DATA QUALITY CONTROL FOR OPENBIM-BASED DIGITAL TWINS IN RETROFIT: A CASE STUDY ON IFC VALIDATION AND INFORMATION REQUIREMENTS

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Abstract

Building Information Modelling provides the geometric and semantic foundation for Digital Twins (DT), but its effectiveness depends on the availability of use-case-specific information. In OpenBIM workflows, Industry Foundation Classes (IFC) models often contain missing or incomplete information, limiting reliable integration with DT platforms. This paper presents an envelope retrofit-oriented data quality control using Information Delivery Specifications (IDS). Minimum requirements were formalized into IDS and validated against an IFC model. Results show that while geometry was generally complete, critical semantics, particularly material and thermal properties, were frequently missing. IDS-based validation enables early detection of data gaps and improves IFC data readiness.

Introduction

The built environment is a major contributor to global energy use and CO_2 emissions (International Energy Agency, 2023), making existing building stock an important target for retrofit interventions aimed at reducing energy use, lowering emissions, and extending operational lifespans.

Digital technologies, particularly Building Information Modelling (BIM) and Digital Twin (DT), offer significant potential to support and optimize retrofit processes (D'Angelo et al., 2022). However, the effectiveness of these technologies is often constrained by persistent interoperability and data exchange challenges.

Building retrofitting aims to enhance energy efficiency (Ma et al., 2025), occupant comfort (Hosamo et al., 2023a), and environmental performance. Traditional retrofit approaches rely primarily on static building properties, historical weather data, and simplified energy models (Feng et al., 2022). Such approaches often fail to capture the true complexity of existing buildings, leading to suboptimal design decisions, unforeseen implementation challenges, and performance outcomes that deviate from predictions, commonly referred to as the energy performance gap (Cuerda et al., 2020).

DTs offer a promising alternative by enabling data-driven retrofit decision-making through continuous monitoring and real-time performance feedback (Ba et al., 2025). By integrating live data streams, DTs can support optimized energy use and improved occupant comfort (Hosamo et al., 2023b). A DT can be defined as a digital replica of a physical asset that integrates data from Internet of Things (IoT) devices with analytics and computational models to represent the state and behavior of the asset across its lifecycle (Agostinelli et al., 2021). DT ecosystems typically consist of a physical asset, its virtual counterpart, and a bidirectional flow of information between them (Hadjidemetriou et al., 2023). Within this context, BIM provides the geometric and semantic foundation of the virtual model, while IoT technologies enable dynamic data acquisition, making BIM and IoT core enablers for DT development in the built environment (Li et al., 2023). BIM models represent the physical and functional characteristics of buildings through both geometric and non-geometric information, providing a structured baseline for simulation, analysis, and decision support (Azhar et al., 2020).

Despite this conceptual synergy, integrating BIM models into DT workflows remains technically challenging due to interoperability limitations (Muchla et al., 2025). Interoperability refers to the ability to exchange and reuse data across heterogeneous software platforms throughout the building lifecycle while minimizing information loss and manual intervention (Agostinelli et al., 2021). In practice, BIM platforms, energy simulation tools, IoT systems, and DT environments often rely on proprietary data structures and inconsistent schemas (Piras et al., 2025). During BIM data exchange, critical semantic information such as thermal properties, material definitions, and equipment specifications may be omitted, misclassified, or improperly mapped due to incomplete information requirements, variations in modelling practices, and IFC export configurations, particularly in workflows using open standards such as IFC and gbXML (Bastos Porsani et al., 2021; Li et al., 2023). These issues hinder the automated linkage of BIM-based static data with dynamic data sources, such as Building Automation Systems (BAS), Building Management Systems (BMS), and IoT sensors, resulting in manual data correction, extended workflows, and unreliable analytics.

While interoperability challenges in BIM–DT integration are well recognized, existing studies predominantly focus on conceptual frameworks or platform-specific implementations. Limited attention has been given to the explicit definition and automated validation of retrofit-oriented information requirements in IFC models prior to DT deployment. As a result, data quality issues are often

identified late in the workflow, reducing scalability and limiting the effectiveness of DT applications for retrofit projects. Accordingly, this study is guided by the following research question: How can minimum, use-case-specific information requirements for envelope retrofit be explicitly defined and automatically validated in IFC models to support DT integration? This paper addresses this gap by proposing a structured approach for defining and validating minimum, use-case-specific information requirements and demonstrates how IDS can be used not only as a checking tool but as a mechanism for improving upstream data definition in envelope retrofit-oriented workflows. The main contributions of this study are:
(1) the definition of a minimum, use-case-specific set of envelope retrofit information requirements, (2) their formalization into machine-interpretable IDS specifications, and
(3) the demonstration of an automated validation workflow to assess IFC data readiness for DT integration.

In this research, the term retrofit refers specifically to building envelope retrofit, focusing on elements that govern heat exchange with the external environment. The proposed approach is demonstrated through a case study on an IFC model. The objective is to improve IFC data readiness and support scalable, openBIM-compliant DT applications for retrofit projects.

Methodology

This study applies a case-study approach to assess IFC data readiness for envelope retrofit-oriented DT integration through requirement definition and IDS-based validation. The methodological workflow consists of five main steps: (1) identification of retrofit-oriented information requirements, (2) formalization of these requirements using IDS, (3) preparation and export of the BIM model to IFC format, (4) validation of IFC models against the defined IDS rules, and (5) analysis of validation results to identify data quality issues.

Figure illustrates the validation workflow used in this study. This workflow represents one stage within a broader process that begins with use-case-based requirement definition, followed by validation (this research), and subsequent model refinement and DT integration in future work.

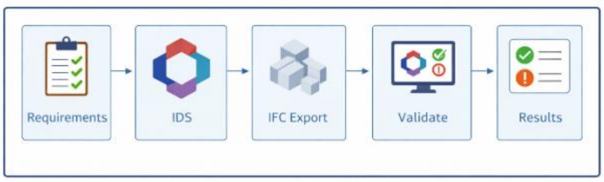


Figure 1: IDS-based validation workflow

The methodology defines information requirements rather than as a general measure of BIM completeness. For the use-case addressed in this study, the minimum set was limited to the static envelope information needed for initial retrofit assessment and subsequent DT use. Requirement selection was based on the information needed for envelope performance evaluation. Although additional information may be available in external sources such as product and material databases or environmental product declarations, these were considered outside the scope of this study. The scope of the IDS was therefore limited to information that could be reliably represented in IFC and automatically validated.

Retrofit-oriented information requirements were identified based on the literature insights, common inputs required for building energy analysis, and domain knowledge relevant to envelope retrofit. The scope was intentionally limited to external envelope elements, including walls, roofs, slabs, windows, and doors, which are central to envelope retrofit assessment. The resulting requirements focus on the presence and correct assignment of envelope-related information, including element identification, material assignment, and the availability of thermal performance properties. Together, these requirements represent a core but non-exhaustive subset of information relevant to the selected use-case. The identified requirements were formalized using buildingSMART IDS (buildingSMART International, 2024), enabling machine-interpretable definition of expected IFC entities, properties, and quantities. In this study, IDS rules were designed to verify information availability and completeness without prescribing how elements must be modelled or requiring specific property values, allowing flexibility across BIM authoring practices. A prototype validation workflow was implemented by exporting a BIM model of an existing building to IFC format and validating it using an IDS-compatible tool.

Case Study and Validation Workflow

Case Study Description

The case study is based on the Future Buildings Laboratory (FBL), a research facility located at Concordia University in Montreal, Quebec. The FBL functions as a living laboratory supporting multidisciplinary research and education in sustainable buildings and infrastructure. The facility provides a controlled environment for testing building technologies and monitoring performance, making it a suitable case study for investigating data readiness in retrofit-oriented DT workflows.

The building is a single-storey structure with approximate plan dimensions of 14.7 m × 7.5 m and an overall height of about 8 m. From a thermal perspective, the facility operates primarily as a single thermal zone; however, it is internally subdivided into four dedicated test cells used for independent experimental studies, along with two mechanical cells. The building is equipped with a compact set of building systems, including an outdoor heat pump unit paired with an indoor air handling unit for heating and cooling, as well as an electric domestic hot water system. These characteristics make the FBL representative of small-scale experimental buildings commonly used in retrofit research and DT development.

BIM Modelling and IFC Export

A three-dimensional BIM model of the FBL was developed using Autodesk Revit to represent the actual building geometry and associated static building information. The model focuses on architectural and envelope components required for retrofit assessment and DT initialization. The BIM model was subsequently exported to the IFC format using IFC 4 and the Reference view MVD to enable open and tool-independent data exchange.

The IFC export was performed without manual post-processing or correction before validation. This approach ensures that the validation results reflect the completeness and correct assignment of information as produced by the BIM authoring and export process, rather than improvements introduced through manual intervention. The exported IFC model served as the sole input for IDS-based validation.

IDS Definition and Scope

To develop the IDS, usBIM.IDSeditor (ACCA software, 2026) was used due to its native support for the buildingSMART IDS standard and its schema-aware environment for defining requirements without manual XML editing. The tool was selected because it is dedicated to requirement authoring rather than model checking, is independent of any specific IFC model, and produces portable IDS definitions accompanied by human-readable documentation. This separation allows IDS validation to be performed independently using an IDS-compatible tool.

Retrofit-Oriented Information Requirements

This section details how retrofit-oriented requirements were selected. The requirements target static building information and should therefore be understood as a minimum information specification for this use-case, rather than as a complete definition of all information that could be relevant to building lifecycle analysis.

These requirements were derived from the information typically needed for envelope performance evaluation. In particular, the selection reflects inputs commonly required by building energy simulation workflows, including geometry and zoning context, material and construction properties, and thermal performance parameters.

The IDS requirements were defined as a core subset that is both (i) retrofit-relevant and (ii) practically checkable in IFC exports across tools. For opaque elements (external walls, roofs, and slabs), requirements emphasize element identification, material assignment, and thermal transmittance properties. For openings (windows and doors), the focus is on thermal transmittance, with quantity information treated as optional.

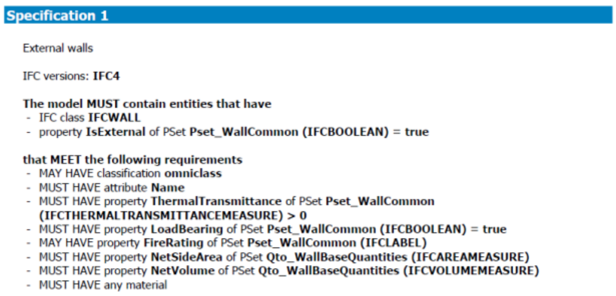
In the IDS structure, each requirement is defined within a Specification that includes an Applicability definition and a set of Requirements, enabling the translation of these information needs into explicit, machine-interpretable validation rules.

Five envelope element categories were selected as the validation scope of the IDS, and requirements were defined for applicable instances of these categories using standard IFC entity types, property sets, and quantity take-off sets. The detailed requirements are summarized in Table 1.

Table 1: Summary of IDS requirements for envelope elements

Element Type	IFC Entity	Properties
External Walls	IfcWall	Name, IsExternal, LoadBearing, ThermalTransmittance, NetSideArea, NetVolume, Material
Roofs	IfcRoof	IsExternal, ThermalTransmittance, GrossArea, Material
Slabs/Floors	IfcSlab	IsExternal, ThermalTransmittance, Material
Windows	IfcWindow	IsExternal, U-value
Doors	fcDoor	IsExternal, ThermalTransmittance

For external walls (Figure), the IDS defines the most extensive set of checks, reflecting the central role of walls in envelope heat transfer. The specification includes identification and applicability conditions to define which elements are evaluated, together with requirements for thermal, material, and quantity-related properties; however, classification and fire rating remain optional to avoid over-constraining IFC exports.


Specification 1

External walls

IFC versions: **IFC4**

The model MUST contain entities that have
- IFC class **IFCWALL**
- property **IsExternal** of PSet **Pset_WallCommon (IFCBOOLEAN) = true**

that MEET the following requirements
- MAY HAVE classification **omniclass**
- MUST HAVE attribute **Name**
- MUST HAVE property **ThermalTransmittance** of PSet **Pset_WallCommon (IFCTHERMALTRANSMITTANCEMEASURE) > 0**
- MUST HAVE property **LoadBearing** of PSet **Pset_WallCommon (IFCBOOLEAN) = true**
- MAY HAVE property **FireRating** of PSet **Pset_WallCommon (IFCLABEL)**
- MUST HAVE property **NetSideArea** of PSet **Qto_WallBaseQuantities (IFCAREAMEASURE)**
- MUST HAVE property **NetVolume** of PSet **Qto_WallBaseQuantities (IFCVOLUMEMEASURE)**
- MUST HAVE any material

Figure 2: External walls specification

For roofs, the IDS specifies external applicability together with thermal, material, and gross area information. For slabs and floors, the IDS includes external applicability, material assignment, and thermal transmittance properties, without additional quantity requirements.

For windows, the IDS requires external applicability and thermal transmittance, while area-related quantities are optional. For doors, the external applicability and thermal transmittance were included, without additional quantity requirements.

Requirements related to dynamic operation (e.g., real-time sensor data, control setpoints, or occupancy schedules), performance targets (e.g., prescribed U-value thresholds or regulatory compliance limits), proprietary or tool-specific parameters (e.g., authoring-tool custom fields), detailed construction layering (e.g., full multi-layer wall build-ups with material thicknesses), and non-retrofit lifecycle data (e.g., construction sequencing or maintenance scheduling) were excluded, as they cannot be consistently expressed, validated, or verified as static information within IFC-based IDS workflows.

In addition, some information that is typically maintained in external sources rather than within the IFC model was excluded. This includes manufacturer-specific product data, detailed material properties, and environmental declaration information such as embodied carbon indicators. While such information may be important for broader sustainability or lifecycle analyses, it falls outside the scope of this study, which focuses on validating the minimum IFC-based information required for retrofit-oriented DT initialization. The resulting set supports early, automated IFC data quality assessment for retrofit-oriented DT integration without defining a comprehensive modelling specification.

Validation Workflow

The validation workflow evaluates IFC data readiness through automated, standards-based checks. The IFC4 model was validated against the defined IDS specifications using BIMcollabZoom (BIMcollab, 2026.), as shown in Figure , which assessed each applicable element and generated element-level pass/fail results. For non-compliant elements, the output included requirement-specific messages indicating missing or incomplete information, such as absent thermal properties, missing material assignments, or missing quantity data.

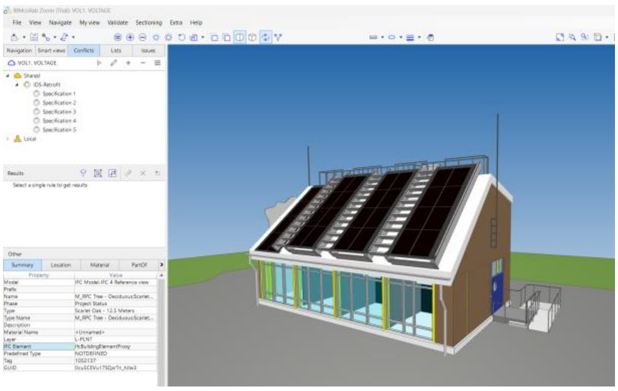


Figure 3: Case study 3D model in BIMcollab

The validation results were then analyzed to identify recurring data gaps across envelope elements and to assess overall IFC data readiness. Non-compliant elements can be traced and corrected in the BIM authoring environment, followed by re-export and re-validation; however, this corrective loop is outside the scope of this study.

Result Analysis and Discussion

Results Analysis

The validation assessed compliance with the retrofit-oriented information requirements defined for envelope elements and showed that a substantial number of applicable elements failed one or more IDS checks. In addition to the pass/fail indicators, the BIMcollabZoom provided detailed Property–Value information for each non-compliant element. These fields are essential for interpreting why elements failed IDS requirements and for distinguishing between geometric completeness and semantic deficiencies. In several cases, elements included correct geometry, dimensions, and basic identifiers, while required attributes such as material assignments, thermal transmittance values, or external applicability flags were undefined or absent. These failures were primarily associated with missing thermal properties and material assignments. This indicates that data gaps are concentrated in the semantic information required for envelope retrofit assessment rather than in geometric representation.

For walls (Figure), the validation output shows repeated failures associated with undefined material assignments and missing thermal transmittance properties, despite the presence of geometric representations and basic element identifiers. It should be noted that the figure primarily shows internal walls. Their inclusion in the validation results indicates that the external applicability condition (e.g., IsExternal) was missing or not correctly assigned, causing these elements to be evaluated against IDS requirements intended for external walls. This highlights the importance of correctly defining applicability attributes in addition to providing required semantic information.

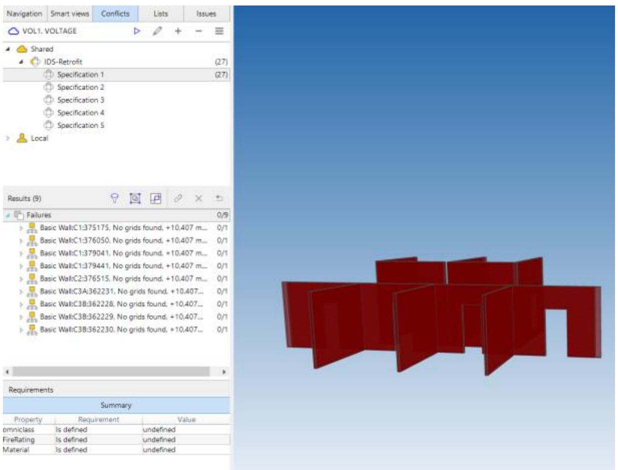


Figure 4: Validation of External Walls

For slabs and floors (Figure), although geometries were present and correctly represented as IfcSlab entities, the absence of material assignments resulted in systematic non-compliance.

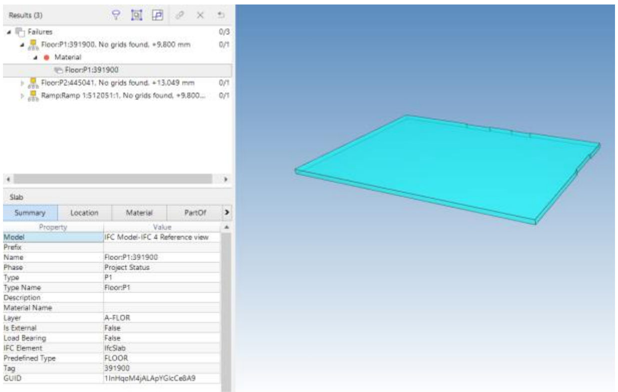


Figure 5: Validation of Slabs/Floors

For windows (Figure), the validation results show that while window geometries and basic dimensional attributes were available, the absence of thermal transmittance properties, particularly U-values prevented compliance with the retrofit-oriented requirements. This suggests that thermal properties were either not defined at the authoring stage or not reliably transferred during IFC export

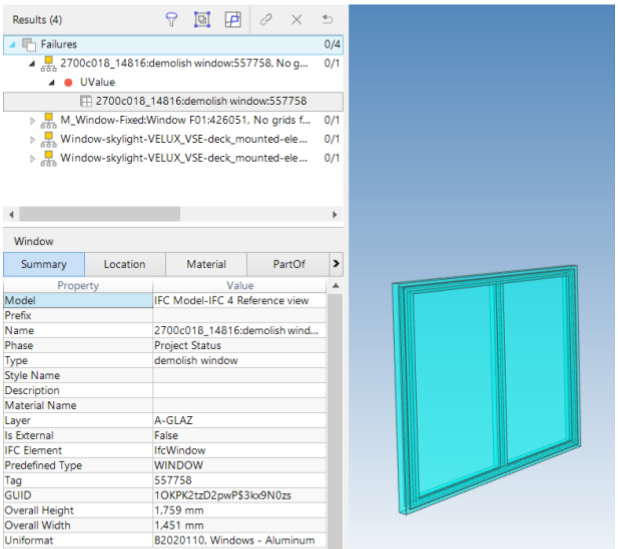


Figure 6: Validation of Windows

For doors (Figure), validation failures were associated with missing thermal transmittance properties and missing or incorrect external applicability information. Even when doors were correctly classified as external and included additional attributes such as fire rating, the lack of thermal performance information resulted in non-compliance with the IDS requirements.

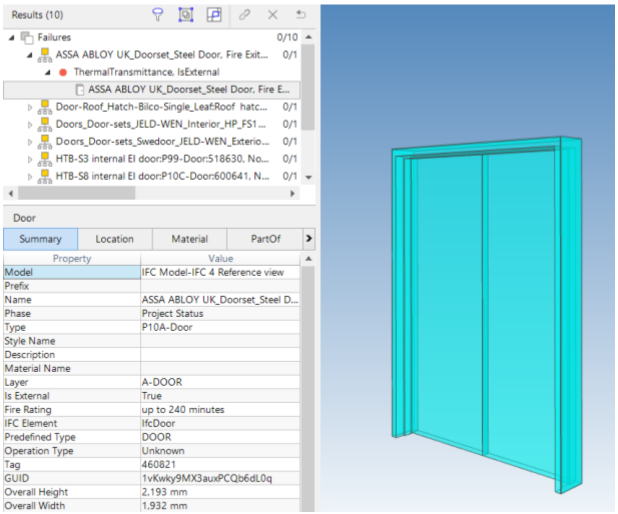


Figure 7: Validation of Doors

Discussion

The validation outcomes highlight a fundamental challenge in using IFC models as a foundation for retrofit-oriented DT workflows: geometric completeness alone does not guarantee data readiness. Although the BIM model provided visually complete representations of envelope elements, the frequent absence of material and thermal properties significantly limits its suitability for retrofit assessment and DT initialization. The findings should be interpreted within the scope of envelope retrofit, as the requirement set does not address system-level or operational retrofit interventions.

The results indicate that IFC data readiness is not solely a technical issue, but also a methodological one related to how information requirements are defined and communicated prior to modelling. In the absence of explicit, use-case-driven requirements, critical attributes such as thermal transmittance and material definitions remain optional, leading to systematic data gaps across the model. This highlights the importance of linking requirement definition to model authoring and export processes rather than relying on implicit assumptions about data availability.

The study also clarifies the role of IDS within the broader process of preparing BIM data for DT use. In this work, IDS was used to validate the minimum set of IFC-embedded information required for the selected use-case. This does not imply that all relevant information must reside within the IFC model. In practice, richer data such as manufacturer-specific product information, material databases, or environmental product declarations may be integrated after the baseline IFC model has been validated. IDS-based validation should therefore be understood as an early quality-control step within a broader workflow that includes model preparation, enrichment, and DT integration. The IDS-based validation approach proved effective in making data deficiencies explicit and traceable. By encoding requirements in a machine-interpretable form, the validation process clearly distinguished between geometric completeness and semantic readiness, identifying missing or incomplete information at the element level. This supports early detection of data gaps before DT integration, where manual correction would otherwise be required.

Despite its advantages, IDS-based validation has several limitations in the context of envelope retrofit-oriented DT workflows. IDS supports verification of the presence and correct assignment of information, but does not assess the accuracy or physical validity of property values. In addition, IDS operates on static IFC data and does not capture dynamic information such as sensor data or operational conditions. Its effectiveness also depends on how models are authored and exported, meaning that variations in modelling practices and export configurations can influence validation outcomes. IDS should therefore be considered a necessary but not sufficient mechanism for ensuring data readiness.

Overall, the results demonstrate that explicitly defined retrofit-oriented information requirements, when validated through IDS, improve transparency regarding IFC data readiness. This enables earlier and more reliable data quality control and provides a practical mechanism for strengthening interoperability between BIM models and DT workflows.

Beyond demonstrating current IDS usage, the study contributes a structured approach for defining and validating minimum information requirements tailored to a specific envelope retrofit use-case.

Conclusion

This study presented an envelope retrofit-oriented approach to assessing IFC data readiness for DT integration using Information Delivery Specifications (IDS). By explicitly defining use-case-specific information requirements and validating them through an automated, standards-based workflow, the study demonstrated how IDS can be used to identify missing and incomplete information in IFC models before DT deployment.

The case study showed that, while the IFC model provided complete geometric representations of envelope elements, essential semantic information, particularly material definitions and thermal performance properties, was frequently absent or only partially defined. Validation results highlight the limitations of relying on visual completeness alone when evaluating IFC models for retrofit-oriented DT workflows.

The findings further indicate that IDS-based validation enables early and repeatable data quality control in a tool-independent manner. They also show that the primary barrier to IFC data readiness is not the data format itself, but the lack of explicitly defined information requirements. By formalizing these requirements in a machine-interpretable form, IDS supports systematic detection of data gaps and facilitates targeted model improvement, reducing the need for manual data correction during later stages of DT integration. This approach provides a practical basis for improving IFC data readiness and supporting DT integration.

This study has limitations: the requirement set focuses on a core subset of retrofit-relevant information rather than a comprehensive specification, and validation was conducted on a single case-study building. While the workflow supports iterative correction of detected issues through model updates and re-validation, the implementation of model corrections and subsequent validation cycles is outside the scope of this study, which focuses on requirement definition and initial data quality assessment. Nevertheless, the proposed workflow is transferable and provides a solid foundation for extending IDS-based validation to broader retrofit scenarios. Beyond demonstrating a practical application, the study provides analytical insights into common patterns of information deficiency in IFC models and highlights the role of explicit requirement definition in improving data readiness.

Future work will expand the requirement scope to additional building systems, integrate semantic linking through the buildingSMART Data Dictionary(bSDD), and explore the combined use of IDS and Information Delivery Manuals (IDM) to better define roles and responsibilities in retrofit-oriented DT workflows.

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Appendix A

Specification 1

External walls
IFC versions: IFC4
The model MUST contain entities that have
- IFC class IFCWALL
- property IsExternal of PSet Pset_WallCommon (IFCBOOLEAN) = true

that MEET the following requirements
- MAY HAVE classification omniclass
- MUST HAVE attribute Name
- MUST HAVE property ThermalTransmittance of PSet Pset_WallCommon (IFCTHERMALTRANSMITTANCEMEASURE) > 0
- MUST HAVE property LoadBearing of PSet Pset_WallCommon (IFCBOOLEAN) = true
- MAY HAVE property FireRating of PSet Pset_WallCommon (IFCLABEL)
- MUST HAVE property NetSideArea of PSet Qto_WallBaseQuantities (IFCAREAMEASURE)
- MUST HAVE property NetVolume of PSet Qto_WallBaseQuantities (IFCVOLUMEMEASURE)
- MUST HAVE any material

Specification 2

Roofs
IFC versions: IFC4
The model MUST contain entities that have
- IFC class IFCROOF
- attribute ObjectType = ROOF

that MEET the following requirements
- MUST HAVE property ThermalTransmittance of PSet Pset_RoofCommon (IFCTHERMALTRANSMITTANCEMEASURE) > 0
- MUST HAVE property IsExternal of PSet Pset_RoofCommon (IFCBOOLEAN) = true
- MUST HAVE property GrossArea of PSet Qto_RoofBaseQuantities (IFCAREAMEASURE)
- MUST HAVE any material

Specification 3

Slabs/Floors
IFC versions: IFC4
The model MUST contain entities that have
- IFC class IFCSLAB
- property IsExternal of PSet Pset_SlabCommon (IFCBOOLEAN) = true

that MEET the following requirements
- MUST HAVE property ThermalTransmittance of PSet Pset_SlabCommon (IFCTHERMALTRANSMITTANCEMEASURE) > 0
- MUST HAVE property IsExternal of PSet Pset_SlabCommon (IFCBOOLEAN) = true
- MUST HAVE any material

Specification 4

Windows
IFC versions: IFC4
The model MUST contain entities that have
- IFC class IFCWINDOW

that MEET the following requirements
- MUST HAVE property UValue of PSet Pset_WindowCommon (IFCLABEL) > 0
- MUST HAVE property IsExternal of PSet Pset_WindowCommon (IFCBOOLEAN) = true
- MAY HAVE property Area of PSet Qto_WindowBaseQuantities (IFCAREAMEASURE)

Specification 5

Doors
IFC versions: IFC4
The model MUST contain entities that have
- IFC class IFCDOOR

that MEET the following requirements
- MUST HAVE property ThermalTransmittance of PSet Pset_DoorCommon (IFCTHERMALTRANSMITTANCEMEASURE) > 0
- MUST HAVE property IsExternal of PSet Pset_DoorCommon (IFCBOOLEAN) = true