digital twin maturity dimensions, and optimal interoperability approaches (see Table 2). This mapping establishes a structured framework for evaluating and addressing the interoperability challenges inherent in transitioning from conventional CDEs to mature digital twin implementations.

Table 2: Interoperability Requirements: Addressing CDE Gaps Through Interoperability Approaches

Interoperability Requirements (Sadeghi et al., 2024)	Description	Addressing CDE Limitations	Supporting Digital Twin Dimensions	Optimal Interoperability Approach based on Their Implementation Impact on SoIS Characteristics
R1: DATA STANDARDIZATION AND PORTABILITY	Facilitate data exchange among systems while maintaining source system autonomy	File-based BIM models, static data structures (COBie handover), document-centric approaches, Proprietary formats, Fragmented schemas	Hierarchy, Geometric/Non-geometric Representation, Synchronization	Unified for asset data models with Federated Implementation approaches
R2: SERVICE STANDARDIZATION	Promote common standards for service management across organizational contexts	Point-to-point integration, basic API management, tightly-coupled interfaces, Protocol inconsistency, Limited service discovery	Connection, Interface, Synchronization	Unified for service contracts with Federated discovery mechanisms
R3: ACCESSIBILITY AND OPENNESS	Ensure open, accessible data with appropriate security and privacy controls	Limited cross-organizational sharing, information silos, restrictive access to asset data, poor visibility across phases	Accessibility, Hierarchy, Interface	Federated for access control with Unified metadata standards
R4: SECURITY AND PRIVACY	Address security and privacy concerns in collaborative environments	Project-level security, basic access controls, perimeter-focused approaches	Accessibility, Connection	Integrated for baseline controls with Federated implementation
R5: DISCOVERABILITY	Establish efficient discovery processes for services and data	Limited metadata management, fragmented information, poor search capabilities, Inadequate contextual discovery	Non-geometric Representation, Geometric Representation, Intelligence, Synchronization	Unified for metadata standards with Federated catalogs

R6: TECHNOLOGICAL NEUTRALITY	Decouple services and functions from underlying technologies	Vendor lock-in, limited technology integration, tight coupling	Connection, Interface, Autonomy	Federated for implementation with Unified abstractions
R7: INTEGRATION/ ORCHESTRATION	Facilitate coordination of complex services across the value chain	Fragmented processes, limited workflow integration, poor coordination, limited automation	Hierarchy, Intelligence, Autonomy	Unified for process models with Federated execution
R8: AUTOMATION AND MACHINE READABILITY	Promote automation to reduce human intervention	Manual workflows, limited automation, human-dependent operations, reactive processes	Autonomy, Intelligence, Synchronization	Unified for automation standards with Federated implementation

4. CONCEPTUAL FOUNDATIONS FOR INTEGRATED INFORMATION ENVIRONMENTS

The limitations of CDEs and the emerging requirements for digital twin implementations point toward the need for a new conceptual framework for information management in the built asset domain. While recent enhancements to CDEs have addressed specific gaps, a more comprehensive approach is required to support true lifecycle integration and cross-organizational collaboration.

4.1 Limitations of Current CDEs in Supporting Advanced Information Managements

The analysis presented in the previous sections reveals significant disparities between current CDE capabilities and the requirements for advanced information management in the built asset domain. These limitations can be categorized into several key areas:

1. **Technical Integration Constraints:** Current CDEs predominantly support file-based exchanges with limited real-time capabilities, insufficient for the continuous bidirectional data flows required by mature digital twins. Despite progress in BIM-IoT integration frameworks (Dave et al. 2018; Tang et al. 2019), these approaches still face significant challenges. Dave et al. (2018) demonstrated integration using open standards but noted persistent difficulties implementing comprehensive event-driven architectures and validation mechanisms. Their implementation highlighted challenges in handling dynamic data flows, underscoring current integration limitations despite meaningful progress.
2. **Semantic Integration Challenges:** Most CDEs implement only basic metadata management with limited relationship mapping capabilities, falling short of the rich semantic web required for sophisticated digital twins. Enhanced CDEs combining BIM and LCA capabilities (Röck et al. 2018; Santos et al. 2019) have advanced beyond basic mappings, but still maintain separate semantic models with predefined mappings between domains. As Röck et al. (2018) noted, maintaining consistent semantics across domains remains challenging as models evolve, limiting automated cross-domain reasoning capabilities.
3. **Process Integration Gaps:** Contemporary CDEs typically support manual workflows with basic automation rules, constraining intelligent orchestration, dynamic processes, and adaptive rules necessary for optimized asset management. These limitations restrict the development of self-optimizing systems with bounded autonomy.
4. **Organizational Integration Barriers:** The project-centric focus of CDEs creates significant discontinuities at project boundaries, limiting cross-organizational collaboration throughout the asset lifecycle. This fragmentation impedes the establishment of dynamic collaboration frameworks needed for lifecycle-spanning information management.

These limitations highlight the need for a new paradigm that transcends traditional CDE approaches to support true lifecycle integration and cross-organizational collaboration in the built asset industry.

4.2 Integrated Information Environments: Conceptual Definition and Requirements

Based on our analysis of digital twin maturity dimensions, Systems-of-Information Systems principles, and interoperability requirements, we propose the concept of Integrated Information Environments (IIEs) as an evolution beyond conventional CDEs. IIEs can be defined as "Comprehensive socio-technical systems that enable seamless information flows across organizational boundaries, systems, and lifecycle phases of built assets, supporting continuous value creation through real-time collaboration, semantic integration, and intelligent decision support while preserving the autonomy and diversity of constituent systems." The fundamental requirements for IIEs include:

1. **Cross-Lifecycle Information Integration:** IIEs must support seamless information flows throughout the entire asset lifecycle, from early design through construction, operations, maintenance, and eventual decommissioning or renovation. This requires mechanisms for maintaining information continuity across project boundaries and organizational transitions.
2. **Real-Time Synchronization Capabilities:** Unlike the batch processing and manual updates characteristic of many CDEs, IIEs require event-driven architectures supporting real-time data flows, automated consistency checks, and continuous validation mechanisms. These capabilities are essential for maintaining synchronization between physical assets and their digital representations. Implementations of BIM-IoT integration (Dave et al. 2018; Tang et al. 2019) have improved operational monitoring capabilities but still fall short of the comprehensive event-driven architecture required for IIEs. Tang et al. (2019) identified significant challenges in real-time integration, noting that while current frameworks provide conceptual models for connectivity, practical implementations still struggle with data verification, continuous synchronization, and handling the volume and diversity of IoT data streams. These enhanced systems typically implement data collection and visualization features but lack the consistency checks and automated validation mechanisms essential for maintaining reliable synchronization between physical assets and their digital representations.
3. **Semantic Interoperability:** Achieving robust semantic interoperability requires IIEs with sophisticated semantic models and dynamic relationship management capabilities that enable consistent cross-domain information interpretation. The integration of LCA with BIM workflows demonstrates this challenge while offering significant opportunities for comprehensive sustainable design (Chen et al. 2024). While enhanced CDEs have implemented semantic connections between building models and environmental data—as demonstrated by Santos et al.'s (2019) cross-domain semantics work and Forth et al.'s (2019) ontology-based approaches—these integrations continue to face challenges with dynamic model evolution and cross-domain reasoning (Röck et al. 2018). Semantic web technologies show promise by providing effective management of disparate data in common formats, while complementary Knowledge Discovery in Databases (KDD) techniques support sophisticated analysis of sustainability indicators (Okonta et al. 2024). Future research must establish semantic foundations that facilitate automated classification, context-aware mappings, and intelligent information discovery while enriching databases with additional lifecycle phases for more holistic sustainability assessments.
4. **Balanced Interoperability Implementation:** IIEs should strategically apply federated, unified, and integrated approaches based on specific requirements:
 - The federated approach (runtime adaptation without imposing models) is particularly valuable for user interfaces and business process execution, where preserving stakeholder autonomy is essential. For example, this enables different organizations to maintain their preferred visualization tools while accessing the same underlying information.
 - The unified approach (common meta-models with semantic equivalence) is ideal for semantic models and data schemas, providing standard concepts while allowing domain-specific extensions. This allows, for instance, both facilities management and sustainability analysis tools to interpret building elements according to their domain needs.
 - The integrated approach (standardized interfaces and templates) works best for core infrastructure and security services, ensuring reliable communication without restricting system diversity. This might include standardized authentication protocols that all systems implement while maintaining their internal security models. This strategic combination balances

standardization needs with flexibility considerations, preserving system autonomy and diversity while enabling effective collaboration across organizational boundaries.

5. **Intelligent Process Orchestration:** IIEs require sophisticated business process management capabilities supporting automated workflows, intelligent orchestration, and adaptive rules. These features enable coordination of complex services across the value chain while preserving operational independence of constituent systems.
6. **Enhanced Security and Governance:** IIEs must implement comprehensive security and governance frameworks addressing the complex challenges of cross-organizational collaboration and information sharing while ensuring confidentiality, integrity, and availability throughout the asset lifecycle.

While these IIE concepts offer promising theoretical foundations for addressing CDE limitations, practical implementation and validation require further research. Comprehensive validation would necessitate case studies across diverse built asset types to evaluate technical performance, process enhancement, organizational value, and implementation feasibility, with particular attention to project-operation transitions and comparative analysis with enhanced CDEs.

5. CONCLUSIONS

The transition from CDEs to IIEs represents a fundamental reconceptualization of information management across organizational boundaries in the built asset industry. Our analysis using digital twin maturity dimensions identified specific gaps in CDE capabilities while establishing requirements for environments that support mature digital twins and advanced information managements. This systematic approach, combined with SoIS principles and strategic interoperability approaches, provides a conceptual framework that enables lifecycle integration and cross-organizational collaboration while preserving system autonomy and diversity. Future research should validate these concepts through industry case studies focusing on project-operation transitions, while addressing standards gaps, organizational barriers, technological readiness, and scalability challenges. The industry's transition to IIEs will require incremental approaches that deliver progressive value, ultimately enabling the full potential of digital twins and lifecycle-spanning information management.

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