

Integrated Information Environments in the Built Asset Industry: A Strategic, Multi-Perspective Framework

by

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Environnements d'information intégrés dans l'industrie des actifs bâtis: un cadre stratégique et multi perspectif

Neda REZAEI

RÉSUMÉ

La fragmentation de l'information constitue un défi majeur pour l'industrie des actifs bâtis, où les approches conventionnelles ne parviennent pas à soutenir les chaînes de valeur intégrée et la pensée cycle de vie. Malgré la conceptualisation théorique des environnements de données communs (EDC) comme « source unique de vérité », les organisations continuent en pratique d'exploiter plusieurs EDC déconnectés parallèlement à d'autres sources d'information. Cette fragmentation limite les échanges d'information continus, contraignant les capacités avancées de modélisation des informations du bâtiment (BIM) et entravant les implémentations de jumeaux numériques (JN) ainsi que les initiatives de transformation numérique. Cette recherche examine les exigences d'un environnement d'information intégré (EII) permettant des flux d'information fluides au-delà des frontières temporelles et organisationnelles tout en préservant l'autonomie des systèmes. À travers une analyse multi-perspective, l'étude identifie des exigences émergentes qui révèlent des capacités dépassant la portée des EDC traditionnels.

En utilisant la méthodologie de recherche en science de la conception (DSR), la recherche caractérise systématiquement les composantes des EII à travers trois niveaux interdépendants: Structure et Signification des Données (établissant les fondations sémantiques et syntaxiques), Échange et Gestion des Données (fournissant une infrastructure d'intégration fédérée), et Consommation et Utilisation des Données (apportant de la valeur aux parties prenantes par le biais d'applications). Une étude de cas menée avec le Conseil national de recherches (CNR) du Canada démontre l'applicabilité du cadre à travers la conception conceptuelle d'une plateforme de construction numérique intégrant les Codes modèles nationaux de construction, les Devis directeurs nationaux et les évaluations du Centre canadien de matériaux de construction. L'architecture de solution guidée par le cadre illustre la capacité du cadre à structurer la progression depuis des systèmes fragmentés vers des environnements intégrés tout en maintenant l'autonomie organisationnelle. En établissant des connaissances fondamentales sur les exigences des EII et en identifiant les mécanismes de progression d'une gestion de l'information centrée sur les projets vers une gestion intégrée au cycle de vie, cette investigation comble une lacune critique dans la littérature et fournit des perspectives pratiques pour les organisations poursuivant des capacités numériques avancées dans un environnement bâti intelligent.

Mots-clés : Environnements d'information intégrés, industrie des actifs bâtis, transformation numérique, intégration de l'information, environnement de données commun

Integrated information environments in the built asset industry: a strategic, multi-perspective framework

Neda REZAEI

ABSTRACT

Information fragmentation poses a significant challenge within the built asset industry, where conventional approaches fail to support integrated value chains and lifecycle thinking. Despite the theoretical conceptualization of Common Data Environments (CDEs) as a "single source of truth", organizations in practice persistently operate multiple, disconnected CDEs alongside other information sources. This fragmentation limits continuous information exchange, constraining advanced Building Information Modeling (BIM) capabilities and hindering Digital Twin (DT) implementations and digital transformation initiatives. This research investigates the requirements for an Integrated Information Environment (IIE) to enable seamless information flows across temporal and organizational boundaries while preserving system autonomy. Through a multi-perspective analysis, the study identifies emergent requirements that reveal capabilities exceeding traditional CDEs scope.

Employing Design Science Research (DSR) methodology, the research systematically characterizes IIE components across three interdependent tiers: Data Structure & Meaning (establishing semantic and syntactic foundations), Data Exchange & Management (providing federated integration infrastructure), and Data Consumption & Use (delivering stakeholder value through applications). A case study with the National Research Council (NRC) of Canada demonstrates the framework's applicability through the conceptual design of a Digital Construction Platform integrating the National Model Construction Codes, National Master Specifications, and Canadian Construction Materials Centre evaluations. The framework-guided solution architecture illustrates its capacity to structure the progression from fragmented systems toward integrated environments while maintaining organizational autonomy. By establishing foundational knowledge about IIE requirements and identifying mechanisms for progression from project-centric to lifecycle-integrated information management, this investigation addresses a critical literature gap and provides practical insights for organizations pursuing advanced digital capabilities in an intelligent built environment.

Keywords: Integrated Information Environments, Built Asset Industry, Digital Transformation, Information Integration, Common Data Environment

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LIST OF ABBREVIATIONS AND ACRONYMS

AIM	Asset Information Model
API	Application Programming Interface
AR	Augmented Reality
BAS	Building Automation Systems
BCF	BIM Collaboration Format
BI	Business Intelligence
BIM	Building Information Modeling/Modelling
BMS	Building Management Systems
BPMN	Business Process Model and Notation
bSDD	buildingSMART Data Dictionary
CAFM	Computer-Aided Facility Management
CAD	Computer-Aided Design
CCMC	Canadian Construction Materials Centre
CDE	Common Data Environment
CDF	Common Data Framework
CMMS	Computerized Maintenance Management System
CSDP	Construction Sector Digitalization and Productivity Challenge Program
DCP	Digital Construction Platform
DSR	Design Science Research
DT	Digital Twin
EDA	Event-Driven Architecture
EDMS	Electronic Document Management System

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ETL/ELT	Extract, Transform, Load/Extract, Load, Transform
GIS	Geographic Information Systems
HTTP	Hypertext Transfer Protocol
ICDD	Information Container for Data Drop
IDM	Information Delivery Manual
IDS	Information Delivery Specification
IFC	Industry Foundation Classes
IIE	Integrated Information Environment
IoT	Internet of Things
IPFS	InterPlanetary File System
iPaaS	Integration Platform as a Service
JSON	JavaScript Object Notation
LCA	Life Cycle Assessment
LCBE	Low Carbon Built Environment Challenge Program
LISI	Levels of Information System Interoperability
LITE	Lifecycle Information Transformation and Exchange
LOIN	Level of Information Need
MVD	Model View Definition
NMCC	National Model Construction Codes
NMS	National Master Specifications
NRC	National Research Council (of Canada)
OGC	Open Geospatial Consortium

OpenCDE	Open Common Data Environment
OWL	Web Ontology Language
PAS	Publicly Available Specification
PDCSS	Platform to Decarbonize the Construction Sector at Scale
PIM	Project Information Model
PLM	Product Lifecycle Management
PSets	Property Set Definitions
RASE	Requirement, Applicability, Selection, Exception
RDF	Resource Description Framework
REST	Representational State Transfer
SAREF	Smart Applications REference ontology
SOA	Service-Oriented Architecture
SOAP	Simple Object Access Protocol
SoIS	Systems-of-Information Systems
SoS	System of Systems
SPARQL	SPARQL Protocol and RDF Query Language
SWRL	Semantic Web Rule Language
UML	Unified Modeling Language
VR	Virtual Reality
WIP	Work in Progress
XML	eXtensible Markup Language

INTRODUCTION

The built asset industry is undergoing significant digital transformation, driven by the need to address persistent challenges such as poor productivity, fragmented value chains, and sustainability imperatives (Okonta et al., 2024; Poirier et al., 2022; Succar & Poirier, 2020; Yousfi et al., 2024). Building Information Modelling (BIM) has emerged as a pivotal technology promoting model-based collaboration and enabling more efficient networked working environments (Jiang et al., 2019; Succar & Poirier, 2020; Turk et al., 2022). However, the full realization of BIM's potential remains hampered by entrenched issues of information fragmentation and lack of interoperability - the ability of independent systems to exchange and meaningfully use information (Kloosterman et al., 2024; Poirier et al., 2022; Succar & Poirier, 2020).

Current Approach: Common Data Environments

In response to information fragmentation challenges, the concept of Common Data Environment (CDE) gained prominence as "a single source of truth" for project-related information throughout the asset lifecycle (Jaskula et al., 2024, 2025; Kloosterman et al., 2024). CDEs evolved from BS1192:2007 through ISO 19650 (2019), establishing international standards for BIM-based collaboration. Modern CDE platforms - including Asite, Viewpoint, Procore, and ProjectWise - provide BIM visualization, communication through open standards like IFC and BCF, and document management capabilities (Bedoiseau et al., 2022; Comiskey et al., 2017; Kloosterman et al., 2024).

The Gap

Despite theoretical promises and progressive evolution, organizations rarely achieve the vision of a unified CDE. In practice, companies operate multiple disconnected systems, using different platforms for design, document management, and operations. This persistent fragmentation reveals fundamental limitations in CDE conceptualization that extend beyond

technical implementation challenges: inadequate semantic foundations for consistent interpretation across organizational boundaries (Jiang et al., 2023; Soman & Whyte, 2020); project-centric paradigms that fail to support lifecycle continuity (Jaskula et al., 2024); centralization tensions that threaten organizational autonomy (Soman & Whyte, 2020); and limited interoperability scope addressing only technical connectivity while neglecting organizational, procedural, and governance dimensions (Ahmed et al., 2024; Poirier et al., 2014; Turk, 2020). The increasing complexity of modern built assets, combined with Digital Twin emergence and sustainability imperatives, reveals these are not merely implementation challenges but fundamental constraints of the CDE paradigm itself.

Problem Statement: The built asset industry lacks a comprehensive framework for creating Integrated Information Environments that can support seamless information flows throughout asset lifecycles while preserving organizational autonomy. Existing approaches, whether Common Data Environments or interoperability frameworks, fail to address the full spectrum of integration requirements spanning semantic foundations, federated architecture, lifecycle continuity, and multi-dimensional interoperability across technical, organizational, and governance domains. This gap prevents organizations from effectively implementing advanced digital capabilities including Digital Twins, automated compliance checking, and sustainability assessments.

Research Question: *What are the requirements for an Integrated Information Environment that enables seamless information flows across asset lifecycle stages and value chains while maintaining system autonomy?*

Research Objectives: To address this question, three specific objectives guide this research:

- **RO1: Identify and systematize essential requirements and components** for Integrated Information Environments that address multi-dimensional interoperability challenges while preserving system autonomy. This establishes what integrated systems must achieve

(requirements) and how these objectives translate into specific technical and organizational components.

- **RO2: Develop a multi-tier framework** that provides systematic guidance for transforming fragmented information systems toward integrated environments capable of supporting advanced digital capabilities. The framework organizes requirements and components across three interdependent tiers addressing data structure and meaning, data exchange and management, and data consumption and use.
- **RO3: Validate the framework's applicability and utility** through real-world evaluation, demonstrating its capacity to guide practical implementation while addressing organizational constraints through systematic application to the National Research Council of Canada's Digital Construction Platform initiative.

Research Contributions: This research makes three primary contributions to knowledge and practice:

- **Theoretical Contribution:** A three-tier framework characterizing Integrated Information Environments through 19 requirements and 18 components that address the full spectrum of interoperability dimensions (semantic, syntactic, conceptual, procedural, organizational, legal/governance, and contextual). The framework advances theoretical understanding by explicitly integrating federated architecture principles with lifecycle information management, bridging the gap between abstract BIM maturity models and actionable implementation guidance.
- **Methodological Contribution:** A systematic approach for translating theoretical interoperability requirements into practical architectural components organized hierarchically across Data Structure & Meaning (Tier 1), Data Exchange & Management (Tier 2), and Data Consumption & Use (Tier 3). This hierarchical organization reveals

critical dependencies; higher-tier capabilities like Digital Twins fundamentally depend on lower-tier semantic foundations and integration infrastructure.

- **Practical Contribution:** Validated implementation guidance demonstrated through the National Research Council case study, where the framework successfully guided integration of three fragmented national resources (Construction Codes, Master Specifications, Product Evaluations) serving diverse stakeholders while preserving departmental autonomy. The case study provides evidence that the framework addresses real-world integration challenges and delivers stakeholder value across multiple organizational contexts.

To achieve these objectives, this investigation employs Design Science Research (DSR) following Peffers et al. (2007)'s six-activity process. The research synthesizes knowledge across eight interconnected domains through literature review, develops the IIE framework through iterative refinement, demonstrates framework application through the NRC case study, and evaluates effectiveness through systematic mapping of integration challenges to framework components.

Chapter 1 examines information fragmentation (Section 1.1), BIM evolution (Section 1.2), CDEs and their limitations (Section 1.4), Digital Twins (Section 1.6), interoperability challenges (Section 1.7), and Digital Thread concepts (Section 1.8), establishing the gap motivating the IIE framework. Chapter 2 details the DSR methodology, literature synthesis approach, framework development process, and evaluation strategy. Chapter 3 presents the three-tier IIE framework with detailed component analysis and the 19 requirements. Chapter 4 presents the NRC case study findings demonstrating framework-guided solution development and systematic validation. Chapter 5 interprets results, examines theoretical and practical contributions, and discusses limitations and future research directions.

CHAPTER 1

LITERATURE REVIEW

This chapter examines the persistent challenge of information fragmentation in the built asset industry and evaluates existing approaches to information integration. Despite decades of digital advancement, the industry continues to struggle with disconnected systems, lifecycle discontinuities, and limited cross-organizational collaboration. Through critical analysis of current technologies, from BIM through CDEs and emerging frameworks, this review identifies fundamental limitations that prevent true information exchange and integration. The analysis establishes that current approaches, while addressing specific aspects of information management, fail to provide solutions for the complex, multi-stakeholder environments characteristic of modern built asset projects. This systematic examination of existing limitations provides the theoretical foundation for Integrated Information Environments (IIEs) to move beyond current fragmented approaches.

1.1 The Persistent Challenge of Information Fragmentation

Information fragmentation represents the fundamental barrier to digital transformation in the built asset industry. Unlike manufacturing industries with integrated supply chains, the built asset sector operates through temporary project coalitions involving multiple autonomous organizations, each maintaining distinct information repositories aligned with specific roles and responsibilities (Kloosterman et al., 2024; Yousfi et al., 2024). This structural fragmentation manifests across two critical dimensions: vertical fragmentation across project phases (design, construction, operation) and horizontal fragmentation across specialized stakeholders (architects, engineers, contractors, facility managers).

The consequences extend beyond mere inefficiency. Information transfer between software platforms causes systematic data degradation, with document-based exchanges and format conversions resulting in semantic loss and reduced machine readability (Soman & Whyte,

2020). These inefficiencies compound throughout project lifecycles, leading to time and cost overruns, reduced design quality, and suboptimal operational performance. More fundamentally, fragmentation prevents the industry from achieving the integrated value chains and lifecycle thinking necessary for sustainability, circular economy principles, and advanced digital capabilities (Jaskula et al., 2024; Shafiq, 2021). Current approaches attempt to address fragmentation through various technological solutions, yet none resolve the underlying structural challenges. The industry requires systematic evaluation of existing approaches to understand why fragmentation persists and what changes are required for true integration.

1.2 Building Information Modeling: Progress and Persistent Limitations

1.2.1 BIM Evolution and Capability Development

Building Information Modeling represents the industry's primary response to information fragmentation challenges. BIM transcends simple geometric representation by incorporating rich datasets including materials, specifications, costs, and scheduling information, fundamentally changing how project teams collaborate (Y. Chen & Jupp, 2019; Godager et al., 2021).

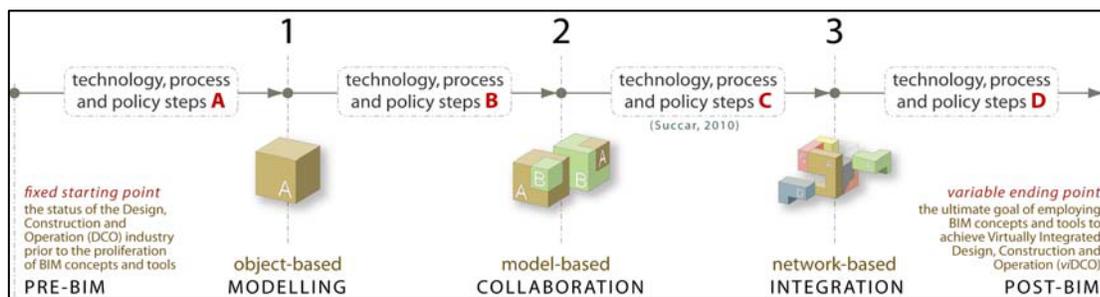


Figure 1.1 BIM Capability Stages

Taken from (Succar, 2009)

Succar's BIM Capability Stages framework demonstrates this evolution from Pre-BIM through to Post-BIM (Figure 1.1). Pre-BIM Status (Stage 0) represents the industry's state prior to BIM

implementation, characterized by conventional practices, often relying on 2D documentation with disjointed information, asynchronous communication, and lack of interoperability. BIM Stage 1 represents Object-Based Modelling, requiring deployment of object-based modelling software tools, signifying a fundamental shift from simple 2D or 3D Computer-aided Design (CAD) to intelligent, object-oriented models. BIM Stage 2 represents Model-Based Collaboration, achieved when organizations participate in multidisciplinary, model-based collaborative projects, moving beyond internal modelling to shared workflows and coordinated information exchange among project participants. BIM Stage 3 represents Network-Based Integration, characterized by network-based solutions such as model servers or BIM-as-a-Service platforms to share object-based models across multiple disciplines, aiming for high integration across the supply chain. Each stage represents transformational rather than incremental change, requiring significant organizational investment and process modification.

1.2.2 OpenBIM and Standardization Efforts

While BIM has significantly improved interaction between software platforms and stakeholders, its transformative potential remains constrained by fundamental interoperability limitations between proprietary systems and data formats (Tsay et al., 2022; Yousfi et al., 2024). These limitations create the information fragmentation challenges. OpenBIM, spearheaded by buildingSMART International, represents a strategic response to these challenges by promoting open standards and vendor-neutral approaches to information exchange. Central to this initiative is the IFC data schema, which serves as the foundational semantic framework enabling cross-platform data exchange regardless of software vendor or professional discipline (Moretti et al., 2022; Tsay et al., 2022; Yousfi et al., 2024). The OpenBIM ecosystem has evolved from simple file-based exchanges toward Application Programming Interface or API-driven integration paradigms. This evolution encompasses specialized infrastructure extensions (IFC Rail, IFC Road) and architectural improvements including enhanced modularity (IFC 5, IFC x) (Figure 1.2) and language neutrality (Okonta et al., 2024; van Berlo et al., 2021).

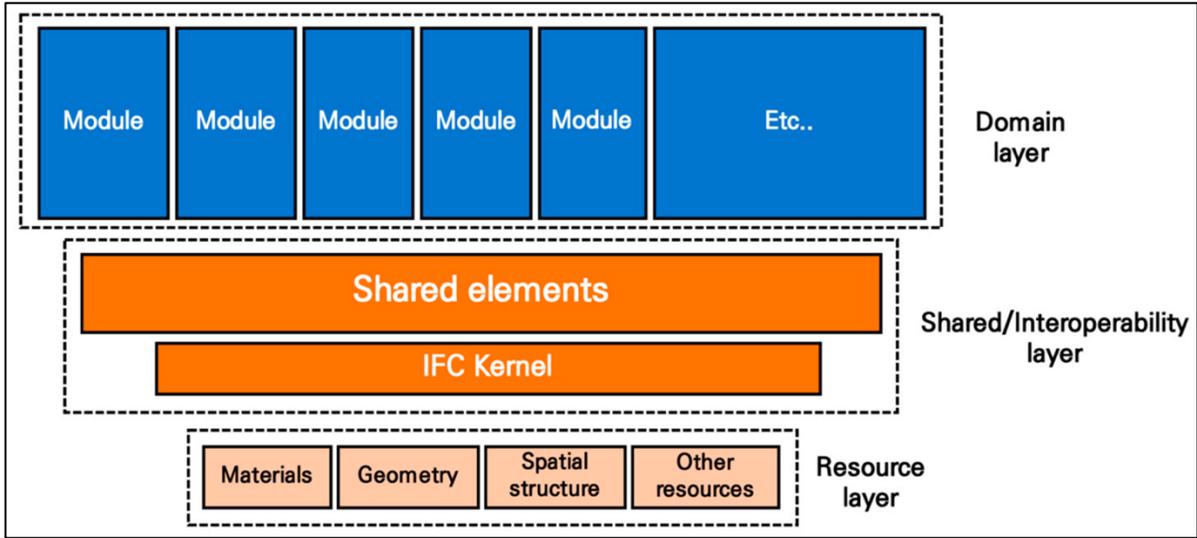


Figure 1.2 The evolution toward modular IFC architecture
 Taken from (Yu et al., 2023)

Table 1.1 presents core openBIM standards, their alignments with current study and shows how they address information fragmentation alongside their limitations.

Table 1.1 Core OpenBIM Standards Ecosystem

Standard	Standard	Alignment with Current Study	Addressing Information Fragmentation
Data Standards			
IFC 4.3	Vendor-neutral building data schema	Semantic foundation for cross-organizational data exchange	Enables platform-independent information sharing
IFC Infrastructure Extensions	Domain-specific schemas (Rail, Road, Bridge)	Multi-domain vocabulary integration	Extends semantic consistency to infrastructure domains

Standard	Standard	Alignment with Current Study	Addressing Information Fragmentation
buildingSMART Data Dictionary (bSDD)	Multilingual semantic reference library	Cross-domain semantic mapping	Standardizes terminology across classifications and languages
Information Container for Data Drop (ICDD)	Multi-model container with semantic links	Federated information packaging for lifecycle handovers	Maintains relationships across heterogeneous datasets
Process Standards			
Information Delivery Manual (IDM)	Process and information requirements specification	Temporal coordination and lifecycle management	Maps stakeholder processes and information needs
Model View Definitions (MVD)	Technical implementation of exchange requirements	Contextual information delivery	Defines precise data exchanges for specific use cases
Information Delivery Specification (IDS)	Machine-readable validation framework	Automated quality validation	Enables automated compliance checking
Communication Standards			
BIM Collaboration Format (BCF)	Issue and change management communication	Real-time collaborative coordination	Software-independent issue tracking with context preservation
OpenCDE API	CDE platform integration standard	Federated system integration	Enables interoperability between CDE platforms

OpenBIM implementation relies on MVDs to facilitate targeted data exchange between applications. In this approach, a sender application generates a native BIM model while a receiver application requires specific data subsets, with exchange requirements specified through IDM and MVD frameworks (Yu et al., 2023) (Figure 1.3). However, this static approach or point-to-point information exchange introduces sustainability challenges that limit its effectiveness in complex, long-term asset management scenarios (Okonta et al., 2024).

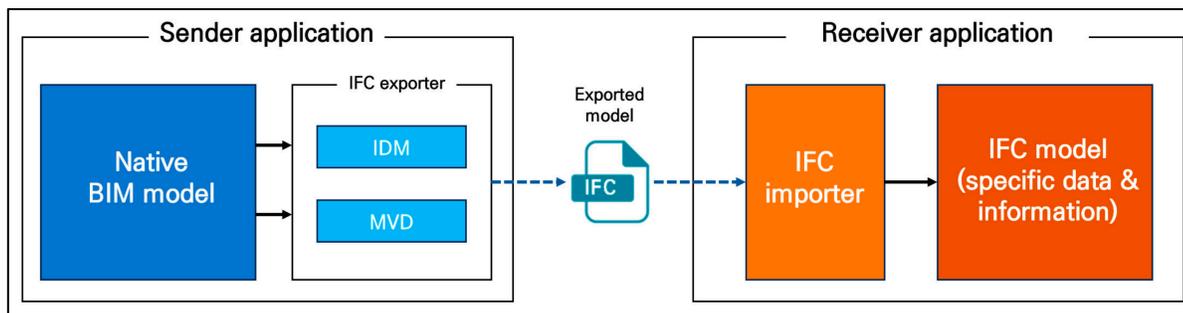


Figure 1.3 BIM data transaction using IDM and MVD

Taken from (Yu et al., 2023)

The buildingSMART Technical Roadmap acknowledges the increasing demands for information environments that can handle larger datasets, integrate with emerging technologies such as IoT and AI, and extend OpenBIM's scope to encompass Smart Cities and Digital Twins (van Berlo et al., 2021). This strategic direction aligns directly with the objectives of enabling seamless information flow across temporal and organizational boundaries.

1.3 From Static Exchange to Dynamic Information Environments

Modern construction projects require deeper semantic connections between information sources than traditional file-based exchanges can provide. Linked Data approaches address this need by creating interconnected webs of information using web technologies rather than isolated data silos. The ifcOWL transformation exemplifies this approach, converting IFC building data into Web Ontology Language (OWL) format to enable semantic reasoning and complex cross-domain queries (Pauwels et al., 2017; Werbrouck, 2019). Fahad (2016)

demonstrated the potential of semantic extension by integrating ifcOWL ontology with buildingSMART Data Dictionary (bsDD) vocabulary, comparing Model View Definition XML (MVDXML) and Semantic Web Rule Language (SWRL) technologies for automated conformance checking. This work exemplifies how semantic technologies can enhance model verification processes through automated validation against predefined standards, directly supporting the quality assurance and validation frameworks essential to the integrated information environments.

In another study, Z. Wang et al. (2022) identified critical limitations in IFC-based approaches, particularly in multi-domain collaborations where sequential, siloed workflows fail to support advanced functions such as maintaining design consistency across disciplines. Their cloud-based BIM (CBIM) solution compiles BIM models as RDF graphs within unified ontologies, enabling BIM models to function as cloud objects with inter-domain connections and seamless change synchronization. The CBIM prototype successfully demonstrated intelligent clash detection and consistency maintenance across multiple domains in a hospital building case study, proving that linked BIM graphs with meaningful semantic relationships can enable advanced applications across federated model environments.

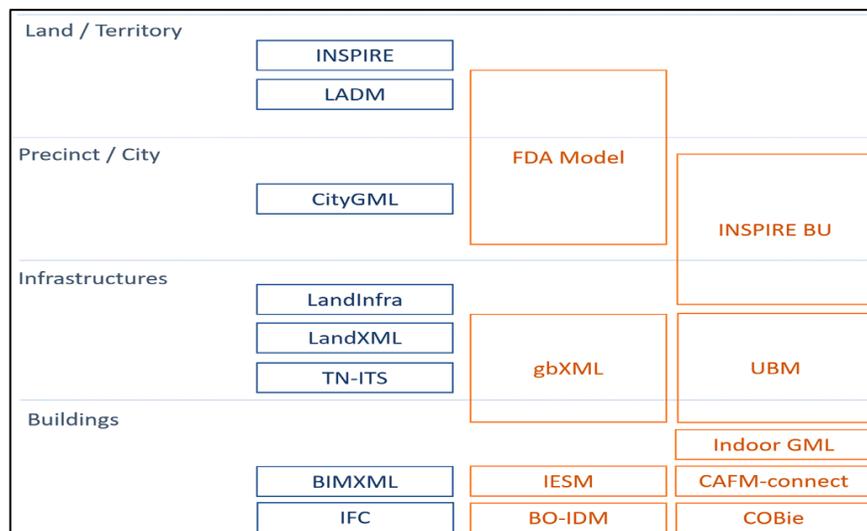


Figure 1.4 Multi-Scales Data Models
 Taken from (Moretti et al., 2022)

Moreover, Moretti et al. (2022) conducted an analysis of data modeling approaches for digital Asset Management applications, revealing that current single-model approaches cannot adequately represent the multiple scales and domains required for comprehensive asset lifecycle management (Figure 1.4). Their research identified two main approaches for developing intermediate data models but concluded that no single data model currently exists capable of spanning all required scales and domains. This finding reinforces this study's approach of federated integration rather than attempting to create monolithic solutions and emphasises on semantic consistency mechanisms that can maintain meaning and relationships across diverse data models and organizational boundaries. The evolution of OpenBIM standards and related research reveals several critical insights. Current OpenBIM standards provide essential semantic foundations (IFC, bSDD) but require enhancement for real-time, federated environments.

1.4 Common Data Environments: Promise Versus Reality

1.4.1 CDE Conceptualization, Structure, and Challenges

Common Data Environments emerged as the operational framework for BIM-based collaboration. A CDE serves as more than a basic cloud repository or an Electronic Document Management System (EDMS); it provides specialized workflows and BIM integration capabilities that establish a single source of truth for project information (Jaskula et al., 2023). The standard CDE structure comprises four main areas, Work in Progress (WIP), Shared, Published, and Archive, with information managed through defined workflows at specified decision points (Comiskey et al., 2017). This centralized approach enables consistent model coordination and ensures data quality through standardized processes (Preidel et al., 2018). CDEs offer significant advantages including enhanced efficiency through standardized exchange environments, improved cross-disciplinary collaboration, structured data management, and better decision support through accessible, centralized information (Michaud et al., 2019; Ren & Zhang, 2021; Yousfi et al., 2024).

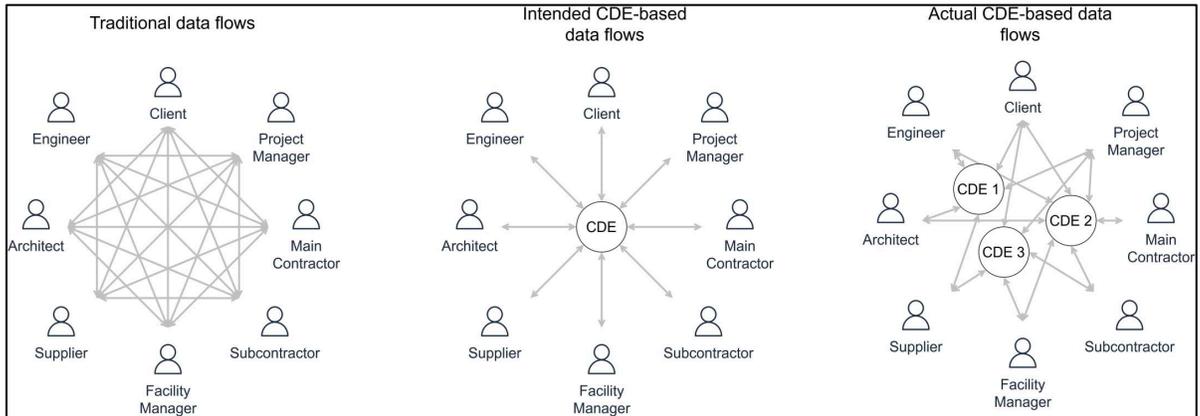


Figure 1.5 Actual CDE-based Information Flows in The built Asset Industry
 Taken from (Jaskula et al., 2025)

Despite theoretical promise, current CDE implementations face multidimensional challenges that limit their effectiveness. Organizations persistently operate multiple, disconnected CDEs alongside other information sources (Figure 1.5) (Jaskula et al., 2025). It creates significant data accountability, transparency, and reliability challenges.

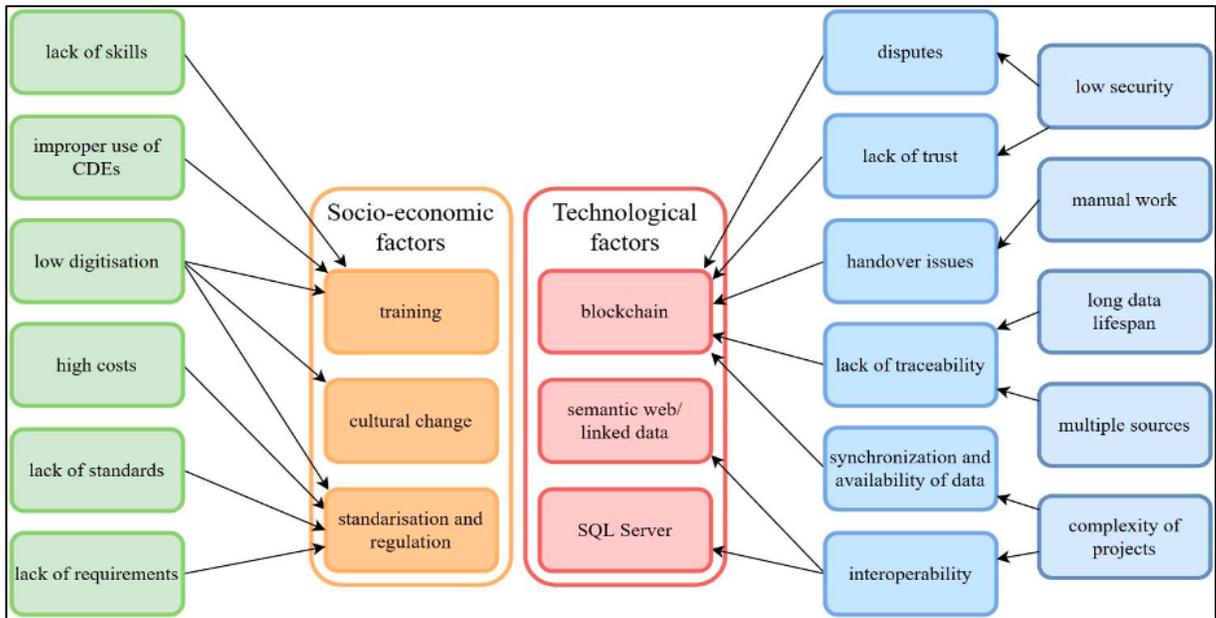


Figure 1.6 CDE Challenges with corresponding means to overcome them
 Taken from (Jaskula et al., 2024)

Jaskula et al.'s analysis revealed that multiple domain-specific tools lead to interoperability issues and poor data quality, with format conversions causing information loss. Even different versions of the same software create compatibility problems. The authors discuss that the lack of a common language due to numerous standards further complicates communication and increases implementation costs (Figure 1.6). Despite open standards such as IFC addressing some interoperability issues, inefficient exporters and importers continue causing information loss during conversions, limiting machine readability and data quality.

1.5 Proposed Solutions to Overcome Information Fragmentation

Several proposed solutions attempt to address information fragmentation through different approaches. Multi-layered CDE frameworks, Enterprise BIM initiatives, blockchain-based trust infrastructure, and the Lifecycle Information Transformation and Exchange (LITE) framework represent the efforts to move beyond project-centric platforms toward lifecycle-oriented environments. However, these approaches exhibit limitations that prevent comprehensive integration solutions.

1.5.1 A Multi-Layered CDE Framework

The multi-layered CDE framework (Figure 1.7) proposed by Bucher & Hall (2020) aims to extend beyond traditional document repositories by integrating geometrically rich BIM models within federated information environments. The framework conceptualizes CDEs across three dimensions: Tool-level (seamless interaction between software applications within a single platform), Platform-level (data exchange between different CDEs within projects or portfolios), and Enterprise-level (connections between CDEs and enterprise systems such as Digital Twins or Asset Information Management platforms).

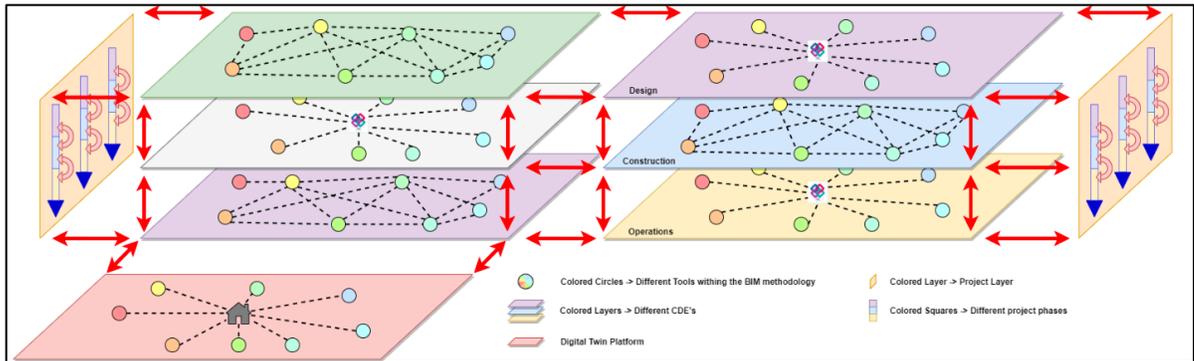


Figure 1.7 A Multi-layered CDE Framework

Taken from (Bucher & Hall, 2020)

This multi-layered approach enables seamless data flow across platforms, supporting automation and decentralized decision-making through comprehensive CDE ontologies to unify disparate data schemas. However, significant limitations constrain its practical application for achieving truly integrated information environments. The framework insufficiently addresses foundational challenges including persistent technical and semantic gaps where IFC limitations, vendor lock-in, and proprietary systems create practical impediments despite conceptual connections. It inadequately handles broader ecosystem integration where multiple simultaneous CDEs create fragmentation, data inconsistency, and traceability issues that mere connectivity cannot resolve. The framework lacks emphasis on granular lifecycle information management, remaining predominantly file-based rather than data-driven, without mechanisms for ensuring data integrity, traceability, and quality across proposed dimensions. Furthermore, it understates profound socio-technical barriers including industry inertia, skills deficits, contractual impediments, and critical human and cultural dimensions of information integration.

1.5.2 Enterprise BIM Adoption

Enterprise BIM represents a strategic evolution extending from individual projects to encompass entire organizational asset portfolios (Godager et al., 2021, 2022). Enterprise BIM establishes centralized, integrated information management frameworks leveraging digital

models for strategic decision-making, operational efficiency, and regulatory compliance enterprise-wide. They Key characteristics include lifecycle focus from design through demolition, holistic integration between people, processes, and digital technologies, enhanced collaboration through shared cloud environments, transformation of Project Information Models (PIM) into maintained Asset Information Models (AIM), and alignment with international standards such as ISO 19650.

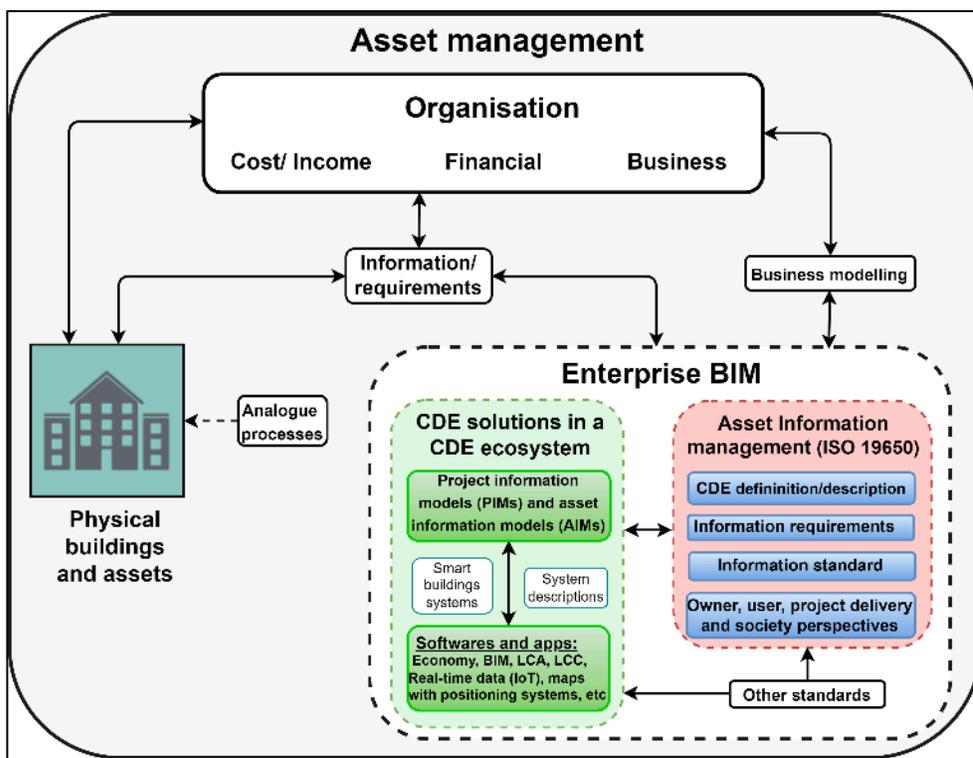


Figure 1.8 Asset Management and Enterprise BIM

Taken from (Godager et al., 2022)

Figure 1.8 depicts Asset Management and Enterprise BIM relation, where Asset Management covers physical assets and digital representation linked by information requirements, with Enterprise BIM supporting Asset Management digitally. Enterprise BIM bridges gaps between project-phase PIMs and operational AIMs, though implementation faces challenges related to organizational structure, data governance, and maintaining consistent information management across asset lifecycles (Godager et al., 2021, 2022). While Godager et al.'s

Enterprise BIM framework provides valuable conceptualization for holistic, lifecycle-based information management in built assets, some limitations constrain its practical realization. The framework's explicitly conceptual nature lacks empirical validation necessary for demonstrating real-world efficacy, while its incomplete scope omits critical areas including information security, exchange protocols, and comprehensive management systems. Technical standardization challenges persist, particularly with deficient BIM-IoT integration standards crucial for real-time monitoring, limited scope of existing standards such as IFC and MVD that focus on new construction rather than operation and maintenance requirements, and fragmented multi-domain data integration across silo systems. Furthermore, the framework's internal enterprise focus inadequately addresses the broader ecosystem perspective required for seamless data sharing with external partners and regulatory bodies within connected digital twin environments.

1.5.3 Blockchain-Based Trust Infrastructure

Jaskula et al. (2025) developed a blockchain-based information management framework (Figure 1.9) that addresses trust and traceability deficits within built asset information workflows through distributed ledger technology implementation. Their approach distinguishes itself by proposing integration rather than replacement of existing CDEs, establishing blockchain as an immutable transaction record system across design, construction, and operation phases. The framework integrates InterPlanetary File System (IPFS) for large file storage, recording only cryptographic hash values on the blockchain to address scalability limitations while maintaining data integrity. While this approach effectively addresses trust and auditability concerns, which are critical barriers in cross-organizational collaboration, it remains fundamentally focused on transaction recording rather than semantic integration. The framework provides mechanisms for verifying what information was exchanged and when, but offers limited capability for ensuring information meaning is preserved across system boundaries or organizational contexts. Additionally, the blockchain solution addresses information provenance without resolving underlying interoperability challenges that prevent seamless information flow between heterogeneous systems and stakeholders.

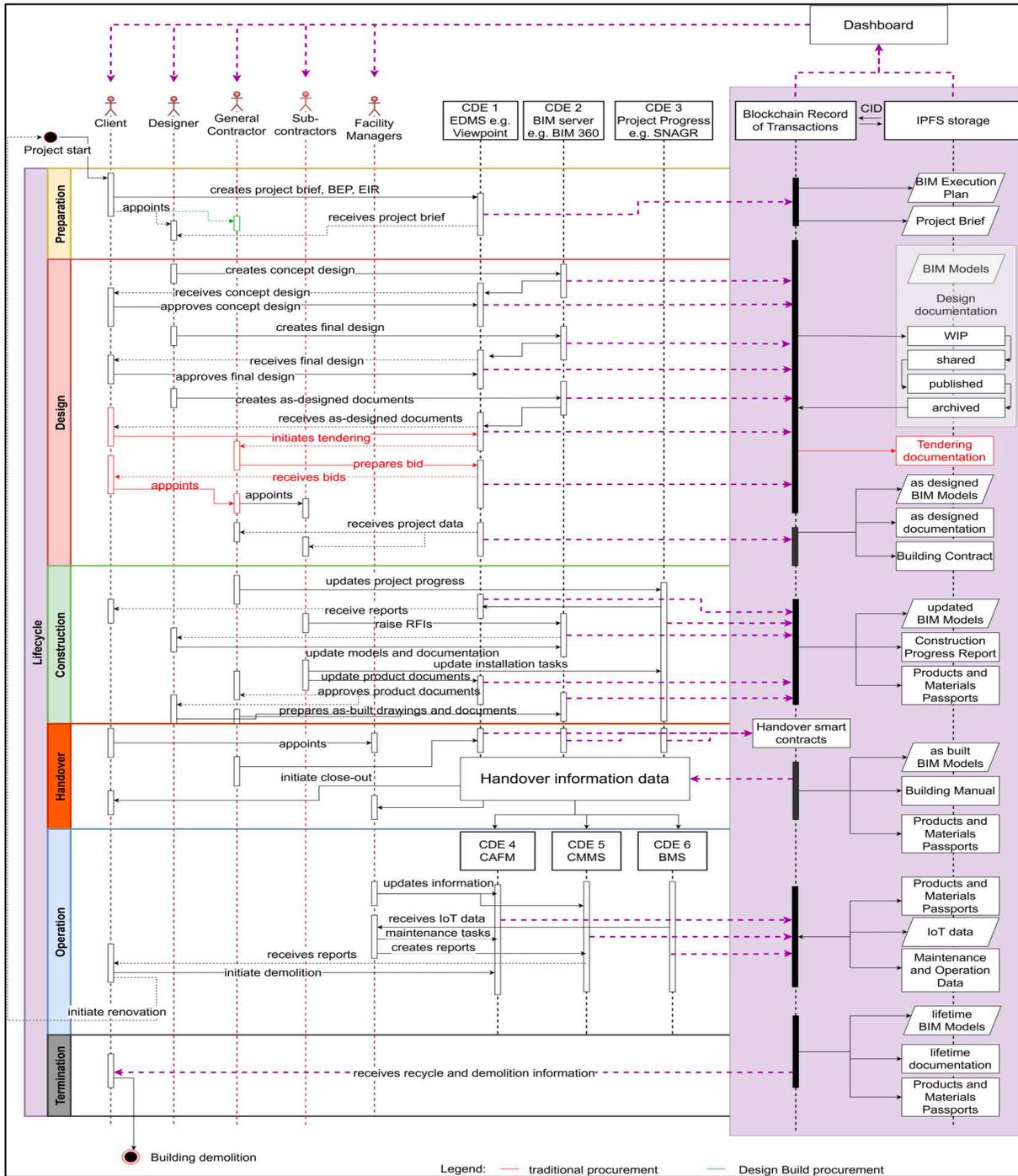


Figure 1.9 Conceptual framework for blockchain-based information management

Taken from (Jaskula et al., 2025)

1.5.4 Lifecycle Information Management Foundations

The Lifecycle Information Transformation and Exchange (LITE) framework (Succar & Poirier, 2020) provides theoretical foundations for information management across asset lifecycles through milestone-based architecture encompassing eight critical transformation points from initial asset intent through reuse considerations (Figure 1.10).

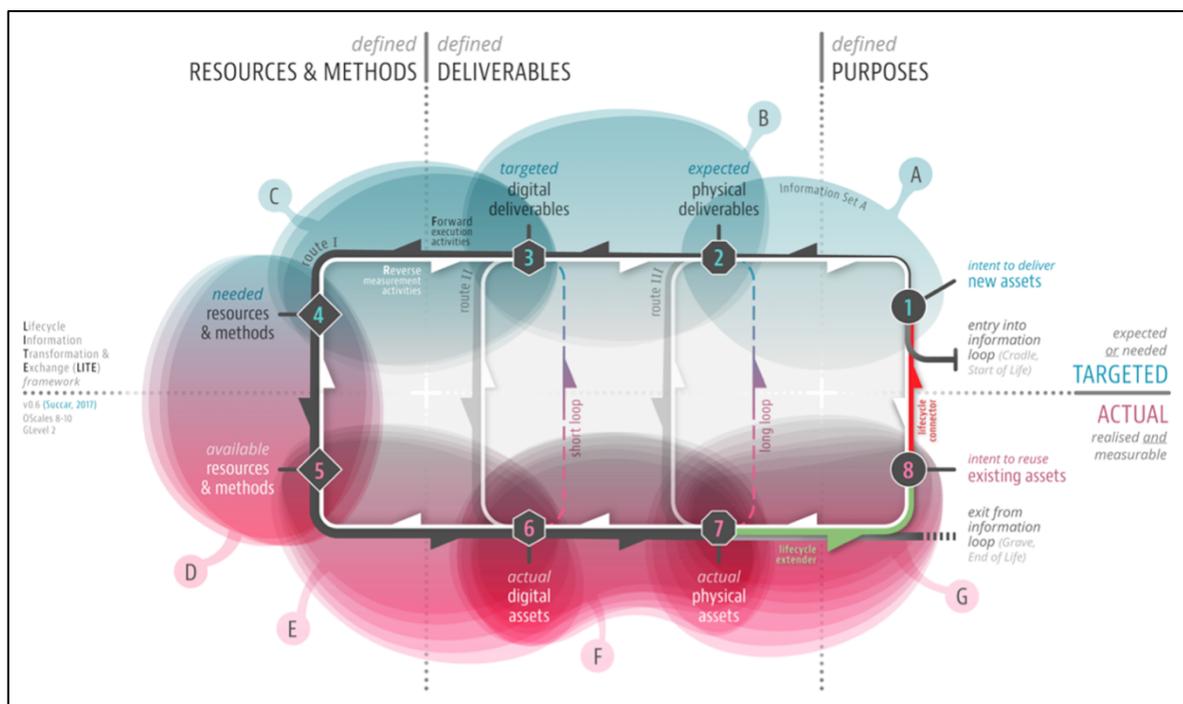


Figure 1.10 Overview of the LITE Framework

Taken from (Succar & Poirier, 2020)

LITE's systematic approach includes Information Statuses distinguishing targeted from actual states, Information States covering purposes, deliverables, and resources, controlled Information Flows through gates, automation-based Information Routes, and five Information Tiers reflecting integration maturity from referenced to optimized levels. LITE's contribution lies in establishing rigorous conceptual foundations for information lifecycle management, providing structured approaches to capture, transform, and exchange information throughout project phases. However, the framework operates within bounded project contexts and lacks

explicit mechanisms for cross-organizational integration. While LITE addresses information transformation within individual assets or projects effectively, it does not resolve interoperability challenges across organizational boundaries or provide systematic approaches to preserve semantic meaning during information exchange between autonomous systems.

1.6 Digital Twins: Advanced Requirements and Integration Challenges

Digital Twin technologies are emerging as an advanced paradigm that builds upon the foundations of BIM by integrating real-time data and enabling bidirectional communication between the physical and virtual assets.

1.6.1 DT's Conceptual Foundations

Digital Twins represent a fundamental evolution beyond static information models, establishing dynamic bidirectional connections between physical assets and virtual counterparts. While definitions vary, core elements consistently include virtual representation of physical assets encompassing properties, conditions, and behaviors; continuous information exchange enabling real-time updates from sensors and IoT devices; and lifecycle mirroring from design through decommissioning (El Jazzar et al., 2020; Minerva et al., 2020; Ramonell et al., 2023). Different organizations offer specific definitions highlighting various aspects: a "Conceptual Ideal for Product Lifecycle Management (PLM)," consisting of a physical system, a virtual system containing all related information, and a link enabling information flow between them (El Jazzar et al., 2020). Moreover, the distinction between Digital Models (no automated exchange), Digital Shadows (one-way data flow), and true Digital Twins (bidirectional automated exchange) is critical. True Digital Twins enable real-time monitoring, analysis, prediction, and autonomous actions through comprehensive architectures (El Jazzar et al., 2020).

1.6.2 Components and Architecture of Digital Twins

A Digital Twin comprises several key components that enable its functionalities (Figure 1.11). The Physical Asset/System represents the real-world entity that the digital twin represents, ranging from buildings and infrastructure to equipment or complex systems such as ports or cities (Klar et al., 2023, 2024). The Virtual Representation serves as the digital counterpart of the physical asset, encompassing its data, models (e.g., BIM), and simulations, evolving throughout the asset's lifecycle (Vieira et al., 2023).

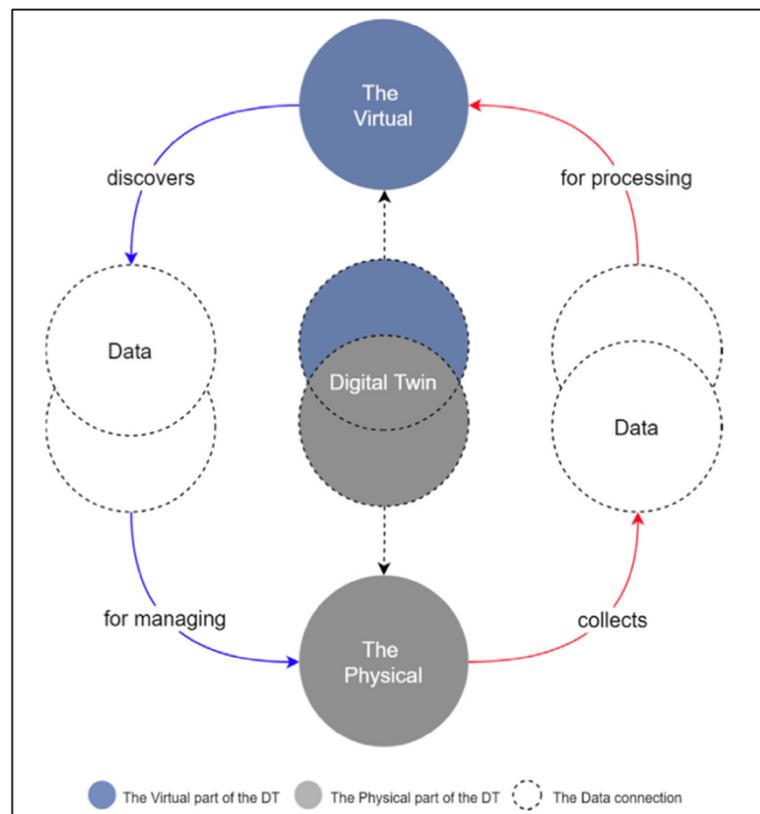


Figure 1.11 The main components of a DT

Taken from (Boje et al., 2020)

Connectivity/Data Integration establishes the crucial link between physical and virtual entities, enabling data flow through sensors, IoT devices, communication networks, and data integration platforms. Real-time data streams from IoT sensor networks connect to high-

fidelity BIM models (Tang et al., 2019). Interoperability remains key, allowing different systems to exchange information with understanding of its meaning (Albouq et al., 2022). Middleware can serve as an intermediary between heterogeneous systems, converting messages between different forms or to standard formats (Albouq et al., 2022). Data Processing and Analytics transforms collected data from physical assets into actionable insights within the digital twin environment through data mining, big data analytics, and potentially cognitive systems exhibiting intelligence through memorization, adaptability, and decision-making (Ali et al., 2024; El Jazzer et al., 2020). The Interface and Visualization component allows users to interact with the digital twin, visualize data, and gain insights, with Augmented Reality (AR) enabling live data visualization of IoT sensors using BIM (Natephra & Motamedi, 2019).

Moreover, several architectural patterns can be employed for implementing Digital Twins: Centralized Architecture involves a single point of integration for data and services (Kendall, 2021); Federated Architecture allows interoperability with services complying with the framework, emphasizing technical and data standards over mandated IT infrastructure, potentially leading to higher adoption (Kendall, 2021); and hybrid approaches dealing with comprehensive interoperability (Albouq et al., 2022).

1.6.3 DT Maturity Levels and System of Systems Thinking

Digital Twin maturity progresses from basic digital representations to highly integrated autonomous systems (Figure 1.12). Early stages focus on data aggregation and visualization for single assets, while intermediate stages incorporate sophisticated analytics, simulation, and bidirectional connectivity enabling predictive maintenance and optimized operations (Vieira et al., 2023). Advanced stages feature interoperable Digital Twins creating "System of Systems (SoS)" approaches that facilitate seamless data exchange across organizational boundaries, enable joint optimization of interconnected systems, support multi-stakeholder governance through shared information landscapes, and leverage common standards for data consistency and semantic understanding (Klar et al., 2023, 2024).

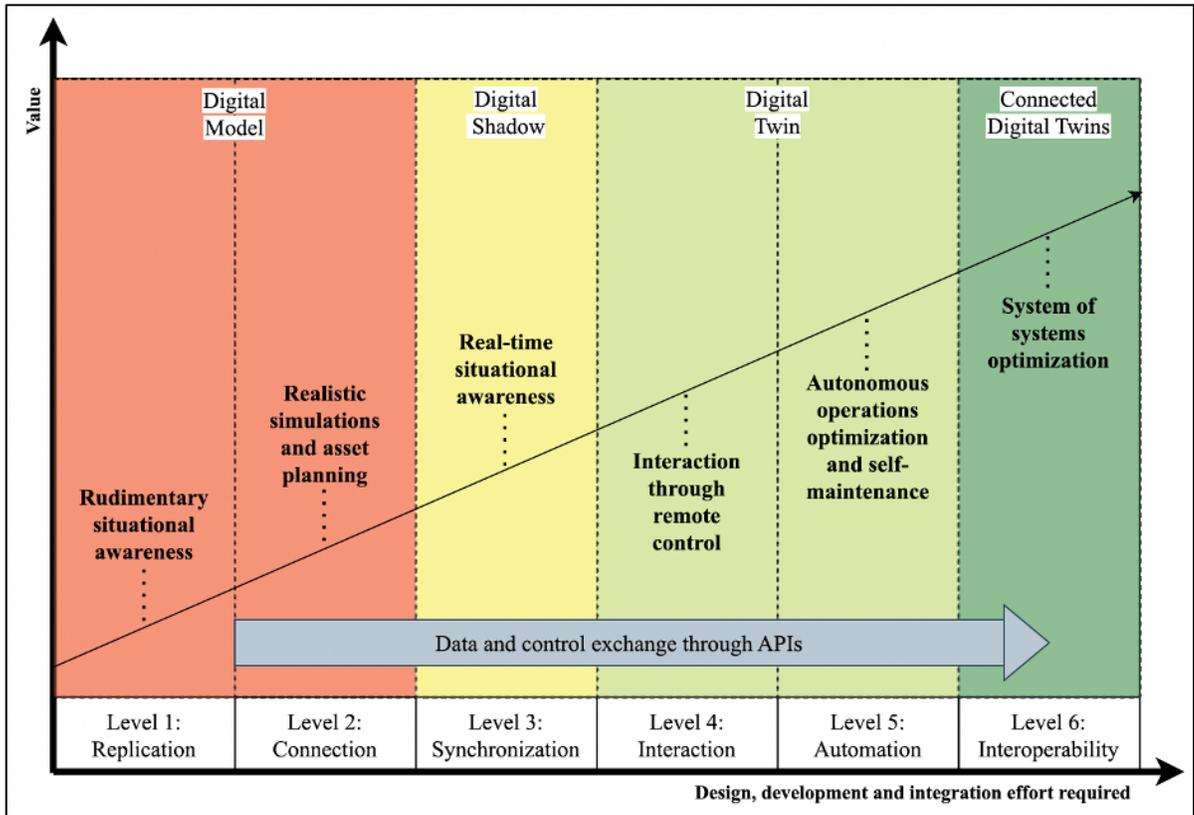


Figure 1.12 Overview of DT Maturity Levels and Their Added Value

Taken from (Klar et al., 2024)

The Open Geospatial Consortium (OGC) endeavors to improve interoperability between systems of systems by focusing on data models and APIs (Atkinson et al., 2022). The journey toward integrated information environments is closely tied to increasing maturity and interoperability of digital twins. By moving beyond isolated digital representations to interconnected systems that can exchange and understand information, the built asset industry can unlock significant value and overcome persistent challenges of information fragmentation (Klar et al., 2024).

1.7 Interoperability: The Multi-Dimensional Integration Challenge

Interoperability, which is the ability of independent systems to exchange and meaningfully use information without special effort, serves as the essential foundation for collaborative digital

environments (Bazzanella & Tzitzikas, 2013; Sadeghi et al., 2024). This capability encompasses not just data exchange but meaningful utilization and seamless interaction, requiring shared syntax (structure) and semantics (meaning) for effective communication.

1.7.1 Interoperability Dimensions and Frameworks

Interoperability operates across multiple dimensions, each addressing specific integration challenges (Ali et al., 2024). The Technical Dimension establishes physical connections and data exchange through hardware, software, and network protocols, forming the baseline requirement but alone cannot ensure meaningful information exchange.

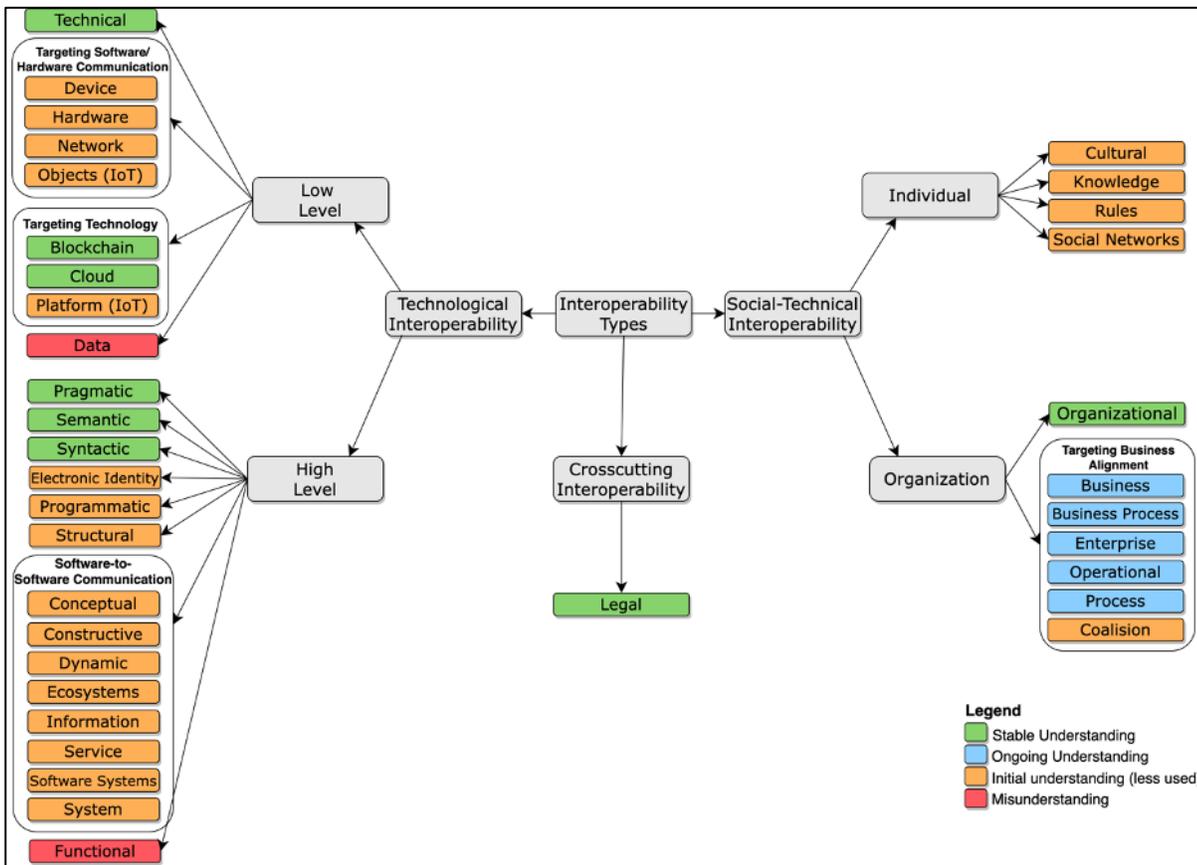


Figure 1.13 Classification of interoperability types
 Taken from (Maciel et al., 2024)

The Semantic Dimension ensures consistent understanding of exchanged information through shared vocabularies, ontologies, and data models, representing a critical challenge where systems must interpret not just data structure but intended meaning. The Organizational Dimension aligns business processes, organizational structures, and collaborative practices among entities, addressing human and procedural factors often overlooked in technical solutions. The Legal Dimension manages regulatory frameworks governing information exchange, ensuring compliance and trust while addressing data ownership, liability, and intellectual property concerns (Ali et al., 2024). Maciel et al. (2024) identified 36 different interoperability types across domains (Figure 1.13), highlighting evolution from purely technical concerns to socio-technical issues.

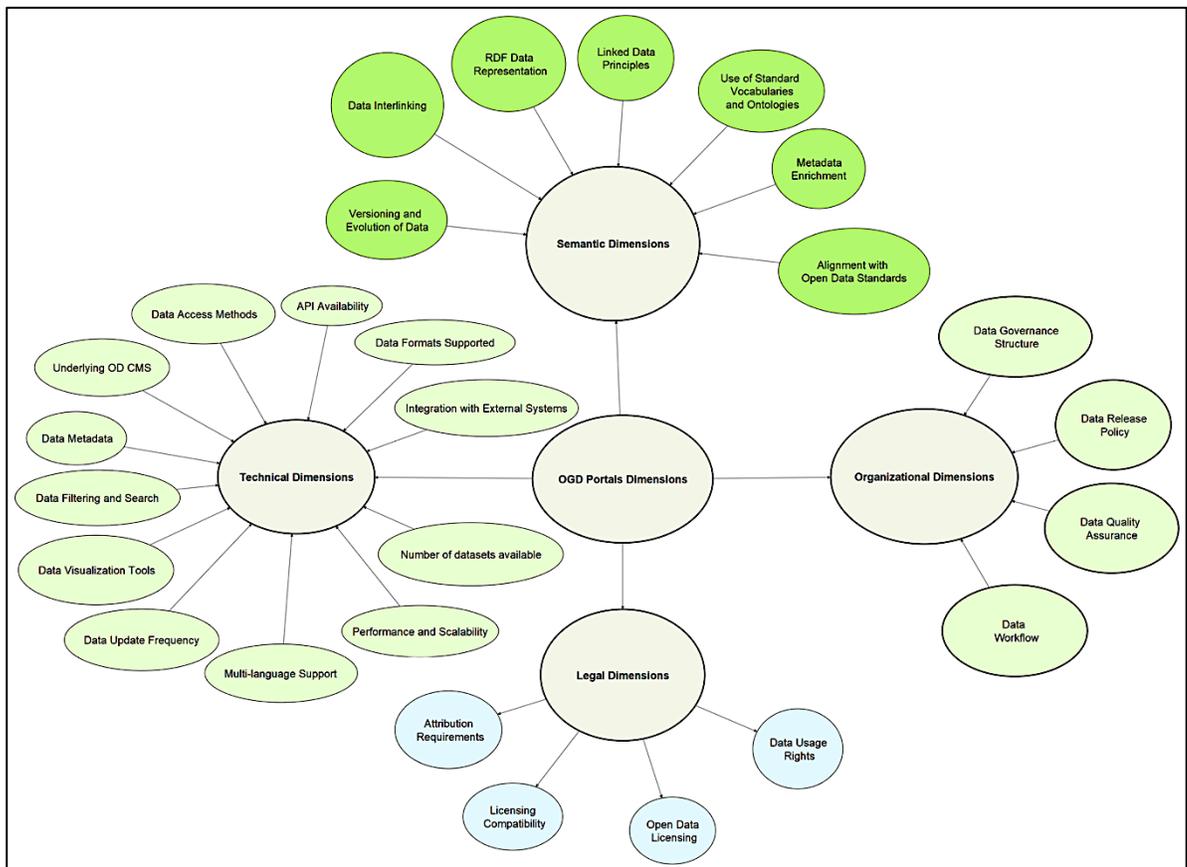


Figure 1.14 TSLO dimensions for the interoperability evaluation

Taken from (Ali et al., 2024)

Moreover, assessment frameworks such as the Technical, Semantic, Legal, and Organizational (TSLO) framework (Figure 1.14) provide structured evaluation tools, while maturity models such as Levels of Information System Interoperability and Levels of Conceptual Interoperability Mode offer hierarchical understanding of interoperability levels (Ali et al., 2024; Fall et al., 2023).

1.7.2 Interoperability Requirements

Effective interoperability requires addressing data standardization and portability, service standardization, data accessibility and openness, security and privacy, discoverability, technological neutrality, service integration/orchestration, and automation with machine-readability (Sadeghi et al., 2024).

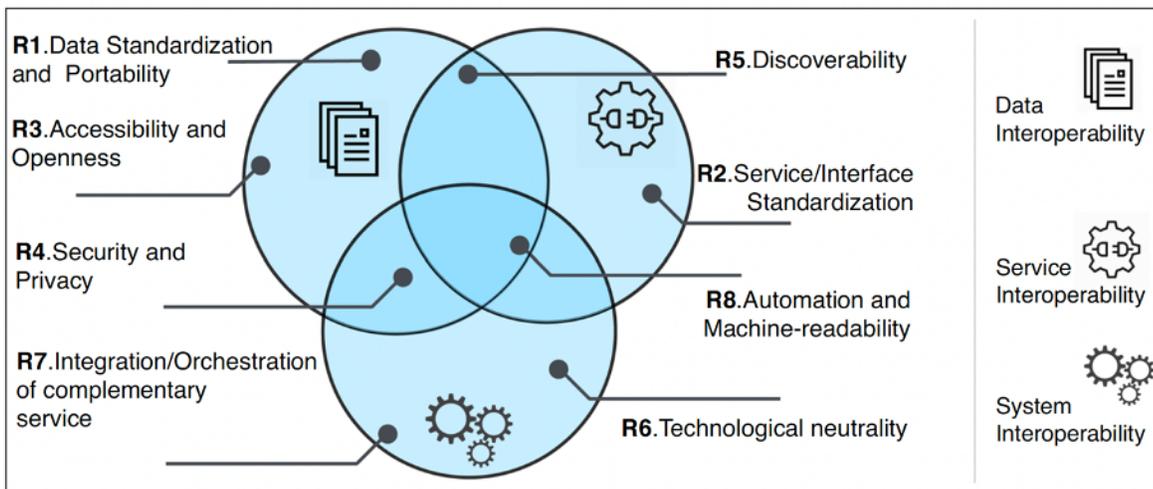


Figure 1.15 The Interoperability Trilogy

Taken from (Sadeghi et al., 2024)

Figure 1.15 depicts the first two facets, Data and Service Interoperability, highlighting fundamental barriers: heterogeneous data and disparate APIs and services. Solutions have typically been narrowly focused, involving specific standards, data models, and technical solutions such as ad hoc plugins. However, limited attention has been given to addressing

interoperability issues among these solutions, frameworks, and standards themselves. This results in isolated groups of systems where systems within each group are highly interoperable but have minimal interoperability with systems in other groups controlled by different organizations. Within Table 1.2 interoperability requirements are described in detail.

Table 1.2 Interoperability Requirements Descriptions
Taken from (Sadeghi et al., 2024)

No.	Requirement
R1	Data standardization and portability: facilitate data exchange among systems to support collaborative data collection and integrated services
R2	Service standardization: promote common standards for service management to enhance interoperability within diverse organizational contexts
R3	Data accessibility and openness: ensure open, accessible data with a focus on legal and technical openness, discoverability, and reusability
R4	Security and privacy: address data security and privacy concerns in competitive enterprise environments, emphasizing control and secure communication
R5	Discoverability: establish an efficient and reliable discovery process vital for service-oriented computing and data-driven systems, while mitigating data heterogeneity challenges
R6	Technological neutrality: encourage technological neutrality by decoupling services and functions from underlying technologies to foster interoperability in complex systems
R7	Integration/orchestration of complementary services: facilitate the integration and orchestration of complex, complementary services to meet evolving user expectations
R8	Automation and machine-readability: promote automation and machine-readability to reduce human intervention

To achieve effective interoperability in large, collaborative environments composed of independent and distributed systems, the presence of standards, unified specifications, and

interfaces is necessary but not sufficient. Sadeghi et al. introduce the third facet: System Interoperability, focusing on system or infrastructure features that facilitate development, establishment, advertisement, distribution, and collaborative use of interoperability-enabling concepts and technologies. These features can significantly reduce loss of autonomy and independence that organizations face when participating in System-of-Systems ecosystems (Sadeghi et al., 2024).

1.7.3 Interoperability Approaches

Fernandes et al. (2022) present a crucial distinction between interoperability and integration fundamental to understanding Systems-of-Information Systems (SoIS) design. SoIS are arrangements of independent information systems from potentially different organizations that interoperate to provide unique capabilities that cannot be achieved by any individual constituent system operating in isolation (Fernandes et al., 2022).

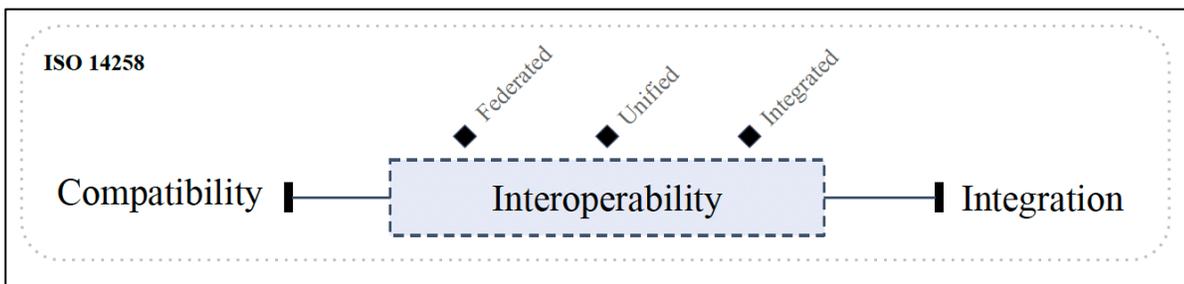


Figure 1.16 The Compatibility-Interoperability-Integration Continuum

Taken from (Fernandes et al., 2022)

According to the authors, integration of SoISs creates functional dependencies that reduce flexibility and resilience, making systems sensitive to failures where local changes may unpredictably impact different parts of the integrated system. In contrast, interoperability promotes a loosely coupled approach where systems remain independent but coordinated, allowing for collaboration while preserving autonomy. The authors conceptualize this relationship as existing on a continuum from compatibility (where systems do not interfere

Ways of dealing with interoperability considering the approaches		A	B	C	D	E	F	G	H
Unified	Common meta-model to establishing semantic	✓	✓	✓	✓	✓	✓	✓	✗
	No imposition of existing models, languages, and methods	✓	✓	✗	✗	✓	✓	✓	✓
Federated	Required adaptation to requirements during runtime	✓	✓	✗	✗	✓	✓	✓	✓
	Dynamic adaptation of the models	✓	✓	✗	✗	✓	✓	✓	✓

A = Autonomy
B = Evolutionary Development
C = Emergent Behavior
D = Connectivity
E = Interdependence
F = Diversity
G = Dynamicity
H = Belonging
 Legend: ✓ = Maintained feature ✗ = Threatened feature

The analysis reveals that each interoperability approach differentially impacts the eight key characteristics of SoIS (Table 1.3). The Integrated Approach poses the greatest threat to SoIS characteristics, particularly autonomy and evolutionary development. The Federated Approach, while maintaining most SoIS characteristics, may face challenges in critical situations requiring fast responses due to time needed for runtime negotiations. The choice of interoperability approach represents a fundamental architectural decision that determines whether the resulting system arrangement can truly function as a SoIS or becomes a more tightly coupled integrated system that compromises the independence and flexibility that define SoISs.

1.7.4 BIM-Specific Interoperability

Within BIM contexts, interoperability challenges extend beyond technical data exchange to encompass organizational and legal dimensions. ISO 19650 standardizes collaborative agreements including BIM Execution Plans (BEP), Master Information Delivery Plans (MIDP), and various information requirements specifications. OpenBIM initiatives and IFC standards aim to improve cross-platform information exchange, though challenges persist with semantic loss during translation and limited bidirectional exchange capabilities, particularly affecting operations and maintenance phases (Ahmed et al., 2024; Turk, 2020).

1.8 Digital Thread: A Foundational Framework

The concept of a Digital Thread represents a fundamental paradigm shift in managing complex engineering systems. It is not merely a technological tool but an approach enabling seamless, continuous, and holistic information flow across the entire lifecycle of an asset, traversing diverse systems, domains, and organizational boundaries (Davari et al., 2021). A Digital Thread can be formally defined as a scalable, configurable, data-driven framework that operates throughout the lifecycle of engineering systems (Wu et al., 2025). Its primary purpose is to integrate lifecycle resources, including systems, tools, data, information, and knowledge, from various sources and formats to support interoperability and decision-making. It serves as a conduit for correlating information across multiple dimensions of digital twins, spanning time and lifecycle stages, types of models, and configuration history, providing a holistic view of an asset from heterogeneous perspectives.

The Digital Thread ensures data consistency by orchestrating data flow, minimizing the risk of "digital waste" at transitions between isolated data silos or separated systems. It links disparate systems across the product lifecycle and throughout the supply chain, enabling quick, reliable, and secure collection, transmission, and sharing of data and information between systems (Wu et al., 2025). The Digital Thread is widely recognized as the prerequisite for a Digital Twin,

encompassing all necessary information and data to create and update that digital twin through continuous data connectivity.

1.8.1 Digital Thread Reference Architecture

Wu et al. (2025) proposed a conceptual architecture inspired by the hierarchical structure of the Data-Information-Knowledge-Wisdom (DIKW) model, including multiple dimensions and functional layers (Figure 1.17). External Dimensions define the context and scenarios for Digital Thread applications, including various domains and system hierarchy levels. Inner Dimensions encompass heterogeneous resources, full lifecycle phases, application scenarios, and enabling technologies.

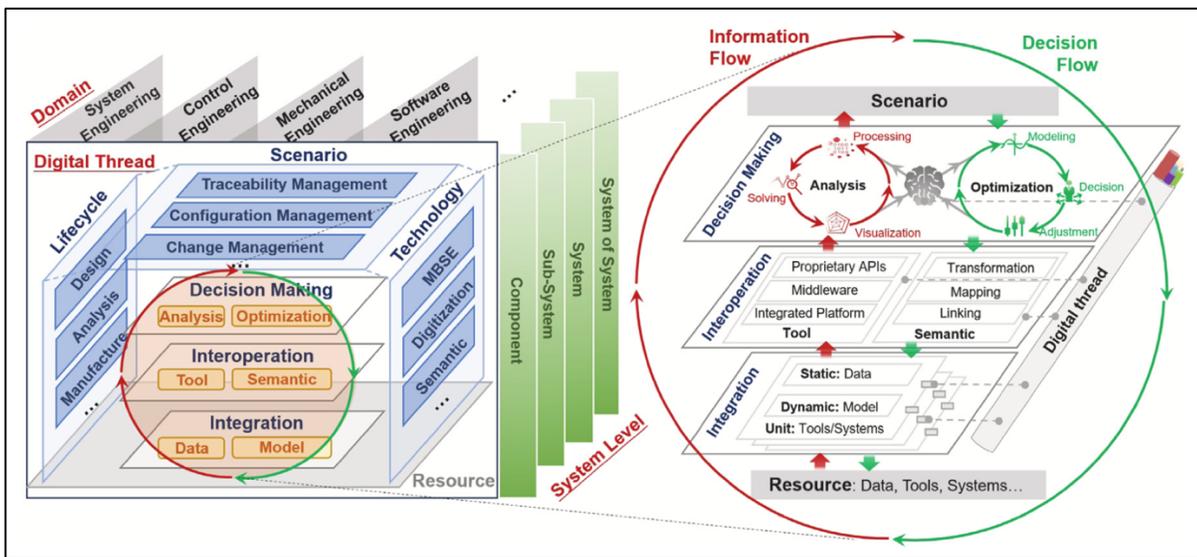


Figure 1.17 Reference architecture of Digital Thread

Taken from (Wu et al., 2025)

Functional Layers include the Integration Layer (gaining valuable information from heterogeneous lifecycle resources), Interoperation Layer (ensuring consistent understanding among stakeholders), and Decision-making Layer (employing intelligent optimization models and algorithms).

1.8.2 Digital Thread Enabling Technologies

The successful implementation of a Digital Thread relies on three categories of advanced technologies (Figure 1.18). Integration Technologies aggregate heterogeneous resources, including Model-Based Systems Engineering for model integration in multidisciplinary systems, Integrated Platforms providing unified environments for information sharing, and Building Information Modeling as a foundational technology providing structured digital representation of physical and functional asset characteristics (Patacas et al., 2020).

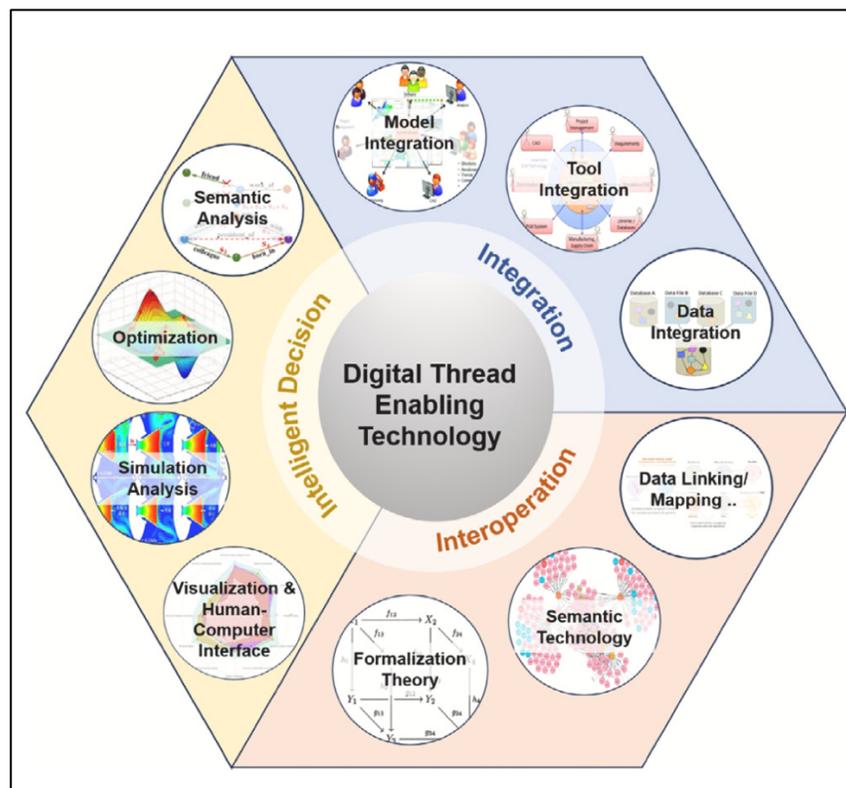


Figure 1.18 Enabling Technologies of Digital Thread

Taken from (Wu et al., 2025)

Interoperation Technologies focus on enabling seamless data exchange and shared understanding across diverse systems. Semantic Technologies and Ontologies provide formal descriptions of concepts and relationships within domains, enabling effective knowledge

management (Sadeghi et al., 2024). Linked Data represents information from different knowledge domains using flexible, generic languages such as RDF, enabling linking of diverse datasets while retaining original context and relationships (Moretti et al., 2022). APIs provide self-describing software interfaces allowing different applications to communicate effectively (Atkinson et al., 2022). Intelligent Decision Technologies leverage data for advanced analysis and decision support, including Artificial Intelligence and Machine Learning for data processing, analysis, and predictive capabilities (Masoumi et al., 2023), Big Data Analytics for unlocking value from massive IoT-generated data (Da Rocha et al., 2022), Cloud Computing for remote data storage and real-time access (Klar et al., 2023), and IoT enabling real-time data collection from physical environments (Ruiz-Zafra et al., 2022).

1.9 Chapter Summary

The examination of existing approaches reveals a critical gap: while individual technologies address specific aspects of information fragmentation, no integrated framework exists to support systematic integration and continuous information exchange across the built asset lifecycle. Despite advances in BIM, openBIM standards, and CDEs, fundamental challenges persist around information fragmentation, lifecycle discontinuity, and limited interoperability. Current solutions inadequately address the socio-technical complexities preventing true integration, creating isolated interoperable groups rather than ecosystem-wide integration. Digital Thread concepts, blockchain, and lifecycle frameworks such as LITE each address specific aspects, yet none systematically tackles the full spectrum of technical, semantic, organizational, procedural, governance, and contextual challenges throughout the information lifecycle. These identified gaps, particularly the absence of cross-organizational collaboration frameworks, directly informed the systematic categorization of IIE components, establishing the empirical foundation for developing requirements that enable lifecycle information integration while addressing both technical integration and socio-technical complexity.

CHAPTER 2

RESEARCH METHODOLOGY

This chapter presents the research methodology employed to address the identified gaps in information integration within the built asset industry. The chapter begins by revisiting the research question and objectives, then details the DSR methodology that guided the investigation. Subsequent sections explain the systematic data collection process, analytical approaches, framework development methodology, and evaluation strategy. The chapter concludes with an overview of the National Research Council of Canada case study that provides empirical validation of the developed framework.

2.1 Research Questions and Objectives

Having outlined the problem statement in the introduction of this thesis, the research is used to form the answer to following fundamental research question: *“What are the requirements for an Integrated Information Environment that enables seamless information flows across asset lifecycle stages and value chains while maintaining system autonomy?”*

To address this central inquiry, the following specific research objectives have been formulated, drawing upon identified challenges of information fragmentation across the built asset lifecycle, limitations of current interoperability approaches, and the need for systematic integration frameworks that preserve organizational autonomy:

- **RO1: Identify and systematize essential requirements and components** for Integrated Information Environments that address multi-dimensional interoperability challenges while preserving system autonomy. This establishes what integrated systems must achieve (requirements) and how these objectives translate into specific technical and organizational components.

- **RO2: Develop a multi-tier framework** that provides systematic guidance for transforming fragmented information systems toward integrated environments capable of supporting advanced digital capabilities. The framework organizes requirements and components across three interdependent tiers addressing data structure and meaning, data exchange and management, and data consumption and use.
- **RO3: Validate the framework's applicability and utility** through real-world evaluation, demonstrating its capacity to guide practical implementation while addressing organizational constraints through systematic application to the National Research Council of Canada's Digital Construction Platform initiative.

These research objectives align with the Design Science Research methodology by establishing both theoretical understanding (knowledge contribution) and practical application (artifact development and evaluation). Through this approach, the research contributes to the body of knowledge in the fields of BIM and OpenBIM, information systems, and SoIS by providing a theoretically grounded and empirically evaluated framework for Integrated Information Environments that can inform future research and practice in enhancing information management and integration within complex, autonomous ecosystems.

2.2 The Design Science Research Methodology

This research adopts Design Science Research (DSR) as its guiding methodological paradigm. DSR is a problem-solving approach focused on developing and validating artifacts to address identified organizational or technical challenges (vom Brocke et al., 2020), specifically in this case, the multi-perspective framework for Integrated Information Environments. Hevner (2007) emphasizes that DSR centers on the creation and evaluation of design artifacts intended to improve existing environments, which directly aligns with this research's objective of developing a framework to overcome current limitations in data environments while enhancing information flow continuity. The methodology's iterative nature, encompassing cycles of design, implementation, and evaluation, facilitates continuous refinement of the IIE framework

based on insights gained throughout the research process. DSR's dual emphasis on research rigor and practical relevance ensures the resulting artifact addresses real-world problems effectively. (Peffer et al., 2007) establish that DSR builds upon prior design science research, provides a process model for conducting DSR, and offers researchers a framework to evaluate design science outputs. The six major activities through which DSR methodology can be effectively applied are summarized in Table 2.1.

Table 2.1 Design science research methodology activities
Taken from (Peffer et al., 2007)

Activity	Description
Activity 1: Problem identification and motivation	Define the specific research problem and justify the value of a solution.
Activity 2: Define the objectives for a solution	Infer the objectives of a solution from the problem definition and knowledge of what is possible and feasible.
Activity 3: Design and development	Create the artifact. Such artifacts are potentially constructs, models, methods, or instantiations.
Activity 4: Demonstration	Demonstrate the use of the artifact to solve one or more instances of the problem.
Activity 5: Evaluation	Observe and measure how well the artifact supports a solution to the problem.
Activity 6: Communication	Communicate the problem and its importance.

2.2.1 Implementation of Design Science Research Methodology

Based on the activities of DSR methodology proposed by (Peffer et al., 2007), this study employs this approach to structure the required activities of the research project (Table 2.2). Each activity is linked to a specific knowledge base, which represents the materials (e.g. models, tools, and etc.) needed to accomplish the DSR activities.

Table 2.2 Activities of DSR methodology

Activity	Description	Knowledge Base
1. Problem Identification and Motivation	Identification of limitations in current data environments and collaborative environments implementations and the need for enhanced information interoperability and continuity within complex systems in the built asset industry. The motivation stems from the benefits of seamless information flows for efficiency, decision-making, and innovation.	<ul style="list-style-type: none"> • Literature on CDE limitations • Research on information fragmentation • Studies on interoperability challenges • SoIS theory • Built asset industry practice • BIM implementation challenges
2. Definition of the Objectives for a Solution	Articulation of specific research objectives that provide clear direction for the design of the IIE framework. The objectives focus on understanding IIE principles, designing a multi-perspective framework, and demonstrating its applicability in a real-world context.	<ul style="list-style-type: none"> • Interoperability frameworks • SoIS architectures • BIM capabilities • Information integration theories • Enterprise architecture principles • Existing CDE implementations
3. Design and Development	Conceptualization and design of the multi-perspective IIE framework, including defining its principles, dimensions (data structure, data exchange, data consumption), and key components.	<ul style="list-style-type: none"> • Interoperability dimensions literature • System integration methodologies • Data exchange standards • Semantic web technologies • Information management frameworks

Activity	Description	Knowledge Base
		<ul style="list-style-type: none"> • Enterprise architecture models • SoIS design principles
4. Demonstration	Application of the developed IIE framework to the NRC of Canada's Digital Construction Platform (DCP) initiative, showcasing how the framework addresses specific information management challenges within a complex organizational setting.	<ul style="list-style-type: none"> • Case study methodologies • Industry implementation strategies • Digital platform architecture • NRC DCP specifications • Implementation protocols • System integration techniques
5. Evaluation	Rigorous assessment of the IIE framework's efficacy based on its performance in the NRC case study and against the defined research objectives. Evaluation focuses on the framework's ability to overcome information flow and continuity limitations, facilitate seamless information flows, and preserve system autonomy.	<ul style="list-style-type: none"> • Evaluation metrics for information systems • DSR evaluation methods • Interoperability assessment frameworks • Performance measurement techniques • User feedback methodologies • Validation approaches
6. Communication	Dissemination of research findings, including the developed IIE framework, its demonstration in the NRC case study, and evaluation results through academic publications, conference presentations, and this dissertation.	<ul style="list-style-type: none"> • Academic publication standards • Research presentation techniques • DSR communication guidelines • Built environment industry channels • Knowledge dissemination frameworks

2.3 Data Collection

A comprehensive approach to data collection was employed to develop the knowledge base necessary for designing the IIE framework. The primary data collection method involved an extensive literature review focused on data environments, interoperability, and information flow challenges, as well as information management approaches in the built asset industry.

2.3.1 Literature Review Process

The literature review was conducted through an analysis of academic publications, industry reports, standards documents, and technical specifications. Sources were identified using scholarly databases including Scopus, Web of Science, IEEE Xplore, and Engineering Village. The literature search employed a structured approach using combinations of key terms and Boolean operators, including:

- ("Integrated Information Environment" OR "IIE") AND ("built asset" OR "construction" OR "AECO")
- ("Common Data Environment" OR "CDE") AND ("limitations" OR "challenges" OR "evolution")
- ("interoperability") AND ("BIM" OR "digital construction" OR "information management")
- ("Systems of Information Systems" OR "SoIS") AND ("integration" OR "interoperability")
- ("Digital Twin" OR "DT") AND ("information flow" OR "integration" OR "built environment")
- ("Digital Thread") AND ("lifecycle information" OR "asset management")
- ("semantic web" OR "linked data") AND ("construction" OR "built environment")
- ("knowledge representation") AND ("BIM" OR "digital construction")

The literature collection process prioritized sources based on relevance, citation impact, publication date (with emphasis on recent developments from 2015-2025), and applicability to the research objectives. Over 200 sources were initially identified, with 110 meeting the inclusion criteria for in-depth analysis based on relevance to research objectives, methodological rigor, and contribution to understanding integration challenges.

2.3.2 Knowledge Base Synthesis

Following the Design Science Research methodology, the collected literature was analyzed and synthesized to establish a knowledge base for the framework design process. This synthesis was organized into structured analytical frameworks to identify patterns, relationships, and research gaps across interconnected domains. The synthesis process involved three systematic stages:

Stage 1: Thematic Categorization - Literature was categorized into eight primary domains that emerged as critical to understanding information integration challenges: (1) Information Fragmentation and Lifecycle Discontinuity, examining the nature and consequences of disconnected information flows across project phases and organizational boundaries; (2) BIM Evolution and Capabilities, analyzing the progression from object-based modeling through collaborative workflows to network-based integration; (3) OpenBIM Standards and Interoperability, evaluating IFC, MVD, IDM, and related standards for semantic and syntactic consistency; (4) Common Data Environments, investigating CDE conceptualization, implementation challenges, and limitations in supporting advanced capabilities; (5) Digital Twins and Advanced Integration, exploring requirements for dynamic bidirectional connections between physical and virtual assets; (6) Interoperability Dimensions and Frameworks, synthesizing multi-dimensional perspectives on technical, semantic, organizational, and contextual interoperability; (7) Systems-of-Information Systems Theory, examining architectural patterns for preserving autonomy while enabling collaboration; and (8) Semantic Web Technologies and Linked Data, analyzing ontologies, knowledge graphs, and federation mechanisms for semantic integration.

Stage 2: Cross-Domain Pattern Analysis - Within each thematic category, literature was analyzed to identify recurring patterns, contradictions, and gaps. This analysis revealed several critical patterns: (a) persistent semantic fragmentation despite technical connectivity advances, where systems exchange data without shared understanding; (b) tension between centralization (efficiency) and federation (autonomy), with project-centric approaches failing to respect organizational boundaries; (c) lifecycle discontinuity at phase transitions, particularly design-to-construction and construction-to-operations handovers; (d) inadequate attention to socio-technical dimensions in technically-focused solutions; (e) gap between Digital Twin conceptualization and practical implementation requirements; and (f) proliferation of domain-specific standards creating "islands of interoperability" rather than ecosystem integration.

Stage 3: Integration Requirements Synthesis - Cross-domain analysis synthesized findings into a preliminary understanding of integration requirements that transcend individual domains. This synthesis identified requirements operating at multiple abstraction levels: foundational requirements establishing semantic consistency, syntactic compatibility, and conceptual alignment; infrastructure requirements specifying architectural patterns, integration mechanisms, and governance frameworks; and application requirements defining stakeholder value delivery through analytics, visualization, and strategic services. This preliminary synthesis directly informed the framework's three-tier structure, with each tier addressing requirements at corresponding abstraction levels.

The knowledge base synthesis produced several key artifacts that guided framework development: a comprehensive problem space model documenting limitations across all interoperability dimensions; a requirements taxonomy organizing integration objectives according to lifecycle stages and stakeholder needs; a technology landscape map positioning existing standards, frameworks, and technologies within integration challenges; a patterns library documenting successful integration approaches and architectural principles from literature; and a gaps analysis identifying areas where existing frameworks fail to provide comprehensive guidance. These artifacts collectively established the theoretical and empirical

foundation for the IIE framework design, ensuring that the framework addressed genuine industry challenges while building upon established knowledge.

2.4 Data Analysis

The collected literature and case study data underwent systematic analysis using multiple complementary approaches to ensure rigorous synthesis and framework development.

Thematic Analysis was employed (Appendix A) to identify recurring themes, patterns, and relationships within the literature. This involved iterative coding cycles where literature segments were assigned codes representing key concepts (e.g., "semantic fragmentation," "organizational autonomy," "lifecycle continuity"). Initial open coding identified over 150 preliminary codes, which were then grouped into higher-level categories through axial coding. Selective coding refined these categories into core themes directly relevant to integration challenges and requirements. This process revealed that information integration challenges operate across multiple interconnected dimensions that cannot be addressed through purely technical solutions, validating the need for a multi-perspective framework.

Comparative Framework Analysis systematically evaluated existing frameworks, standards, and approaches against identified integration requirements. Each framework (e.g., multi-layered CDE, Enterprise BIM, LITE, Digital Thread) was assessed according to criteria including comprehensiveness (coverage of interoperability dimensions), prescriptiveness (actionable guidance versus conceptual description), empirical validation (real-world implementation evidence), and architectural specificity (clarity regarding technical implementation). This analysis revealed that while individual frameworks address specific aspects effectively, none provides comprehensive guidance spanning semantic foundations, federated infrastructure, and stakeholder value delivery simultaneously. The gaps identified through this comparative analysis directly informed the IIE framework's scope and structure.

Gap Analysis synthesized findings from thematic and comparative analyses to explicitly identify areas where existing approaches fail to meet integration requirements. This analysis employed a structured matrix mapping identified challenges (rows) against existing solutions (columns) to systematically identify coverage gaps. The analysis revealed critical gaps including: absence of comprehensive semantic standardization frameworks spanning ontologies, terminologies, data schemas, and information requirements; limited architectural guidance for federated integration preserving organizational autonomy; inadequate lifecycle continuity mechanisms supporting information flows across decades-long asset lifecycles; insufficient attention to socio-technical dimensions including organizational change, governance, and stakeholder engagement; and lack of systematic progression pathways from current fragmented states toward integrated target states.

Requirements Synthesis translated identified gaps into explicit framework requirements through a systematic derivation process. Each identified gap was analyzed to determine underlying causes (technical, organizational, procedural); stakeholder impacts (which groups experience negative consequences); and prerequisite capabilities (what foundational elements must exist to address the gap). This analysis produced a hierarchical requirements structure where high-level objectives (e.g., "enable seamless information flows") decompose into mid-level requirements (e.g., "establish semantic consistency") which further decompose into specific capabilities (e.g., "implement shared ontologies," "standardize terminologies"). This hierarchical structure directly informed the framework's three-tier organization, with each tier addressing requirements at corresponding abstraction levels.

Pattern Recognition and Abstraction identified recurring architectural patterns, design principles, and success factors across diverse contexts. This involved analyzing successful integration initiatives documented in literature to extract generalizable principles applicable across contexts. Identified patterns included: federated architecture enabling collaboration without centralization; semantic-first approaches establishing shared understanding before technical integration; layered abstraction separating concerns across semantic, infrastructure, and application tiers; standards-based integration avoiding vendor lock-in; and modular,

incremental implementation reducing adoption risk. These patterns were abstracted into design principles guiding framework architecture, ensuring that the framework reflects proven approaches rather than untested theoretical constructs.

Case Study Analysis (detailed in Section 2.7) employed the developed framework as an analytical lens for understanding NRC's integration challenges, validating framework comprehensiveness and applicability. The analysis systematically mapped NRC challenges to framework components, revealing coverage across all framework tiers and validating that the framework captures real-world problems rather than focusing on narrow technical subsets.

2.5 Development of the Framework

The development of the multi-perspective framework for Integrated Information Environments represents the central artifact creation activity in this Design Science Research investigation, informed by the synthesized knowledge base and systematic data analysis.

2.5.1 Framework Development Method

The framework was developed iteratively through multiple refinement cycles, following the "build and evaluate" loop inherent in Design Science Research methodology. The development process comprised four interconnected phases:

Phase 1: Conceptualization - Based on identified requirements and theoretical underpinnings from literature synthesis, a conceptual model of the IIE framework was developed, defining its core structure, organizing principles, and foundational elements. This phase drew upon existing interoperability frameworks, SoIS architectural patterns, data integration principles, and Digital Twin conceptualizations. The conceptual model established the framework's three-tier structure reflecting the recognition that information integration operates across multiple abstraction levels: foundational semantic and syntactic resources (Tier 1), operational infrastructure and governance (Tier 2), and stakeholder-facing applications and services (Tier

3). This tiered structure emerged from requirements synthesis revealing hierarchical dependencies where higher-tier capabilities depend upon lower-tier foundations.

Phase 2: Design Elaboration - The conceptual model was elaborated into detailed specifications defining relationships between framework elements, dependencies across tiers, and mappings to concrete technologies and standards. Visual representations, including tier diagrams, component relationship maps, and information flow models, were developed to articulate the framework's structure and functionality. This phase specified 18 distinct components organized across three tiers, with each component defined through: purpose and scope, key subcomponents and elements, enabling technologies and standards, relationships to other components, and implementation considerations. Component specifications drew extensively from literature on semantic web technologies (ontologies, linked data), integration middleware (APIs, message brokers, ETL tools), platform architectures (SOA, microservices, event-driven), and application services (analytics, visualization, collaboration).

Phase 3: Requirements Derivation - Framework requirements were systematically derived by translating component specifications into actionable objectives that integrated systems must achieve. This translation process involved analyzing each component to identify integration objectives the component addresses, challenges the component resolves, prerequisites for component realization, and dependencies on other components. The derivation process produced 19 requirements organized hierarchically across three tiers, with each requirement explicitly linked to one or more framework components specifying how the requirement is realized. This traceability ensures coherence between "what integrated systems must achieve" (requirements) and "how they achieve it" (components).

Phase 4: Iterative Refinement - The framework underwent multiple refinement cycles based on formative evaluation activities including: expert consultations with BIM researchers and industry practitioners, providing feedback on framework relevance, completeness, and clarity; comparative validation against existing frameworks and standards, ensuring consistency with established principles while addressing identified gaps; preliminary application to NRC

context, revealing areas requiring clarification or elaboration; and internal consistency checking, verifying logical coherence across framework elements. Each refinement cycle produced updated component specifications, clearer articulation of requirements, and refined visual representations. The iterative process continued until the framework achieved sufficient maturity for systematic case study validation.

2.5.2 Conceptualization of Requirements and Dimensions of an IIE

Based on literature synthesis and requirements analysis, the IIE framework was designed to embody the following key characteristics that distinguish it from existing approaches:

Autonomy Preservation - The IIE is explicitly designed to facilitate interoperability without requiring constituent information systems to relinquish individual autonomy or adopt uniform standards and technologies. This principle reflects the recognition that the built asset industry's structure, characterized by temporary project coalitions involving multiple independent organizations, makes centralized integration approaches infeasible. The framework's federated architecture patterns (SOA, microservices, event-driven) operationalize this principle by enabling systems to maintain operational independence while collaborating through standardized interfaces.

Heterogeneity Support - The framework explicitly accommodates the inherent heterogeneity of systems within SoIS arrangements, recognizing that diversity in technologies, processes, and organizational contexts represents industry reality rather than a problem to eliminate. Heterogeneity support manifests through semantic resources enabling consistent interpretation despite diverse data models, syntactic resources supporting multiple exchange formats and protocols, and flexible integration patterns accommodating synchronous, asynchronous, batch, and federated exchanges.

Lifecycle Continuity - Unlike project-centric approaches that fragment at lifecycle transitions, the framework explicitly addresses information continuity across decades-long asset lifecycles.

Lifecycle continuity is enabled through: metadata capturing provenance and temporal context across transitions, process models formalizing handover workflows and information requirements, federated architecture supporting long-term data accessibility without requiring system consolidation, and strategic domain applications leveraging historical data for asset optimization.

Multi-Dimensional Integration - The framework provides coordinated capabilities across all interoperability dimensions identified in literature, recognizing that integration failures typically result from narrow focus on technical connectivity while neglecting semantic, organizational, or governance dimensions. Multi-dimensional coverage is achieved through: Tier 1 addressing semantic, syntactic, and conceptual dimensions, Tier 2 addressing technical and organizational dimensions, and Tier 3 addressing procedural and contextual dimensions through stakeholder-facing applications.

Incremental Implementability - Recognizing resource constraints and organizational maturity variations, the framework supports modular, incremental implementation rather than requiring comprehensive adoption. The tier structure enables staged progression where organizations can: implement foundational Tier 1 capabilities before infrastructure development, deploy Tier 2 integration selectively based on priorities, and develop Tier 3 applications incrementally as needs emerge. This incremental approach reduces adoption risk and accommodates diverse organizational capacities.

Standards Alignment- The framework explicitly leverages established international standards and open specifications rather than proposing proprietary approaches. Standards alignment includes: IFC and MVD for BIM data exchange, buildingSMART Data Dictionary for semantic resources, ISO 19650 for CDE workflows and information management, OWL and RDF for semantic web technologies, and OpenAPI and REST for service interfaces. This alignment ensures the framework builds upon proven foundations while avoiding vendor lock-in.

The framework dimensions were conceptualized through synthesis of multiple interoperability frameworks identified in literature, particularly extending the TSLO (Technical, Semantic, Legal, Organizational) framework (Ali et al., 2024) to address built asset industry specifics. The resulting dimensional structure includes:

- **Semantic Dimension:** Addressing the meaning of information and ensuring exchanged data is understood consistently across organizational contexts. This dimension encompasses ontologies defining formal conceptual structures, terminologies providing standardized vocabularies, classifications organizing domain concepts hierarchically, and conceptual models establishing common information structures. The semantic dimension received particular emphasis based on literature findings that semantic fragmentation represents the most fundamental barrier; systems achieving syntactic compatibility without semantic alignment exchange data without meaningful understanding (Boje et al., 2020; Hagelien et al., 2021; Jiang et al., 2023).
- **Syntactic Dimension:** Addressing the technical structure of information and enabling systems to parse and process exchanged data; This dimension encompasses data formats specifying physical representation, communication protocols defining transmission rules, schema definitions formalizing structural constraints, and query languages enabling information retrieval. While necessary for integration, literature synthesis revealed that syntactic interoperability alone proves insufficient without semantic alignment (Herle et al., 2020).
- **Conceptual Dimension:** Addressing the abstract models and representations underlying information systems; This dimension encompasses data models defining entity relationships and constraints, representation languages formalizing model specifications, Model View Definitions specifying context-specific subsets, and conceptual alignment mechanisms mapping between heterogeneous models. This dimension emerged as distinct from semantic and syntactic dimensions through analysis revealing that systems may share

syntactic standards and semantic vocabularies while employing incompatible underlying conceptual models (Jiang et al., 2019; Poirier et al., 2022; Soman & Whyte, 2020).

- **Procedural Dimension:** Addressing the processes and workflows governing information production, exchange, and consumption; This dimension encompasses process models formalizing activity sequences, information uses specifying functional applications, validation rules defining quality criteria, and workflow management orchestrating information container lifecycles. Literature synthesis revealed that technical and semantic interoperability without procedural alignment results in inefficient, error-prone processes (Abanda et al., 2025).
- **Organizational Dimension:** Addressing the human, structural, and cultural factors influencing collaboration; This dimension encompasses governance frameworks defining decision rights and accountabilities, organizational structures determining relationships and interfaces, stakeholder engagement mechanisms, and capability development programs. Literature consistently identified organizational barriers as primary impediments to integration, validating the need for explicit organizational dimension treatment (Poirier et al., 2014).
- **Legal/Governance Dimension:** Addressing regulatory, contractual, and liability concerns; This dimension encompasses data ownership and intellectual property rights, liability allocation for information quality, regulatory compliance mechanisms, and contractual frameworks governing information exchange. While less technically oriented, literature revealed that unresolved legal concerns frequently prevent organizations from implementing technically feasible integration solutions (Bazzanella & Tzitzikas, 2013).
- **Contextual Dimension:** Addressing the situational factors influencing information relevance and interpretation; This dimension encompasses project delivery methods affecting collaboration patterns, industry practices determining stakeholder expectations, lifecycle stages requiring different information granularities, and use case specifics

determining fitness-for-purpose criteria. The contextual dimension ensures the framework accommodates diversity across project types, organizational contexts, and application scenarios (Ahmed et al., 2024; Poirier et al., 2014).

These dimensions collectively form the framework's multi-perspective structure, with each tier addressing multiple dimensions simultaneously through coordinated components. The three-tier organization reflects the insight that different dimensions require attention at different abstraction levels: semantic and conceptual dimensions primarily addressed through Tier 1 foundational resources, organizational and technical dimensions primarily addressed through Tier 2 infrastructure, and procedural and contextual dimensions primarily addressed through Tier 3 applications. However, dimensional coverage is not exclusive to single tiers; rather, each dimension requires coordinated attention across multiple tiers, with the framework ensuring this coordination through explicit component relationships and dependencies.

2.6 Evaluation Process

The evaluation of the developed IIE framework represents a critical step in the research process, guided by the principles of Design Science Research and structured according to established DSR evaluation frameworks.

2.6.1 DSR Evaluation Framework

The evaluation approach draws upon the DSR Evaluation Framework proposed by Pries-Heje et al. (2008) and extended by Venable et al. (2012), which structures evaluation along two primary dimensions: naturalistic versus artificial evaluation, and ex ante versus ex post evaluation. Naturalistic evaluation emphasizes evaluation of an artifact in real environments with actual users and authentic organizational contexts, providing strong evidence for practical applicability but requiring significant resources and time. Artificial evaluation occurs in controlled settings with simulated conditions, theoretical arguments, or laboratory experiments, enabling more focused testing of specific artifact properties but providing weaker

evidence for real-world effectiveness. Ex ante evaluation assesses artifacts before full instantiation, evaluating designs, models, and conceptual frameworks through theoretical analysis, expert judgment, and preliminary applications. This approach enables early identification of potential issues and iterative refinement before costly implementation. Ex post evaluation assesses fully instantiated artifacts through deployment in operational environments, measuring actual performance and impact. This provides strongest evidence for artifact effectiveness but requires complete implementation. Figure 2.1 illustrates the DSR Evaluation Framework's four quadrants formed by these dimensions, each representing different evaluation strategies with distinct strengths and appropriate application contexts.

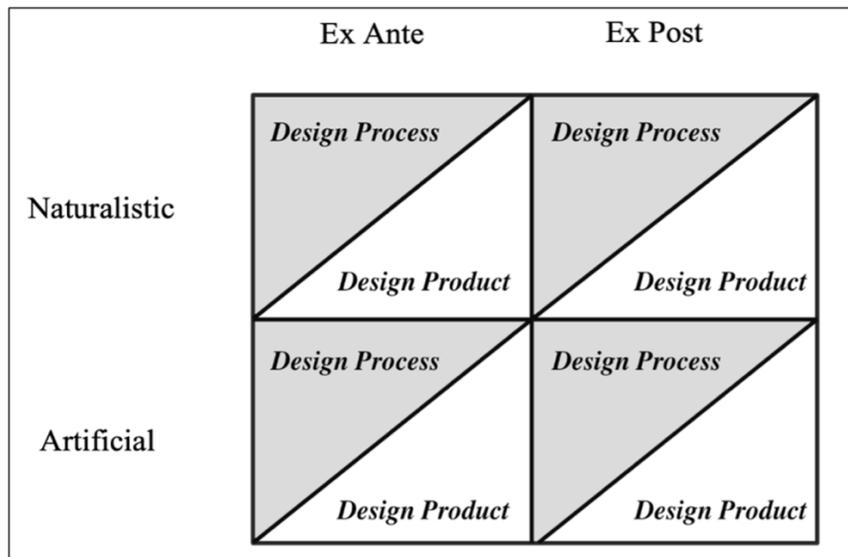


Figure 2.1 DSR Evaluation Framework

Taken from Pries-Heje et al. (2008)

Venable et al. (2012) extended this framework by proposing evaluation strategies and methods selection frameworks (Figures 2.2 and 2.3) that guide researchers in choosing appropriate evaluation approaches based on artifact characteristics, research goals, and available resources.

DSR Evaluation Strategy Selection Framework		Ex Ante	Ex Post
			<ul style="list-style-type: none"> •Formative •Lower build cost •Faster •Evaluate design, partial prototype, or full prototype •Less risk to participants (during evaluation) •Higher risk of false positive
Naturalistic	<ul style="list-style-type: none"> •Many diverse stakeholders •Substantial conflict •Socio-technical artifacts •Higher cost •Longer time - slower •Organizational access needed •Artifact effectiveness evaluation •Desired Rigor: "Proof of the Pudding" •Higher risk to participants •Lower risk of false positive – safety critical systems 	<ul style="list-style-type: none"> •Real users, real problem, and somewhat unreal system •Low-medium cost •Medium speed •Low risk to participants •Higher risk of false positive 	<ul style="list-style-type: none"> •Real users, real problem, and real system •Highest Cost •Highest risk to participants •Best evaluation of effectiveness •Identification of side effects •Lowest risk of false positive – safety critical systems
Artificial	<ul style="list-style-type: none"> •Few similar stakeholders •Little or no conflict •Purely technical artifacts •Lower cost •Less time - faster •Desired Rigor: Control of Variables •Artifact efficacy evaluation •Less risk during evaluation •Higher risk of false positive 	<ul style="list-style-type: none"> •Unreal Users, Problem, and/or System •Lowest Cost •Fastest •Lowest risk to participants •Highest risk of false positive re. effectiveness 	<ul style="list-style-type: none"> •Real system, unreal problem and possibly unreal users •Medium-high cost •Medium speed •Low-medium risk to participants

Figure 2.2 A DSR evaluation strategy selection framework

Taken from Venable et al. (2012)

DSR Evaluation Method Selection Framework	Ex Ante	Ex Post
Naturalistic	<ul style="list-style-type: none"> •Action Research •Focus Group 	<ul style="list-style-type: none"> •Action Research •Case Study •Focus Group •Participant Observation •Ethnography •Phenomenology •Survey (qualitative or quantitative)
Artificial	<ul style="list-style-type: none"> •Mathematical or Logical Proof •Criteria-Based Evaluation •Lab Experiment •Computer Simulation 	<ul style="list-style-type: none"> •Mathematical or Logical Proof •Lab Experiment •Role Playing Simulation •Computer Simulation •Field Experiment

Figure 2.3 A DSR evaluation method selection framework

Taken from Venable et al. (2012)

The DSR evaluation process comprises four systematic steps as summarized in Table 2.3, providing structured guidance for planning and executing rigorous evaluation activities.

Table 2.3 DSR Evaluation Process

Taken from Venable et al. (2012)

Process	Description
1 Identify the context of evaluation	<ul style="list-style-type: none"> • What are evaluands? (e.g. models, concepts, etc.) • Nature of the proposed artifact (framework, architecture, etc.) • What properties should be evaluated? (comprehensiveness, applicability, utility) • Goals and purposes of evaluation.

Process	Description
	<ul style="list-style-type: none"> • Constrains in the research environment (time, access, resources) • What resources are available? (e.g. people, budget) • How rigorous must the evaluation be? (Preliminary or detailed evaluation) • Which aspects or properties are more important, less important, nice to have, and irrelevant.
2 Match contextual factors	Match the needed contextual factors with one of the quadrants demonstrated in Figure 2.1, 2.2 and 2.3 to determine appropriate evaluation strategy.
3 Select evaluation method(s)	<p>Select appropriate method(s) to evaluate the artifact.</p> <p>Examples of methods can be:</p> <ul style="list-style-type: none"> • Ex ante & naturalistic: action research, focus groups, case studies • Ex ante & artificial: mathematical/logic proof, criteria-based evaluation, theoretical arguments • Ex post & naturalistic: action research, longitudinal case studies, field surveys • Ex post & artificial: controlled experiments, simulations, prototyping
4 Design DSR evaluation	Design specific detailed evaluations following established research methods literature (e.g., case study protocols, survey instruments, experimental designs)

2.6.2 Implementation of DSR Evaluation Framework and Processes

Following the structured process outlined in Table 2.3, this research implemented a multi-faceted evaluation approach appropriate for the framework's nature and research objectives.

Evaluation Context Identification: The evaluation assessed the Integrated Information Environment framework comprising requirements organized across three tiers, component specifications detailing technical and organizational capabilities, and the hierarchical architectural structure. Critical properties evaluated include comprehensiveness in capturing integration challenges across all interoperability dimensions, coherence ensuring logical consistency across framework elements, prescriptiveness providing actionable guidance, and applicability for guiding real-world initiatives. The evaluation pursued formative goals during framework development through iterative refinement, transitioning to summative goals for final validation. Several constraints shaped the evaluation design: access constraints dependent on NRC collaboration, resource constraints precluding multiple case studies, and maturity constraints recognizing that comprehensive validation requires years of longitudinal study beyond master's research scope. Framework properties were prioritized with comprehensiveness, coherence, and prescriptiveness critical for foundational validity; applicability and utility important for practical contribution; and feasibility assessment desirable for implementation guidance.

Contextual Factors Matching and Method Selection: This research positioned primarily in the ex-ante naturalistic quadrant with supplementary ex ante artificial evaluation. The framework was evaluated through application to the NRC DCP case study, representing naturalistic evaluation within a real organizational context conducted ex ante by evaluating framework design rather than operational implementation. This approach provided strong evidence for framework applicability while accommodating timeline constraints. Supplementary ex ante artificial evaluation occurred through theoretical analysis, criteria-based evaluation against DSR quality criteria, and expert review. The primary evaluation method employed systematic case study application to the NRC DCP initiative, assessing the framework's capacity to guide problem diagnosis, solution architecture development, and stakeholder validation. Supplementary methods included expert review through structured feedback sessions with academic experts and industry practitioners, alongside comparative analysis positioning the framework relative to established approaches and international digital construction initiatives.

Detailed Evaluation Design: The evaluation design comprised three integrated activities providing triangulated evidence. Theoretical validation assessed framework consistency with SoIS theory, interoperability frameworks, and BIM capability theories, while verifying alignment with international standards including ISO 19650, IFC specifications, buildingSMART standards, and semantic web standards. Internal consistency analysis examined logical coherence through dependency mapping, requirement traceability, and completeness checking. Case study evaluation provided primary empirical validation through systematic framework application to NRC DCP. Challenge mapping identified NRC's integration challenges and mapped them to framework tiers, requirements, and components, validating comprehensiveness across multiple interoperability dimensions. Solution architecture development demonstrated that framework tiers provided explicit organizational structure guiding translation from abstract requirements to concrete architectural decisions. Requirements elicitation systematically captured NRC DCP requirements using framework components as scaffolding. Nine-month stakeholder engagement through workshops, interviews, and review cycles provided qualitative validation that framework-guided solutions address genuine organizational needs and constraints.

Expert review and comparative analysis provided supplementary validation through structured consultation addressing framework relevance, completeness, coherence, prescriptiveness, and novelty. International alignment analysis compared framework with digital construction initiatives including DigiPLACE, ACCORD, CHEK, and D-COM, validating that the framework captures concerns common across diverse contexts. Convergent evolution where independent initiatives arrived at similar architectural principles provided evidence that the framework reflects fundamental integration requirements. The integrated evaluation approach combining theoretical validation, case study application, and expert review provided triangulated evidence for framework validity. While comprehensive validation would require longitudinal studies tracking implementations to operational maturity, the evaluation design provided sufficient rigor for establishing the framework's theoretical contribution and practical utility within master's research constraints.

2.7 Case Study: Implementation at the National Research Council (NRC)

The National Research Council of Canada's Digital Construction Platform initiative provided an ideal validation context for the IIE framework due to its complexity, national significance, and multi-stakeholder nature spanning all interoperability dimensions.

2.7.1 Project Presentation: The NRC Implementation

The NRC manages three critical but fragmented information resources for Canada's construction industry: National Model Construction Codes (NMCC) comprising five model codes establishing minimum requirements for building safety, health, and energy efficiency developed through five-year revision cycles; National Master Specifications (NMS) providing over 780 specification sections organized using MasterFormat™ and UniFormat™ classifications, updated quarterly by industry expert committees; and Canadian Construction Materials Centre (CCMC) offering evaluation services assessing innovative construction materials for code compliance through rigorous technical assessment.

These resources serve complementary functions; codes define regulatory requirements, specifications detail compliant assemblies, and evaluations verify product suitability, yet operate as independent information silos. Each resource is managed by a separate NRC department with distinct governance structures and development processes, information is maintained in heterogeneous formats without automated integration mechanisms, terminology and conceptual models differ without formal semantic mappings, and users must manually navigate separate systems to establish connections between provisions, specifications, and compliant products.

The NRC DCP initiative aims to create an integrated digital environment enabling seamless information access and exchange across these resources to support enhanced accessibility through unified discovery mechanisms, automated compliance checking linking machine-readable requirements with BIM models, innovation adoption connecting evaluations with

code provisions, sustainability support integrating environmental performance data for lifecycle assessment, and regulatory modernization enabling digital building permit processes. The initiative operates within complex organizational context requiring federated governance preserving departmental autonomy, accommodation of multi-level jurisdictional variations, service to diverse stakeholder groups with different information needs, and strategic alignment with Canada's construction sector digitalization and decarbonization programs. This complexity makes the NRC DCP ideal for testing the IIE framework across semantic, syntactic, conceptual, procedural, organizational, and strategic integration dimensions.

2.7.2 Evaluation Process of the NRC Implementation

The NRC case study evaluation was conducted through systematic framework application across different project phases, providing empirical evidence for framework utility and applicability.

Problem Diagnosis and Challenge Mapping began with systematic analysis of NRC's current state through documentary review of code development processes, specification workflows, evaluation procedures, and IT infrastructure specifications, complemented by semi-structured interviews with key stakeholders across departments, IT teams, and strategic leadership. Identified challenges were systematically mapped to IIE framework tiers, requirements, and components using structured templates, revealing coverage across all three tiers and 16 of 18 framework components and demonstrating that the framework captures the full spectrum of integration problems across multiple interoperability dimensions simultaneously.

Solution Architecture Development assessed whether the framework provides actionable guidance by using the three-tier structure as the primary organizing principle for NRC DCP architecture development. Tier 1 components guided semantic standardization decisions, data schema alignment, and information requirement specifications; Tier 2 components guided federated CDE architecture, API gateway patterns, and governance frameworks; and Tier 3

components guided service specifications for compliance checking, lifecycle assessment, and stakeholder-facing applications. Six facilitated workshops with cross-functional teams refined framework-based solutions and validated that proposed approaches address genuine needs while respecting organizational constraints, with resulting architecture demonstrating direct instantiation of framework structure and stakeholder acceptance providing qualitative validation of framework utility.

Requirements Specification evaluated whether the framework enables systematic requirements capture by using framework components as organizational scaffolding for requirements workshops addressing each tier sequentially. The framework-guided process produced comprehensive specifications spanning all integration dimensions simultaneously - semantic, syntactic, organizational, procedural, and strategic requirements - validating that framework structure prevents common failure patterns where requirements focus narrowly on technical aspects while neglecting equally important organizational or governance concerns.

Throughout all phases, iterative feedback loops allowed stakeholder reactions to inform framework refinements, implementation challenges to reveal areas requiring clearer guidance, successful applications to identify effective practices, and comparative analysis with international initiatives to contextualize findings. The evaluation acknowledges inherent limitations including single case context requiring additional validation for private sector generalizability, ex ante timing assessing framework guidance rather than operational outcomes, nine-month timeline capturing planning phases but not long-term implementation, and government agency context differing from private firms regarding standardization mandates and competitive dynamics. Despite these limitations, the systematic multi-phase evaluation provided substantial evidence that the IIE framework captures real-world integration challenges, provides actionable guidance for solution architecture development, and enables systematic requirements specification.

It is vital to note that this thesis manuscript was developed with assistance from AI language models (Claude by Anthropic) for writing and editing support. These were employed to help

improve sentence structure and clarity, ensure consistent terminology usage, and enhance overall readability of the manuscript. All conceptual contributions represent original intellectual work.

2.8 Chapter Summary

This chapter presented the research methodology employed to develop and validate the Integrated Information Environment framework. The Design Science Research approach provided systematic guidance through problem identification, solution objectives definition, framework design and development, demonstration through NRC case application, evaluation of effectiveness, and communication of findings. Data collection through systematic literature review synthesized knowledge across eight interconnected domains, revealing critical insights including persistent semantic fragmentation despite technical connectivity, tension between centralization and federation, lifecycle discontinuities at phase transitions, and inadequate attention to socio-technical dimensions.

Data analysis employed thematic analysis, comparative framework analysis, gap analysis, requirements synthesis, and pattern recognition to identify integration requirements and design principles. Framework development proceeded through iterative refinement involving conceptualization establishing three-tier structure, design elaboration specifying 18 components, requirements derivation producing 19 actionable objectives, and refinement based on expert feedback. The framework embodies six key characteristics: autonomy preservation through federated architecture, heterogeneity support, lifecycle continuity, multi-dimensional integration, incremental Implementability, and standards alignment.

The evaluation strategy combined ex ante naturalistic evaluation through NRC case study with ex ante artificial evaluation through theoretical analysis and expert review. The four-phase case study systematically assessed framework comprehensiveness, coherence, prescriptiveness, applicability, and utility. The NRC Digital Construction Platform provided ideal validation context due to multi-resource fragmentation, federated organizational structure, national-scale complexity, and strategic sustainability objectives. Nine-month systematic framework

application across problem diagnosis, solution architecture development, and requirements specification provided substantial empirical evidence for framework validity and utility, while acknowledging limitations inherent in single-case, ex ante evaluation within master's research constraints.

CHAPTER 3

INTEGRATED INFORMATION ENVIRONMENTS FRAMEWORK

Part of this chapter was presented in CSCE Construction Specialty Conference in July 2025.

3.1 The Need for Integrated Information Environments (IIEs)

The literature review in Chapter 1 identified fundamental limitations constraining information management effectiveness within the built asset industry: information fragmentation across project phases and organizational boundaries creates exchange discontinuities resulting in value loss and coordination inefficiencies (Jaskula et al., 2024; Kloosterman et al., 2024); insufficient interoperability extends beyond technical data exchange to encompass semantic, syntactic, organizational, procedural, and contextual dimensions that prevent seamless collaboration (Ahmed et al., 2024; Poirier et al., 2014); and project-centric, document-oriented paradigms prove inadequate for supporting dynamic, interconnected requirements of advanced capabilities such as Digital Twins and advanced analytics (Vieira et al., 2023).

Existing frameworks address specific aspects but fail to provide comprehensive multi-perspective approaches. (Bucher & Hall, 2020)'s multi-layered CDE framework remains conceptually abstract regarding implementation mechanisms and socio-technical barriers; (Godager et al., 2021, 2022) Enterprise BIM approach lacks empirical validation and consideration of federated exchange protocols; Jaskula et al. (2025)'s blockchain-based framework focuses on transaction recording rather than broader ecosystem integration. The convergence of these limitations creates a critical gap: the absence of systematic frameworks supporting both lifecycle information continuity and cross-organizational integration while preserving organizational autonomy. This gap becomes increasingly problematic as the industry moves toward Digital Twin implementations and advanced analytics requiring unprecedented levels of information integration and real-time coordination.

3.2 Integrated Information Environment Framework Overview

This chapter presents an IIE framework that systematically addresses identified limitations through a structured, multi-perspective approach, synthesizing lifecycle continuity principles with multi-dimensional interoperability requirements to provide a pathway from fragmented systems toward integrated environments capable of supporting advanced capabilities.

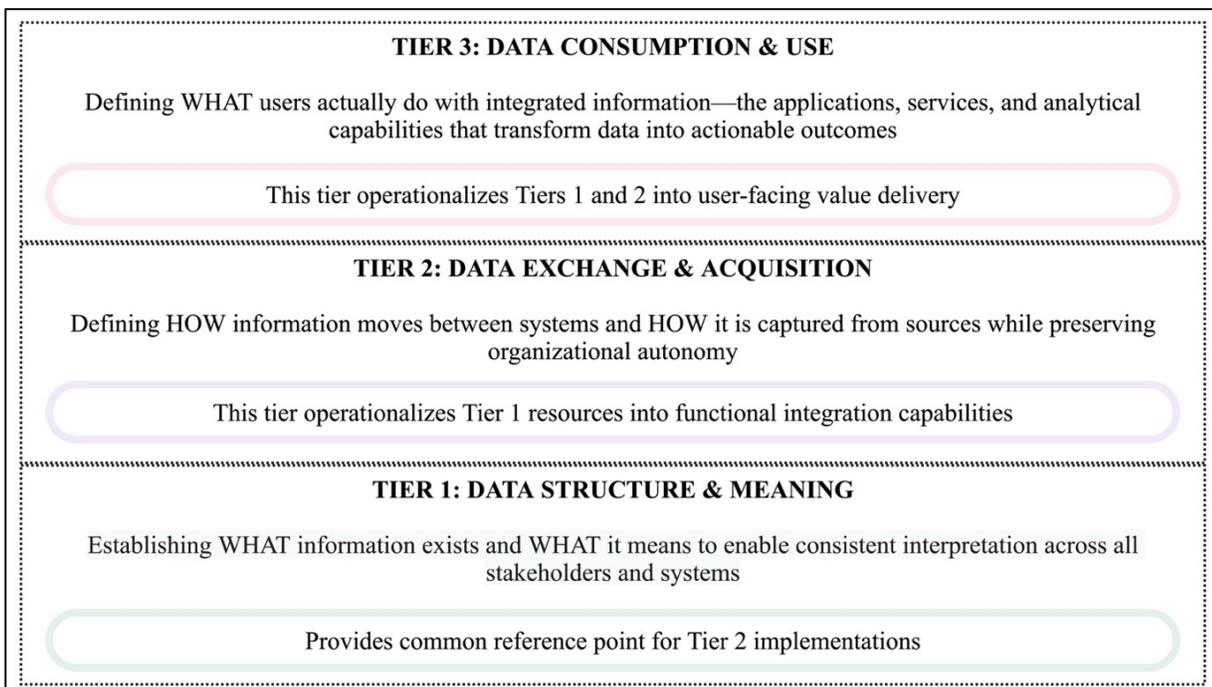


Figure 3.1 Integrated Information Environment Tiers

Figure 3.1 illustrates the framework's three-tier structure, each addressing distinct but complementary integration aspects. The following sections present the framework architecture through systematic progression: Section 3.3 establishes core requirements defining what integrated systems must achieve; Section 3.4 specifies technical and organizational components necessary for realizing these requirements; subsequent sections detail each tier's components and their interrelationships.

3.3 Integrated Information Environment Requirements

The requirements presented in Figure 3.2 define the framework's objectives, derived from systematic analysis of industry limitations and interoperability challenges (Appendix A). These requirements establish the foundation for the three-tier structure and guide specification of technical components necessary for their realization.

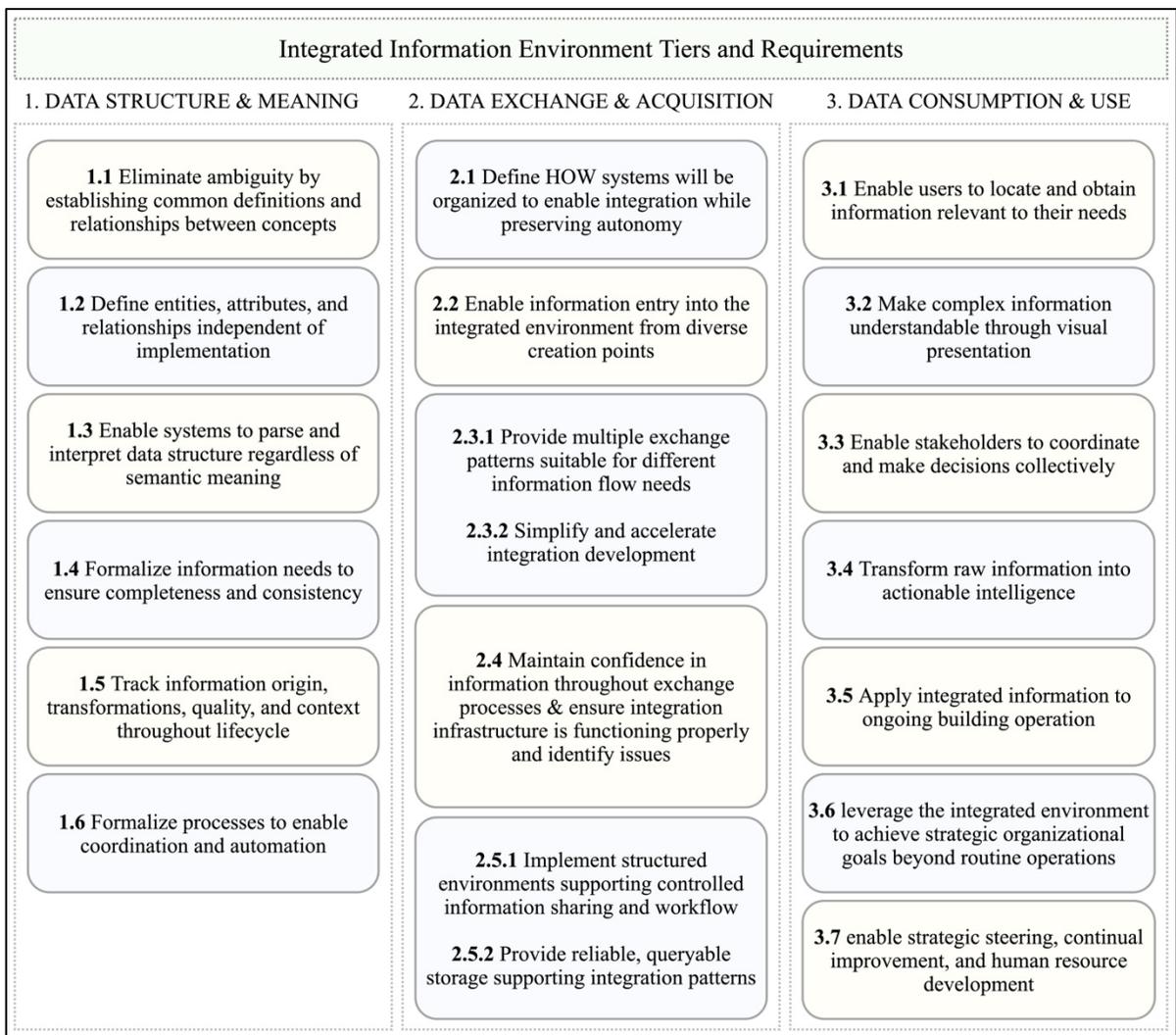


Figure 3.2 Integrated Information Environment Requirements

The requirements emerge from three converging sources. First, the literature review revealed persistent failure patterns: information fragmentation creates exchange discontinuities (Jaskula

et al., 2024; Kloosterman et al., 2024); insufficient interoperability spans multiple dimensions beyond technical exchange (Ahmed et al., 2024; Poirier et al., 2014); and project-centric paradigms prove inadequate for advanced BIM capabilities such as Digital Twins and advanced analytics (Vieira et al., 2023).. Each limitation translates into corresponding requirements: semantic fragmentation necessitates eliminating ambiguity through common definitions (Requirement 1.1); organizational silos require integration architectures preserving autonomy (Requirement 2.1); workflow discontinuities demand stakeholder coordination capabilities (Requirement 3.3). Second, existing framework gaps inform specific requirements. Lack of federated protocols, and narrow transaction focus generate requirements for formalizing coordination processes (1.6), providing flexible exchange patterns (2.3.1), and implementing structured information sharing environments (2.5.1). This convergence validates the necessity for requirements addressing both technical integration and socio-technical complexity. Third, the requirement structure reflects recognition that integration operates across multiple abstraction levels with interdependent objectives, driving the framework's three-tier organization.

Tier 1 (Data Structure & Meaning) establishes foundational semantic and syntactic consistency for unambiguous interpretation, addressing: "Can systems understand each other?" Requirements focus on eliminating conceptual ambiguity (1.1), defining standardized structures (1.2), enabling syntactic parsing (1.3), formalizing information needs (1.4), tracking provenance and quality (1.5), and establishing process coordination (1.6). Without these foundations, higher-level integration remains superficial.

Tier 2 (Data Exchange & Acquisition) addresses operational infrastructure: "How do systems connect while preserving autonomy?" Requirements specify architectural patterns for federated exchange: defining architectures preserving independence (2.1), enabling information entry from diverse points (2.2), providing flexible exchange patterns (2.3.1, 2.3.2), maintaining confidence through governance (2.4), and implementing structured environments with reliable storage (2.5.1, 2.5.2). This tier translates semantic foundations into operational reality, recognizing industry fragmentation demands federation over centralization.

Tier 3 (Data Consumption & Use) focuses on stakeholder value: "How do capabilities translate into business outcomes?" Requirements ensure integration serves practical purposes: enabling information access (3.1), providing visualization (3.2), supporting collaborative decision-making (3.3), transforming data into intelligence (3.4), applying information to operations (3.5), achieving strategic goals (3.6), and enabling continuous improvement (3.7). Without Tier 3, integration becomes technical achievement without stakeholder value.

This requirement structure provides the conceptual foundation for component architecture. Each tier necessitates specific components: Tier 1 requires semantic resources, data schemas, syntactic resources, information specifications, metadata standards, and process models; Tier 2 mandates platform architectures, data acquisition mechanisms, integration middleware, governance frameworks, and CDE infrastructure; Tier 3 guides information access services, visualization capabilities, collaborative tools, analytics engines, operational systems, strategic applications, and organizational development functions. The hierarchical dependency, where Tier 3 depends upon Tier 2 implementing Tier 1 standards, informs the component architecture's layered structure, ensuring systematic progression from fragmented systems toward integrated environments. Section 3.4 details these components, translating requirement objectives into concrete specifications.

3.4 Integrated Information Environment Components

This section presents the technical and organizational components necessary for realizing the requirements established in Section 3.3. The components are organized according to the three-tier structure, with each tier building upon capabilities established in lower tiers while enabling functionality in higher tiers.

Tier 1: Data Structure & Meaning: establishes foundational semantic and syntactic resources enabling information consistency and unambiguous interpretation across organizational boundaries. This tier systematically addresses the spectrum from abstract conceptualization to contextual information requirements (Ali et al., 2024; Herle et al., 2020; Maciel et al., 2024).

The components progress from defining abstract concepts and shared vocabularies through formal data structures, technical exchange mechanisms, detailed information requirements, contextual metadata, and process governance models.

3.4.1 Semantic Resources

Semantic Resources (Figure 3.3) provides the intellectual infrastructure necessary for achieving semantic interoperability, ensuring that systems and stakeholders share a common, unambiguous understanding of the meaning of exchanged information (Ali et al., 2024). Ontologies form the core of this infrastructure, representing formal, standardized specifications of domain knowledge by defining concepts, their properties, and intricate relationships, thereby supporting high-level reasoning and inference capabilities (Figay et al., 2015; Gispert et al., 2023; Ramonell et al., 2023). Unlike schemas which emphasize efficient data storage, ontologies prioritize conceptual rigor, with languages such as OWL providing the formal representation mechanism (Da Rocha et al., 2022; Gispert et al., 2023; Pauwels et al., 2017).

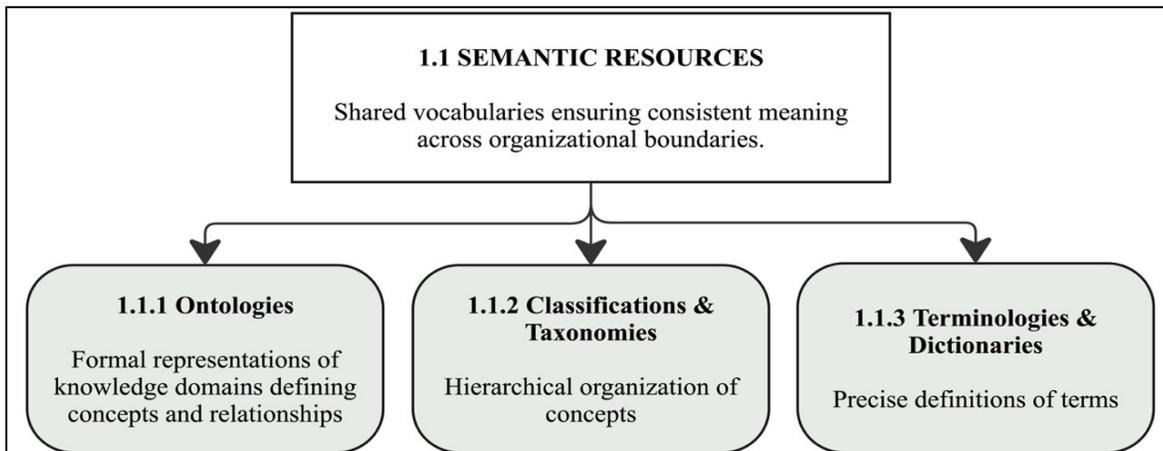


Figure 3.3 Intellectual infrastructure necessary for achieving semantic interoperability

Complementing this formal structure, Classifications & Taxonomies, such as UniClass, OmniClass and MasterFormat, provide hierarchical systems for organizing domain concepts, which is vital for structuring data, supporting object retrieval, and standardizing categorization

across projects and organizations (Heaton et al., 2019; Sanchez et al., 2017; Succar et al., 2013). Terminologies & Dictionaries (e.g., the buildingSMART Data Dictionary and BIM Dictionary) furnish precise definitions for terms, acting as shared vocabularies to ensure consistent interpretation and eliminating conflicting uses of language across organizational boundaries (Poirier et al., 2022).

3.4.2 Models & Data Schemas

The Conceptual Models (Figure 3.4) establishes the abstract, often standardized, blueprints that define the primary information structures and representations within the built asset domain, bridging the gap between formal semantics and physical implementation; Data Models define the core structures, rules, and relationships for organizing information elements, with the IFC serving as the predominant common data schema for neutral BIM data exchange, supporting inter-domain communication (Jiang et al., 2019; Poirier et al., 2022). Crucially, Schema Definitions (e.g., IFC, CityGML, XSD for XML) provide the formal structural specifications, ensuring that the syntax of the data is well-defined and machine-readable for consistent processing by recipient systems (Soman & Whyte, 2020).

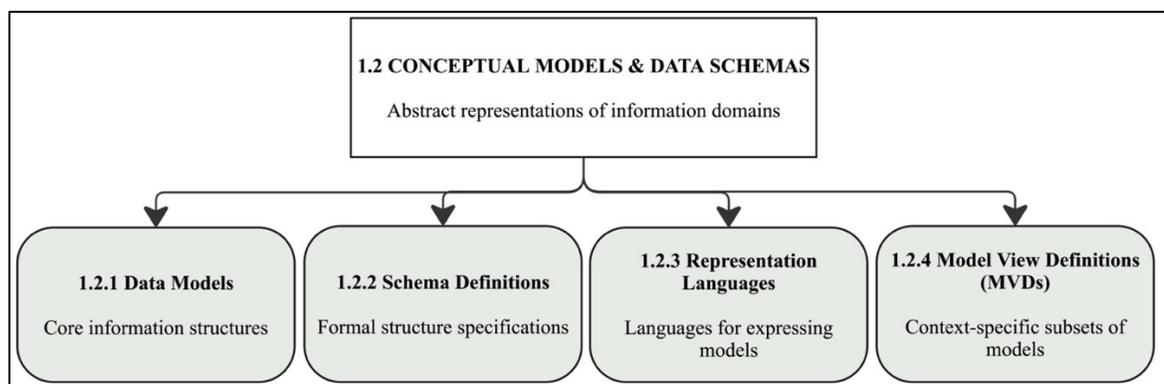


Figure 3.4 Primary information structures and representations

Conceptualization is often formalized using Representation Languages, such as the Unified Modeling Language (UML) for visualizing model structure, EXPRESS for defining IFC schemas, or the OWL for formally expressing semantic models (Abanda et al., 2025; Karan et

al., 2016). To manage the complexity and scale of comprehensive data models, MVDs define context-specific subsets of the core model (e.g., IFC), specifying the exact content and relationships required for a specific exchange purpose or workflow, thereby translating process requirements into technical specifications for software implementation (Moretti et al., 2022; Ren & Zhang, 2021).

3.4.3 Syntactic Resources

Syntactic Resources (Figure 3.5) ensure technical and structural consistency, addressing how information is physically packaged and transmitted, thereby achieving syntactic interoperability, which is a necessary prerequisite for semantic alignment (Herle et al., 2020). Data Formats specify the standardized physical representation (e.g., XML, JSON, or RDF serializations such as N-Triples) of the information containers (Gaynor et al., 2014). The foundation is also provided by agreed-upon transmission rules in Communication Protocols (such as HTTP or MQTT), which define the technical layer for network connectivity and data transfer (Bazzanella & Tzitzikas, 2013).

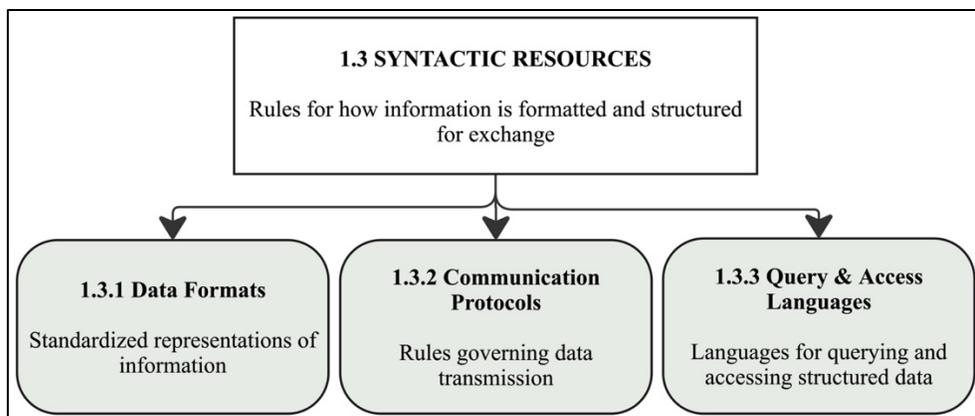


Figure 3.5 Technical and structural consistency components

Different device manufacturers in an IoT context often use different communication protocols, necessitating well-defined models and scalable adapters (Agostinho et al., 2016). Lastly, the utility of this structured data is realized through Query & Access Languages; for instance,

SPARQL is the standard language for interrogating semantically structured data (RDF graphs), enabling efficient retrieval and complex analytical querying across interconnected datasets (Pauwels et al., 2017; Tang et al., 2019).

3.4.4 Information Requirements

The Information Requirements component (Figure 3.6) operationalizes the framework's goals by specifying WHAT information stakeholders need, WHEN they need it, and HOW detailed it must be, focusing on the quality and utility of the information deliverables (Poirier et al., 2022). IDS define information requirements in a machine-readable format, specifying how objects, classifications, properties, and units must be exchanged, which enables automated validation of delivered datasets against contractual and technical specifications (Forth et al., 2023). The IDS complements the MVD process for defining information exchanges (De Gaetani et al., 2020). The framework uses Level of Information Need (LOIN), standardized under ISO/DIS 7817, to provide a structured, purpose-driven methodology for defining the required extent and granularity of geometric, alphanumeric, and documentation information for specific project milestones (Forth et al., 2023; Vieira et al., 2023).

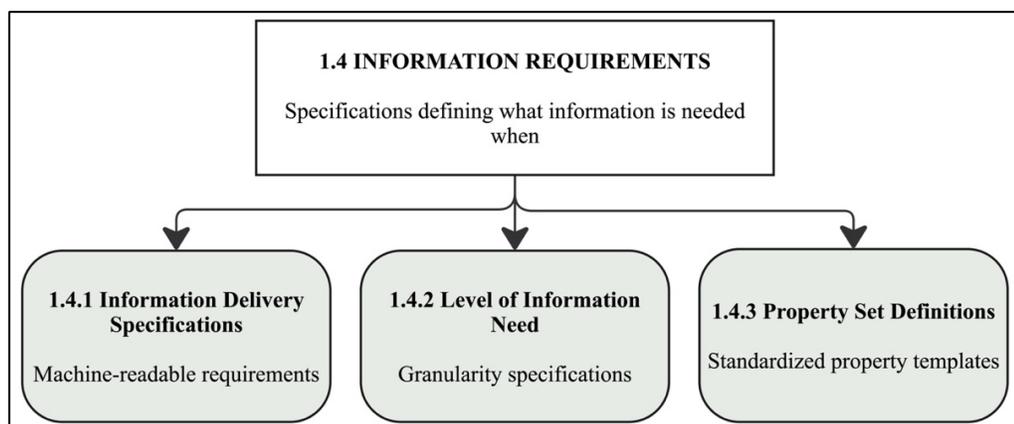


Figure 3.6 Information requirements components

Moreover, to manage complex, domain-specific metadata, Property Set Definitions (PSets) provide standardized templates for attaching necessary non-geometric attributes (properties)

to data objects, managing these extensions outside the core data schema to enhance model richness while maintaining interoperability (van Berlo et al., 2021; Yu et al., 2023).

3.4.5 Metadata

Metadata components (Figure 3.7) addresses the necessity of providing contextual information about the data itself, which is vital for discoverability, trust, and long-term asset management. Descriptive Metadata such as Dublin Core metadata elements provide information necessary for indexing, searchability, and comprehension - including elements such as file naming conventions, classification assignments, and unique identifiers (e.g., Globally Unique Identifiers or URIs), which are fundamental for referencing data consistently across disparate systems (Corcho et al., 2024). Consistent metadata assignment (e.g., classification metadata) is critical for filtering information containers. Provenance Metadata records the history and origin of the information, establishing a crucial chronological record of ownership, custody, transformations, and confidence scores, thereby assuring the trustworthiness and traceability of digital assets throughout their lifecycle (Sadeghi et al., 2024).

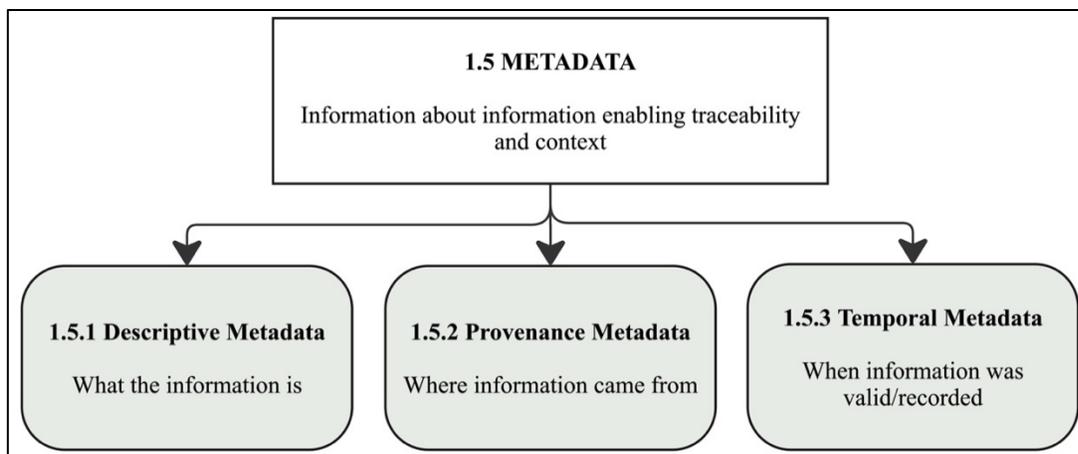


Figure 3.7 Metadata Components

Finally, Temporal Metadata captures time-specific context, such as when data was recorded, when it was valid, or version history, which is increasingly critical for Digital Twin implementations that integrate real-time or time-series sensor data (Da Rocha et al., 2022).

3.4.6 Process & Workflow Models

The final conceptual pillar, Process & Workflow Models (Figure 3.8), ensures that the flow of information defined by the prior components is mapped to practical execution mechanisms and governed by defined constraints. Process Models formally represent the "what to do" and "how to do it," mapping activities, actors, and resources through established flow diagramming languages such as BPMN or UML, often formalized through methodologies such as IDM (Abanda et al., 2025). These processes articulate Information Uses, defining the specific functional application of the information required for project outcomes (e.g., clash detection, quantity take-off, performance simulation, energy analysis) (Sattler et al., 2019; Succar et al., 2016).

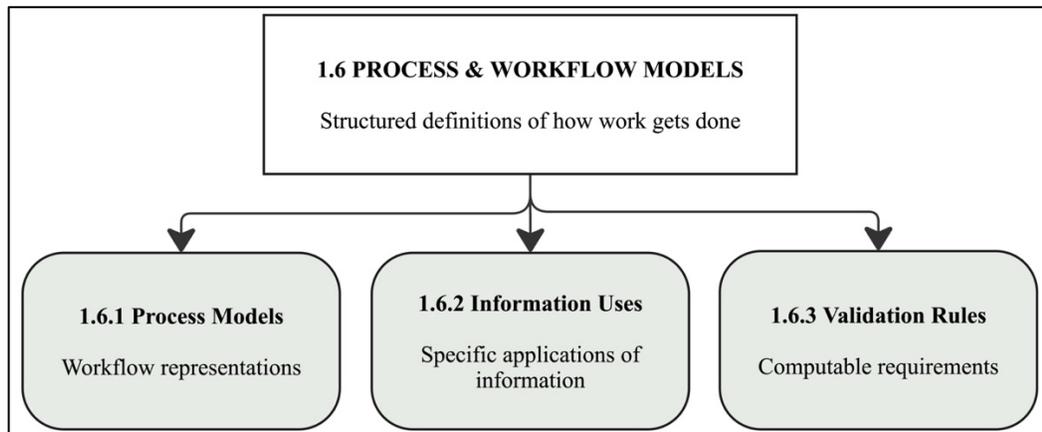


Figure 3.8 Process and workflow models components

To enforce quality and consistency within these workflows, Validation Rules provide computable criteria (e.g., integrity checks or rules formulated using rule languages such as Semantic Web Rule Language, SWRL) against which data containers can be automatically checked, supporting quality assurance procedures specified in the CDE environment

(Werbrouck, 2019). Validation rules also cover checking the content of a BIM file against building codes and regulations.

The articulation of Tier 2: Information Exchange & Management represents the operational instantiation of the semantic and syntactic definitions established in Tier 1. This tier delineates the architectural mechanisms, technical tools, and governance practices required to realize dynamic, distributed, and high-fidelity information flow within the built asset lifecycle, effectively translating abstract interoperability standards into actionable technical infrastructure. This tier has a clearer progression from architecture to ingestion, transport, governance, and finally, management and persistence.

3.4.7 Platform Architecture Patterns: High-level Blueprints

The component Platform Architecture Patterns (Figure 3.9) is paramount within Tier 2, as it prescribes the requisite high-level structural blueprints for connecting heterogeneous, autonomous information systems into a cohesive SoIS (Fernandes et al., 2022), a topology inherently demanded by the dynamic, fragmented nature of the built asset industry. These patterns address key architectural considerations, such as complexity, scalability, and the preservation of autonomy, by defining the structural relationships and communication modalities between constituent systems (Atkinson et al., 2022; Urgese et al., 2022).

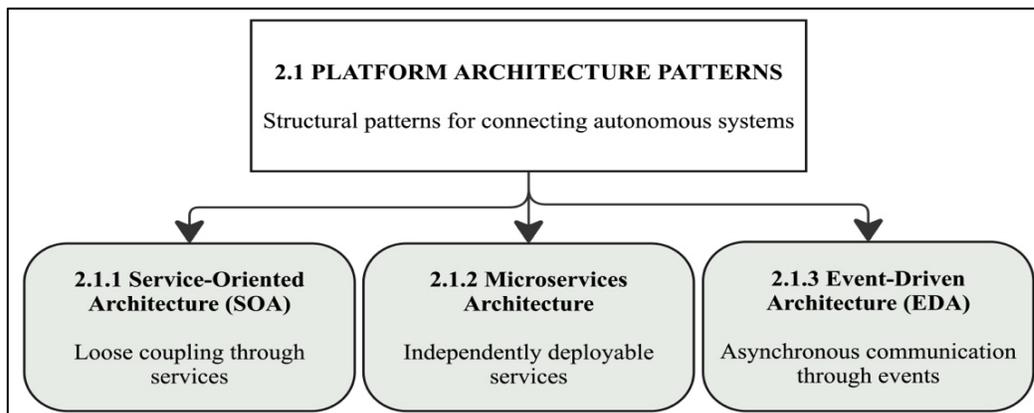


Figure 3.9 high-level structural blueprints for connecting heterogeneous IS

SOA acts as a premier framework for integrating complex and heterogeneous computing environments, structuring interactions around reusable services accessed via communication protocols (Elmir et al., 2015; Isikdag, 2015). This architectural style is pivotal for achieving interoperability, promoting loose coupling, platform independence, and organizational flexibility, which are critical features for managing complex information models such as BIM (Isikdag, 2015; Tang et al., 2019). SOA relies on specific SOA Components to manage service provision and consumption (Urgese et al., 2022) including Service Providers, Service Consumers/Clients who interact with these services to utilize their capabilities, and Service Registry/Repository which is essential for the full SOA architecture.

Moreover, Microservices Architecture is an evolutionary step built upon SOA principles, characterized by developing systems as a collection of smaller, self-contained, and independently deployable services (Minerva et al., 2020; Zarko et al., 2017). This approach inherently supports the modularity, flexibility, and scalability required for IIE development, especially for cloud-based deployment (Minerva et al., 2020). Realizing microservices requires specific Microservices Patterns and robust Microservices Infrastructure such as Communication Patterns (e.g. API Gateways).

Event-Driven Architecture (EDA) complements SOA and Microservices by enabling asynchronous, non-blocking communication via events (Yu et al., 2023). This pattern is highly valuable for managing complex, stateful interactions across distributed systems, such as integrating dynamic sensor data (IoT) with static BIM geometry (Isikdag, 2015; Tang et al., 2019). Event-driven exchanges are promoted in standards contexts such as the Open Industrial Interoperability Ecosystem (OIIE) to facilitate object-based, incremental updates rather than bulk file transfers. The architecture supports continuous engineering practices by providing input and feedback between engineering phases, particularly enabling feedback loops necessary for real-time adjustments and evolutionary development (Urgese et al., 2022).

All these architectural patterns converge on the necessity of supporting specific Exchange Scenario Views that define the operational goals and informational context of the data

exchange. The complexity of interoperability demands analyzing the information needed for specific application-oriented scenarios, such as coordination, handover, analysis, cost estimation, scheduling, and energy analysis.

3.4.8 Data Acquisition: Information Ingestion

Data Acquisition (Figure 3.10) encompasses the varied methods and technologies employed to capture raw or structured information from its diverse sources, serving as the necessary ingress points for the IIE. BIM Authoring and Model Integration involves extracting structured data from native BIM software, often facilitated via APIs or through neutral, standardized exchange formats such as IFC, governed by specifications such as MVDs (Afsari et al., 2016; Z. Chen et al., 2024).

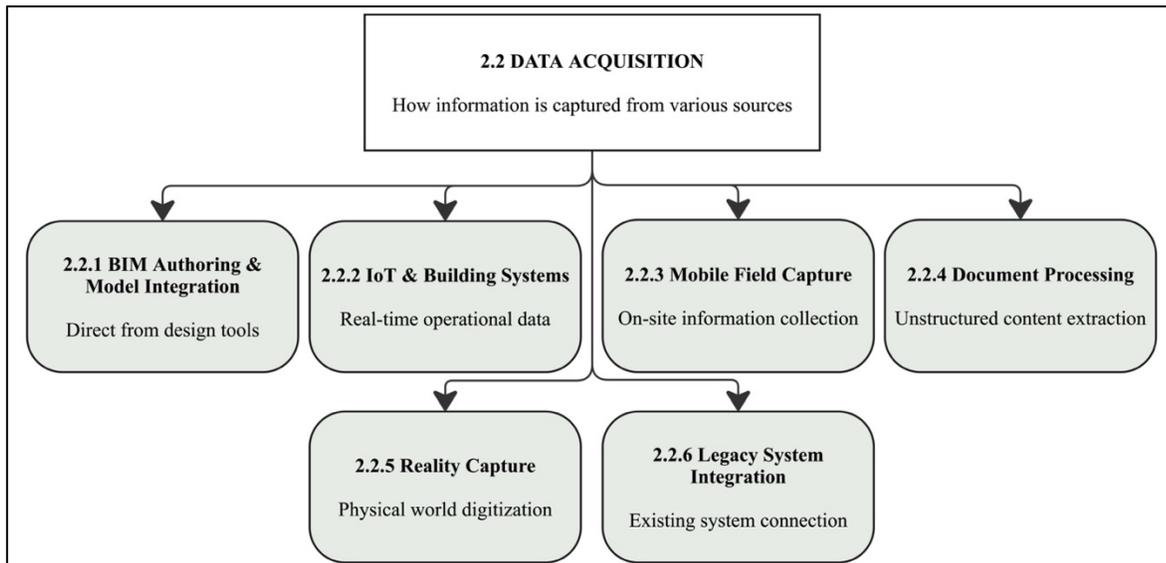


Figure 3.10 Information ingestion components

Integration of IoT & Building Systems is essential for acquiring real-time, dynamic data streams from smart devices and sensor networks, which requires standardized protocols and SOA patterns for seamless fusion with static BIM context (Okonta et al., 2024; Ruiz-Zafra et al., 2022). Reality Capture systems, such as laser scanning, acquire physical environment data which then needs to be aligned and integrated with existing digital models. Furthermore,

methods such as Mobile Field Capture facilitate the collection of asset inspection and maintenance data, while Document Processing digitizes unstructured information containers (Abanda et al., 2025). Addressing institutional inertia, Legacy System Integration involves providing technical solutions, often mediated by middleware or wrapping services within SOA, to connect older, heterogeneous systems that were not originally designed for modern interoperability (Agostinho et al., 2015; Panetto et al., 2016).

3.4.9 Integration Mechanisms & Middleware: How Data Moves with What Tools

Integration Mechanisms (Figure 3.11) specify the precise modalities and temporal characteristics governing information exchange between systems.

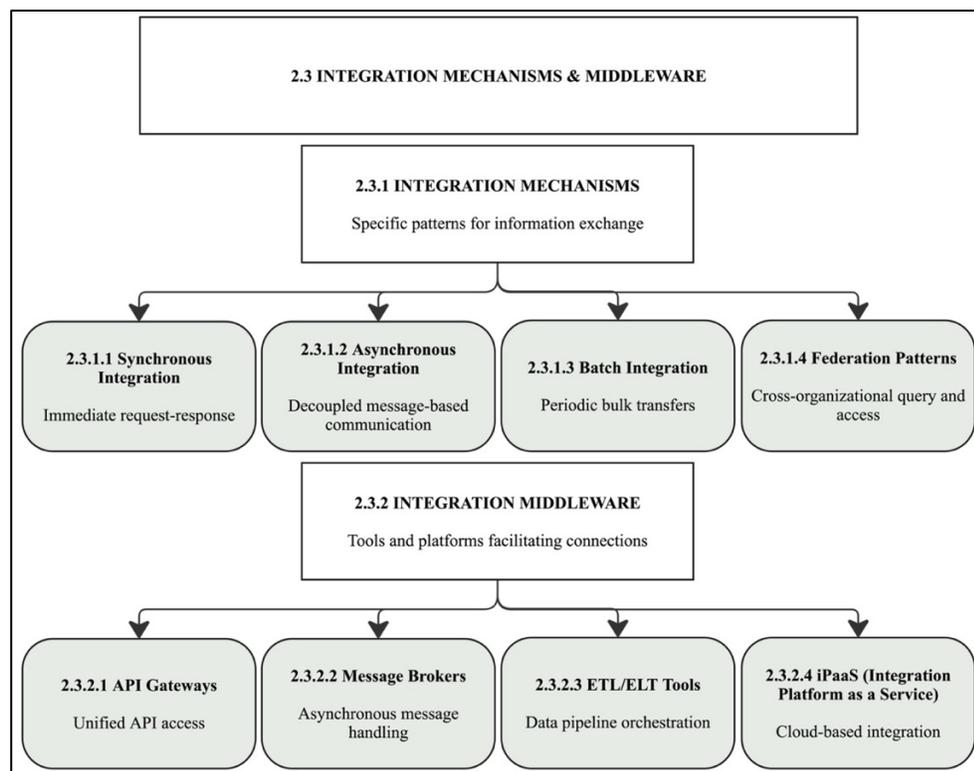


Figure 3.11 Characteristics governing information exchanges

Integration Middleware consists of the specialized software tools and platforms that technically facilitate the seamless connection and data transformation between heterogeneous constituent

systems. Integration mechanisms are defined by the required Synchronous Integration (immediate request-response) capabilities, necessary for real-time interactions and immediate data retrieval in service-oriented contexts (Isikdag, 2015). Conversely, Asynchronous Integration, often relying on mechanisms such as message brokers, is critical for managing non-blocking, event-driven data flows, such as continuous sensor data updates in an IoT environment (Isikdag, 2015). For handling large volumes of accumulated data, Batch Integration involves periodic bulk transfers, often necessary for the exchange of traditional file-based assets (e.g., IFC files) or when updating large repositories using ETL processes (De Gaetani et al., 2020). A sophisticated form of data interaction is realized through Federation Patterns, enabling cross-organizational query and access capabilities where data resides independently but is made accessible and usable through agreed-upon interfaces, semantics, and standardized access languages (Fernandes et al., 2022; Herle et al., 2020; Wu et al., 2025). These federation patterns are crucial for supporting interoperability between platforms such as BIM and GIS by ensuring semantic connectivity through technologies such as Linked Data (Graziano et al., 2023).

API Gateways and specialized interfaces (e.g., RESTful APIs, OGC SensorThings API) are critical for exposing standardized access points to data and services, enabling tool interoperability and the discovery, query, and publication of data offerings (Atkinson et al., 2022; Oukes et al., 2019; Wu et al., 2025). API Gateways which are points of entry for services, manage routing and providing essential cross-cutting concerns (e.g., security) in microservices architectures. Message Brokers are essential components for managing asynchronous, event-driven communication models, particularly for distributing real-time updates and sensor data across the network via publish-subscribe patterns (Isikdag, 2015). ETL/ELT Tools (Extract, Transform, Load/Extract, Load, Transform) are necessary for data level integration, mediating the extraction of data from one source, transforming its structure or format, and loading it into a target repository (Lam et al., 2024). Lastly, iPaaS (Integration Platform as a Service) offers cloud-based solutions to systematically manage and integrate applications, frameworks, and data across different platforms, often serving as a key component for implementing SOA principles in complex enterprise ecosystems (Sadeghi et al., 2024).

3.4.10 Information Governance & Assurance

This category moves beyond mere exchange to focus on guaranteeing the reliability, integrity, security, and performance of the integrated environment, addressing the requirements for trustworthiness throughout the lifecycle (Bazzanella & Tzitzikas, 2013) (Figure 3.12). Data Quality & Management are paramount for ensuring the fitness-for-purpose and integrity of information exchanged across organizational boundaries.

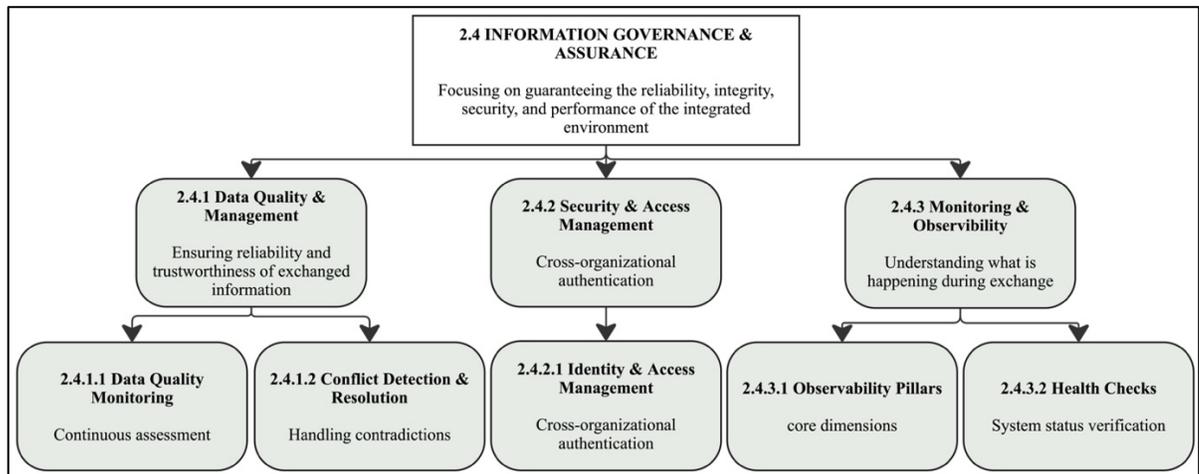


Figure 3.12 Trust, Security, Quality, and Monitoring

Data Quality Monitoring and validation are essential to verify that information meets predetermined compliance, quality, and accuracy requirements (Completeness - Required information present (against Tier 1 IDS), Accuracy - Values correct and within ranges, Consistency - Agreement across sources, Timeliness - Data freshness, Validity - Schema and rule conformance) (Godager et al., 2022; Munir et al., 2020; Preidel et al., 2016). This includes the implementation of Conflict Detection & Resolution mechanisms to address information inconsistencies, such as those arising during the iterative exchange between different model types (e.g., architectural and structural models) (Ren & Zhang, 2021). Identity & Access Management (IAM) systems are vital components for governing access, rights, and authorization, securing the data exchange processes, especially in decentralized or federated environments (e.g. Identity federation through OAuth 2.0, OpenID Connect, SAML 2.0)

(Werbrouck, 2019). Furthermore, the application of cryptographic Trust, often realized through technologies such as blockchain or distributed ledgers, is emerging as a mechanism for creating tamper-proof records and ensuring high levels of data integrity and traceability in decentralized data environments (Maciel et al., 2024; Werbrouck, 2019).

Moreover, Monitoring & Observability are critical functions for ensuring the operational quality, performance, and reliability of a dynamic Integrated Information Environment, particularly important in complex SoIS environments where unplanned emergent behaviors can occur (Fernandes et al., 2022; Panetto et al., 2016). Monitoring relies on collecting and analyzing Observability Pillars (such as metrics, logs, and traces) to understand the internal state and performance of systems, facilitating rapid diagnosis of issues (Agostinho et al., 2015). Regular Health Checks also provide real-time status assessments of system components and interfaces, vital for maintaining continuous service delivery.

3.4.11 CDE & Data Persistence: Centralized Management and Storage

As mentioned in the literature review (Chapter 1, Section 1.4), the CDE Infrastructure is the mandated collaborative workspace and agreed source for information management in line with standards such as ISO 19650 (Jaskula et al., 2025). Moreover, Data Storage & Repositories define the persistent and transient locations where information resides during its lifecycle journey within an Integrated Information Environment (Figure 3.13). The CDE manages information through Information Containers, which are the fundamental units of managed data within the CDE workflow (Werbrouck, 2019). The CDE is underpinned by Workflow Management, which organizes the information container lifecycle across defined stages (e.g., Work in Progress, Shared, Published, Archived) and dictates the required approvals for state transitions (Jaskula et al., 2025).

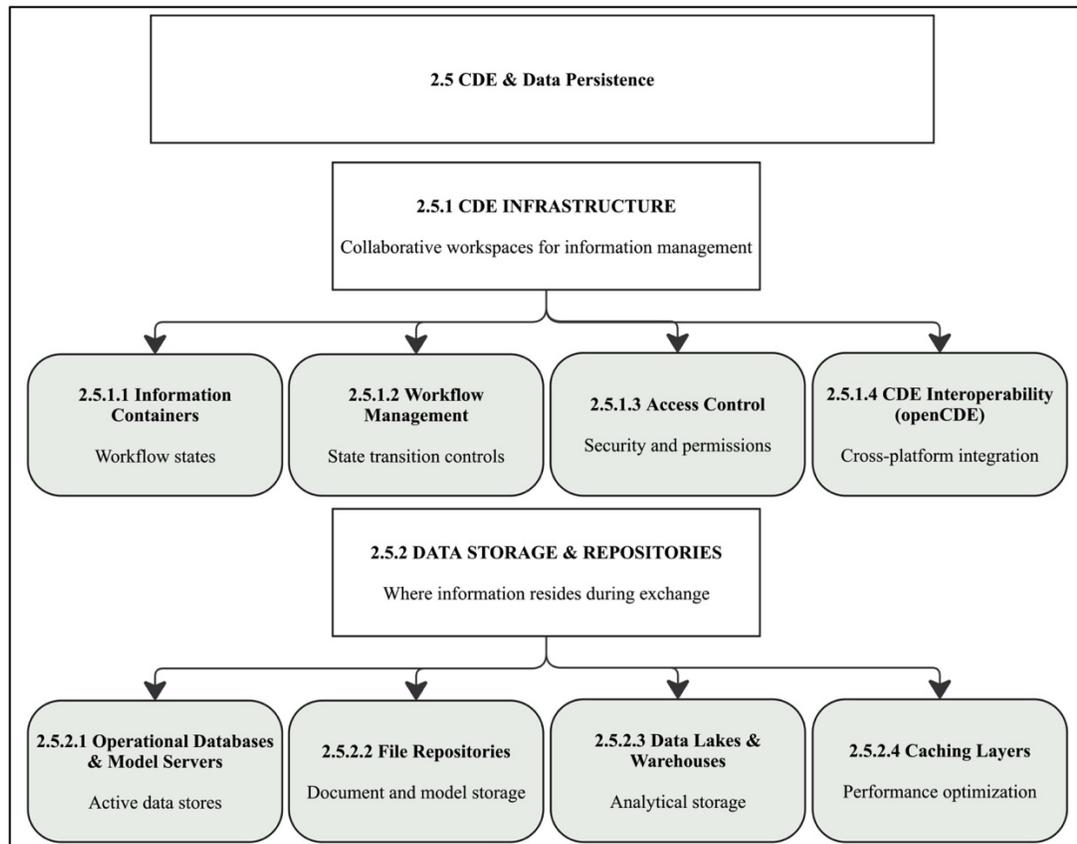


Figure 3.13 Centralized Management and Storage

Strict Access Control mechanisms are crucial within the CDE to ensure information security and guarantee the authenticity and integrity of information by defining user rights, aligning with security-minded approaches (ISO 19650-5) (Tao et al., 2021). Finally, CDE Interoperability (openCDE) represents the ongoing industry push toward standardized, object-based API interfaces to enable seamless communication between disparate CDE solutions, a crucial step for achieving semantic connectivity across project platforms (Preidel et al., 2016; Werbrouck, 2019).

BIM objects and associated data may be stored in Operational Databases (such as object or object-relational databases in model servers such as BIMserver.org) or as traditional File Repositories (storing IFC files) (Afsari et al., 2016; Isikdag, 2015). Since access across the IIE should be immediate and location-independent, data repositories should utilize cloud systems as their technological foundation (Preidel et al., 2018). For optimizing retrieval speed and

managing the variance in data transfer latency inherent in loosely coupled architectures, Caching Layers can temporarily store frequently accessed data (Isikdag, 2015). To manage the increasing volume and variety of heterogeneous data types (e.g., streaming sensor data, historical reports, geometric models) and support advanced analytics, specialized Data Lakes & Warehouses are needed to be employed (Kotha & Gopal, 2021; Ruiz-Zafra et al., 2022). Crucially, achieving semantic interoperability requires these repositories to support graph-based semantic representations, such as triple stores (RDF), for ontologies and linked data, enabling the formal organization and query of knowledge domains (Hagelien et al., 2021).

The articulation of Tier 3: Data Consumption & Use moves the IIE framework beyond the technical scaffolding of Tiers 1 and 2 to realize the ultimate goal of transforming organized, managed information into actionable outcomes for various stakeholders across the built asset lifecycle. This tier defines the application layer, focusing on how integrated systems must be configured to support efficient querying, analysis, visualization, collaboration, and enterprise-wide strategic planning.

3.4.12 Information Access & Retrieval

The effectiveness of information consumption relies intrinsically on the capability of users to locate and retrieve specific data elements from vast, heterogeneous repositories. Information Access & Retrieval (Figure 3.14) addresses this capability, ensuring information is findable and usable regardless of the underlying data complexity. The interaction modes illustrate that the appropriate mechanism depends heavily on the user's level of awareness regarding their information need. When requirements are precisely known, direct querying is possible; otherwise, exploratory browsing is necessary. Therefore, systems must support sophisticated Query Interfaces enabling stakeholders to interrogate information repositories using visual interfaces, natural language, or specialized languages such as SPARQL for Linked Data structures (Jiang et al., 2019; Tang et al., 2019).

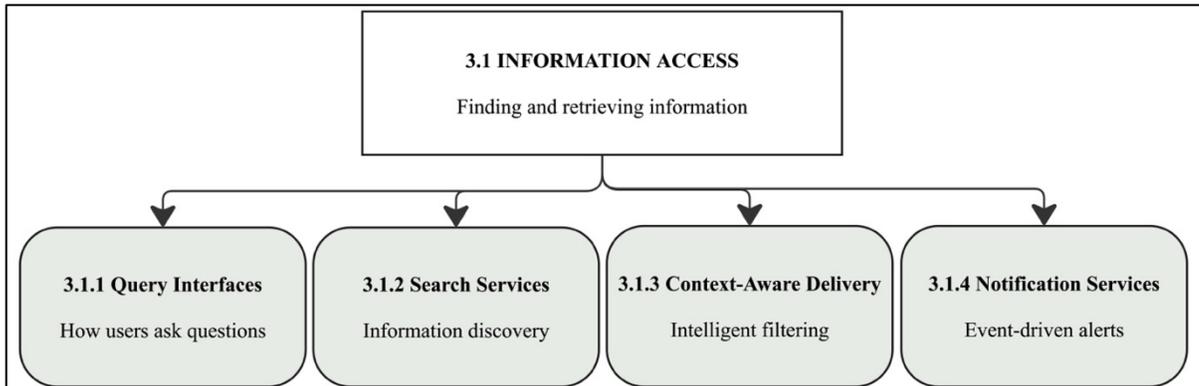


Figure 3.14 Information Access & Retrieval

Search Services leverage robust indexing, categorization, and standardized naming conventions applied during the information production phase (Tier 2) to facilitate easier information consumption. The implementation of specialized querying capabilities, particularly the ability to retrieve and manipulate specific targeted data sets from complex BIMs without requiring expert knowledge of the underlying schema, remains a significant research need (Sattler et al., 2019). Context-Aware Delivery applies Dynamic MVD application. Tier 1 MVDs automatically and Notification Services support the unilateral provision of information to users who may not be aware of their needs or the content availability, a mode of interaction crucial for proactively supporting decision-making processes across project stages. Context-Aware Delivery and Notification Services address information delivery, particularly in dynamic environments such as Smart Cities or Digital Twins.

3.4.13 Visualization & Interface

Visualization is the critical communication mechanism that translates complex data structures, especially those originating from multi-domain and multi-scale models, into meaningful representations tailored for specific user profiles and decision-making contexts (Vieira et al., 2023). This component (Figure 3.15) is fundamental to ensuring the generated insights are effectively communicated to stakeholders who range from technical operators to strategic decision-makers (Vieira et al., 2023).

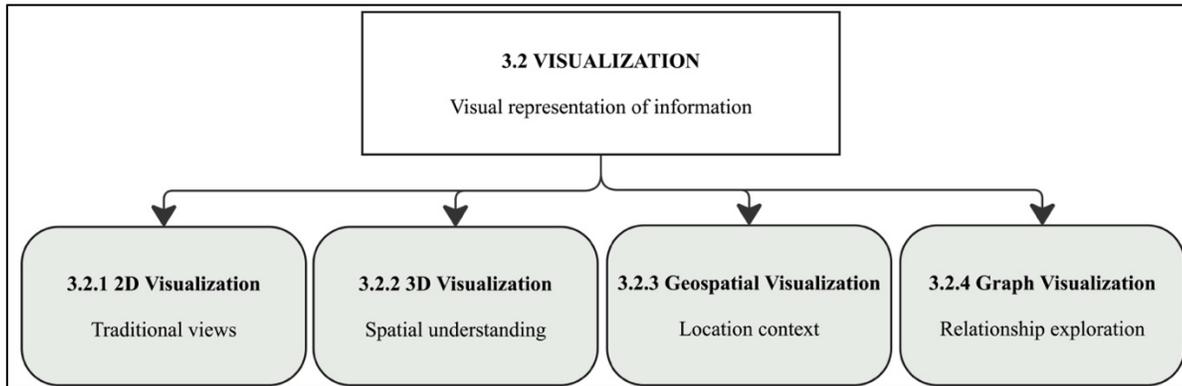


Figure 3.15 Visualization & Interface

An IIE must support traditional 2D Visualization (e.g., standardized drawings and charts) and 3D Visualization (e.g., BIM models and digital mock-ups) (Herle et al., 2020; HIJAZI & DONAUBAUER, 2017; Sanchez et al., 2017). Beyond these, sophisticated integrations require Geospatial Visualization, enabling the combination of design data with asset location information, often by linking BIM/CAD data with GIS through standardized interfaces such as the OGC SensorThings API framework (Graziano et al., 2023; Moretti et al., 2022). For systems leveraging Semantic Web technologies, Graph Visualization is necessary for representing and exploring complex knowledge graphs and ontologies that formally define conceptual entity relationships (Tang et al., 2019). This specialized capability, which is crucial for interacting with knowledge graphs and semantic representations, allows users to visualize and navigate complex ontological relationships, such as the is-a or has-a relationships defined in the domain ontology, enabling the inference of new knowledge (Pauwels et al., 2017). The overall system Interface must be intuitive, open, and user-centric, often exposed via standardized APIs to support cross-domain application development (Dave et al., 2018). Advanced interactions often involve immersive environments facilitated by technologies such as AR and VR (Botín-Sanabria et al., 2022; Vieira et al., 2023).

3.4.14 Collaborative Management Tools

Collaboration focuses on providing the requisite software capabilities and defined processes for stakeholders to work together efficiently and resolve information conflicts across

disciplinary and organizational boundaries. This capability (Figure 3.16) is deeply intertwined with the underlying process dimensions of interoperability (Poirier et al., 2014).

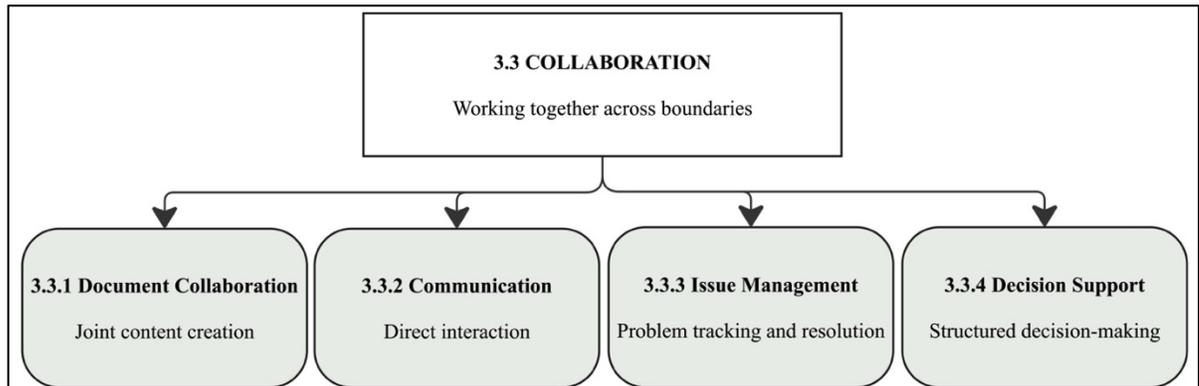


Figure 3.16 Collaborative Management Tools

Effective collaboration relies on robust Document Collaboration and Communication platforms, typically centered within the CDE structure defined in Tier 2 (Jaskula et al., 2025; Preidel et al., 2016). Tools such as the BCF facilitate Issue Management and change coordination by structuring feedback related to model conflicts and deficiencies (Jiang et al., 2019). The systematic definition of processes, often through Process Models using graphical representations such as BPMN, facilitates easier understanding and negotiation of workflows among diverse stakeholders (Abanda et al., 2025). Ultimately, these tools support consensus-based Decision Support, particularly critical during complex design phases where decision-making is intensive. For systems supporting Digital Twins, this collaborative layer also governs who has Accessibility to information and who should participate in the collaborative decision-making process (Vieira et al., 2023).

3.4.15 Specialized Analytics & Value Assessment

Analysis (Figure 3.17) encompasses the technical capabilities used to derive value and insight from integrated information, moving beyond mere visualization to leverage the semantic richness and consistency achieved in Tier 1.

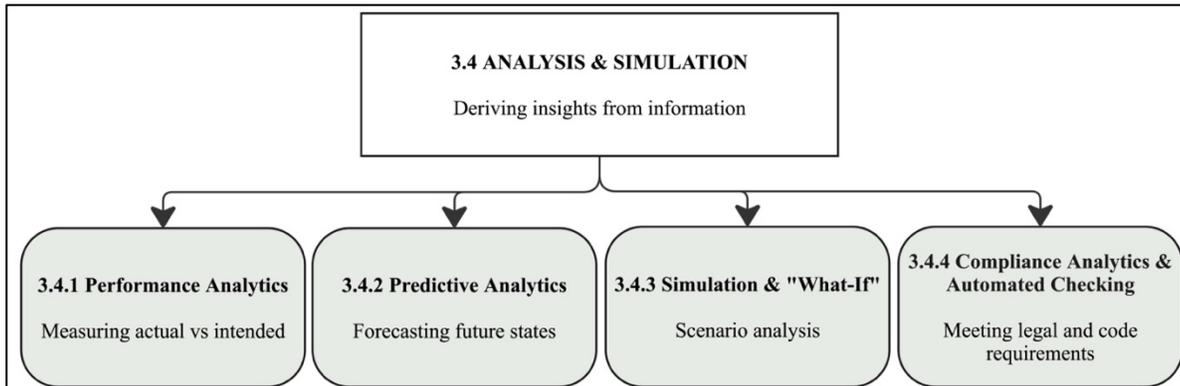


Figure 3.17 Specialized Analytics & Value Assessment

Performance Analytics and Predictive Analytics capabilities rely on aggregating and analyzing data collected over time (e.g., real-time sensor data from IoT & Building Systems) to monitor KPIs and predict future outcomes, thereby enabling proactive decision-making (El Jazzer et al., 2020). The adoption of sophisticated, adaptive, and intelligent analytical approaches, such as Artificial Intelligence and Machine Learning, augments decision support by offering deeper insights (Godager et al., 2021). Simulation & "What-If" capabilities are integral, particularly in the design and operation phases, for assessing various scenarios and optimizing asset performance (Botín-Sanabria et al., 2022; Herle et al., 2020). This requires seamless integration between BIM data models and specialized domain software, such as energy analysis models, which hinges on solving data interoperability issues related to different data formats and semantics (Hosseini Gourabpasi et al., 2025; Tchouanguem Djuedja et al., 2019). Moreover, Compliance Analytics & Automated Checking mechanisms provide automated validation of models against contractual requirements, building codes, and regulations through rule-based checking (Jaskula et al., 2025; Ren & Zhang, 2021; Tchouanguem Djuedja et al., 2019). This process formalizes normative documents into well-defined rules (RASE methodologies), specifies requirements using frameworks such as IDS (Tier 1), and employs computational engines such as SWRL, SPARQL, or DL reasoners to validate BIM models against domain expert-provided rules (Forth et al., 2023; Jiang et al., 2023; Pauwels et al., 2017).

3.4.16 Holistic and Enterprise Information Use

Comprehensive operational services (Figure 3.18) are essential for efficient built asset management, requiring enhanced data access, visualization, and maintenance efficiency (Munir et al., 2020).

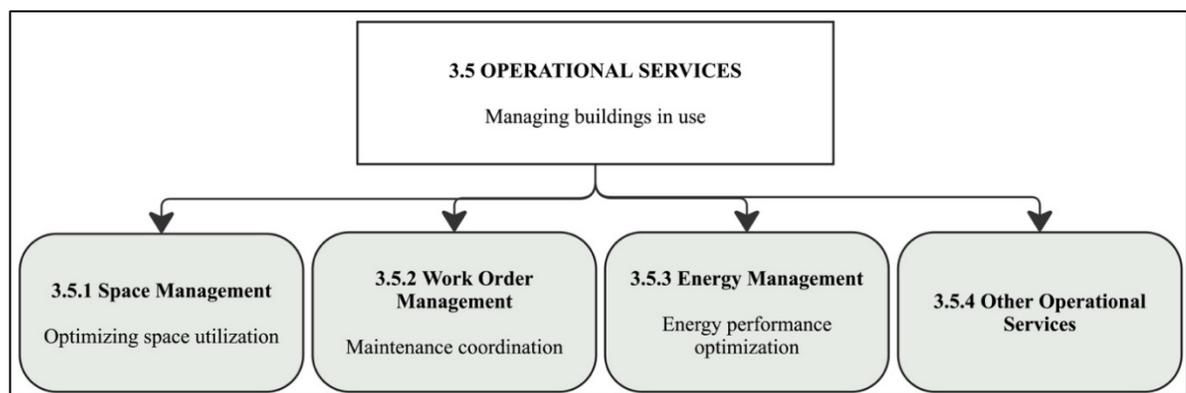


Figure 3.18 Holistic and Enterprise Information Use

Work Order Management coordinates maintenance activities through BIM-based frameworks that enable automatic scheduling and linking maintenance tasks to BIM objects (Kim et al., 2018; Patacas et al., 2020). BIM models create AIM exported to CAFM/CMMS systems, which store maintenance history for trend analysis (Kim et al., 2018; Motamedi et al., 2019). Semantic Web technologies and ontologies link IFC objects with FM work records, enhancing data accessibility and enabling searches for historical records related to specific building elements (Kim et al., 2018). Energy management and optimization represent prominent integrated information applications, driven by regulatory demands and buildings' significant energy consumption (Gispert et al., 2023). Integrating BIM with LCA and Building Energy Modeling (BEM) tools enables simulation of energy consumption, environmental impact assessment, and operational carbon analysis by extracting geometric, material, and thermal properties (Massafra & Gulli, 2023; Seano, 2024). Semantic web technologies facilitate real-time building performance monitoring, allowing facility managers to query sensor data and receive actuation suggestions via web-based interfaces (Munir et al., 2020; Pauwels et al., 2017). Additionally, BIM enables spatial management functions including space inventory,

maintenance planning, and utilization optimization, with geometric boundaries serving as thermal zones for energy analysis (Patacas et al., 2020; Tsay et al., 2022). These operational services alongside other services collectively leverage data access, visualization, and maintenance efficiency to realize BIM's business value across the asset portfolio.

3.4.17 Strategic Domain Applications

This category (Figure 3.19) groups specialized, high-impact application domains that leverage the integrated environment to achieve strategic organizational goals beyond routine operations. **Sustainability & Environmental Assessment:** This area specifically applies integrated data for LCA, Life Cycle Costing (LCC), and supporting sustainable design decisions (Forth et al., 2019; Llatas et al., 2024; Santos et al., 2019). It requires highly granular and validated data to accurately link material compositions and quantities with external Life Cycle Inventory (LCI) databases (such as Ökobaumat) (Forth et al., 2023; Röck et al., 2018).

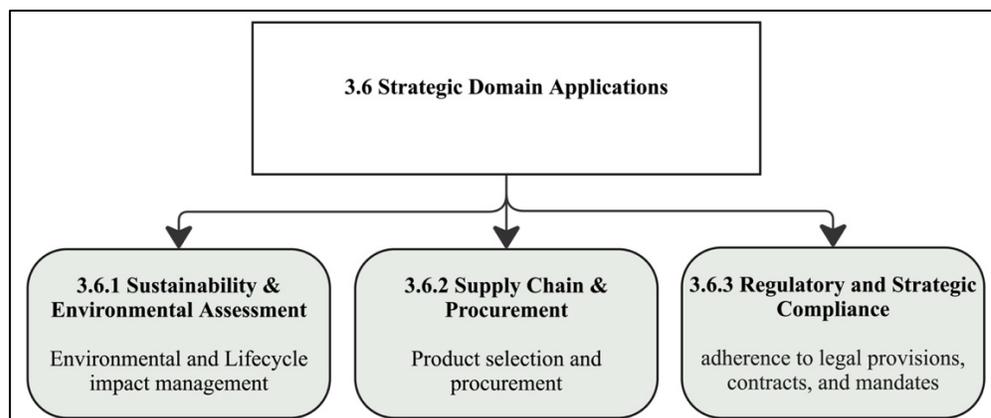


Figure 3.19 Strategic Domain Applications

Supply Chain & Procurement: This focuses on improving logistics and material acquisition. It involves linking BIM model components with manufacturer data, product data templates (PDTs) (Poirier et al., 2022), and external e-market services (Sattler et al., 2019). Geospatial data analysis using GIS is integrated to manage and optimize complex logistics tasks, such as tracking supplier locations and minimizing transport emissions (Karan et al., 2016). **Regulatory**

and Strategic Compliance: While technical compliance checking is handled in Analysis (3.4), this component covers the formal adherence to legal provisions, contracts, and strategic mandates, such as identifying necessary legal requirements and policies during the project lifecycle (Succar & Poirier, 2020).

3.4.18 Organizational Development & Intelligence

This cluster (Figure 3.20) focuses on generating overarching organizational benefits, enabling strategic steering, continual improvement, and human resource development, supported by the data generated throughout an Integrated Information Environment.

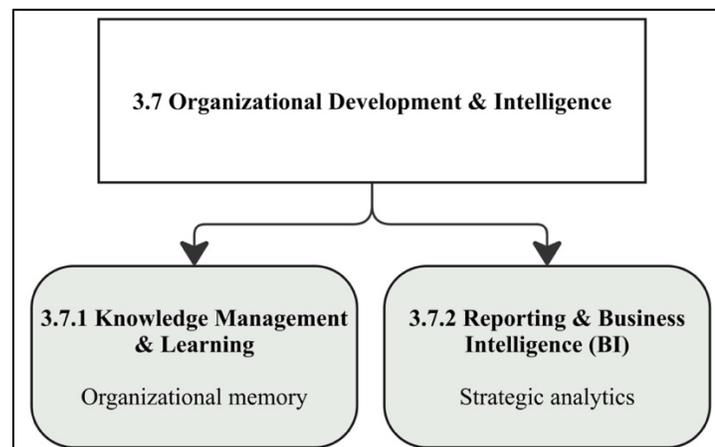


Figure 3.20 Organizational Development & Intelligence

Knowledge Management & Learning: This involves transforming project data into transferable organizational knowledge (the DIKW hierarchy). It includes capturing lessons learned after cyber incidents (Turk et al., 2022) and building employee proficiency through formalized structures such as the BIM Competency Hierarchy. This taxonomy organizes measurable abilities into tiers (e.g., Domain, Execution), sets, topics, and granular items, often requiring standardized BIM terminology (BIM Dictionary) for consistent definition and assessment (Succar et al., 2013). **Reporting & Business Intelligence (BI):** This function focuses on providing executive insights and metrics for performance monitoring (Albouq et al., 2022). It involves generating standardized reports to measure BIM performance, compare results against

benchmarks (Sanchez et al., 2017), and support strategic decision-making by tracking organizational goals and maturity levels. This enables feedback loops that promote continuous improvement across the enterprise.

3.5 IIE Framework Components Overview

Table 3.1 provides a comprehensive overview of all 18 framework components organized across the three tiers, presenting their primary purpose, and their key elements. This structured overview demonstrates how components work coordinately across tiers to address the complete spectrum of integration requirements, from establishing semantic foundations through operational infrastructure to stakeholder value delivery.

Table 3.1 Comprehensive Overview of IIE Framework Components

Tier & Component	Primary Purpose	Key Elements
TIER 1: DATA STRUCTURE & MEANING		
1.1 Semantic Resources	Establish shared conceptual understanding and eliminate semantic ambiguity across organizational boundaries	<ul style="list-style-type: none"> • Ontologies (formal domain knowledge) • Classifications & Taxonomies (hierarchical organization) • Terminologies & Dictionaries (precise definitions)
1.2 Conceptual Models & Data Schemas	Define abstract blueprints for information structures bridging semantics and implementation	<ul style="list-style-type: none"> • Data Models (IFC core structures) • Schema Definitions (formal specifications) • Representation Languages (UML, EXPRESS) • Model View Definitions (context-specific subsets)

Tier & Component	Primary Purpose	Key Elements
1.3 Syntactic Resources	Ensure technical consistency in data packaging and transmission	<ul style="list-style-type: none"> • Data Formats (physical representation) • Communication Protocols (transmission rules) • Query & Access Languages (data interrogation)
1.4 Information Requirements	Specify what information is needed, when, and at what detail level	<ul style="list-style-type: none"> • Information Delivery Specifications (machine-readable requirements) • Level of Information Need (granularity definitions) • Property Set Definitions (standardized metadata templates)
1.5 Metadata	Provide contextual information about data for discoverability and trust	<ul style="list-style-type: none"> • Descriptive Metadata (indexing, identification) • Provenance Metadata (origin, history, transformations) • Temporal Metadata (time-specific context, versioning)
1.6 Process & Workflow Models	Map information flows to execution mechanisms and governance constraints	<ul style="list-style-type: none"> • Process Models (activity mapping) • Information Uses (functional applications) • Validation Rules (quality criteria)
TIER 2: DATA EXCHANGE & MANAGEMENT		
2.1 Platform Architecture Patterns	Define high-level structural blueprints for connecting autonomous systems	<ul style="list-style-type: none"> • Service-Oriented Architecture (SOA) • Microservices Architecture • Event-Driven Architecture (EDA)
2.2 Data Acquisition	Capture information from diverse sources as IIE ingress points	<ul style="list-style-type: none"> • BIM Authoring & Model Integration • IoT & Building Systems Integration • Reality Capture • Mobile Field Capture • Legacy System Integration

Tier & Component	Primary Purpose	Key Elements
2.3 Integration Mechanisms & Middleware	Facilitate seamless connection and transformation between heterogeneous systems	<ul style="list-style-type: none"> • Synchronous Integration (real-time) • Asynchronous Integration (event-driven) • Batch Integration (periodic bulk) • Federation Patterns (distributed query) • API Gateways • Message Brokers • ETL/ELT Tools • iPaaS platforms
2.4 Information Governance & Assurance	Guarantee reliability, integrity, security, and performance	<ul style="list-style-type: none"> • Data Quality Management • Identity & Access Management • Monitoring & Observability
2.5 CDE & Data Persistence	Provide structured collaborative workspace and persistent storage	<ul style="list-style-type: none"> • Information Containers • Workflow Management • Access Control • OpenCDE Interoperability • Operational Databases • File Repositories • Data Lakes & Warehouses • Catching
TIER 3: DATA CONSUMPTION & USE		
3.1 Information Access & Retrieval	Enable users to locate and obtain relevant information efficiently	<ul style="list-style-type: none"> • Query Interfaces (visual, natural language, SPARQL) • Search Services (indexing, categorization) • Context-Aware Delivery • Notification Services
3.2 Visualization & Interface	Translate complex data into meaningful representations	<ul style="list-style-type: none"> • 2D Visualization (drawings, charts) • 3D Visualization (BIM models) • Geospatial Visualization (BIM-GIS integration)

Tier & Component	Primary Purpose	Key Elements
		<ul style="list-style-type: none"> • Graph Visualization (ontologies) • AR/VR Interfaces
3.3 Collaborative Management Tools	Enable coordinated decision-making across boundaries	<ul style="list-style-type: none"> • Document Collaboration platforms • Communication Tools • Issue Management (BCF) • Process Visualization (BPMN) • Decision Support Systems
3.4 Specialized Analytics & Value Assessment	Transform data into actionable intelligence	<ul style="list-style-type: none"> • Performance Analytics • Predictive Analytics (AI/ML) • Simulation & "What-If" Analysis • Compliance & Automated Checking (rule-based)
3.5 Holistic and Enterprise Information Use	Support comprehensive operational asset management	<ul style="list-style-type: none"> • Work Order Management • CAFM/CMMS Integration • Energy Management & Optimization • Spatial Management • Real-time Performance Monitoring
3.6 Strategic Domain Applications	Achieve strategic organizational goals beyond routine operations	<ul style="list-style-type: none"> • Sustainability & Environmental Assessment (LCA/LCC) • Supply Chain & Procurement • Regulatory & Strategic Compliance
3.7 Organizational Development & Intelligence	Generate enterprise-wide benefits and continuous improvement	<ul style="list-style-type: none"> • Knowledge Management & Learning (DIKW hierarchy) • BIM Competency Development Reporting & Business Intelligence

Cross-Tier Dependencies and Interactions: The framework's effectiveness emerges from systematic dependencies between tiers:

- **Tier 1 → Tier 2:** Semantic resources, data schemas, and information requirements (Tier 1) enable meaningful data exchange and quality validation (Tier 2). Without shared

ontologies and standardized formats, integration infrastructure exchanges data without understanding.

- **Tier 2 → Tier 3:** Integration infrastructure and governance mechanisms (Tier 2) provide the reliable data flows necessary for analytics, visualization, and strategic applications (Tier 3). Without robust exchange mechanisms, services cannot access required information.
- **Tier 3 → Tier 1 (Feedback):** Application experiences and user requirements (Tier 3) inform evolution of semantic resources and information requirements (Tier 1), creating continuous improvement loops.

This component overview demonstrates that the IIE framework addresses integration systematically across all necessary dimensions, from abstract semantics through operational infrastructure to tangible business value, with each component contributing specific capabilities within a coherent architectural vision.

3.6 IIE Framework Benefits: Stakeholder Value Proposition

Table 3.2 demonstrates how the IIE framework delivers measurable value across diverse stakeholder groups throughout the built asset lifecycle. The table systematically maps specific benefits to seven stakeholder categories, from information creators, exchangers, and consumers to asset owners, organizations, strategic decision-makers, and the industry ecosystem, with explicit traceability to framework enablers across the three tiers. This multi-perspective value proposition demonstrates that the framework addresses not merely technical integration but delivers tangible business outcomes serving all stakeholder categories, from operational efficiency improvements to strategic transformation and industry-wide coordination.

Table 3.2 Stakeholder Value Proposition

Stakeholder Group	Benefits	IIE Framework Enablers
Information Creators (Architects, Engineers, Modelers)	<ul style="list-style-type: none"> • Clear, machine-readable requirements (IDS, LOIN) eliminate ambiguity • Standardized semantic resources (ontologies, bSDD) reduce rework • Automated validation against contractual specifications before submission • Context-aware MVDs guide precise information production • Property set definitions (PSets) provide structured metadata templates 	Tier 1: IDS, LOIN, MVDs, PSets, Semantic Resources Tier 2: Validation services, CDE workflow management
Information Exchangers (Platform Providers, IT Integrators, BIM Managers)	<ul style="list-style-type: none"> • Multiple architecture patterns (SOA, Microservices, EDA) for diverse integration needs • Quality monitoring and conflict detection ensure reliability • Provenance metadata maintains accountability and traceability • API gateways and message brokers facilitate seamless connectivity 	Tier 2: Platform Architecture Patterns, Integration Mechanisms, Governance & Assurance, CDE Infrastructure
Information Consumers (Contractors, Facility Managers, Operators, Regulators)	<ul style="list-style-type: none"> • Intuitive query interfaces and search services across federated repositories • Multi-dimensional visualization (2D, 3D, geospatial, graph) aids comprehension • Specialized analytics (performance, predictive, compliance) provide actionable insights • Collaborative tools (BCF, issue management) facilitate coordination 	Tier 3: Information Access & Retrieval, Visualization, Analytics, Collaborative Tools

Stakeholder Group	Benefits	IIE Framework Enablers
	<ul style="list-style-type: none"> Context-aware delivery and notifications support proactive decision-making 	
Asset Owners & Operators	<ul style="list-style-type: none"> Digital Twins enable predictive "predict-and-prevent" maintenance strategies Real-time IoT integration with BIM supports data-driven operational decisions Comprehensive AIM support lifecycle value realization Work order management and CMMS integration streamline maintenance activities Energy management optimization reduces operational costs and carbon footprint 	Tier 3: Digital Twins, Operational Services, Energy Management, Work Order Management
Organizations (Enterprises, Project Teams)	<ul style="list-style-type: none"> Federated architecture preserves organizational autonomy and control Standards-based approach (ISO 19650, IFC, buildingSMART) avoids vendor lock-in Modular, incremental implementation (microservices) reduces adoption risk openCDE interoperability increases market options and flexibility Knowledge management transforms project data into organizational intelligence 	Tier 2: Federated Architecture, CDE Infrastructure, openCDE Tier 3: Knowledge Management, Business Intelligence
Strategic Decision-Makers (Executives, Portfolio Managers)	<ul style="list-style-type: none"> Business Intelligence and reporting provide executive insights and KPIs Performance benchmarking against industry standards supports strategic planning Sustainability analytics (LCA/LCC) enable evidence-based environmental decisions 	Tier 3: Reporting & BI, Sustainability Assessment, Supply Chain Integration, Organizational Development

Stakeholder Group	Benefits	IIE Framework Enablers
	<ul style="list-style-type: none"> • Supply chain optimization improves logistics and procurement efficiency • BIM maturity assessment enables continuous organizational improvement 	
The Built Asset Industry (Ecosystem-wide)	<ul style="list-style-type: none"> • Semantic interoperability (ontologies, terminologies) reduces fragmentation across domains • Standardized exchange scenarios (IDM/MVD) eliminate redundant data requests • Automated compliance checking reduces regulatory approval cycles • Lifecycle data continuity (design→construction→operations) enhances sustainability • SoIS architecture accommodates industry heterogeneity while enabling collaboration 	All Tiers: Semantic Resources, Process Models, Validation Rules, Integration Patterns, Digital Twin Lifecycle Support

3.7 Current State Assessment and Defining Requirements

IIE implementation begins with assessing the organization's existing information management landscape through comprehensive inventory of current systems and data sources, identification of information silos and fragmentation points, mapping of information flows and handover processes across lifecycle phases and disciplinary boundaries, evaluation of organizational autonomy requirements in federated environments, and documentation of technical and interoperability gaps. This assessment employs analytical tools including the BIM Maturity Matrix for capability benchmarking, interoperability assessment frameworks, and process mapping techniques (BPMN) to visualize workflows and inefficiencies. Outputs establish the business case by quantifying fragmentation costs and articulating integration value. Requirements definition translates organizational challenges into actionable objectives by: identifying concrete use cases requiring seamless information flow (design coordination,

compliance checking, handover, predictive maintenance) and prioritizing based on business value and feasibility; explicitly defining stakeholders and their information needs for each use case; specifying lifecycle phase coverage (design, construction, operations, maintenance, renewal); establishing non-functional requirements (performance, security, scalability); and defining success criteria and KPIs for objective evaluation. This process leverages Tier 1 components (Information Uses, IDM methodology, Exchange Scenario Views) to formalize requirements while ensuring Tier 3 capabilities align with strategic objectives, creating clear traceability from technical implementation to business outcomes.

3.8 Chapter Summary

This chapter presented the Integrated Information Environment framework as a systematic solution to information fragmentation in the built asset industry through a three-tier architecture that preserves organizational autonomy while enabling seamless information flows. Tier 1 (Data Structure & Meaning) establishes semantic, syntactic, and conceptual foundations through six components ensuring consistent interpretation across systems (Sections 3.4.1 - 3.4.6). Tier 2 (Data Exchange & Management) provides integration infrastructure through federated architecture patterns, data acquisition mechanisms, and governance frameworks enabling collaboration without sacrificing independence (Sections 3.4.7 - 3.4.11). Tier 3 (Data Consumption & Use) delivers stakeholder value through information access, visualization, analytics, and strategic applications (Sections 3.4.12 - 3.4.18). The framework's effectiveness depends on cross-tier interactions where value emerges from coordinated capabilities; automated compliance checking requires Tier 1 formalized rules, Tier 2 exchange infrastructure, and Tier 3 services functioning coherently. The stakeholder value proposition demonstrates that systematic treatment of different interoperability dimensions produces measurable benefits across all categories, from operational efficiency improvements to strategic transformation and ecosystem-wide coordination. The framework provides actionable guidance for digital transformation while maintaining flexibility for diverse organizational contexts across the built asset industry.

CHAPTER 4

RESEARCH RESULTS

This chapter validates the Integrated Information Environment framework (Chapter 3) through its systematic application to the National Research Council of Canada's Digital Construction Platform initiative. The validation demonstrates how the IIE's requirements and components guided development of solutions addressing information fragmentation across Canada's national construction codes, specifications, and product evaluations. Through systematic application of the three-tier framework structure, the research establishes empirical evidence for the framework's capacity to capture integration challenges, and prescribe actionable solutions that preserve organizational autonomy while enabling seamless information flows.

4.1 Case Study Methodology

4.1.1 Rationale for Case Selection

The NRC DCP initiative presents integration challenges that directly test the framework's core propositions across multiple dimensions:

Multi-Resource Fragmentation: The NRC manages three critical but fragmented resources—National Model Construction Codes (NMCC), National Master Specifications (NMS), and Canadian Construction Materials Centre (CCMC) product evaluations. These resources currently operate as independent silos with inconsistent terminology, heterogeneous data formats, distinct conceptual models, asynchronous development cycles, and independent departmental governance structures. This multi-dimensional fragmentation tests whether the framework's requirements comprehensively define integration objectives and whether the framework's components capture the technical and organizational capabilities necessary to address real-world challenges across semantic, syntactic, conceptual, procedural, and organizational dimensions.

Federated Organizational Structure: The three resource areas function as autonomous departments with independent governance, budgets, and decision-making processes. Any integration solution must preserve this autonomy rather than forcing centralization. This organizational reality directly tests whether the framework's Tier 2 requirements for preserving autonomy translate into actionable federated architecture components.

National-Scale Multi-Stakeholder Context: The NRC DCP affects diverse stakeholder groups across Canada's construction industry: federal/provincial/municipal government agencies, architects, engineers, contractors, manufacturers, and regulatory bodies. This diversity tests whether the framework's Tier 3 requirements for stakeholder value delivery can accommodate varying organizational contexts.

Strategic Sustainability Objectives: The DCP supports Canada's Platform to Decarbonize the Construction Sector at Scale (PDCSS), requiring integration to support lifecycle assessment, carbon accounting, and material passports. This strategic context tests whether the framework addresses both operational integration and strategic value delivery beyond technical interoperability.

4.1.2 Validation Approach

The validation employed the IIE framework as a conceptual lens guiding NRC DCP development from problem diagnosis through solution design to implementation planning. This Design Science Research ex-ante evaluation approach assesses framework utility by examining whether: (1) framework requirements comprehensively capture real integration objectives, (2) framework components provide actionable specifications for realizing these requirements, and (3) the hierarchical tier structure reflects genuine implementation dependencies.

The validation process consisted of systematic steps:

Problem Diagnosis Using Framework Requirements: Analysis of NRC's current state to identify fragmentation challenges, explicitly mapping each challenge to framework requirements and interoperability dimensions.

Solution Architecture Structured by Framework Tiers: Development of NRC DCP architecture using the framework's three-tier structure as organizing principle, with Tier 1 components guiding semantic/syntactic/conceptual standardization, Tier 2 components guiding integration infrastructure design, and Tier 3 components guiding service delivery specification.

Component Operationalization Analysis: Systematic mapping of framework components to concrete NRC implementations, validating that all components found instantiation and that specifications provided actionable guidance.

Iterative Stakeholder Validation: Nine-month engagement with NRC stakeholders through workshops, interviews, and review cycles to validate that framework-guided solutions address genuine organizational needs and constraints.

4.1.3 Data Collection and Analysis

The case study employed multiple data collection methods:

- **Documentary Analysis:** Review of existing NRC documentation including code development processes, specification management workflows, product evaluation procedures, and IT infrastructure specifications.
- **Stakeholder Interviews:** Semi-structured interviews with key personnel from NMCC, NMS, and CCMC departments, IT infrastructure teams, and strategic leadership.
- **Workshop Sessions:** Nine-month systematic engagement through facilitated workshops with stakeholders across NRC's three resource areas, comprising: (1) Contextual Analysis of existing infrastructure; (2) Development and Refinement of Digitalization Scenarios; (3) Stakeholder Engagement with key decision-makers; (4) Documentation and Reporting of requirements and system specifications.
- **Comparative Analysis:** Review of international initiatives (DigiPLACE (Mirarchi et al., 2021), ACCORD (Breitenfelder et al., 2023), CHEK (CHEK, 2022), and D-COM) to contextualize NRC requirements and validate framework components against global best practices.

Analysis proceeded through iterative cycles of framework application, stakeholder feedback incorporation, and solution refinement, enabling both validation of framework requirements and components and their continuous improvement based on empirical insights.

4.2 NRC Challenge Analysis and Framework Mapping

4.2.1 NRC Context: Three Fragmented Resources

The NRC manages three critical resources for Canada's built asset industry, each developed and maintained independently:

- **National Model Construction Codes (NMCC):** Five codes (Building, Fire, Plumbing, Energy, Farm) defining regulatory requirements for building performance and safety. Developed through 5-year revision cycles involving expert committees, public consultation, and provincial/territorial coordination. Content managed in XML but published primarily as static PDFs.
- **National Master Specifications (NMS):** Library of 780+ specification sections for construction products and systems, organized using MasterFormat™ and UniFormat™ classifications. Updated quarterly through industry expert committees. Content managed in multiple formats (XML, relational database, unstructured data) and distributed through third-party platforms.
- **Canadian Construction Materials Centre (CCMC):** Product evaluation service assessing construction products for code compliance. Publishes technical evaluations serving as trusted evidence for regulators. Assessment data managed in relational databases with limited structured data extraction capabilities.

These resources serve complementary functions. Codes define requirements, specifications detail compliant assemblies, evaluations verify product suitability; yet operate as isolated information silos, forcing stakeholders to manually establish connections between regulatory provisions, technical specifications, and compliant products. This fragmentation directly contradicts the framework's foundational requirements for eliminating ambiguity

(Requirement 1.1), enabling information entry from diverse sources (Requirement 2.2), and enabling efficient information access across resources (Requirement 3.1).

4.2.2 Systematic Challenge Mapping to Framework Components

Table 4.1 maps identified fragmentation challenges to specific IIE framework requirements and components, demonstrating that the framework's structure comprehensively captures real-world integration problems and prescribes appropriate solutions. The mapping reveals the logical pathway: challenges validate specific requirements (what must be achieved), which necessitate specific components (how to achieve it).

Table 4.1 NRC Challenges Mapped to IIE Framework Tiers & Components

Challenge Description	Problem Manifestation	IIE Requirements & Framework Tier(s)	Validation Implication
Semantic Fragmentation	Inconsistent terminology across resources (e.g., "fire resistance rating" vs. "fire protection performance"); building component classifications in codes don't align with specification naming or CCMC product categories	Req 1.1: Eliminate ambiguity by establishing common definitions and relationships between concepts - Tier 1	Captures semantic integration objectives; prescribes standardization mechanisms
Syntactic Fragmentation	Heterogeneous data formats (XML for codes, multiple formats for specifications, relational databases for CCMC) prevent automated exchange; require manual conversion	Req 1.3: Enable systems to parse and interpret data structure regardless of semantic meaning - Tier 1	Identifies parsing objectives; specifies technical exchange standards
Conceptual Fragmentation	Distinct underlying models: NMCC uses regulatory requirement structure, NMS	Req 1.2: Define entities, attributes, and relationships	Establishes need for common conceptual foundation;

Challenge Description	Problem Manifestation	IIE Requirements & Framework Tier(s)	Validation Implication
	uses product-execution model, CCMC uses assessment-compliance framework; no formal mappings enable integration	independent of implementation - Tier 1	provides schema specifications
Process Fragmentation	Asynchronous content development cycles (NMCC: 5-year, NMS: quarterly, CCMC: on-demand) operate independently without coordination mechanisms	Req 1.6: Formalize processes to enable coordination and automation - Tier 1	Identifies coordination needs; prescribes process formalization mechanisms
Information Requirements Ambiguity	Implicit requirements for what information is needed, when, and at what level of detail; no machine-readable requirement definitions	Req 1.4: Formalize information needs to ensure completeness and consistency - Tier 1	Defines specification objectives; provides formalization standards
Provenance & Quality Gaps	No tracking of information origin, transformations, or quality metrics across resources	Req 1.5: Track information origin, transformations, quality, and context throughout lifecycle - Tier 1	Establishes traceability objectives; specifies metadata standards
System Isolation	Each resource area operates separate IT systems with minimal integration points; no unified access mechanisms	Req 2.1: Define HOW systems will be organized to enable integration while preserving autonomy - Tier 2	Prescribes federated integration objective; provides architectural patterns
Manual Data Acquisition	Information transfer between systems requires manual	Req 2.2: Enable information entry into	Identifies automation needs;

Challenge Description	Problem Manifestation	IIE Requirements & Framework Tier(s)	Validation Implication
	extraction, transformation, and loading; no automated ingestion	the integrated environment from diverse creation points - Tier 2	specifies ingestion mechanisms
Limited Exchange Patterns	Single file-based exchange pattern; no support for incremental updates or real-time synchronization	Req 2.3.1: Provide multiple exchange patterns suitable for different information flow needs - Tiers 2	Defines flexibility objectives; prescribes synchronous, asynchronous, batch patterns
Absence of Quality Assurance	No automated validation of data quality, consistency, or completeness across resources	Req 2.4: Maintain confidence in information throughout exchange processes & ensure integration infrastructure is functioning properly - Tier 2	Establishes validation objectives; specifies quality monitoring mechanisms
Infrastructure Fragmentation	No common data environment: each resource uses different systems for storage and workflow	Req 2.5.1: Implement structured environments supporting controlled information sharing and workflow - Tier 2	Defines structured environment needs; prescribes CDE infrastructure
Limited Accessibility	No unified discovery or query mechanisms; users must know which resource to access and navigate separately	Req 3.1: Enable users to locate and obtain information relevant to their needs - Tier 3	Identifies access objectives; specifies search and query services
Interpretation Barriers	Complex technical content difficult for non-experts to	Req 3.2: Make complex information	Defines usability objectives;

Challenge Description	Problem Manifestation	IIE Requirements & Framework Tier(s)	Validation Implication
	understand; no visualization tools	understandable through visual presentation - Tier 3	prescribes visualization capabilities
Disconnected Workflows	Design, specification, procurement, and compliance workflows operate independently; no integrated tooling	Req 3.3: Enable stakeholders to coordinate and make decisions collectively - Tier 3	Establishes collaboration needs; specifies workflow coordination tools
Manual Compliance Checking	Code compliance verification requires human interpretation of provisions against design documents; no automated checking	Req 3.4: Transform raw information into actionable intelligence - Tier 3	Defines intelligence objectives; prescribes rule-based automation
Operational Disconnection	No connection between integrated data and ongoing building operations	Req 3.5: Apply integrated information to ongoing building operation - Tier 3	Identifies operational application needs; specifies operational management systems
No Lifecycle Assessment Support	Environmental performance data from CCMC evaluations cannot be systematically linked to code-compliant design alternatives in specifications	Req 3.6: Leverage the integrated environment to achieve strategic organizational goals beyond routine operations - Tier 3	Establishes strategic value objectives; enable LCA integration

This systematic challenge mapping validates that the framework's requirements comprehensively capture NRC's integration challenges across all three tiers and multiple interoperability dimensions (semantic, syntactic, conceptual, procedural, organizational, and

strategic). Each identified challenge maps to specific framework requirements that prescribe appropriate solutions, demonstrating the framework's capacity to guide problem diagnosis and solution specification.

4.3 Framework-Guided Solution Development

The systematic challenge mapping (Section 4.2, Table 4.1) established that the framework's requirements capture NRC's integration objectives. This section demonstrates how the framework's three-tier structure and component specifications guided the translation from requirements to concrete architectural decisions, validating the framework's capacity to provide actionable implementation guidance.

4.3.1 Three-Tier Architecture as Direct Framework Instantiation

The proposed NRC DCP architecture directly instantiates the framework's three-tier structure, with explicit correspondence between framework tiers and solution layers (Figure 4.1).

Tier 1 (Digital Resources) establishes foundational resources addressing semantic, syntactic, and conceptual fragmentation identified in challenge mapping. The NRC DCP's Tier 1 implementation operationalizes framework requirements 1.1-1.6 through specific component instantiations: A. Development of common terminology through bSDD integration, establishing shared definitions for building concepts across NMCC, NMS, and CCMC domains. B. Mapping between regulatory requirement structures (NMCC), product-execution models (NMS), and assessment frameworks (CCMC) using IFC as common schema foundation. C. Standardization on XML and JSON formats with defined communication protocols enabling automated parsing across resources. D. Development of IDS defining machine-readable requirements for code compliance checking and specification validation. E. Implementation of metadata standards capturing resource origin, version history, and quality metrics. F. Documentation of content development processes using BPMN notation, enabling coordination across asynchronous development cycles.

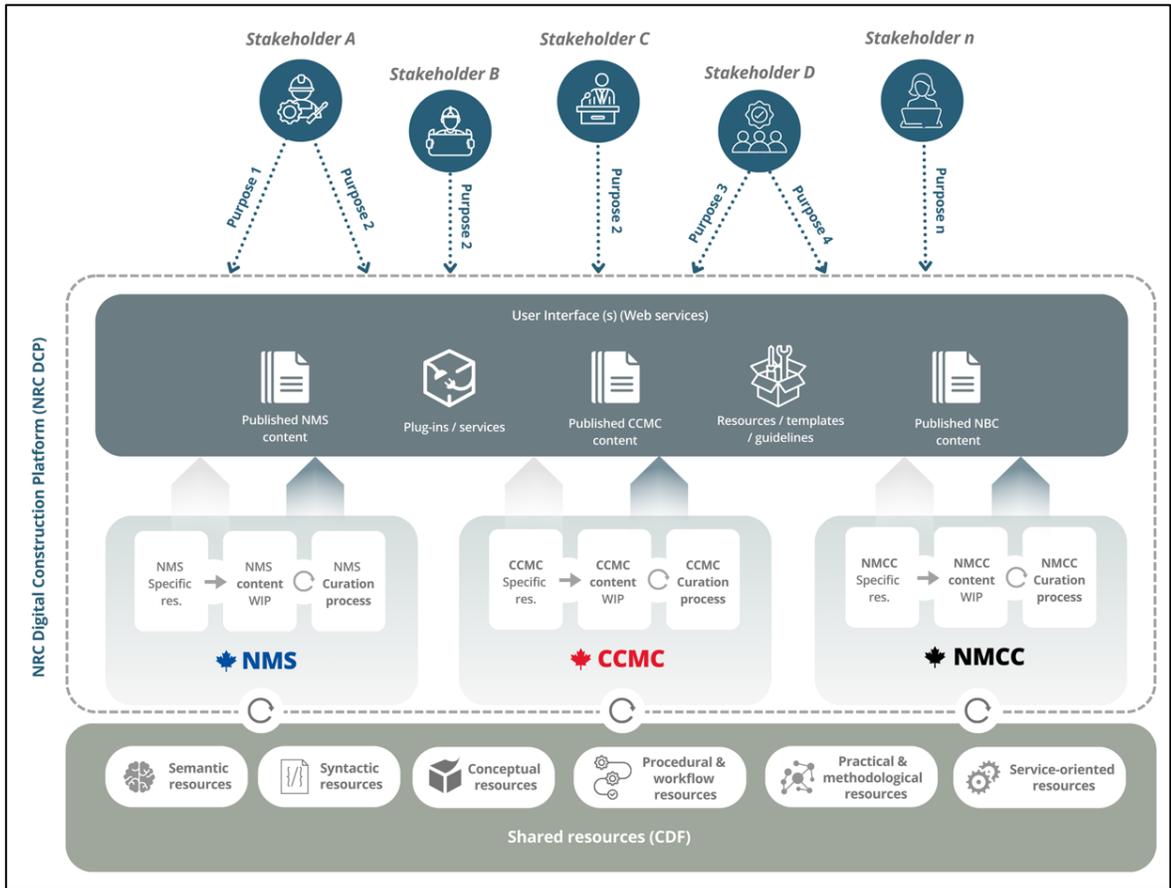


Figure 4.1 NRC's Digital Construction Platform layered framework

Taken from (Poirier et al. 2024)

Tier 2 (Integration Infrastructure) provides federated architecture addressing organizational silos and system isolation while preserving departmental autonomy. The NRC DCP's Tier 2 implementation operationalizes framework requirements 2.1-2.5.2 through architectural patterns and technical infrastructure: A. Implementation of SOA with microservices patterns, enabling each department (NMCC, NMS, CCMC) to maintain independent Common Data Environments while exposing standardized service interfaces for cross-resource integration. B. Development of API-based ingestion mechanisms extracting data from departmental CDEs without disrupting established workflows. C. Implementation of synchronous APIs for real-time queries, asynchronous message brokers for update notifications, batch ETL processes for bulk transfers, and federation patterns enabling cross-resource queries without data

duplication. D. Automated validation checking data completeness against IDS specifications, consistency verification across resources, and monitoring dashboards tracking integration health. E. Implementation of openCDE standards enabling interoperability between departmental CDEs while maintaining standardized workflow states (Work in Progress, Shared, Published, Archive).

Tier 3 (Services & Applications) delivers stakeholder value through applications addressing workflow fragmentation and enabling advanced capabilities. The NRC DCP's Tier 3 implementation operationalizes framework requirements 3.1-3.7: A. Cross-resource search enabling stakeholders to locate relevant codes, specifications, and product evaluations through single query interface rather than navigating separate systems. B. Web-based interfaces presenting integrated content with intuitive navigation, hyperlinks connecting related provisions across resources, and visual representations of code-specification-product relationships. C. BCF-based issue tracking coordinating feedback between regulatory bodies and industry professionals throughout development approval processes. D Rule-based checking services validating BIM models against machine-readable code requirements (IDS), generating compliance reports identifying non-conformances. E. Integration enabling facility managers to access specifications and product evaluations directly from asset models during maintenance planning. F. Lifecycle assessment services linking CCMC environmental performance data with code-compliant design alternatives in specifications, supporting PDCSS decarbonization objectives through material passport generation and carbon accounting.

This direct correspondence between framework requirements, components, and NRC DCP architectural decisions validates that the framework provides actionable guidance translating from conceptual objectives through technical specifications to concrete implementation choices. The framework identified what foundational resources are needed (Tier 1), how to integrate while preserving autonomy (Tier 2), and what services deliver stakeholder value (Tier 3), with each tier's requirements and components providing specific implementation direction.

4.3.2 Federated Integration Infrastructure

The framework's Tier 2 explicitly prescribes federated architecture as fundamentally suited for the System-of-Systems nature of the built asset industry (Section 3.4.7). Requirement 2.1 ("Define HOW systems will be organized to enable integration while preserving autonomy") and its realization through Platform Architecture Patterns component (specifying SOA, Microservices, and Event-Driven Architecture) provided concrete architectural guidance that directly shaped NRC DCP design decisions. Rather than adopting a centralized system consolidating NMCC, NMS, and CCMC into a single monolithic platform, which would have violated Requirement 2.1 and encountered organizational resistance, the NRC DCP employs federated patterns as prescribed by framework components. Figure 4.2 illustrates the resulting architecture and information flows.

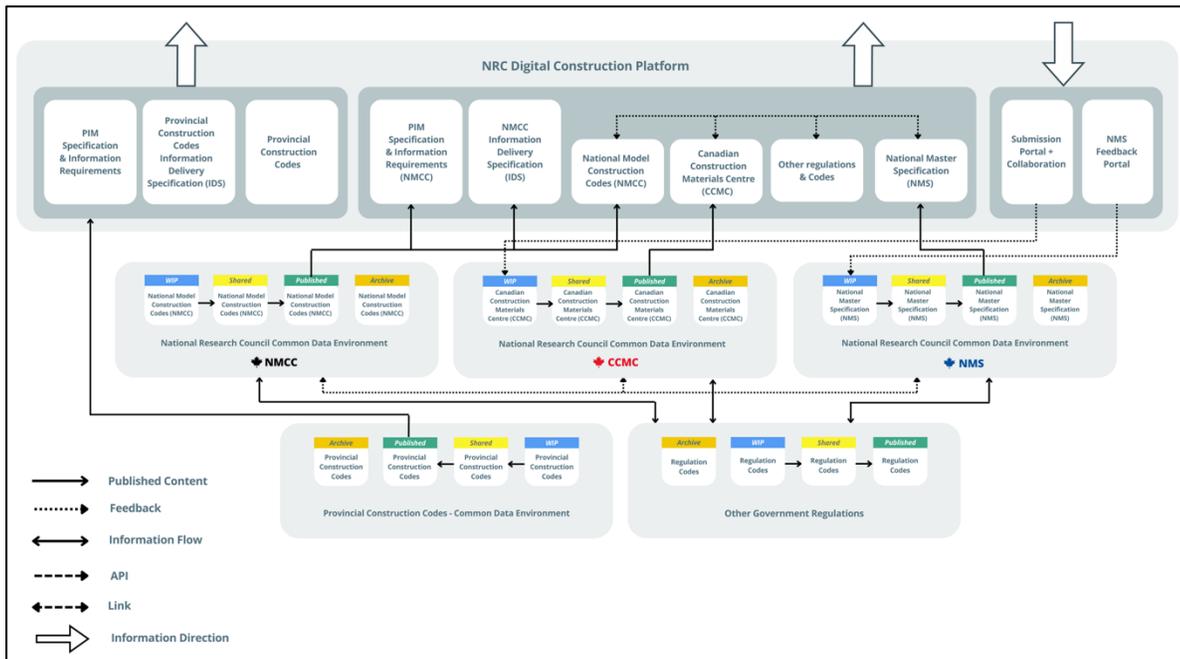


Figure 4.2 NRC DCP detailed architecture and information flow

Taken from (Poirier et al. 2024)

- Each department maintains independent governance and decision-making authority.
- Each resource area retains its own CDE with established workflows.
- Integration occurs through standardized service interfaces without disrupting departmental operations.

4.3.3 Service Delivery and Stakeholder Value

The framework's Tier 3 requirements (3.1-3.7) and components ensure that integration infrastructure translates into measurable stakeholder value rather than becoming a technical achievement without business benefits. This section demonstrates service delivery specifications for each NRC resource area, validating that the framework addresses diverse stakeholder needs while maintaining architectural coherence.

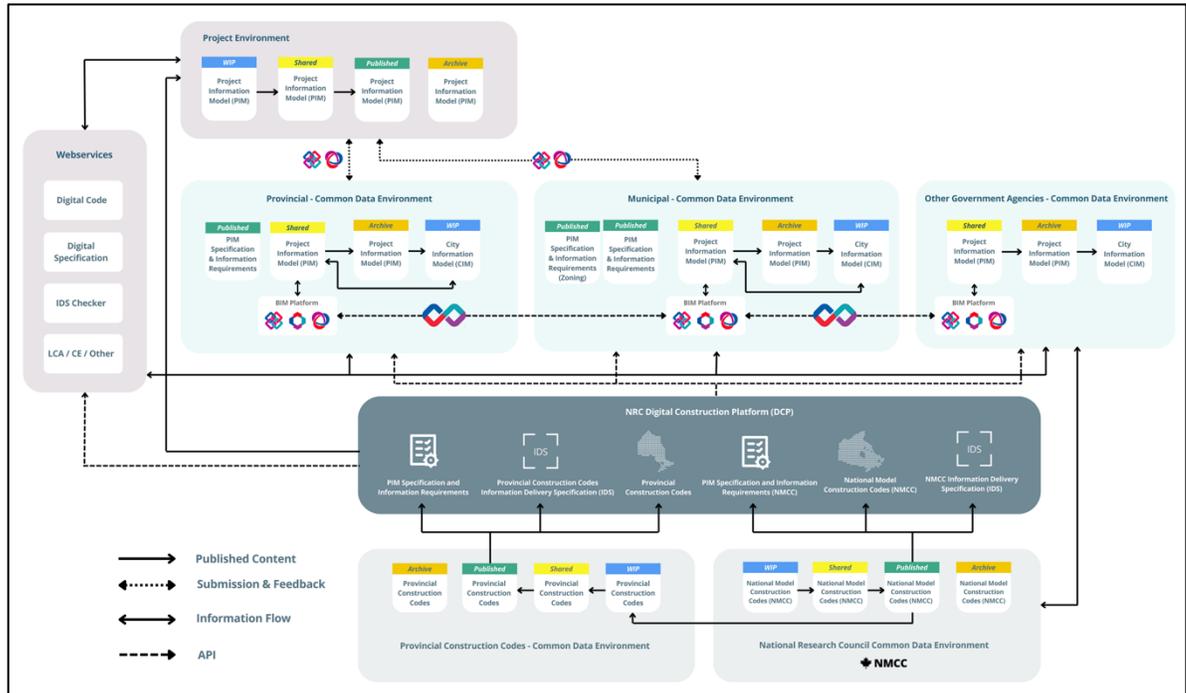


Figure 4.3 Overview of the NMCC connection to the NRC Digital Construction Platform
 Taken from (Poirier et al. 2024)

NMCC Service Ecosystem: The NMCC leverages the NRC Digital Construction Platform to publicly share building code content with industry professionals, government regulators, and third-party software providers through interconnected data environments (Figure 4.3). This service ecosystem directly implements framework Tier 3 requirements through specific service instantiations. Industry professionals can access NMCC content, including PIM Specifications, Information Requirements, and IDS files for automated code checks, directly from the NRC DCP, via web services, or through applicable regulatory bodies. Third-party vendors connect via APIs to provide services such as digital code management, rule configuration, compliance checking (land use, building permit, and urban regulations), and building permit application services. Provincial and municipal regulatory bodies operate separate CDEs that connect to the NRC DCP via openCDE API connections, enabling IFC format BIM file submissions and BCF feedback throughout the development approvals process. Regulatory environments follow a standardized CDE structure (Work in Progress, Shared, Published, Archive), with submitted PIMs populating city information models or digital twins for centralized reporting, management, and planning. Provincial and regional codes adapt NMCC content for local needs and publish back to the NRC DCP, creating an ecosystem for regulatory collaboration from pre-consultation through project completion.

NMS Service Ecosystem: The NMS utilizes the NRC Digital Construction Platform to publicly share standardized specification content with industry professionals and third-party software providers through integrated digital workflows (Figure 4.4). This service delivery model demonstrates how framework guidance accommodates different resource characteristics while maintaining architectural consistency. Industry professionals access the latest NMS content directly from the NRC DCP or through API-connected applications, with organizations able to customize 'tailored' NMS versions per project requirements while maintaining standardization. The NRC NMS CDE follows a structured approach (Work in Progress, Shared, Published, Archive), automatically pushing published content to the NRC DCP where it is linked via hyperlinks to referenced codes, regulations, and other NRC published content. Third-party vendors access NMS content through web services and Digital Specifications

Services that provide foundational data for compliance checking and rule application functions.

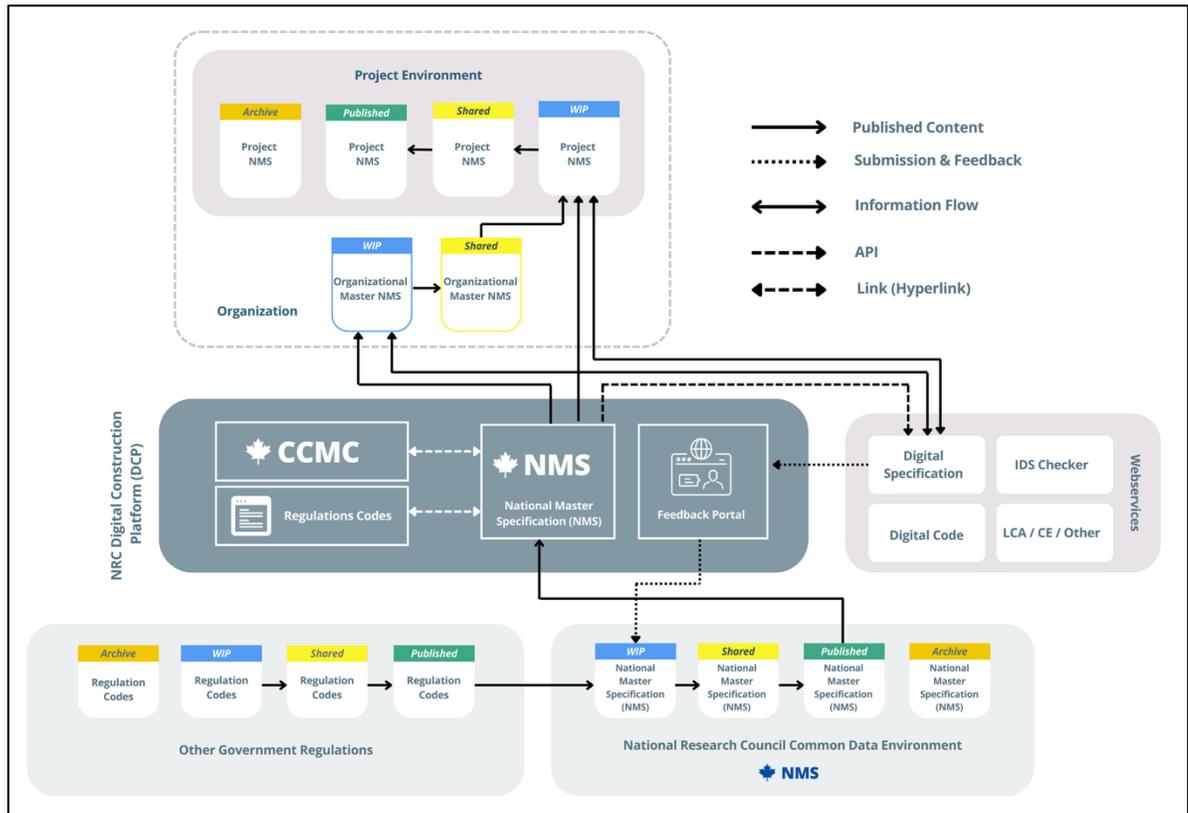


Figure 4.4 Overview of the NMS connection to the NRC Digital Construction Platform
Taken from (Poirier et al. 2024)

Other government agencies collaborate within their own CDEs and share regulatory publications with the NRC CDE for potential publication by mutual agreement. The platform provides specification writers, architects, and engineers with resources, templates, and feedback mechanisms to support effective content utilization and continuous improvement based on user input.

CCMC Service Ecosystem: The CCMC leverages the NRC Digital Construction Platform to publicly share construction product evaluation content with manufacturers, industry

professionals, and third-party software providers through coordinated submission and collaboration workflows (Figure 4.5).

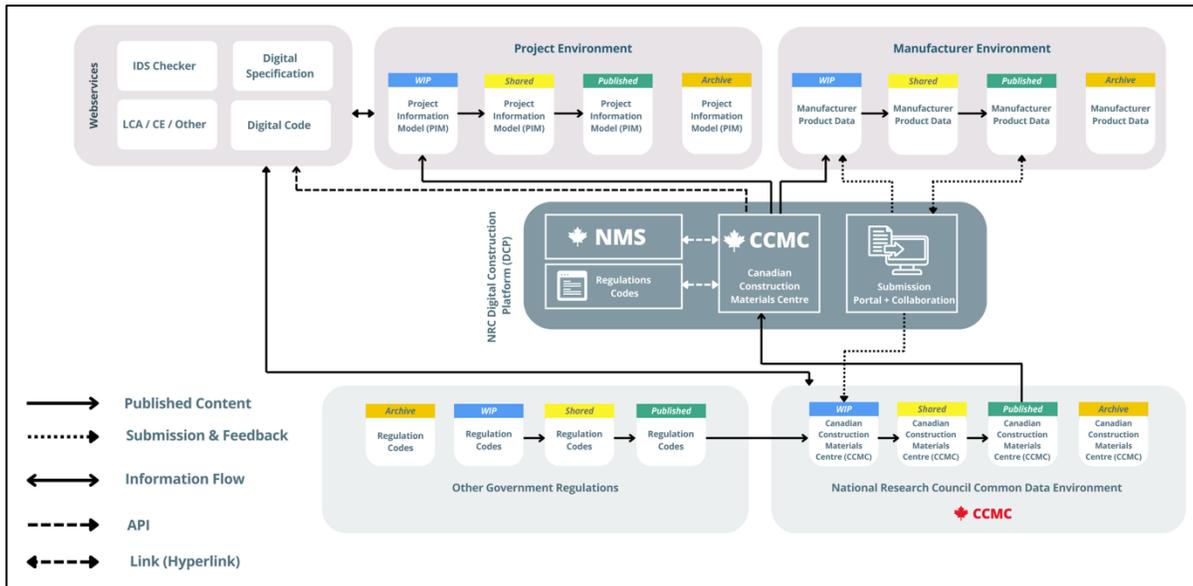


Figure 4.5 Overview of the CCMC connection to the NRC Digital Construction Platform
 Taken from (Poirier et al. 2024)

This ecosystem addresses unique stakeholder needs (manufacturer submissions, evaluation transparency) while maintaining architectural coherence with NMCC and NMS implementations. Manufacturers submit material applications through the NRC DCP Submission Portal, which are processed within the NRC CCMC CDE while utilizing the platform for collaboration and feedback throughout the evaluation process. Industry professionals access CCMC content, including material passports, product data templates, and services related to circular economy and LCA/LCCA, directly from the NRC DCP or through API-connected applications and web services. The NRC CCMC CDE follows a structured lifecycle (Work in Progress, Shared, Published, Archive), with published content pushed to the NRC DCP and linked via hyperlinks to referenced codes, regulations, and other NRC content sectors. CCMC's committees are integrated into the NRC DCP workflow for relevant assessments and decision-making. Other government agencies operate within their own CDEs and share regulatory publications with the NRC CDE for publication by mutual agreement,

creating an integrated ecosystem that supports low-carbon material validation and standardized environmental impact assessment aligned with LCBE program objectives.

4.4 Framework Components Operationalization in NRC DCP

Having presented the framework-guided solution architecture (Section 4.3), this section validates the framework's comprehensiveness and utility by demonstrating that all framework components found concrete instantiation and that the framework provides actionable guidance for real-world integration challenges.

4.4.1 Component Operationalization Evidence

Table 4.2 systematically maps each framework component to its concrete instantiation within the NRC DCP, demonstrating complete operationalization across all three tiers.

Table 4.2 Framework Components Operationalization in NRC DCP

Framework Component	NRC DCP Implementation Evidence
TIER 1: DATA STRUCTURE & MEANING	
1.1 Semantic Resources	<ul style="list-style-type: none"> - bSDD integration for standardized terminology across NMCC, NMS, and CCMC - Cross-resource terminology mapping bridging regulatory language (NMCC), product vocabulary (NMS), and assessment terms (CCMC) - Integration with MasterFormat™ and UniFormat™ - Multilingual support (English/French) meeting Canadian bilingual requirements
1.2 Conceptual Models & Data Schemas	<ul style="list-style-type: none"> - IFC adopted as foundational common schema for cross-resource integration - Mapping between NMCC regulatory requirement structures, NMS product-execution models, and CCMC assessment-compliance frameworks - IFC-SG considerations for Canadian-specific requirements (climate zones, seismic categories) - Bridging schemas enabling translation between NMCC article numbering, NMS section numbering, and CCMC evaluation structures

Framework Component	NRC DCP Implementation Evidence
	<ul style="list-style-type: none"> - Extension of IFC property sets for Canadian regulatory concepts
1.3 Syntactic Resources	<ul style="list-style-type: none"> - XML and JSON standardization with defined structural schemas - IFC STEP Physical File format for BIM model submissions - RESTful HTTP for synchronous requests, MQTT for asynchronous notifications - OpenCDE API standardized interfaces for platform interoperability - Query language support: SPARQL for semantic queries (future), SQL for relational access
1.4 Information Requirements	<ul style="list-style-type: none"> - IDS development for machine-readable NMCC code requirements enabling automated compliance checking - LOIN framework application specifying information granularity across project milestones - PIM Specifications detailing BIM submission requirements for building permits - Property Set Definitions standardizing CCMC product data attributes - Exchange Requirements defining information flows between NMCC-NMS-CCMC
1.5 Metadata	<ul style="list-style-type: none"> - Descriptive metadata: Dublin Core elements, file naming (ISO 19650), classification linking (bSDD), GUIDs - Provenance metadata: Complete tracking from committee proposal through approval for all three resources - Temporal metadata: Version control for 5-year NMCC cycles, quarterly NMS updates, on-demand CCMC evaluations
1.6 Process & Workflow Models	<ul style="list-style-type: none"> - BPMN documentation of NMCC code development, NMS specification development, CCMC evaluation processes - Coordination mechanisms across asynchronous cycles (5-year NMCC, quarterly NMS, on-demand CCMC) - ISO 19650 CDE workflow structure (WIP, Shared, Published, Archive) across all three CDEs - IDM methodology for formalizing NMCC-NMS, NMS-CCMC, CCMC-NMCC information exchanges - Approval gates and validation checkpoints ensuring quality before state transitions
TIER 2: DATA EXCHANGE & MANAGEMENT	

Framework Component	NRC DCP Implementation Evidence
2.1 Platform Architecture	<ul style="list-style-type: none"> - Service-Oriented Architecture enabling independent departmental CDEs with standardized interfaces - Microservices patterns for modular, independently deployable services (compliance checking, search, retrieval) - Event-Driven Architecture for asynchronous communication (code amendments trigger specification reviews)
2.2 Data Acquisition	<ul style="list-style-type: none"> - API-based ingestion from departmental CDEs without disrupting workflows - IFC file submission portal with automated validation - CCMC manufacturer submission portal with structured data entry - IoT integration provisions for future Digital Twin capabilities - Legacy system integration via custom adapters and ETL for NMCC XML, NMS databases
2.3 Integration Mechanisms	<ul style="list-style-type: none"> - Synchronous: Real-time RESTful APIs for cross-resource queries - Asynchronous: Message brokers for update notifications across CDEs - Batch: Scheduled ETL for bulk transfers during major updates - Federation: Cross-resource queries without data duplication using Linked Data principles - API Gateway managing cross-cutting concerns - Message Brokers (Kafka) for event distribution
2.4 Information Governance	<ul style="list-style-type: none"> - Data quality monitoring: Completeness (IDS), consistency (cross-resource), accuracy, timeliness - Identity & Access Management: RBAC, federation with external identity providers - Trust infrastructure: Digital signatures, blockchain considerations for audit trails - Monitoring & Observability: Metrics, logs, distributed tracing, alerting, dashboards - Security compliance: ISO 27001 principles
2.5 CDE & Data Persistence	<ul style="list-style-type: none"> - Three departmental CDEs (NMCC, NMS, CCMC) with ISO 19650 workflow structure - Information containers with metadata tracking status, ownership, review history - OpenCDE API enabling interoperability with municipal, provincial, manufacturer CDEs

Framework Component	NRC DCP Implementation Evidence
	<ul style="list-style-type: none"> - Cloud infrastructure: Hybrid architecture (private for sensitive, public for published content) supporting central DCP aggregation
TIER 3: DATA CONSUMPTION & USE	
3.1 Information Access	<ul style="list-style-type: none"> - Cross-resource search - Multiple query interfaces: natural language, SPARQL endpoint (future) - Context-aware delivery based on user role, location (municipal officials see jurisdictional adaptations) - Hyperlinking: Code articles → specifications → product evaluations (bidirectional navigation) - Notification services: Subscriptions, change alerts, saved search notifications
3.2 Visualization	<ul style="list-style-type: none"> - Responsive web applications with accessibility compliance, bilingual interface - Code-specification-product relationship visualization via interactive network graphs - BIM viewers integrated with BCF for issue tracking during regulatory review - Geospatial visualization showing jurisdiction, climate zones, seismic categories - AR/VR considerations for immersive code education (future)
3.3 Collaborative Tools	<ul style="list-style-type: none"> - BCF for model-based issue communication throughout development approvals - CCMC collaboration portals for manufacturer-evaluator interaction - Public review mechanisms for NMCC code change proposals with comment management - Committee collaboration tools: Discussion forums, document collaboration, meeting management
3.4 Specialized Analytics	<ul style="list-style-type: none"> - Rule-based BIM compliance checking against IDS-formalized NMCC requirements - Compliance report generation with BCF issue files for non-conformances - Rule configuration supporting jurisdictional variations (provincial/territorial/municipal) - Performance analytics: Common non-conformances, approval timelines, design quality trends

Framework Component	NRC DCP Implementation Evidence
	<ul style="list-style-type: none"> - Predictive analytics considerations using machine learning on historical compliance data (future)
<p>3.5 Enterprise Information Use</p>	<ul style="list-style-type: none"> - Digital building permit services: Electronic submission, automated pre-screening, BCF review, digital issuance - Product data management linking CCMC evaluations with NMS specifications for material selection - LCA integration connecting CCMC environmental data with code-compliant design alternatives - FM support: Asset Information Models linked to specifications and product evaluations - Digital Twin provisions for real-time performance monitoring (future)
<p>3.6 Strategic Applications</p>	<ul style="list-style-type: none"> - Material passports with product composition, performance, environmental attributes, end-of-life options - LCA and carbon accounting supporting PDCSS decarbonization objectives - Supply chain integration via PDTs and manufacturer API connections - Regulatory modernization: Evidence-based code development using compliance analytics
<p>3.7 Organizational Development</p>	<ul style="list-style-type: none"> - Training programs for industry professionals, building officials, manufacturers, NRC staff - Standards development: BIM execution plans, IDS, LOIN definitions, naming conventions - Business Intelligence dashboards: Platform adoption, content utilization, service performance - Knowledge management: Technical documentation, lessons learned, best practices, communities of practice - BIM competency framework with skills assessment and certification

This systematic mapping demonstrates complete component coverage across all three tiers, validating the framework's comprehensiveness in providing technical and organizational specifications for integration.

4.4.2 Validation Evidence: Framework Comprehensiveness

The systematic mapping exercises in Sections 4.2.2 and 4.4.1 provide convergent evidence validating the IIE framework across multiple dimensions.

Complete Requirements and Component Coverage Table 4.1 demonstrates that all framework requirements (1.1-3.7) address genuine NRC challenges spanning semantic fragmentation, syntactic incompatibility, conceptual misalignment, process coordination, infrastructure isolation, and stakeholder value delivery across three tiers. Table 4.2 demonstrates that all 18 framework components found concrete instantiation in the NRC DCP. This complete coverage validates that the framework captures the full spectrum of integration needs rather than focusing narrowly on specific technical or organizational aspects.

Requirements-to-Components Traceability The convergent evidence reveals clear pathways from challenges through requirements to components. Semantic fragmentation validates Requirement 1.1 ("eliminate ambiguity"), realized through Semantic Resources component (1.1) via bSDD integration. Organizational silos validate Requirement 2.1 ("preserve autonomy"), realized through Platform Architecture component (2.1) via federated SOA. Manual compliance checking validates Requirement 3.4 ("transform to intelligence"), realized through Specialized Analytics component (3.4) via IDS-based automation. This traceability validates that requirements define "what to achieve" while components specify "how to achieve it," with implementations demonstrating "what was achieved."

Hierarchical Dependency Validation Cross-tier dependencies validate the framework's hierarchical structure. Automated compliance checking (Tier 3) requires machine-readable requirements (Tier 1: Information Requirements), integration infrastructure (Tier 2: Data Acquisition and Integration Mechanisms), and visualization tools (Tier 3: Visualization and Collaborative Tools). Lifecycle assessment (Tier 3) requires semantic standardization (Tier 1: Semantic Resources), integration mechanisms (Tier 2: Integration Mechanisms), and analytics

services (Tier 3: Specialized Analytics and Strategic Applications). These dependencies confirm that higher-tier capabilities fundamentally depend upon lower-tier foundations.

Autonomy Preservation Through Federated Architecture The organizational silos challenge maps to Requirement 2.1 and Platform Architecture component (2.1) prescribing federated SOA. The NRC DCP operationalization, three departmental CDEs maintaining independent governance while achieving technical integration through standardized interfaces, validates that the framework treats autonomy preservation as design principle. Stakeholder feedback confirmed that centralized consolidation would encounter insurmountable organizational resistance; the framework's federated prescription enabled the solution to proceed.

Multi-Dimensional Interoperability Coverage NRC's integration problems span all interoperability dimensions: semantic (inconsistent terminology), syntactic (heterogeneous formats), conceptual (distinct models), procedural (asynchronous workflows), organizational (departmental silos), legal/governance (regulatory requirements), and contextual (diverse stakeholder needs). The framework addresses these through coordinated components: semantic via Tier 1 Semantic Resources and Conceptual Models; syntactic via Tier 1 Syntactic Resources and Tier 2 Integration Mechanisms; organizational via Tier 2 Platform Architecture and Tier 3 Collaborative Tools; procedural via Tier 1 Process Models and Tier 2 CDE Infrastructure; legal/governance via Tier 2 Information Governance and Tier 3 Strategic Applications; contextual via Tier 3 Information Access and Organizational Development.

Standards-Based Implementation Table 4.2's technology mapping demonstrates framework guidance translates into standards-grounded implementations: buildingSMART standards (IFC, IDS, bSDD, openCDE), ISO standards (19650, 7817), semantic web technologies (RDF, SPARQL), enterprise integration patterns (SOA, microservices, EDA), and open-source infrastructure (PostgreSQL, MongoDB, Neo4j, Elasticsearch, Kafka). This standards alignment increases adoption feasibility, reduces implementation risk, avoids vendor lock-in, and ensures long-term viability.

Convergent International Validation Comparative analysis with international initiatives, DigiPLACE (Finland), ACCORD (UK), CHEK (Netherlands), D-COM (Australia), reveals convergent evolution toward similar principles: federated architecture, semantic standardization (bSDD, IFC), machine-readable requirements, lifecycle continuity, openCDE interoperability, and API-driven integration. This convergence validates that the framework captures fundamental requirements rather than context-specific solutions.

Framework Validation Achievement The convergent evidence provides substantial empirical support for the framework's validity and utility. The framework successfully captures real-world integration challenges across all interoperability dimensions, prescribes actionable solutions, maintains logical coherence from objectives through solutions to outcomes, reflects genuine implementation dependencies, addresses organizational realities through autonomy preservation, builds upon established international standards, and aligns with independent initiatives demonstrating generalizability. While comprehensive validation requires longitudinal studies tracking operational maturity, the systematic ex-ante evaluation through the NRC case study provides sufficient evidence for establishing the framework's theoretical contribution and practical utility, demonstrating that it addresses the research question by systematically identifying requirements (19 across three tiers), specifying realization components (18 providing technical and organizational capabilities), and demonstrating applicability through real-world case study.

4.5 Research Objectives Achievement

The NRC case study validation provides empirical evidence addressing the research objectives:

- **RO 01:** Identified and systematized the essential requirements and components for Integrated Information Environments that address multi-dimensional interoperability challenges while preserving system autonomy. Section 4.2.2 demonstrated systematic identification of challenges across all interoperability dimensions, mapping to 19 framework requirements organized across three tiers. Section 4.4.1 demonstrated that all

- 18 framework components provide the technical and organizational specifications necessary for addressing these challenges.
- **RO 02:** Developed a multi-tier framework that provides systematic guidance for transforming fragmented information systems toward integrated environments capable of supporting advanced digital capabilities. Section 4.3 demonstrated how the framework's three-tier structure guided NRC DCP architecture development from foundational semantic resources through integration infrastructure to stakeholder-facing services, with each tier providing specific implementation direction for semantic standardization (Tier 1), federated integration (Tier 2), and value delivery (Tier 3).
 - **RO 03:** Validated the framework's applicability and utility through real-world evaluation, demonstrating its capacity to guide practical implementation while addressing organizational constraints. The NRC case study demonstrated that framework requirements comprehensively capture integration challenges (4.2.2), framework components prescribe actionable solutions (4.4.1), the three-tier structure reflects genuine implementation dependencies (4.3), and federated architecture principles address organizational realities where departmental autonomy is non-negotiable (4.3.2). Nine-month stakeholder engagement validated that framework-guided solutions address genuine organizational needs.

4.6 Chapter Summary

This chapter validated the Integrated Information Environment framework through systematic application to the National Research Council of Canada's Digital Construction Platform initiative, demonstrating the framework's capacity to guide transformation from fragmented systems toward integrated environments while preserving organizational autonomy. The NRC DCP case presented integration challenges across three fragmented resources, NMCC, NMS, and CCMC product evaluations, operating independently with inconsistent terminology, heterogeneous data formats, distinct conceptual models, asynchronous development cycles, and separate departmental governance. These challenges directly tested the framework's comprehensiveness across semantic, syntactic, conceptual, procedural, organizational, and

strategic dimensions. Systematic challenge mapping revealed complete problem coverage. This validation demonstrated that the framework's multi-dimensional structure captures real-world integration problems rather than focusing narrowly on specific technical aspects. The mapping further revealed the logical pathway from challenges through requirements to components, validating the framework's coherent structure where requirements define integration objectives and components specify realization mechanisms.

The NRC DCP architecture directly instantiated the framework's three-tier structure: The framework's explicit prescription of federated architecture patterns addressed NRC's organizational reality where departmental independence is non-negotiable, validating that the framework treats autonomy preservation as design principle rather than constraint. The validation provides strong empirical evidence that the IIE framework captures integration challenges and prescribes actionable architectural guidance addressing real-world organizational needs and constraints. The framework successfully addresses all three research objectives: identifying essential requirements and components for IIEs while preserving autonomy, providing systematic guidance for transformation from fragmented to integrated systems, and demonstrating applicability through real-world evaluation accommodating organizational realities.

CHAPTER 5

DISCUSSION

This chapter synthesizes the research findings, examining their theoretical and practical implications for Integrated Information Environments in the built asset industry. The discussion addresses the research question and objectives, evaluates the framework's contributions and limitations, and positions findings within the broader digital transformation context.

5.1 Addressing the Research Question and Objectives

The central research question asked: *"What are the requirements for an Integrated Information Environment that enables seamless information flows across asset lifecycle stages and value chains while maintaining system autonomy?"*

The research provides an answer through a multi-tiered framework addressing information integration while preserving organizational independence. The IIE framework demonstrates that seamless information flows require coordinated development across three fundamental layers: Tier 1 (Data Structure & Meaning) establishes semantic, syntactic, and conceptual foundations for consistent interpretation; Tier 2 (Data Exchange & Management) provides integration infrastructure through federated architecture patterns; and Tier 3 (Data Consumption & Use) delivers stakeholder value through applications and services. The NRC case study revealed that these tiers function through dynamic interactions and feedback loops. Cross-tier integration patterns demonstrate that higher-tier functionality depends upon lower-tier capabilities, while implementation experiences inform evolution of foundational resources. This bidirectional relationship represents a key strength of the framework, enabling holistic information integration through continuous refinement and adaptation across all tiers.

Research Objective 01 sought to develop understanding of essential IIE dimensions, and components that address data environments and continues information exchange limitations while preserving system autonomy. The framework achieved this through systematic identification of 18 components considering different interoperability dimensions (semantic, syntactic, conceptual, procedural, organizational, legal/governance, contextual) and lifecycle stages, synthesized into an architectural approach transcending project-centric CDE paradigms. The framework's federated architecture specifically preserves autonomy, enabling systems to maintain independence while collaborating through standardized interfaces.

Research Objective 02 aimed to design a multi-perspective framework introducing IIE requirements explicitly considering all interoperability dimensions. The three-tier structure provides structured treatment across dimensions and lifecycle stages. Table 4.1's mapping of NRC challenges to framework dimensions demonstrates capacity for systematic problem identification across all dimensions simultaneously, avoiding technology-first approaches that neglect semantic, organizational, or procedural barriers.

Research Objective 03 required demonstrating framework applicability through real-world implementation. The NRC DCP case study provided compelling evidence through systematic translation of framework dimensions into operational architecture, and the comprehensive requirements specification. International comparison revealed convergent evolution - independent initiatives arrived at similar principles - suggesting the framework captures fundamental requirements rather than context-specific solutions.

5.2 Theoretical Contributions

5.2.1 Advancing Systems-of-Information Systems Theory

This research extends SoIS theory into built asset contexts, contributing empirical evidence for an under-explored domain. While SoIS concepts exist in aerospace and manufacturing, their application to temporary project coalitions such as those found in construction remains limited.

The research validates Fernandes et al.'s (2022) distinction between integration, interoperability, and compatibility, demonstrating that integration approaches requiring common templates fail when systems serve distinct organizational purposes with different governance structures. The framework extends SoIS theory by incorporating lifecycle continuity dimensions critical for managing information across decades-long asset lifecycles, distinguishing built assets from manufacturing contexts with shorter, more homogeneous lifecycles. The inclusion of interoperability dimensions specifically adapted to the built asset characteristics represents a theoretical contribution extending existing frameworks such as TSLO.

5.2.2 Bridging BIM Capability and Implementation Infrastructure

The research contributes to BIM knowledge by demonstrating how advanced BIM capabilities depend upon systematic development of integration infrastructure. Existing BIM maturity frameworks—such as Succar's BIM Capability Stages describing progression toward "network-based integration" (Stage 3) and ISO 19650's information management maturity progression, articulate desired end-states without providing systematic guidance about the technical and organizational infrastructure required to achieve them. These frameworks describe *what* advanced capabilities look such as but offer limited insight into *how* organizations develop the foundations necessary for progression.

The IIE framework addresses this gap by making explicit what existing capability models assume: that semantic standardization (Tier 1), federated architecture (Tier 2), and advanced services (Tier 3) must develop in coordinated fashion to achieve true interoperability. Where capability models describe network-based integration as a goal, the IIE framework specifies the precise components enabling it; shared ontologies and terminologies for semantic consistency, SOA and microservices patterns for federated connectivity, API gateways and message brokers for information exchange, and analytics and visualization services for value realization. This operationalization provides actionable guidance missing from conceptual frameworks, enabling organizations to translate abstract objectives into concrete

developments. The framework extends BIM thinking beyond project-centric perspectives to encompass enterprise and ecosystem scales, aligning with Enterprise BIM concepts while providing more concrete architectural guidance. The NRC case study demonstrates how BIM principles extend to national-scale information infrastructure supporting regulatory, specification, and product evaluation functions, illustrating that the integration challenges addressed by the framework exist across all organizational scales.

5.2.3 Digital Twin Foundations

The research clarifies foundational requirements for Digital Twin implementations in built assets. While substantial work on Digital Twin architectures exists both within the built asset domain and other industries, these architectures tend to be generic and ill-suited for the evolutionary nature of the built asset industry, where temporary project coalitions, fragmented organizational structures, and decades-long asset lifecycles create distinct challenges. The framework clarifies that Digital Twins represent advanced applications (Tier 3) depending critically upon semantic resources (Tier 1) and integration infrastructure (Tier 2). The framework's identification of specific prerequisites; semantic integration between static BIM and dynamic IoT data, real-time integration mechanisms, provenance tracking, federated data management provides theoretical clarity about Digital Twin architecture adapted to the built asset industry's unique characteristics, including the need to preserve organizational autonomy and accommodate heterogeneous systems across extended lifecycles.

5.2.4 Positioning the IIE Framework Within Existing Research

To contextualize this research's contribution, this section compares and contrasts the IIE framework with some key existing frameworks that have addressed information integration in the built asset industry: the Multi-Layered CDE framework (Bucher & Hall, 2020), and ISO 19650-based information management approaches.

Bucher & Hall (2020)'s framework conceptualizes CDEs across three dimensions: Tool-level (seamless interaction within platforms), Platform-level (exchange between different CDEs), and Enterprise-level (connections between CDEs and enterprise systems such as Digital Twins). Both frameworks recognize that integration operates across multiple abstraction levels and that single-platform solutions prove inadequate for industry complexity. Both acknowledge the need for connections between project-centric CDEs and enterprise systems supporting Digital Twins and Asset Information Management. The multi-layered CDE framework remains predominantly conceptual regarding implementation mechanisms. It insufficiently addresses foundational challenges including persistent semantic gaps, inadequate lifecycle information management (remaining file-based rather than data-driven), and socio-technical barriers. The IIE framework advances beyond this conceptual approach by providing concrete component specifications for each tier. Where Bucher & Hall identify *what* needs connection (tools, platforms, enterprises), the IIE framework specifies *how* through Tier 2 components (Platform Architecture Patterns, Integration Mechanisms & Middleware, Information Governance). Critically, the IIE framework begins with Tier 1 foundations (semantic resources, conceptual models, syntactic resources); elements absent in the multi-layered CDE framework yet essential for meaningful interoperability. The IIE framework's explicit treatment of federated architecture as design principle (rather than assuming centralized integration) represents a fundamental architectural departure addressing industry reality of organizational autonomy.

From the other hand, ISO 19650 standards series provides international frameworks for information management using BIM, covering concepts and principles (Part 1), asset delivery phase (Part 2), asset operational phase (Part 3), information exchange (Part 4), and security management (Part 5). Both ISO 19650 and the IIE framework emphasize structured information requirements (OIR, AIR, PIR, EIR in ISO 19650; formalized Information Requirements in IIE Tier 1), workflow management through defined stages, and lifecycle perspective extending beyond project delivery. Both recognize the importance of information governance and security. ISO 19650 primarily provides process guidance, defining roles, responsibilities, workflows, and documentation requirements, but offers limited technical

specifications for how to achieve interoperability. The standard assumes CDE infrastructure exists without prescribing architecture. The IIE framework complements ISO 19650 by providing the technical and architectural specifications ISO 19650 assumes. Tier 1 operationalizes ISO 19650's information requirements through concrete components (IDS, LOIN, PSets, semantic resources). Tier 2 specifies the integration infrastructure ISO 19650 workflows depend upon (SOA patterns, API gateways, message brokers, ETL tools). Tier 3 demonstrates how ISO 19650-compliant processes deliver tangible value through applications. The IIE framework explicitly addresses System-of-Systems theory and federated architecture, recognizing that organizations will maintain multiple CDEs requiring interoperability, whereas ISO 19650 implicitly assumes single-CDE project contexts. The IIE framework's treatment of semantic and syntactic interoperability dimensions through dedicated Tier 1 components represents capabilities essential for ISO 19650 implementation success yet not specified within the standard itself. This comparison reveals the IIE framework's unique positioning: it provides the technical and organizational specificity that the multi-layered CDE framework lack, while offering the implementation architecture that ISO 19650 assumes but does not prescribe. The IIE framework thus represents not a replacement for but a synthesis and extension of existing research, the multi-layered CDE's recognition of abstraction levels, and ISO 19650's process rigor, while adding the technical architectural specifications, federated patterns, and interoperability treatment these frameworks individually lack.

5.3 Practical Contributions

The primary practical contribution is a structured framework translating abstract interoperability concepts into actionable guidance. The framework provides: problem diagnosis structure enabling systematic fragmentation identification; solution architecture templates offering clear organizational logic; and stakeholder value articulation connecting capabilities to business benefits. Moreover, the framework addresses critical barriers impeding industry transformation including fragmentation challenges through different interoperability approaches; vendor lock-in through open standards and federated architecture; lifecycle discontinuity through explicit lifecycle stage treatment; and skills gaps through component-

based capability development scaffolding. The NRC case study demonstrates framework application for national-scale digital infrastructure development. The framework's principles - federated architecture, standards-based integration, lifecycle continuity - provide sound foundations for public sector investments. The framework reveals interdependencies between different standards families, suggesting opportunities for more coordinated standards development. Treatment of automated compliance checking and digital permitting provides pathways for regulatory modernization.

5.4 Critical Limitations

The framework creates implementation complexity. It requires organizations to consider numerous interdependent components across three tiers, potentially exceeding capacity of smaller organizations with limited digital maturity. While modular structures enables staged implementation, the research does not fully develop prioritization strategies for organizations with different maturity levels and resources. The research relies on a single case study within a government agency context. While NRC provides significant complexity, it differs from private sector construction in several ways: government standardization mandates may not apply to private firms; national scale differs from typical project or regional scales; regulatory functions create different stakeholder relationships. These contextual differences limit generalizability. The framework may require adaptations for private firms with competitive sensitivities, SMEs with limited resources, international projects, and specific project types.

Several framework components depend on emerging technologies: ontology-based semantic integration requires scarce specialized expertise; automated compliance checking faces challenges in formalizing provisions requiring professional judgment; Digital Twins encounter substantial technical challenges around real-time integration and infrastructure requirements; blockchain for provenance faces performance, privacy, and governance challenges. The framework's forward-looking orientation toward emerging technologies creates risk that implementations may encounter technological barriers not fully addressed. While addressing organizational interoperability dimensions, the framework provides limited guidance on

change management processes necessary for adoption. Implementation requires substantial organizational changes - new roles and responsibilities, modified workflows, different skill sets, cultural shifts toward information sharing - that the framework does not adequately address. Future research should incorporate change management frameworks addressing stakeholder engagement, capability development, pilot project design, and incentive structures.

5.5 Future Research Directions

Future research should address: domain-specific adaptations for infrastructure, residential, and industrial contexts; international context variations exploring different regulatory approaches and industry structures; SME simplification developing minimum viable implementations; AI integration for automated ontology development and semantic mapping; effectiveness metrics development creating standardized assessment tools; longitudinal impact studies tracking multi-year implementations; organizational change research investigating adoption processes and change management; governance frameworks for federated environments; and regulatory modernization enabling digital compliance checking and permitting.

5.6 Chapter Summary

This chapter critically examined the IIE framework, demonstrating successful achievement of research objectives through a multi-tiered approach to information integration. Theoretical contributions include advancing SoIS theory in built asset contexts, bridging BIM capabilities with implementation architecture, and clarifying Digital Twin foundations. Practical contributions provide actionable industry guidance, address transformation barriers, and inform policy development. Critical evaluation revealed important limitations: framework creates complexity; single case study limits generalizability; substantial resource requirements challenge adoption; technology maturity dependencies create risks; organizational change receives insufficient treatment; and measurement challenges limit rigorous evaluation. These limitations indicate important future research directions for framework refinement and validation.

CONCLUSION

This research addressed a critical gap in the built asset industry: the lack of comprehensive frameworks for creating Integrated Information Environments that enable seamless information flows while preserving organizational autonomy. Through Design Science Research methodology (Chapter 2), the investigation produced a three-tier framework with 19 requirements and 18 components (Chapter 3), validated through the National Research Council of Canada Digital Construction Platform case study (Chapter 4).

Research Contributions

This research makes three primary contributions:

- **Theoretical Contribution:** A comprehensive three-tier framework characterizing Integrated Information Environments through 19 requirements and 18 components addressing semantic, syntactic, conceptual, procedural, organizational, legal/governance, and contextual interoperability dimensions. The framework bridges the gap between abstract BIM maturity models and actionable implementation guidance by explicitly integrating federated architecture principles with lifecycle information management.
- **Methodological Contribution:** A systematic approach for translating interoperability requirements into architectural components organized hierarchically across Data Structure & Meaning (Tier 1), Data Exchange & Management (Tier 2), and Data Consumption & Use (Tier 3). This hierarchical organization reveals critical dependencies; higher-tier capabilities like Digital Twins fundamentally depend on lower-tier semantic foundations.
- **Practical Contribution:** Validated implementation guidance through the NRC case study, where the framework successfully guided integration of three fragmented national resources (Construction Codes, Master Specifications, Product Evaluations) while

preserving departmental autonomy. The framework produced a comprehensive solution architecture demonstrating practical utility beyond theoretical constructs.

Key Findings

The research established four critical findings. First, seamless information integration requires coordinated development across three interdependent tiers rather than isolated technical solutions. Second, federated architecture principles are essential; construction's structure of temporary coalitions among autonomous organizations makes centralized approaches infeasible. The NRC case study validated that three independent departments successfully integrated their resources without surrendering autonomy. Third, semantic interoperability represents the foundational dimension upon which all other integration forms depend; without shared ontologies and formal data models, syntactic compatibility provides limited value. Fourth, integration must extend across complete asset lifecycles rather than focusing exclusively on project delivery, with explicit treatment of lifecycle transitions necessary for sustainability objectives, circular economy principles, and Digital Twin implementations.

Research Limitations

Several limitations must be acknowledged. The framework validation relies on a single case study (NRC), limiting generalizability claims. The evaluation represents ex ante assessment of solution design rather than ex post evaluation of implemented systems in operational use. The master's research scope necessarily constrained investigation depth, with detailed component-specific implementation guidance and maturity assessment tools representing valuable extensions beyond this study. Finally, while System-of-Information Systems principles suggest broader applicability, validation focused specifically on the built asset industry.

Future Research Directions

This research opens several promising avenues. Multiple case studies across diverse organizational contexts would strengthen generalizability evidence. Longitudinal implementation studies tracking framework-guided initiatives over multiple years would provide ex post validation. Development of operationalization tools, including detailed implementation guides, maturity assessment instruments, and component-specific templates, would enhance practical utility. Investigation of emerging technologies (AI, machine learning, blockchain) within the IIE framework would extend applicability to next-generation digital transformation. Finally, domain-specific adaptations could explore framework application beyond building construction to infrastructure, healthcare facilities, and smart cities.

Implications

For theory, the framework advances understanding of federated integration approaches and operationalizes multi-dimensional interoperability within actionable architectural guidance. For practice, organizations can use the 19 requirements to assess integration maturity, the 18 components as architectural targets, and the three-tier structure to inform implementation sequencing. The NRC case study demonstrates practical application methodology: systematic challenge mapping, federated solution architecture development, and detailed roadmap creation. For policy, the framework provides evidence-based guidance for regulatory requirements and standards development, reinforcing the need for open data standards while suggesting that mandates should enable rather than prescribe specific platforms.

The built asset industry stands at a critical juncture in its digital transformation journey. This research addresses the systematic framework gap through the Integrated Information Environment framework; a comprehensive, theoretically grounded, empirically validated approach demonstrating that integration is achievable through federated architectures built on shared semantic foundations rather than centralized platforms requiring organizational restructuring. As the industry pursues ambitious sustainability objectives and Digital Twin

implementations, the IIE framework provides the systematic guidance necessary to translate digital transformation aspirations into operational reality.

APPENDIX A

CODING PROCESS FOR IIE REQUIREMENTS DERIVATION

Table-A A-1 documents the complete qualitative coding process used to derive the 19 Integrated Information Environment requirements from literature analysis. The three-stage coding methodology moved from specific problems identified in literature (open codes) through thematic categorization (axial codes) to actionable requirements (selective codes).

A.1 Coding Methodology

Open Coding: Identified specific problems, gaps, and limitations from literature.

Axial Coding: Grouped related problems into thematic categories representing integration challenges.

Selective Coding: Refined themes into 19 actionable requirements organized across three tiers.

Table-A A-1 IIE Requirements Derivation

Req ID	Problem/Gap Identified	Open Codes from Literature	Axial Code (Theme)	Requirement (Selective Code)	Key Literature Sources
1.1	Semantic fragmentation prevents consistent interpretation of information across organizational and disciplinary boundaries	Semantic ambiguity, Terminology inconsistency, Interpretation variance, Definition conflicts, Meaning fragmentation, Conceptual misalignment	Semantic Interoperability	Define WHAT information means: Eliminate ambiguity through common definitions	(Abanda et al., 2025; Fernandes et al., 2022; Jaskula et al., 2024; Klar et al., 2024; Kloosterman et al., 2024; Ramonell et

Req ID	Problem/Gap Identified	Open Codes from Literature	Axial Code (Theme)	Requirement (Selective Code)	Key Literature Sources
					al., 2023; Urgese et al., 2022)
1.2	Heterogeneous data structures and proprietary schemas prevent meaningful information exchange across systems	Schema heterogeneity, Model incompatibility, IFC limitations, Structural diversity	Conceptual Interoperability	Define entities, attributes, and relationships independent of implementation	(Doe, 2021; Jiang et al., 2019; Maciel et al., 2024; Minerva et al., 2020; Tchouanguem Djuedja et al., 2019; van Berlo et al., 2021; Z. Wang et al., 2022)
1.3	File format barriers and syntactic incompatibilities prevent systems from parsing exchanged data	Format incompatibility and Proprietary barriers, Parsing failures and Model size, Encoding barriers, Version conflicts, Syntax errors (Inefficient Exporters and Importers)	Syntactic Interoperability	Enable systems to parse and interpret data structure regardless of semantic meaning	(Doe, 2021; Jaskula et al., 2024; Tchouanguem Djuedja et al., 2019; Turk et al., 2022; van Berlo et al., 2021; Z. Wang et al., 2022)
1.4	Unclear information requirements lead	Requirement ambiguity, Information	Information Requirements	Formalize information needs to	(Abanda et al., 2025; Poirier et al., 2022;

Req ID	Problem/Gap Identified	Open Codes from Literature	Axial Code (Theme)	Requirement (Selective Code)	Key Literature Sources
	to over-delivery, under-delivery, and stakeholder confusion about needed data	overload, Missing critical data, Unclear specifications, LOIN underutilization		ensure completeness and consistency	Vieira et al., 2023; Yousfi et al., 2024)
1.5	Unknown data lineage, unclear ownership, and quality uncertainty create trust deficits in information exchange	Provenance gaps, Quality uncertainty, Ownership ambiguity, Lineage gaps, Trust deficits, Metadata absence, Accountability challenges	Metadata & Governance	Track information origin, transformations, quality, and context throughout lifecycle	(Abanda et al., 2025; Bedoiseau et al., 2022; Jaskula et al., 2024; Tao et al., 2021; Turk et al., 2022)
1.6	Workflow discontinuities and timing misalignments prevent information from flowing when needed	Workflow breaks, Timing misalignment, Process fragmentation, Coordination failure, Sequential silos	Procedural Interoperability	Define WHEN information flows: Formalize process models and workflow coordination	(Abanda et al., 2025; Jaskula et al., 2024, 2025; Klar et al., 2023; Urgese et al., 2022)
2.1	Centralization approaches threaten organizational autonomy; temporary coalitions require	Centralization resistance and Control Loss, Autonomy preservation needs, Multiple disconnected	Federated Architecture	Define HOW systems integrate: Specify federated architecture patterns	(Bedoiseau et al., 2022; Fernandes et al., 2022, 2022; Preidel et al., 2018; Ribeiro et al.,

Req ID	Problem/Gap Identified	Open Codes from Literature	Axial Code (Theme)	Requirement (Selective Code)	Key Literature Sources
	integration without control loss	systems, Federation requirement, Organizational independence, Coalition dynamics		preserving autonomy	2023; Urgese et al., 2022)
2.2	Information generated at multiple distributed points cannot be captured with single-source architectures	Distributed data generation, Multi source capture, IoT integration gaps, Sensor data challenges, Entry point diversity	Data Acquisition	Enable information entry into the integrated environment from diverse creation points	(Botín-Sanabria et al., 2022; Klar et al., 2024; Kloosterman et al., 2024; Masoumi et al., 2023; Ramonell et al., 2023)
2.3.1	Static point-to-point exchange patterns insufficient; need both real-time and batch processing capabilities	Exchange pattern rigidity, Real time needs, Batch processing requirements, Change synchronization	Exchange Flexibility	Provide flexible synchronous and asynchronous exchange patterns	(Doe, 2021; Klar et al., 2023; Minerva et al., 2020; Urgese et al., 2022; Xie et al., 2022)
2.3.2	One-way information flows inadequate; systems need both event-driven push and demand-driven pull	Directional constraints, Push mechanisms needed, Pull capabilities lacking, Query functionality	Integration Mechanisms	Simplify and accelerate integration development	(Da Rocha et al., 2022; Doe, 2021; Fernandes et al., 2022; Jaskula et al., 2024; Klar et

Req ID	Problem/Gap Identified	Open Codes from Literature	Axial Code (Theme)	Requirement (Selective Code)	Key Literature Sources
		gaps, Publish subscribe absent			al., 2023; Ramonell et al., 2023; van Berlo et al., 2021)
2.4	Trust deficits, security gaps, and governance absence undermine stakeholder confidence in information	Trust deficit, Quality assurance gaps, Governance absence, Security vulnerabilities, Identity management issues, Reliability concerns, Accountability problems	Information Governance	Maintain confidence in information throughout exchange processes & ensure integration infrastructure is functioning properly	(Jaskula et al., 2024; Kloosterman et al., 2024; Patacas et al., 2020; Tao et al., 2021; Tumulak et al., 2024; Turk et al., 2022)
2.5.1	Organizations operate multiple disconnected CDEs; lack of structured collaboration workspaces creates coordination challenges	CDE fragmentation, Multiple disconnected platforms, Workspace coordination failures, Collaboration barriers, CDE multidimensional challenges	Collaboration Infrastructure	Implement structured Common Data Environments for collaboration	(Jaskula et al., 2023, 2024, 2025)

Req ID	Problem/Gap Identified	Open Codes from Literature	Axial Code (Theme)	Requirement (Selective Code)	Key Literature Sources
2.5.2	Data scattered across systems with storage fragmentation creating reliability and access concerns	Storage fragmentation, Data persistence challenges, Access barriers, Reliability issues, Distributed storage needs	Data Persistence	Provide reliable, queryable storage supporting integration patterns	(Doe, 2021; Kloosterman et al., 2024; Ramonell et al., 2023; Tao et al., 2021; Xie et al., 2022)
3.1	Stakeholders cannot find or retrieve needed information; access barriers prevent effective information use	Access barriers, Findability challenges, Retrieval difficulties, Role based access gaps, Search inadequacy	Information Access	Enable stakeholder information access and retrieval based on roles and needs	(Atkinson et al., 2022; Corcho et al., 2024; Jaskula et al., 2023; Ramonell et al., 2023; Z. Wang et al., 2022; Werbrouck, 2019)
3.2	Raw data difficult to interpret; visualization gaps prevent stakeholders from understanding information	Interpretation difficulty, Visualization gaps, Interface inadequacy, Comprehension barriers, Model visualization needs	Visualization & Interface	Make complex information understandable through visual presentation	(Abanda et al., 2025; Heidari et al., 2024; Lam et al., 2024; Patacas et al., 2020)
3.3	Decision-making silos and	Collaboration failure, Decision	Collaborative	Enable stakeholders	(Bedoiseau et al., 2022; Klar

Req ID	Problem/Gap Identified	Open Codes from Literature	Axial Code (Theme)	Requirement (Selective Code)	Key Literature Sources
	coordination breakdowns prevent effective stakeholder collaboration	silos, Coordination breakdown, Asynchronous communication barriers, Stakeholders disconnect	Management	to coordinate and make decisions collectively	et al., 2023; Kloosterman et al., 2024)
3.4	Data exists but insights not derived; analytics capabilities missing to extract value from integrated information	Insight extraction gaps, Analytics absence, Intelligence generation lacking, Value unrealized, Predictive capabilities missing, Advanced functions unsupported	Analytics & Intelligence	Transform raw information into actionable intelligence	(Jussen et al., 2024; Vieira et al., 2023)
3.5	Operations disconnect design information doesn't reach operators; operational insights don't feedback to design	Operations disconnect, Execution gaps, Design to operations break, Feedback loop absence, Process integration failure	Operational Services	Apply integrated information to ongoing building operation and services	(Abanda et al., 2025; Jaskula et al., 2024; Klar et al., 2024; Patacas et al., 2020; Urgese et al., 2022)
3.6	Integration doesn't serve strategic goals;	Strategic misalignment, Sustainability	Strategic Applications	Achieve strategic objectives	(Atkinson et al., 2022; Botín-

Req ID	Problem/Gap Identified	Open Codes from Literature	Axial Code (Theme)	Requirement (Selective Code)	Key Literature Sources
	sustainability, Digital Twin, and compliance objectives unmet	objectives unmet, Digital twin prevented, Compliance checking not automated, Circular economy unsupported, Domain application gaps		through domain-specific applications	Sanabria et al., 2022; Poirier et al., 2022; Yousfi et al., 2024; Yu et al., 2023)
3.7	Organizations don't learn from integrated data; intelligence generation and continuous improvement absent	Organizational learning gaps, Intelligence generation missing, Improvement mechanisms absent, Knowledge capture failure, Strategic steering lacking	Organizational Development	Enable organizational development and continuous intelligence	(Abanda et al., 2025; Tumulak et al., 2024; Vieira et al., 2023)

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