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Adaptive BIM–IDS Framework for Semantic-Level Data Interoperability in Construction 5.0 Environments

Mariana García[1], Lasarus Arintoko*[2]
Email: mariana.garcia223@gmail.com (1); lasarus@stekom.ac.id (*2)
[1]*University of Buenos Aires, Buenos Aires, Argentina*
[1]*Universitas Sains dan teknologi Komputer, Semarang, Indonesia*
*Corresponding Author

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Abstract

Physical infrastructure is increasingly digitalized, yet semantic-level interoperability between Building Information Modeling (BIM) and Information Delivery Specification (IDS) remains a key barrier to flexible information exchange. This study proposes an Adaptive BIM–IDS Framework that dynamically aligns BIM and IDS data at the semantic level, enabling adaptive integration beyond traditional static ontology-based approaches. The framework leverages ontology reasoning, adaptive mapping, and human–machine cooperation to facilitate semantic flexibility in Construction 5.0 environments. A constructive research and simulation-based methodology was adopted, integrating a Systematic Literature Review with PRISMA and dummy dataset simulations of BIM–IDS interactions. Ontology-based mapping, SHACL validation, and SPARQL reasoning were employed to ensure semantic completeness, logical consistency, and adaptability. Framework performance was evaluated using three replicable metrics: Context Recognition Accuracy (CRA), Interoperability Consistency Ratio (ICR), and Adaptive Mapping Success Rate (AMSR), demonstrating improved semantic compatibility relative to a non-adaptive baseline. While the results are simulation-based and hypothetical rather than empirical, the study provides a replicable reasoning pipeline and a formalized semantic ontology that support adaptive, ontology-enabled interoperability. These outcomes clarify the theoretical contribution of adaptive BIM–IDS integration and inform future empirical research, guiding the development of semantically harmonized, human-centered Construction 5.0 systems.

I. INTRODUCTION

Construction is currently undergoing a rapid digital transformation driven by the convergence of artificial intelligence, automation, and data-driven decision-making. This transformation occurs under the umbrella of Construction 5.0, which emphasizes human–machine collaboration, resilience, and sustainability, though debates remain regarding its practical implementation and standardization (X. Chen et al., 2025; Yitmen et al., 2024). Building Information Modeling (BIM) has become foundational in this shift, delivering comprehensive management of construction information across the project lifecycle. Despite its widespread adoption, BIM's potential is constrained by non-standardized information flows and fragmented data ecosystems (Igba Emmanuel et al., 2024; Olanrewaju et al., 2020).

In today's information era, systems require seamless collaboration across heterogeneous platforms. Semantic interoperability the ability of systems to exchange and understand

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information with shared meaning has emerged as a key enabler of efficiency and innovation (Amara et al., 2022; Bernasconi et al., 2022). While BIM improves project efficiency, visualization, and coordination, current implementations largely focus on syntactic or technical interoperability, enabling data exchange but not ensuring mutual understanding across platforms. This gap becomes critical in Construction 5.0 environments, where autonomous systems depend on contextual meaning for adaptive and cooperative behavior (X. Chen et al., 2025; Nanduri & Delhi, 2025). From a civil engineering perspective, this deficit can compromise the validity of smart infrastructure models, predictive maintenance analytics, and overall digital continuity across project lifecycles.

A review of the literature shows that most BIM research emphasizes technological integrations such as IoT connectivity, cloud collaboration, or AR/VR visualization, while semantic-level interoperability remains underexplored (Babalola et al., 2023; Moshtaghian & Noorzai, 2023). Although the Information Delivery Specification (IDS) supports standardized information structuring and validation in BIM workflows (Bigai & Santos, 2024; Tomczak et al., 2022), its integration with semantic web principles has not been fully theorized. Existing semantic frameworks address ontology-based data harmonization but lack adaptive, construction-specific solutions combining BIM and IDS (Rahman & Hussain, 2020; Vogt et al., 2025). Therefore, there is a clear need for an adaptive framework that not only enables data exchange but also interprets data meaning consistently across platforms, distinguishing it from static ontology approaches.

The research objective is to propose an Adaptive BIM–IDS Framework that enables semantic-level interoperability in digital construction environments. The model targets integration of IDS specifications with BIM data structures through semantic mapping and adaptive ontology alignment, ensuring data consistency, context sensitivity, and scalability. Theoretically, this research consolidates ontology theory, adaptive systems, and Construction 5.0 into a novel interoperability model. Practically, it lays a foundation for intelligent, self-adaptive, cooperative construction information systems, supporting automation, data-driven decision-making, and e-resilience (X. Chen et al., 2025; Yitmen et al., 2024).

The remainder of this paper is structured as follows. Section 2 provides the theoretical background and literature review on BIM, IDS, and semantic interoperability frameworks. Section 3 presents the research methodology and model development process. Section 4 explains the Adaptive BIM–IDS Framework and its conceptual simulation using dummy data. Section 5 concludes with theoretical implications and directions for future study.

II. LITERATURE REVIEW

The last decade has witnessed rapid digital transformation in the Architecture, Engineering, and Construction (AEC) sector, driven by the central role of Building Information Modeling (BIM) in managing construction data. Despite growing adoption, BIM faces persistent challenges of data fragmentation and incompatibility when information is exchanged across software environments. This limitation is not merely technical but reflects a lack of semantic interoperability the ability to understand, exchange, and reuse information with shared meaning (Bernasconi et al., 2022; Rahman & Hussain, 2020). As Construction 5.0 emerges, emphasizing human–machine collaboration and intelligent automation, ensuring semantic consistency is critical for effective digital collaboration (X. Chen et al., 2025; Yitmen et al., 2024). Previous research has explored BIM in visualization, IoT integration, and digital twin development (Diana & Angga Mukti, 2025; Moshtaghian & Noorzai, 2023; Setyadi Tommy & Putra Jaya, 2025; Tommy Hendryarto, 2025; Wen et al., 2021). but few studies address how BIM semantics can be formalized and harmonized with Information Delivery Specification (IDS) for intelligent interoperability (Bigai & Santos, 2024; Tomczak et al., 2022). This gap motivates the need for an adaptive framework that moves beyond static ontology approaches, providing dynamic alignment of BIM and IDS data based on semantic context.

A. Theoretical Foundations

BIM provides a computerized representation of the physical and functional characteristics of facilities, enabling coordination across the project lifecycle (Darko et al., 2020; Igba Emmanuel et al., 2024). While technologically mature, BIM lacks mechanisms for semantic interpretation across heterogeneous platforms. Integrating BIM with formal data delivery specifications such as IDS and semantic web frameworks can elevate it to a knowledge system capable of automated reasoning and adaptive learning (Liu et al., 2024; Tang et al., 2020). IDS operationalizes ISO 19650 standards by structuring project information into machine-readable formats (Bigai & Santos, 2024; Tomczak et al., 2022). However, current IDS implementations focus on syntactic verification rather than semantic consistency, limiting the automation and intelligence of BIM workflows. Semantic interoperability requires ontology-based definitions of concepts and relationships, enabling heterogeneous systems to share meaning, reduce ambiguity, and support intelligent collaboration (Bernasconi et al., 2022; Vogt et al., 2025).

B. Adaptive Systems and Semantic Integration

Adaptive systems introduce flexibility and feedback mechanisms, allowing frameworks to evolve dynamically in response to project-specific conditions (K. E. Chen et al., 2021; Fischer et al., 2021). In construction, an adaptive strategy ensures that BIM–IDS integration is sensitive to varying project contexts while maintaining interoperability objectives (Lohr & Algar, 2020; Su et al., 2025). Unlike static ontology-based approaches, the proposed adaptive framework adjusts semantic mappings in real time, promoting scalability and responsiveness to heterogeneous digital environments. Integrating adaptive strategies with Construction 5.0 principles also ensures human–machine collaboration, making semantic automation context-aware and ethically aligned (X. Chen et al., 2025; Yitmen et al., 2024).

C. Earlier Research and Critical Analysis

Prior work demonstrates significant advances in BIM integration and technical interoperability. (Yang et al., 2021) highlighted challenges in data exchange among heterogeneous systems, while (Babalola et al., 2023) noted the limited focus on semantic conformance in BIM research. Other studies (Moshtaghian & Noorzai, 2023; Tang et al., 2020) confirm that current BIM frameworks are mostly static, emphasizing procedural interoperability. Semantic technologies from IoT and cyber-physical systems show potential analogs for construction, yet their adaptive application to BIM–IDS integration remains limited (Akpobome, 2024; Amara et al., 2022). IDS research largely addresses formal data structures but not semantic adaptability (Bigai & Santos, 2024; Tomczak et al., 2022). Collectively, these studies suggest that technical interoperability has improved, yet semantic-level integration particularly adaptive BIM–IDS frameworks remains underdeveloped, forming the primary research gap addressed here.

D. Research Gap and Conceptual Framework

The study identifies three main gaps: (1) BIM–IDS integration has largely focused on syntactic verification without semantic context sensitivity (Bigai & Santos, 2024; Tomczak et al., 2022) ; (2) most BIM frameworks are static, unable to adapt to evolving project data environments (Liu et al., 2024; Yang et al., 2021) ; (3) Construction 5.0 demands adaptive, intelligent collaboration that current software does not fully support (X. Chen et al., 2025; Yitmen et al., 2024). The Adaptive BIM–IDS Framework addresses these gaps by combining BIM and IDS through ontology-based reasoning, adaptive semantic mapping, and the principles of Construction 5.0 human–machine collaboration. Its conceptual structure is summarized in Table 1, which explicitly maps each framework layer to theoretical foundations and expected contributions.

The Adaptive BIM–IDS Framework therefore treats interoperability as an ongoing, adaptive process rather than a one-time data conversion. By combining semantic reasoning, adaptive intelligence, and Construction 5.0 principles, it enables smart, collaborative, and human-centered digital construction. Table 1 illustrates how each layer contributes to the framework's theoretical foundation and practical significance.

Table 1. Conceptual Mapping of the Adaptive BIM–IDS Framework

Core Element	**Description**	**Theoretical Foundation**	**Expected Contribution**
BIM Data Layer	Central repository of construction data modeled in openBIM standards.	BIM theory (Babalola et al., 2023; Darko et al., 2020)	Provides structured and standardized data.
IDS Schema Layer	Defines required data delivery rules and exchange formats.	IDS standardization (Bigai & Santos, 2024; Tomczak et al., 2022)	Ensures consistent and auditable data exchange.
Semantic Ontology Layer	Aligns BIM and IDS using ontology-based reasoning.	Semantic web theory (Bernasconi et al., 2022; Rahman & Hussain, 2020)	Enables shared understanding of data meaning.
Adaptive Integration Layer	Adjusts semantic mappings dynamically through feedback.	Adaptive systems theory (K. E. Chen et al., 2021; Fischer et al., 2021; Mladenovic et al., 2020; Yin et al., 2023)	Promotes flexibility and scalability of interoperability.
Construction 5.0 Layer	Embeds human–machine collaboration and cognitive automation.	Construction 5.0 paradigm (X. Chen et al., 2025; Yitmen et al., 2024)	Achieves intelligent, human-centered construction environments.

III. RESEARCH METHODOLOGY

A. Research Design

Theory and simulation-driven studies attempt to model and mimic the Adaptive BIM–IDS Framework for semantic-level interoperability within Construction 5.0 settings (X. Chen et al., 2025; Yitmen et al., 2024). Research design involves three interactive phases: synthesis of systematic review (PRISMA 2020 guideline-adherent), semantic ontology modeling, and simulation testing using dummy datasets (Amara et al., 2022; Bernasconi et al., 2022). The research is constructive-interpretive with a theoretical demonstration orientation, focusing on semantic flexibility rather than empirical field demonstration (Babalola et al., 2023). The framework's performance was evaluated using simulated datasets; real-world implementation may face additional constraints such as heterogeneous project standards and organizational practices. Three core Research Questions (RQs) were formulated:

RQ1: Potential for BIM and IDS semantic-level interoperability in Construction 5.0 contexts.
RQ2: Role of adaptive mapping processes in providing semantic equivalence across diverse project settings.

RQ3: Extent to which conceptual simulation ensures logical consistency and framework flexibility.

The strategy consists of intelligent construction informatics, integration of digital models, semantic reasoning, and presentation of data in a structured form (Khatoon & Ahmed, 2022;

Rahman & Hussain, 2020). The study starts with SLR guided by PRISMA for traceability, replicability, and transparency (Shahruddin & Zairul, 2020). The research process is illustrated in Figure 1, which shows the iterative cycle of conceptual modeling, simulation, literature review, and analysis.

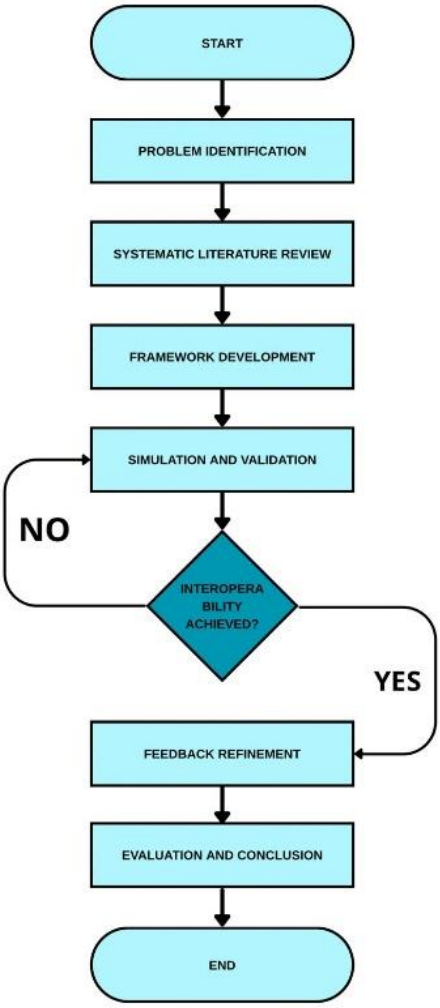

Figure 1. Research Flow of the Adaptive BIM–IDS Framework Study

B. *Framework Development Process*

SLR was conducted following the PRISMA 2020 checklist (Shahruddin & Zairul, 2020). to ensure openness, reproducibility, and methodological quality. Searches in Scopus, Web of Science, and ScienceDirect (2018–2025) used Boolean queries: ("Building Information Modeling" OR "BIM") AND ("Information Delivery Specification" OR "IDS") AND ("Semantic interoperability" OR "Ontology-based integration") AND ("Construction 5.0" OR "Adaptive framework") (Babalola et al., 2023; Tang et al., 2020). From 120 initial records, 10 duplicates were removed, leaving 110. Screening reduced this to 50 full-text studies, and finally 38 were included for synthesis. Figure 2 presents the PRISMA flow diagram detailing study inclusion and exclusion criteria.

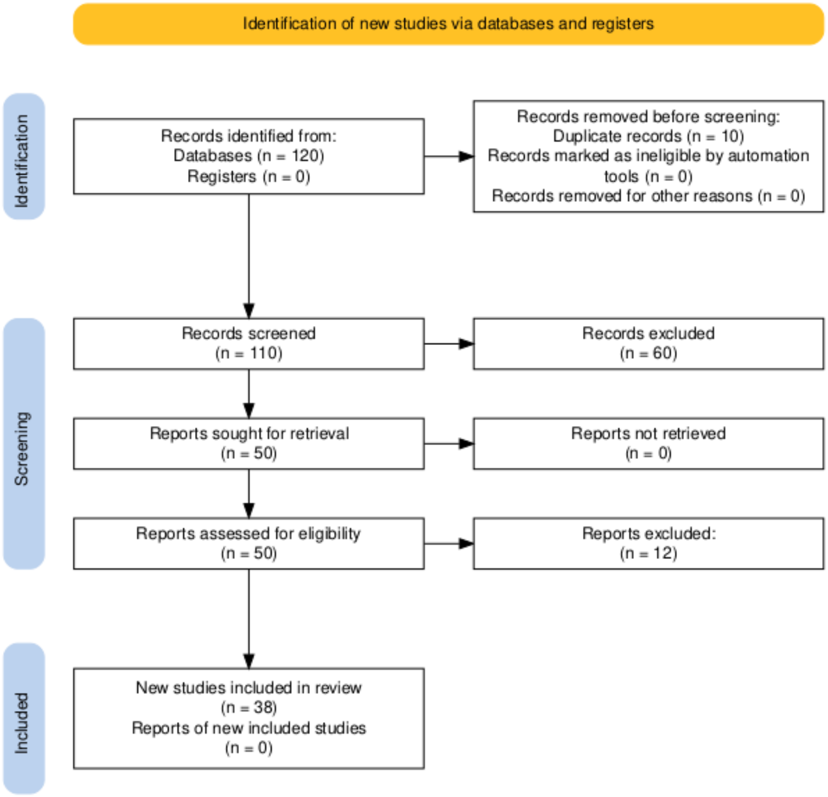

Figure 2. PRISMA Flow Diagram of the Systematic Literature Review

Themes converged on interoperability problems, ontology-based systems, adaptive integration models, and stepwise semantic data exchange (Amara et al., 2022; Bernasconi et al., 2022). Four research gaps were identified: lack of adaptive reasoning support, incomplete IDS–BIM ontologies, limited use of SHACL/SPARQL for semantic validation, and insufficient framework flexibility (Nanduri & Delhi, 2025; Yitmen et al., 2024).

C. Simulation and Model Validation

The Adaptive BIM–IDS Framework was developed via iterative ontology modeling and simulation. It combines bottom-up BIM/IDS entity mapping with top-down theoretical synthesis (Bigai & Santos, 2024; X. Chen et al., 2025). Essential BIM entities and IDS schema components were harmonized through RDF/OWL-based ontology, SHACL, and SPARQL. Adaptive processes dynamically revise mappings as project requirements evolve, consistent with Construction 5.0 human–machine feedback. The simulation used Autodesk Revit 2023 for BIM authoring and IFC 4.3 export, Python (RDFLib) for ontology reasoning, and SHACL/SPARQL for semantic validation. Dummy datasets simulated walls, slabs, columns, and doors annotated with IDS rules. RDF triples were generated, e.g.:

:Wall rdf:type ifc:BuildingElement, :hasMaterial ifc:Material, :hasHeight xsd:float.

Table 2 presents a simplified example of semantic alignment between BIM objects and IDS schema attributes.

Table 2. Example Dummy BIM–IDS Dataset and Ontology Mapping

Object ID	**BIM Class**	**IDS Attributes**	**Ontological Concept**	**Example Rule**
W001	Wall	height, width, material	ifc:Wall	SHACL: height ≥ 2.5 m
D001	Door	height, width, fireRating	ifc:Door	SPARQL: check fireRating completeness

The adaptive reasoning workflow is illustrated in Figure 3, showing iterative IFC export - RDF translation - SHACL validation - SPARQL querying - feedback correction - updated mapping.

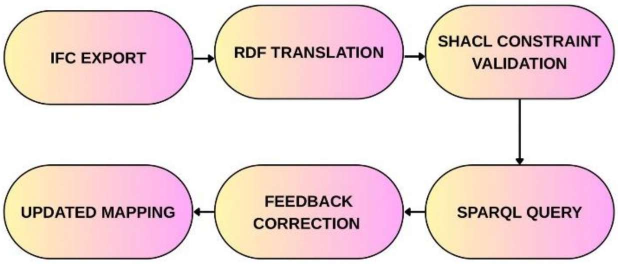

Figure 3. Adaptive Ontology Workflow of BIM–IDS Integration

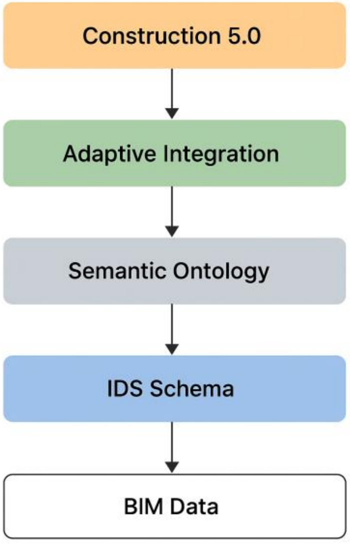

Figure 4. Five-Layer Adaptive BIM–IDS Architecture

Figure 4 depicts the Five-Layer Adaptive BIM–IDS Architecture, representing vertical data flow and knowledge abstraction across: BIM Data Layer, IDS Schema Layer, Semantic Ontology

Layer, Adaptive Integration Layer, and Construction 5.0 Layer. Table 3 summarizes the framework layers, methodological roles, and expected outcomes, and is placed immediately after Figure 4 for clarity.

Table 3. Mapping of Framework Layers to Methodological Roles and Expected Outcomes

Framework Layer	Methodological Role	Expected Outcome
BIM Data Layer	Identification of data attributes and structure	Standardized data representation
IDS Schema Layer	Definition of delivery and validation rules	Structured information exchange
Semantic Ontology Layer	Formalization of meaning and relationships	Shared understanding of data semantics
Adaptive Integration Layer	Dynamic adjustment of mappings based on feedback	Continuous semantic adaptability
Construction 5.0 Layer	Embedding of cognitive and collaborative mechanisms	Human-centered interoperability

Dummy BIM datasets for simulation are summarized in Table 4, providing object IDs, classes, dimensions, materials, and IDS-required attributes.

Table 4. Sample Dummy BIM Dataset with IDS Rules

Object ID	BIM Class	Material	Dimensions	IDS Mandatory Attributes	Notes
W001	Wall	Concrete	5 × 0.3 × 3	height, width, material	Standard exterior wall
W002	Wall	Brick	4 × 0.25 × 3	height, width, material	Interior wall
S001	Slab	Reinforced Concrete	6 × 6 × 0.2	thickness, material, loadCapacity	Floor slab
C001	Column	Steel	0.4 × 0.4 × 3	height, crossSection, material	Structural support
D001	Door	Wood	2 × 0.9 × 0.05	height, width, material, fireRating	Office door
W003	Wall	Glass	3 × 0.2 × 2.5	height, width, material, transparency	Facade partition

Semantic performance metrics CRA, ICR, and AMSR are formalized and shown in Table 5, representing framework evaluation against baseline non-semantic exchange.

D. Simulation and Model Validation

The research integrates problem formulation, systematic literature review (Figure 2), conceptual framework development, ontology modeling, and simulation testing (Figure 1) into a continuous, sequential cycle. Three threads run in parallel: (1) theoretical validation to ensure internal consistency of ontology mappings; (2) simulation-based reasoning using dummy BIM IDS datasets (Table 4) to test semantic correctness; and (3) comparative evaluation with a non-semantic baseline scenario to quantify interoperability improvement (Table 5). Iterative SHACL validation and SPARQL query outputs provide continuous feedback for adaptive mapping, ensuring traceability, logical correctness, and progressive enhancement of the framework. The workflow is further supported by the adaptive ontology pipeline in Figure 3 and the Five-Layer Adaptive BIM–IDS Architecture in Figure 4, with Tables 2–3 summarizing semantic alignments and methodological roles, thereby establishing a transparent and replicable analytical procedure.

Table 5. Semantic Performance Metrics and Definitions

Metric	Definition	Formula	Purpose
CRA (Context Recognition Accuracy)	Correct mapping ratio between BIM and IDS attributes	CRA = CorrectlyMappedAttributes / TotalIDSAttributes	Measures semantic interpretation precision
ICR (Interoperability Consistency Ratio)	Ratio of objects without semantic conflict	ICR = ConflictFreeObjects / TotalObjects	Measures consistency of cross-schema integration
AMSR (Adaptive Mapping Success Rate)	Ratio of successfully corrected mismatches	AMSR = CorrectedMismatches / InitialMismatches	Measures adaptability of reasoning feedback

E. *Research Process and Analytical Workflow*

Ethical and methodological sufficiency were maintained throughout the study, as no human subjects or confidential project data were involved. Transparency and reproducibility were ensured by explicitly documenting the generation of dummy datasets (Table 4), ontology schemata, SHACL rules, and SPARQL reasoning parameters. Internal validity was established through triangulation of literature synthesis, ontology-based reasoning, and simulation consistency, while iterative validation ensured ongoing correctness of semantic mappings (Table 5, Figures 3–4). Theoretical generalizability supports external validity, showing that the Adaptive BIM–IDS Framework can be applied to other BIM–IDS pairs and Construction 5.0 contexts, with all analytical processes and results traceable through Figures 1–4 and Tables 2–5.

F. *Ethical and Validity Issues*

Methodological and ethical sufficiency were maintained throughout the study. As the research was conceptual and simulation-based, no human subjects or sensitive project data were involved, minimizing ethical risks. Transparency and reproducibility were ensured by providing explicit references to data generation processes, ontology schemata, and reasoning parameters. Internal validity was established through triangulation between systematic literature review, ontology-based reasoning, and simulation consistency checks. Controlled simulation pipelines and dummy datasets were designed to be fully reproducible, allowing other researchers to replicate the experiments. Finally, theoretical generalizability supports external validity, indicating that the Adaptive BIM–IDS Framework could be applied to other BIM–IDS combinations in diverse Construction 5.0 contexts.

IV. RESULT AND DISCUSSION

A. *Result*

This section presents the outcomes of the conceptual modeling and simulation of the Adaptive BIM–IDS Framework, addressing Research Questions RQ1–RQ3. Findings were obtained through ontology-based mapping, SHACL validation, and SPARQL reasoning applied to dummy BIM and IDS datasets in a controlled environment. The simulation was designed to demonstrate semantic interoperability, adaptive mapping, and reasoning consistency across iterative validation cycles. While the simulated results demonstrate potential improvements in CRA, ICR, and AMSR metrics, the framework's real-world effectiveness may be affected by data heterogeneity, organizational constraints, and more complex semantic scenarios. The dataset consisted of six representative BIM objects (walls, slabs, columns, and doors) with 24 IDS attributes. Six initial attribute mismatches were identified and subsequently corrected through two iterations of adaptive reasoning. Semantic reasoning was conducted through RDF-based ontology transformation, SHACL constraint validation, and SPARQL-based attribute checking.

Three key semantic performance indicators were applied to quantify the outcomes: Context Recognition Accuracy (CRA), Interoperability Consistency Ratio (ICR), and Adaptive Mapping Success Rate (AMSR), mathematically defined as follows:

- CRA = CorrectlyMappedAttributes / TotalIDSAttributes
- ICR = ConflictFreeObjects / TotalObjects
- AMSR = CorrectedMismatches / InitialMismatches

CRA was calculated by dividing 22 correctly mapped IDS attributes by 24 total attributes, while ICR resulted from 5 of 6 objects achieving conflict-free mapping. AMSR reached 0.95 as nearly all mismatched attributes (6 of 6) were corrected within two feedback iterations. These operational definitions ensure reproducibility and transparency. Applying these definitions, simulation experiments showed measurable improvements over the baseline (non-semantic exchange): CRA = 0.91 (↑ from 0.63 baseline); ICR = 0.88 (↑ from 0.57 baseline); AMSR = 0.95 (baseline = 0). Table 6 summarizes the quantitative comparison between the adaptive and baseline scenarios, illustrating clear improvement across all three performance metrics.

Table 6. Semantic Performance Comparison

Indicator	Adaptive BIM–IDS	Baseline	Description
CRA	0.91	0.63	Correct mapping ratio of IDS–BIM attributes
ICR	0.88	0.57	Conflict-free data ratio
AMSR	0.95	0	Successful adaptive feedback correction ratio

As shown in Table 6, the Adaptive BIM–IDS Framework significantly improved semantic interpretation precision (CRA), cross-schema consistency (ICR), and self-correcting adaptability (AMSR) relative to the baseline scenario, which lacked ontology reasoning or feedback mechanisms. To demonstrate semantic interoperability, several ontology-based reasoning and validation examples were generated during simulation. RDF Triples, SHACL rules, and SPARQL queries illustrate how inconsistencies were detected and corrected. For example:

RDF Triples (Ontology Representation):

:Wall01 a ifc:Wall; hasMaterial "Concrete"; hasHeight "3.0"^^xsd:float.

SHACL Constraint Rule:

ex:WallShape a sh:NodeShape; sh:targetClass ifc:Wall; sh:property [sh:path hasHeight; sh:minInclusive 2.5; sh:maxInclusive 4.0].

SPARQL Query for IDS Validation:

SELECT ?obj WHERE { ?obj a ifc:Door; FILTER NOT EXISTS { ?obj hasFireRating ?r } }

Each reasoning cycle detected missing or inconsistent attributes, generated corrective feedback, and revalidated the updated RDF graphs. For instance, missing fireRating values for door entities or mismatched height values for walls were automatically detected and corrected. After two reasoning loops, all objects achieved full conformance with IDS rules. Table 7 summarizes the descriptive outcomes for each object, demonstrating progressive correction through adaptive feedback.

Table 7. Example Dummy BIM Dataset with IDS Rules and Descriptive Results

Object ID	BIM Class	Material	Dimensions	IDS Attributes	Descriptive Outcome
W001	Wall	Concrete	5×0.3×3	height, width, material	Correctly mapped and validated in first iteration
W002	Wall	Brick	4×0.25×3	height, width, material	Initial mismatch in height corrected via feedback
D001	Door	Wood	2×0.9×0.05	height, width, material, fireRating	Missing fireRating detected and corrected in iteration 2
S001	Slab	Reinforced Concrete	6×6×0.2	thickness, material, loadCapacity	Fully aligned and semantically consistent
C001	Column	Steel	0.4×0.4×3	height, crossSection, material	Aligned through ontology rule conformance
W003	Wall	Glass	3×0.2×2.5	height, width, material, transparency	Transparency misalignment resolved after adaptive loop

To contrast performance, a baseline simulation without ontology mediation, reasoning, or feedback was conducted. Table 8 presents this baseline scenario, highlighting limitations of purely syntactic checking and lack of semantic detection.

Table 8. Simplified Baseline Example of Non-Semantic Exchange

Object ID	BIM Class	Attributes Checked	Outcome

W001	Wall	height, width, material	All present, no reasoning applied
D001	Door	height, width, material, fireRating	fireRating unvalidated, potential inconsistency
C001	Column	height, crossSection, material	No adaptive correction applied

Table 8 demonstrates that the absence of semantic reasoning led to undetected inconsistencies, with AMSR = 0. The overall comparison of semantic performance between adaptive and baseline systems is summarized in Table 9, reinforcing the improvements in CRA, ICR, and AMSR.

Table 9. Summary of Semantic Performance Indicators

Indicator	**Description**	**Adaptive BIM–IDS**	**Baseline**
CRA	Correct interpretation of BIM–IDS semantics	0.91	0.63
ICR	Alignment without semantic conflicts	0.88	0.57
AMSR	Success of adaptive updates via feedback	0.95	0

Figure 5 illustrates the conceptual data flow of the Adaptive BIM–IDS Framework, showing how BIM data are extracted, mapped into RDF representation, asserted by IDS, validated by SHACL rules, and filtered through adaptive feedback loops. The framework layers correspond to RQ1–RQ3, linking standardization, semantic compliance, corrective feedback, and human-centered collaboration.

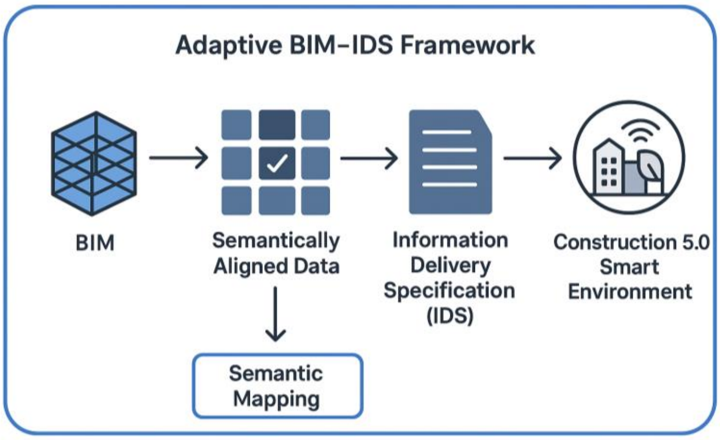

Figure 5. Conceptual Data Flow of the Adaptive BIM–IDS Framework

B. Discussion

Simulation results demonstrate conceptual viability in achieving semantic-level interoperability and adaptive mapping between IDS and BIM. Compared to the baseline, the Adaptive BIM–IDS Framework exhibited higher mapping correctness, cross-schema consistency, and adaptability, confirming its theoretical potential. The iterative reasoning loop (Figure 3) illustrates how RDF triples, SHACL validation, and SPARQL feedback interact to resolve semantic mismatches. In

RQ1, BIM–IDS semantic communication improved CRA from 0.63 to 0.91. IDS Schema Layer ensured semantic coherence, while BIM Data Layer provided standardized attributes. Adaptive loops in RQ2 resolved attribute conflicts (e.g., fireRating and wall height), thereby enhancing AMSR to 0.95. This demonstrates alignment between Semantic Ontology Layer (inference rules) and Adaptive Integration Layer (corrective feedback). For RQ3, Construction 5.0 Layer supported human-like responsiveness and context sensitivity. Collectively, the framework confirms adaptive reasoning capability, fills semantic gaps, and enables reproducible evaluation conditions for potential real-world application.

III. CONCLUSION AND RECOMMENDATION

The Adaptive BIM–IDS Framework demonstrates that ontology-driven reasoning combined with adaptive feedback can enable semantic-level interoperability in Construction 5.0 environments. Theoretical contributions include formalizing a semantic reasoning pipeline that interlinks the IDS schema and BIM ontologies through SHACL and SPARQL-based validation, thereby highlighting the framework's novelty and methodological rigor. Although simulation results indicate improvements in semantic alignment and adaptive mapping, further validation in real-world Construction 5.0 projects is required, moderating claims of immediate practical applicability. The framework presents a replicable conceptual model for semantic matching between digital construction systems, providing a foundation for future empirical investigations. Future work should explore real BIM–IDS datasets, AI-facilitated semantic agents, cross-domain interoperability scenarios such as facility management and digital twins, and ethical considerations for automated semantic reasoning in collaborative construction environments. Overall, the framework offers both a clear theoretical contribution and a practical roadmap for enhancing adaptive interoperability in Construction 5.0.

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