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Towards interoperable building energy performance simulation: A digital Twin perspective

Iryna Osadcha [a], Egle Klumbyte [a], Andrius Jurelionis [a], Paulius Spudys [a], Timo Hartmann [b], Shayan Saket [c], Damian Harasymczuk [c], Paris Fokaides [a,d,*]

[a] Faculty of Civil Engineering and Architecture, Kaunas University of Technology, Studentų St. 48, LT-51367, Kaunas, Lithuania
[b] Systemtechnik Baulicher Anlagen, Technische Universität Berlinontecht, Gustav-Meyer-Allee 25, 13355, Berlin, Germany
[c] Contecht GmbH, Dietzgenstraße 40, 13156, Berlin, Germany
[d] School of Engineering, Frederick University, 7, Y. Frederickou St., 1036, Nicosia, Cyprus

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ABSTRACT

Seamless integration between Building Information Modeling (BIM) and Building Energy Performance Simulation (BEPS) plays an important role in the sustainable design and operation of buildings. This study explores the main causes of interoperability issues in the BIM-to-BEPS workflow, highlighting the limitations of the standardization framework and file-based data exchange methods. Analysis of domain-specific ISO standards showed that most focus on organizational processes and overlook semantic interoperability, which is essential for automated data exchange. An experimental evaluation of two BIM-to-BEPS workflows using Autodesk Revit, EnergyPlus, and TRNSYS further confirmed that even when open data standards such as IFC are used, translation errors in both geometry and semantics are common and require significant manual correction. The paper argues that reliance on file-based exchange creates barriers to interoperability and proposes a shift toward semantic web technologies, linked data, and API integration to better support the widespread adoption of Digital Twins.

1. Introduction

With the increasing digitization of the Architecture, Engineering, Construction, Operations (AECO) sector, BIM has become an important source of data to support various simulations that evaluate building design and performance. However, BIM models are static and often do not update frequently after the design stage, making it difficult to assess the operational performance of a building. In this context, Digital Twin technology offers a solution by enabling the management of dynamic multi-source data required for simulations at the Use stage. As Sacks et al. (2020) suggest, a Digital Twin is more than just an evolution of the BIM model; it is a system for organizing data, information, and knowledge about an asset or environment that can be created at any point in time, even in the absence of a BIM model, by collecting and integrating heterogeneous data about the asset or environment [1].

The following definitions are used for the concepts considered in this study. The concept of the Digital Twin was first introduced by Dr. Grieves in 2002 as a "Conceptual Ideal for Product Lifecycle Management". Over time, the terminology evolved, and in 2010, the term "Digital Twin" was officially coined during Dr. Grieves' collaboration with NASA [2]. However, within the AECO sector, it

* Corresponding author. Faculty of Civil Engineering and Architecture, Kaunas University of Technology, Studentų St. 48, LT-51367, Kaunas, Lithuania.

E-mail address: eng.fp@frederick.ac.cy (P. Fokaides).

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remains a broad concept without a standardized definition. The recent ISO/IEC 30173:2023 standard defines a Digital Twin as "*a digital representation of a physical entity, with data connections that facilitate synchronization between physical and digital states at an appropriate rate*" [3]. Although the term is interpreted slightly differently in various publications, they share common elements: a) sensors or measuring devices that capture real-time data; b) a digital replica of the physical entity that updates based on the captured data; and c) the use of this digital replica for visualization, simulation and testing of solutions that can be applied to the physical entity or process [4].

Building Information Modeling, according to ISO 16757–1:2015 standard, is "*the process of constructing a model that contains information about a building for all phases of the building life cycle*" [5]. ISO 29481–1:2016 defines BIM as "*the use of a shared digital representation of a built object to facilitate design, construction, and operation processes to form a reliable basis for decisions*" [6]. In practice, the BIM model is data-rich, object-oriented, and parametric, providing data that meets the needs of different users throughout the building's lifetime. BIM facilitates collaboration between project stakeholders by serving as a centralized source of up-to-date information, ensuring that all parties are working with the same set of data [7].

Building Energy Performance Simulation (BEPS) is governed by the EU Energy Performance of Buildings Directive (EPBD) and the ASHRAE Standard 189, both of which promote the environmental sustainability of buildings. According to Di Biccari et al. (2022), Building Performance Simulation (BPS) is a methodology that uses mathematical models to simulate the performance of a building under specific boundary conditions [8]. The terms BPS, BEPS, and Building Energy Modeling (BEM) are often used interchangeably. For example, the EnergyPlus user manual notes that terms such as Building Energy Modeling, Building Performance Simulation, Building Energy Simulation, and Building Performance Modeling are frequently used to refer to the same concept [8,9]. The interchangeable use of the terms can be confusing, but they generally refer to the application of simulation methods to evaluate a building's design or performance to achieve higher sustainability standards.

According to ISO/IEC 2382:2015 standard, interoperability is defined as "*the ability to communicate, execute programs, or transfer data between different functional units in a way that requires the user to have little or no knowledge of the unique characteristics of those units*" [10]. In the BIM-to-BEPS context, interoperability means that data stored in a BIM model at any stage of its development should be accurately transferred to the BEPS tool without information loss, errors, or the need for manual intervention. In practice, however, this level of interoperability has not yet been achieved, and manual corrections and additional data input or removal are often required to ensure the accuracy of the simulation model.

This study examines interoperability within the BIM-to-BEPS process and how it is defined and addressed in relevant ISO standards in the domains of Digital Twin, BIM and building sustainability. It pays particular attention to terminology and procedural guidance, which set key expectations to be met in practical implementation. To assess how well it is implemented in current practices, two workflows using different software setups were tested. The study addresses the research question: *To what extent do current BIM-to-BEPS workflows fulfill the interoperability requirements outlined in ISO standards, and what gaps persist in enabling effective Digital Twin integration?*

The structure of the paper is as follows: Section 2 presents the background of the study, including an overview of BIM and BEPS software, the concept of interoperability within the BIM-to-BEPS process and Digital Twins, and domain-specific standardization. Section 3 explains the research methodology. Section 4 details the analysis of ISO standards, focusing on terminology and procedures that enable interoperability. Section 5 describes the experimental evaluation of interoperability in the BIM-to-BEPS process. Section 6 presents the verification and validation of results, evaluating the practical alignment between formal standardization efforts and BIM-to-BEPS data transformation. Finally, the conclusion summarizes the implications and limitations of the study and suggests directions for future research.

2. Background

2.1. BIM and BEPS software

The BIM-based BEPS process, unlike traditional simulation methods that create an energy model from scratch, uses a BIM model

Table 1
Overview of BIM software.

BIM Software	Type	Developer	Platform	Data Exchange Formats
Autodesk Revit	BIM	Autodesk	Desktop	IFC, gbXML, RVT, DWG, DGN, COBie
Graphisoft Archicad	BIM	Graphisoft (Nemetschek Group)	Desktop	IFC, gbXML, PLN, DWG, DXF
Rhino + Grasshopper	BIM-lite	Robert McNeel & Associates (TLM, Inc.)	Desktop	IFC (via plugins), 3DM, OBJ, STL, gbXML (via Ladybug)
SketchUp	BIM-lite	Trimble Inc.	Desktop/Web	IFC (via plugin), SKP, gbXML
Solibri	BIM Quality Assurance/Control	Solibri (Nemetschek Group)	Desktop	IFC, BCF, SMC
xBIM	BIM	Open source	Web-based/APIs	IFC, BCF
Twinmotion	Visualization/BIM	Epic Games	Desktop	FBX, SKP, C4D, OBJ, DirectLink from Revit/Archicad

that already includes building design, materials, and technical systems data to generate the BEPS input file. Two types of BEPS software can be used for analysis and optimization of the energy performance of a building: conventional and advanced [7]. Conventional simulation tools use programming languages and numerical methods to generate the model and run the simulation; advanced tools use equation-based modeling and object-oriented languages such as Modelica. From a software architecture perspective, BEPS tools often consist of two main components: a graphical user interface (GUI) and a simulation engine. GUIs, such as OpenStudio or DesignBuilder, provide an interface for the modeling, while simulation engines, such as EnergyPlus, perform the underlying calculations. Based on the simulation engines used, software can be divided into two groups: those using the calculation engines developed by the US Department of Energy (DOE), such as EnergyPlus, and those using proprietary engines, such as IES-VE or TRNSYS. Tables 1 and 2 present an overview of commonly used BIM and BEPS software, including the platforms they operate on (desktop or web-based) and the data exchange formats they support.

Required data inputs and simulation assumptions may differ across various BEPS tools. In general, an energy simulation software requires data on the building structure (geometry, materials, thermal characteristics, spaces, and thermal zones), HVAC system data, location and associated weather data, and boundary conditions for simulation. Other required inputs may include occupancy data, operation schedules, or data on specific HVAC components. BEPS tools may rely on white-box modeling (physical models), which provides good prediction accuracy without the need for additional measurement data [11]. However, physical models have limitations when it comes to dynamic performance modeling [12]. As a result, gray-box models are increasingly being used, as they integrate building monitoring data to provide a more comprehensive analysis.

BIM is widely used in practice and contains much of the information needed for BEPS. As shown in Tables 1 and 2, major vendors such as Autodesk or Nemetschek Group are attempting to facilitate seamless data transfer and enable interoperability between software. However, this integration is still largely locked within their proprietary suites. In practice, mapping data from exchange files (such as IFC or gbXML) into a format suitable for the simulation engine is a common approach [13]. IFC and gbXML are commonly used data exchange formats in the BIM-to-BEPS process. They serve as open standards for interoperability but differ in their focus and

Table 2
Overview of BEPS software.

BEPS Software	Developer	Platform	Simulation Engine	Engine Type	Simulation Approach	Data Exchange Formats
IDA ICE	EQUA Simulation AB	Desktop	IDA Simulation Kernel	Proprietary	Advanced	IDA format, XML, IFC, gbXML (via import)
Autodesk Green Building Studio	Autodesk	Web-based	EnergyPlus (cloud-based)	DOE	Conventional	gbXML
Autodesk Insight	Autodesk	Web-based	EnergyPlus	DOE	Conventional	gbXML, RVT
DesignBuilder	DesignBuilder Software Ltd	Desktop	EnergyPlus	DOE	Conventional	IDF (EnergyPlus), gbXML, IFC (limited)
TRNSYS	Univ. of Wisconsin + TESS	Desktop	TRNSYS Kernel	Proprietary	Advanced (modular, with FORTRAN components)	TRNSYS-specific (*.Tpf, *.Inp), CSV
OpenStudio	NREL	Desktop	EnergyPlus	DOE	Conventional	IDF, gbXML, IFC (via plugin), OSM
EnergyPlus	U.S. Department of Energy	Desktop (Command Line Interface)	EnergyPlus	DOE	Conventional	IDF, epw (weather), CSV
EcoDesigner/STAR	Graphisoft	Desktop (plugin)	VIP-Energy	Proprietary	Conventional	gbXML, IFC
IES-VE	Integrated Environmental Solutions	Desktop	Apache Sim	Proprietary	Conventional	gbXML, IFC, IDF, DXF
TRACE 700	Trane Technologies	Desktop	TRACE Simulation Engine	Proprietary	Conventional	gbXML, IDF, DXF
Lesosai	E4tech Software SA	Desktop	Lesosai Engine	Proprietary	Conventional	gbXML, XML
RIUSKA	Granlund Group	Desktop	IDA Simulation Kernel	Proprietary	Advanced	gbXML, IFC (via Archicad), XML
ESP-r	Univ. of Strathclyde	Desktop	ESP-r Simulation Engine	Open source (low maintenance)	Conventional	ESP-r native, CSV, limited IFC
cQUEST	cove.tool Inc.	Web-based	EnergyPlus	DOE	Conventional	gbXML, IFC, IDF
Simergy	Digital Alchemy + LBNL	Desktop	EnergyPlus	DOE	Conventional	IDF, IFC, gbXML
Ladybug Tools	Open source	Desktop (Grasshopper)	EnergyPlus (via OpenStudio)	DOE	Conventional	gbXML, EPW, IDF (via EnergyPlus)
TAS	EDSL	Desktop	TAS Simulation Kernel	Proprietary	Conventional	gbXML, IDF, IFC
OpenBuildings Energy Simulator (pr. Hevacomp)	Bentley Systems	Desktop	EnergyPlus	DOE	Conventional	gbXML, IDF, DXF

structure. gbXML is specifically tailored for energy modeling, while IFC is a broader schema that includes a wide range of asset-related information [7].

2.2. Interoperability in the BIM-to-BEPS process

When discussing interoperability in the BIM-to-BEPS process, we refer to the exchange of information between different software platforms, essentially, interoperability between information systems, or system-to-system interoperability, as defined by Turk (2020) [14]. However, from a systems theory perspective, interoperability can be understood more broadly. Systems may also involve people, which introduces a distinction between technical (system-to-system) and non-technical interoperability (person-system or person-person). This classification, outlined by Turk (2020), is also reflected in other frameworks. For example, the New European Interoperability Framework describes four levels of interoperability: legal, organizational, semantic, and technical [15]. In these terms, the legal and organizational levels involve human interactions. In the AECO sector, the focus has traditionally been on technical or system-to-system interoperability. Achieving system-to-system interoperability requires a common language and unified processes, which in turn demand standardization [14]. One way to implement this is through the use of open standards that are accessible and required for use.

Several taxonomies describing different types and levels of information system interoperability are summarized in Table 3, along with examples of software used in the BIM-to-BEPS process.

Currently, BIM-to-BEPS information exchange heavily relies on open standards such as IFC. IFC, developed and maintained by buildingSMART (formerly the International Alliance for Interoperability), is a globally adopted standard for data exchange in the AECO. The IFC schema represents a monolithic data model designed to cover all aspects of the domain. This provides significant benefits, including semantic consistency and internal data compatibility, but also leads to a high complexity, as it covers the entire spectrum of the built environment, from buildings to roads, railways, bridges, tunnels, geotechnical assets, ports, and waterways (as of IFC 4.4). It also includes a range of relevant domains, such as HVAC or building controls, which contribute to its size and complexity [18]. Initially, IFC was encoded using the EXPRESS modeling language based on ISO 10303–11:2004, with XML used for property set templates [19]. Due to its underlying EXPRESS architecture, IFC is not limited to file-based information exchange; however, file-based exchange remains the primary method of data transmission. Additionally, the IFC mainly addresses information related to the building design phase and lacks a straightforward approach to integrate as-built data and dynamic information from the Use stage [4,18].

Despite the significant contribution of IFC to information exchange in the AECO sector, the schema is frequently criticized, a concern likely to grow as the volume and diversity of built environment data continue to increase. The rigid structure of IFC limits the ability to easily extend or incorporate new data, creating a bottleneck in data flow across the multidisciplinary AECO domain [20]. Earlier efforts to support use case-based IFC information exchange led to the development of the Model View Definition (MVD) concept, which was also widely explored in BIM-to-BEPS processes. Several MVDs were created, such as the Energy Analysis View, Space Boundary Addon View, Architectural Design to Building Energy Analysis, Indoor Climate Simulation to HVAC Design, Curtain Wall Design to Energy Analysis, Architectural Design to Thermal Simulation, and Nordic Energy Analysis. However, although it was possible for stakeholders to create their own MVDs as use-case-specific subsets of IFC, challenges such as limited interoperability across MVDs and the necessity for software vendors to implement these views hindered widespread adoption. As a result, many remained at

Table 3
Taxonomies of information system interoperability.

Source	Taxonomy	Description	Software Example
Petrie, 1992 [16]	Federated systems	No automation. Each system has its own data model. Manual interfacing between the systems	Autodesk Revit + EnergyPlus
	Unified systems	Semi-automated data exchange using translators. Common syntax and semantics, but systems still maintain their own data models	Graphisoft Archicad + IES-VE
	Integrated systems	Full integration and automation. A single, shared data model across systems	Autodesk Revit + Autodesk Insight
Levels of Information Systems Interoperability (LISI), US Department of Defense, 1998 [17]	Level 0 - Isolated	No connectivity or automation. Systems don't exchange data. Manual information exchange	Autodesk Revit + MS Excel
	Level 1 - Connected	Systems are connected via proprietary formats. Homogeneous data is shared	Autodesk Revit + Autodesk Green Building Studio
	Level 2 - Functional	Systems work together using translators to share heterogeneous data. Application-level integration	OpenStudio + EnergyPlus
	Level 3 - Domain	Integrated databases with common environments. Multi-tool collaboration within a Common Data Environment	Autodesk Revit + DesignBuilder
	Level 4 - Enterprise	Full cross-domain collaboration and data exchange across multiple domains	Autodesk Revit + BIM 360 + Autodesk Insight
Turk, 2020 [14]	Interfaced systems	Manual or semi-automated interfaces with custom translators for each connection	Autodesk Revit + IDA ICE
	Loosely coupled systems	Common schemas are used to translate data between systems. Each system retains independence	Autodesk Revit + TRNSYS
	Tightly coupled systems	Systems share a unified schema and function as parts of a single ecosystem	SketchUp + OpenStudio

the proposal or draft stage, lacking standardization and broad use [21]. Currently, buildingSMART recommends the use of Information Delivery Specification (IDS) to define machine-interpretable exchange requirements for each specific use case.

Although the use of open data exchange formats aims to enhance system-to-system interoperability, the principle that "what is sent is the same as what is understood" remains unmet. Numerous studies consistently report recurring issues in BIM-to-BEPS data transmission related to geometry representation and semantic data. A study by Di Biccari et al. (2022), which reviewed 103 publications on BIM-to-BEPS interoperability, found that 64 % reported geometry-related problems. Additionally, 38 % of the studies reported semantic issues [8]. Another study by Kamel et al. (2019) categorized errors resulting from the file-based exchange of information through IFC into three types: syntax, semantics, and visualization [11].

Frequent interoperability issues in the BIM-to-BEPS process, as reported in the publications, are summarized in Table 4. The publications were selected from the Web of Science Core Collection using a query: *(((AK=(Building Information Modeling OR BIM OR Building Energy Performance Simulation OR BEPS OR Industry Foundation Classes OR IFC OR Building Energy Modeling OR BEM OR Building Performance Simulation OR BPS OR Data Exchange OR interoperability)) AND LA=(English)) AND DT=(Article) AND OA=(Open Access) AND PY=(2015–2024))*.

From the reviewed studies, several barriers in the BIM-to-BEPS process have been identified:

1. *Lack of seamless workflows in commonly used BIM-to-BEPS toolchains.* EnergyPlus and Autodesk Revit are the most commonly used BEPS and BIM software respectively. However, this workflow includes intermediate steps. Geometry is typically converted using GUIs, as EnergyPlus does not provide a visualization interface. Frequent use of alternative tools such as SketchUp to simplify geometry modeling highlights the need for more streamlined workflows.
2. *File-based data exchange.* IFC remains the main exchange format but presents challenges in both geometry and semantics. Nearly all analyzed studies reported persistent geometric errors, such as inaccuracies in 2nd level spatial boundary representations, spatial hierarchies, and unenclosed zones. These issues arise because the BIM model, while rich and detailed, is not inherently designed for

Table 4
Interoperability issues reported in publications.

Paper	Objective of Research	Building LC Stage	BIM software	BEPS software	Data Exchange Format	Other Software	Interoperability Issues
[22]	The BACN2BIM tool to link Building Automation and Control Networks with BIM	Use	N/D	N/D	IFC	ThingBoard, PostgreSQL	Errors in geometry accuracy
[23]	Methodology for sustainable re-design using BIM, point clouds, and energy simulation	Design for renovation	Autodesk Revit	EnergyPlus	IFC, IDF	Faro Scene	The study acknowledges a lack of interoperability, but does not specify the errors
[24]	Synthetic data set based on energy and thermal simulation for an ANN training	Use	Sketchup	TRNSYS17	IDF	TRNBuild, MS Power BI	Manual creation of the model's geometry
[25]	Potential of graph and computational geometry processing to reduce IFC requirements for energy modeling	Use, Design for renovation	Autodesk Revit	Energy Plus	IFC	Bimeo FC ARtoBuild	Overlapping walls, redundant segments, errors in surface connections
[26]	MVD for BIM to BEPS information exchange	N/D	N/D	EnergyPlus	IFC	IfcDoc, Modelica	Errors in geometry representation
[27]	The Common Boundary Intersection Projection algorithm for generation 2nd level space boundary topology	N/D	Autodesk Revit	Not specified	IFC	Solibri Model Checker	Errors in 2nd level space boundaries
[28]	The method of automatic processing of 3D thermal clouds to generate a semantic model	Use	Autodesk Revit	TRNSYS, EnergyPlus	gbXML, IDF	DesignBuilder, CloudCompare	Errors in geometry accuracy
[29]	The methodology to extend IFC with energy concepts, including the PHPP	Design, Use	Autodesk Revit	N/D	IFC, gbXML	MS Excel	Loss of information, geometrical inaccuracies
[30]	Methodology and tool for direct translation of BIM to BEPS	Design	Autodesk Revit	N/D	IFC	Modelica, IfcOpenShell	Loss of semantic data, missing information on material properties, errors in connections between entities
[31]	Case study research on the potential and shortcomings of BIM-to-BEM	Design, Use	Autodesk Revit, SketchUp	EnergyPlus	gbXML, IDF	N/D	Errors in thermal zone boundaries, manual addition of material properties, doubled surfaces, errors in boundary conditions of zones

energy simulation. Increasing the accuracy of the geometry tends to improve the simulation results, but most BEPS tools rely on a simplified representation of the building [32]. This creates a trade-off between the richness of the BIM model and the required level of simplification. To address this, the concept of MVDs has been broadly explored for creating energy-specific subsets of BIM [26, 29]. Despite these efforts, including several IFC extensions in the HVAC, electrical, and building control domains, IFC remains unsuitable for direct energy simulation. As a result, numerous custom algorithms and plug-ins have been developed to perform similar functions, yet none have achieved widespread adoption among practitioners.

3. *Graph-based methods in BIM-to-BEPS are promising but limited in handling geometry.* Graph-based data models are gaining increasing interest in the energy domain. These models offer more flexibility in managing dynamic building data, which is often stored in "flat" formats such as CSV. Additionally, they eliminate the need for direct file-based information exchange. For example, Mediavilla et al. (2023) proposed a methodology that uses graph representations and computational geometry processing to reduce reliance on IFC files [25]. However, while ontologies and knowledge graphs can efficiently handle semantic information, challenges related to geometry representation persist.
4. *AI-driven methods in BIM-to-BEPS are promising but immature.* The increasing influence of AI across various sectors is also affecting BIM-to-BEPS processes. For example, Santos-Herrero et al. (2022) proposed a methodology that uses ANNs as a predictive model based on operating temperatures and energy consumption data. This reliance on the predictive model reduces the need for frequent energy simulations [24]. While promising to improve the BEPS process, this approach remains largely experimental.
5. *Processing and semantic enrichment of scan-based data remain semi-automated.* The need to improve the energy efficiency of buildings with long operational histories has led to energy simulation being frequently used during the Use and Renovation stages. As a result, laser scanning and thermal imagery are seen as promising solutions for gathering information when updated documentation is unavailable [23,28]. Although these techniques are not new, they still face challenges related to raw data processing, object recognition, and the lack of semantic information, often requiring extensive manual intervention.

2.3. Interoperability and simulation in digital twins

According to the ISO/IEC 30173:2023, simulation is one of the core technologies used to create and operate a Digital Twin with predictive capabilities [3]. Unlike stand-alone simulations, Digital Twin offers broader opportunities to evaluate the performance of the building from multiple perspectives [33]. Yeung et al. (2022) proposed criteria for evaluating simulation capabilities in Digital Twin [34], which are adopted in Table 5.

To connect the data in Digital Twins, existing approaches range from schema-less storage in native formats to the use of semantic web technologies and linked data. Given the heterogeneity of the information that Digital Twins may incorporate, monolithic data models are often insufficient. Instead, this complexity can be better managed through multiple smaller and interconnected ontologies [18]. From the perspective of the Data – Information – Knowledge – Wisdom (DIKW) pyramid, the data layer in Digital Twin may consist of raw time-series data collected by sensors or smart meters. ISO/TR 23262:2021 standard defines data as "*a reinterpretable representation of information in a formalized manner suitable for communication, interpretation, or processing*" [35]. Time-series sensor data is often stored and managed in "flat" formats, such as tables with large numbers of records. Due to the lack of a defined schema, raw data does not have a meaningful structure [4]. While it offers some degree of flexibility, they are not sufficiently interoperable and must be structured and analyzed by the user before being used in simulations. Only processed and analyzed data can form the information layer. ISO/TR 23262:2021 similarly defines information as *"meaningful data"* [35].

An increasing number of studies are focusing on the use of knowledge graphs to integrate real-time sensor data with contextual building information [36–38]. Earlier, Pauwels et al. (2017) highlighted the potential of the semantic web and linked data to enhance interoperability in the AECO industry [39]. While interoperability can be enabled through use-case-specific and vendor-neutral information exchange, ontological modeling supports cross-domain linking. According to Pauwels et al. (2017), interoperability refers to the ability to exchange the same content across multiple applications, whereas linking across domains involves combining different content from multiple applications [39]. Ontologies provide a formal, machine-readable specification of a domain. In the BEPS field, several ontologies have been developed, such as the Building Performance Ontology (BOP), Digital Construction – Energy Ontology (DICES), BIMERR Key Performance Indicator Ontology, and Smart Energy Aware Systems (SEAS), among others. To promote ontology

Table 5
Criteria for simulation in Digital Twins.

Primary Criteria		Secondary Criteria	
Relevance	degree to which the output of the simulation tool meets its intended purposes	Flexibility	simulation's capacity to adapt its structure and its modularity
Explainability	ease of results interpretation	Extensibility	ease of adding and modeling new components
Comprehensiveness	accounting for predicted and unexpected changes in building behavior	Calibratability	number of simulation parameters that can be adjusted based on updated information
Resolution	level of detail in breaking down systems into individual components	Automatability	degree to which the processes of modeling, extending, and calibrating can be automated
Fidelity	accuracy of the emulation of the characteristics and the behavior of the building	BIM Integration	the amount of BIM-derived data used in simulation
Reusability	versatility across building types, technical systems, life cycle stages, and geographic locations		

reuse, several services have been created, such as "Smartcity.linkeddata.es" - ontology catalogues for smart cities and related fields (e.g., energy, buildings) [40], as well as volunteer-driven initiatives such as "Existing Smart Building Domain Ontologies Comparison" [41]. However, these services are not actively maintained and updated. Although ontologies offer a promising solution for addressing semantic interoperability, challenges remain in the geometric representation. While there are ontologies that provide structures for describing geometry and topology, such as the Ontology for Managing Geometry (OMG), File Ontology for Geometry formats (FOG), Building Element Ontology (BEO), and Building Topology Ontology (BOT), the process of converting geometry from IFC to graph remains complex [42,43].

2.4. Domain-specific standardization

Standardization is seen as a key approach to improving productivity by defining common working practices and a basis for collaboration. However, despite the intention of the standards to provide clarity in work processes, both practitioners and academics often struggle to understand the evolving relationships between standards and how they can be applied to support their daily activities [44,45]. In addition, the increasing number of standards makes it difficult to stay up-to-date with the terminology and concepts they specify.

According to Laakso et al. (2012), a standard is defined as an approved specification that offers a limited set of solutions to current or potential problems [46]. These solutions are developed to meet the needs of stakeholders and are intended for repeated or continuous use. In technical fields, standards are developed in close connection with the technology. Standardization can occur early or late in relation to the maturity of the technology. Early standardization can shape and potentially limit the evolution of technology, while late standardization tends to be more constrained by existing industry practices and interests. De Vries et al. (2006) classify standards based on their relationship to technology development as anticipatory, concurrent, or retrospective, depending on whether they guide the creation of new solutions or formalize existing ones [47].

According to Turk (2020), standardization is most applicable to open information systems that clearly document how they exchange information and interact with other systems [14]. However, software vendors often tend to keep systems closed, enabling interoperability only within their ecosystems. This creates significant challenges for achieving interoperability across multi-vendors platforms. Table 6 presents various levels of interoperability in information systems, along with examples from the BIM-to-BEPS process.

In the AECO industry, national standards developed by local bodies have traditionally played a dominant role. Founded in 1947, the International Organization for Standardization (ISO) is the world's largest standards development organization and publisher of international standards. For the Digital Twin domain, relevant standards are developed by the ISO/TC 184/SC 4 and ISO/IEC JTC 1/SC 41 committees. In the context of BIM, standards are developed by the ISO/TC 59/SC 14, ISO/TC 59/SC 13, ISO/TC 59/SC 17, and ISO/TC 10/SC 8 committees. For building sustainability, energy and thermal performance, standards are mainly developed by the ISO/TC 163/SC 2, ISO/TC 163/SC 3, ISO/TC 178, ISO/TC 205, ISO/TC 267, ISO/TC 59/SC 14, and ISO/TC 59/SC 17 committees.

3. Research methodology

The study adopts a mixed-methods approach, combining ISO standards analysis with a practical assessment of interoperability in a BIM-to-BEPS process. The methodology consists of three main phases: 1) collection and analysis of ISO standards, 2) experimental assessment of interoperability in the BIM-to-BEPS process using two software combinations (with and without an intermediate GUI), 3) verification and validation (comparing the experimental findings with results derived from standard analysis).

3.1. ISO standards collection and analysis

In the first phase, an analysis of ISO standards was performed to identify documents relevant to the study domains: Digital Twin, BIM, and BEPS. BEPS-related standards were interpreted as those concerning sustainability in the built environment, including energy

Table 6
Levels of interoperable systems.

Level	Description	Example
Closed	Data model and file format are proprietary, controlled by the vendor, and not publicly available. Interoperability is limited to the vendor's ecosystem	Autodesk DWG, RVT; Bentley DGN
Open	File format specification is published by the vendor, allowing limited third-party support. The data model may still be proprietary	Autodesk DXF, SketchUp SKP
Machine-readable	Structured and parseable data formats with clearly defined schemas. While not necessarily standardized, they can be interpreted and used by machines without manual intervention	XML, JSON, EXPRESS
Semantic/Ontology-based	Utilizes shared vocabularies and ontologies based on linked data principles. Enables semantic interoperability by allowing machines to interpret data meaning, reason across domains, and support automated querying	RDF, OWL, IfcOWL
Industry standard	Widely adopted within the industry and supported by multiple tools, but not officially standardized by international bodies. Often initiated by industry consortia	gbXML
International standard	Formally standardized and maintained by international standards organizations. Promoted or required to use	IFC (ISO 16739)

efficiency, building performance evaluation, and environmental data exchange. Only international standards published by the ISO were considered. Standards developed by national standardization bodies or the European Committee for Standardization (CEN) were excluded. Relevant ISO standards were manually retrieved from the ISO Online Browsing Platform and classified according to:

- Standard identification (number, title, year of publication)
- Responsible technical committee
- Relevance to the study domains (DT, BIM, BEPS)

A qualitative content analysis was used to assess how each standard engages with the concept of interoperability. This involved manual review of the full text of each standard and categorization of its content according to the following parameters:

- *Core principles*: explicit or implicit references to interoperability. Explicit references include direct mention of interoperability requirements or objectives. Implicit references suggest interoperability through descriptions of integration, data exchange, or system collaboration, even if the term itself is not used.
- *Procedures for enabling interoperability:* whether the standard offers mechanisms or guidelines to support data exchange. This includes references to modeling schemas, specification of data exchange formats or interface requirements.
- *Terminology and definitions:* whether the standard provides a definition of interoperability. Definitions were classified into four clusters: unique (original or divergent from other sources), identical (precisely matches a referenced standard), synonymous (similar in meaning but slightly rephrased), and conflicting (conceptually inconsistent with the other standards).
- *Geometry support:* evaluation of whether the standard acknowledges or provides guidance for exchanging geometric data or geometric accuracy requirements.
- *Semantic structure*: evaluation of whether the standard defines semantic data schemas, classification systems, or metadata descriptors to support machine readability.

To identify and visualize relationships among standards, a graph-based network analysis was conducted using Gephi software. Standards from other domains were included in the graph if they were normatively referenced or cited at least twice across all standards under review. This network approach enabled the discovery of mediating standards, i.e., those not directly linked to the study domains but acting as bridges between other documents.

3.2. Experimental assessment of interoperability in the BIM-to-BEPS process

The second phase of the study focused on the practical examination of interoperability between BIM and BEPS software. The objective was to identify errors in data flow arising from insufficient interoperability. Two workflows were tested:

- Procedure 1: Autodesk Revit → Autodesk Green Building Studio/Insight → SketchUp → EnergyPlus
- Procedure 2: Autodesk Revit → Custom C# parser (xBIM Toolkit) → TRNSYS

The experimental workflow was divided into four stages: 1) retrieval of data from the BIM model, 2) transformation and evaluation of the exported model, 3) configuration of the simulation model, and 4) finalization of the energy model. At each stage, data transfer errors were classified into two categories: geometric and semantic. To evaluate the level of manual interventions required at each stage, the process support was categorized as manual, semi-automatic, or automated.

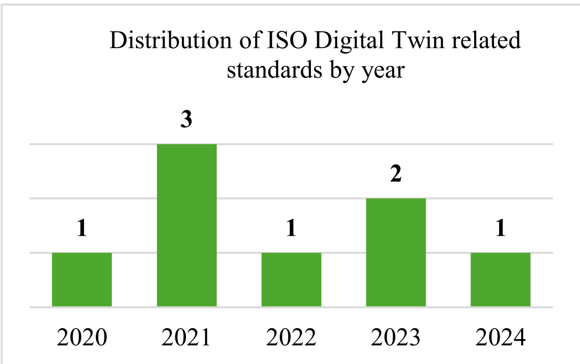

Fig. 1. Distribution of the ISO Digital Twin-related standards by year.

3.3. Verification and validation

The final phase involved examining whether the principles and procedures outlined in standards were implemented in software-based data exchange. Based on a qualitative analysis of ISO standards, key expectations regarding interoperability were identified: 1) support for standardized data exchange formats, 2) provision of a semantic structure, and 3) accurate geometric data translation. The errors identified during the experimental assessment were analyzed and linked to the theoretical expectation. As a result, gaps between the standardization framework in the domain and current practices, as well as potential pathways for improving interoperability, were highlighted.

4. ISO standards analysis

To analyze how the concept of interoperability is addressed in standards, a total of 154 ISO standards were manually selected from the ISO website and distributed across the paper's domains. The distribution of the standards by year of publication and by responsible technical committee is presented in Figs. 1–6.

The initial screening of standards included Contents, Scope, Normative References, and Terms and Definitions sections. This step helped to assess the relevance of each document before full-text analysis. A total of 26 ISO standards were included in the final dataset, as shown in Table 7. The main inclusion criterion was the presence of either explicit or implicit references to the concept of interoperability. Subsequently, a qualitative content analysis was conducted. The results of the qualitative analysis are presented in two summary tables: Table 8 provides results related to Core Principles and Procedures for enabling interoperability; Table 9 presents results related to Terminology, Geometry, and Semantics. To visualize interconnections between standards, a network graph was created (Fig. 7). The network includes not only the standards within the scope of Digital Twin, BIM, and BEPS domains, but also additional ISO standards frequently referenced in the Normative References section (Table 10).

4.1. Terminology and definitions across ISO standards

4.1.1. General definition

The definition of interoperability as *"the ability of two or more systems or applications to exchange information and to mutually use the information that has been exchanged"* is consistently found across several ISO/IEC standards: ISO/IEC 30173:2023 [3], ISO/IEC 20924:2024 [48], and ISO/IEC TR 30172:2023 [49]. Each of these references earlier sources: ISO/IEC 22123–1:2023 [50] or ISO/TS 27790:2009 [51]. Ultimately, all trace the definition back to the IEEE Standard Computer Dictionary (1990) [52].

Similarly, ISO/TR 23262:2021 defines interoperability as "*the capability of two or more functional units to process data cooperatively"* [35]. This aligns with the broader interpretation provided by ISO/IEC 2382:2015, which describes interoperability as *"the capability to communicate, execute programs, or transfer data among various functional units in a manner that requires the user to have little or no knowledge of the unique characteristics of those units"* [10]. This standard replaced the earlier ISO/IEC 2382–1:1993 "Information technology - Vocabulary Part 1: Fundamental terms", while retaining the original definition of interoperability.

4.1.2. Types of interoperability

ISO/IEC 20924:2024 provides a definition of *transport interoperability* as *"interoperability where information exchange uses an established communication infrastructure between the participating systems, including between components of an IoT system"* [48]. This definition is sourced from ISO/IEC 19941:2017 [53]. Notably, while ISO/IEC 20924 provides definitions for general and IoT-specific terms, it omits a Digital Twin-specific interpretation. ISO/IEC 19941:2017 further defines different types of interoperability, which are later adopted in ISO/IEC 22123–1:2023. These include [53]:

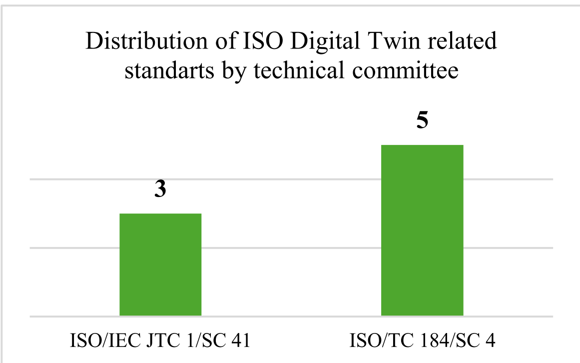

Fig. 2. Distribution of the ISO Digital Twin-related standards by technical committee.

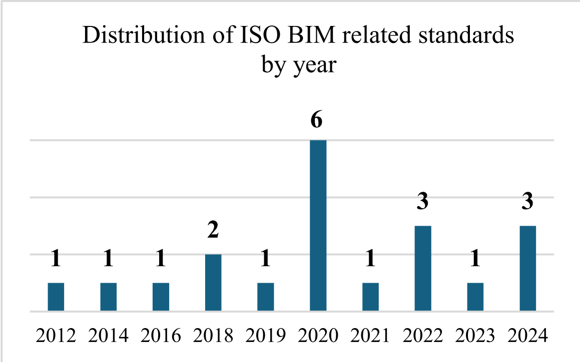

Fig. 3. Distribution of the ISO BIM-related standards by year.

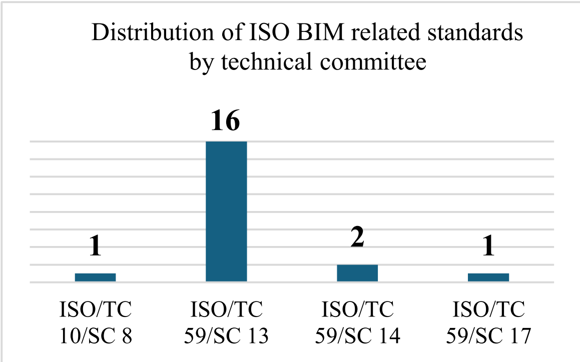

Fig. 4. Distribution of the ISO BIM-related standards by technical committee.

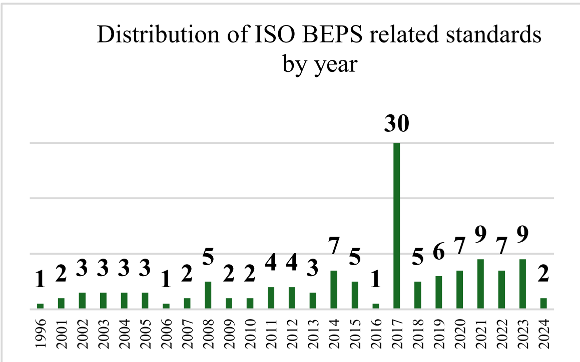

Fig. 5. Distribution of the ISO BEPS-related standards by year.

- *Cloud interoperability:* ability of a cloud service customer's system to interact with a cloud service, or the ability for one cloud service to interact with other cloud services, by exchanging information according to a prescribed method to obtain predictable results.
- *Syntactic interoperability:* the formats of the exchanged information can be understood by the participating systems.
- *Semantic data interoperability:* the meaning of the data model within the context of a subject area is understood by the participating systems.
- *Behavioural interoperability:* the actual result of the exchange achieves the expected outcome.
- *Policy interoperability:* compliance with the legal, organizational, and policy frameworks applicable to the participating systems.

4.1.3. Inconsistency in definitions

A definitional inconsistency arises in ISO/TR 23262:2021, which defines *semantic interoperability* as *"the capability of two or more systems to communicate and exchange data through specified data formats and communication protocols"*. It cites ISO 18308:2011 as its

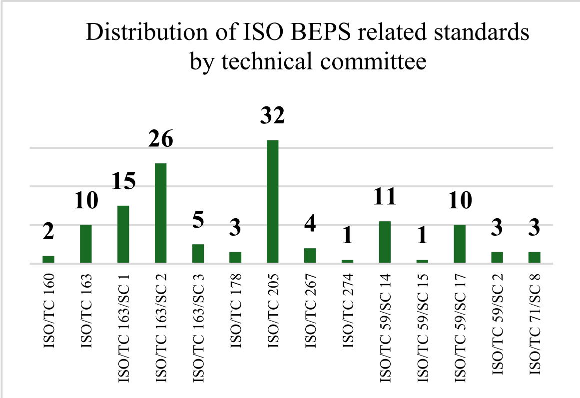

Fig. 6. Distribution of the ISO BEPS-related standards by technical committee.

Table 7
Initial screening and final dataset of ISO standards.

Number of ISO standards	Digital Twin-related	BIM-related	BEPS-related	∑
Initial dataset	8	20	126	**154**
Final dataset	5	12	9	**26**

source. However, according to ISO 18308:2011, *semantic interoperability* is actually *"the ability for data shared by systems to be understood at the level of fully defined domain concepts"* [54]. The cited definition corresponds instead to *syntactic interoperability*. This suggests a misinterpretation or citation error within ISO/TR 23262:2021.

Some other analyzed standards provide domain-specific interpretations of interoperability. ISO 23247–2:2021 defines interoperability as a function of "Interoperability support Functional Entities", which enables integration between digital twins and other systems such as ERP and PLM [55]. ISO 16484–1:2024 defines interoperability as *"a seamless interworking of devices and functions in a system and the ability of the system to work with or use the parts or equipment of another system"* [56]. Previously, ISO 16484–2:2004 defined interoperability as *"the capability of devices of different types and from different manufacturers to exchange information and commands over a communication network"* [57]. However, this standard has been withdrawn and replaced by ISO 16484–2:2025, in which the definition of interoperability is no longer included [58].

4.2. *Procedures to enable interoperability*

In the dataset analyzed, 15 ISO standards outline various procedures with differing levels of detail to support interoperability. We classified these standards based on the specific type of interoperability they aim to facilitate. To ensure clarity, we use the interoperability model defined in the New European Interoperability Framework, which provides the following definitions [15]:

- *Organizational interoperability* means documenting and integrating or aligning business processes and the relevant information exchanged.
- *Semantic interoperability* ensures that the precise format and meaning of exchanged data and information are preserved and understood between parties. The semantic aspect refers to the meaning of data elements and the relationship between them (vocabularies and schemes). The syntactic aspect refers to describing the exact format of the information to be exchanged.
- *Technical interoperability* covers the applications and infrastructures linking systems and services; this includes interface specifications, interconnection and data integration services, and communication protocols.

4.2.1. *Organizational interoperability*

Half of the standards in the dataset (7 ISO standards) provide guidelines for enabling interoperability among various stakeholders involved throughout the building lifespan. In the *BIM domain*, ISO 19650–4:2022 provides general guidelines to ensure the quality of information exchange [59]. It outlines key criteria such as conformance, continuity, communication, consistency, and completeness. While it encourages the use of common data environments, open schemas (e.g., IFC), and open data formats, it does not define specific implementation procedures. ISO 29481–1:2016 establishes a link between construction business processes and the information required at different stages of a building's lifecycle [6]. It focuses on the use of the Information Delivery Manual (IDM) and MVD, and it also emphasizes the role of metadata to support machine readability. ISO 29481–2:2012 addresses stakeholder collaboration in building construction projects using IDM. It includes an interaction framework and templates to support structured information exchange [60]. ISO 19650–2:2018 provides guidance on defining informational requirements during the delivery phase of construction

Table 8
Content analysis: interoperability concept and procedural guidance.

Committee	Committee Domain	Standard Number	Year	Standard Title	References to Interoperability	Procedures to Enable Interoperability
Digital Twin Domain						
ISO/IEC JTC 1/SC 41	Internet of things and digital twin	ISO/IEC 20924	2024	Internet of Things (IoT) and digital twin - Vocabulary	Explicit	No
		ISO/IEC TR 30172	2023	Internet of Things (IoT) -Digital twin - Use cases	Explicit	No
		ISO/IEC 30173	2023	Digital twin - Concepts and terminology	Explicit	No
ISO/TC 184/SC 4	Industrial data	ISO 23247-2	2021	Automation systems and integration - Digital twin framework for manufacturing - Part 2: Reference architecture	Implicit	No
		ISO 23247-4	2021	Automation systems and integration - Digital twin framework for manufacturing - Part 4: Information exchange	Implicit	Yes
BIM Domain						
ISO/TC 59/ SC 13	Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM)	ISO/TR 23262	2021	GIS (geospatial)/BIM interoperability	Explicit	Yes
		ISO 21597-1	2020	Information container for linked document delivery - Exchange specification - Part 1: Container	Implicit	Yes
		ISO 19650-4	2022	Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM) - Information management using building information modelling - Part 4: Information exchange	Explicit	Yes
		ISO 23387	2020	Building information modelling - Data templates for construction objects used in the life cycle of built assets - Concepts and principles	Implicit	No
		ISO 23386	2020	Building information modelling and other digital processes used in construction - Methodology to describe, author and maintain properties in interconnected data dictionaries	Implicit	No
		ISO 29481-1	2016	Building information models - Information delivery manual - Part 1: Methodology and format	Implicit	Yes
		ISO 29481-2	2012	Building information models - Information delivery manual - Part 2: Interaction framework	Implicit	Yes
		ISO 29481-3	2022	Building information models - Information delivery manual - Part 3: Data schema	Implicit	Yes
		ISO 19650-2	2018	Organization and digitization of information about buildings and civil engineering works, including BIM - Information management using BIM - Part 2: Delivery phase of the assets	Implicit	Yes
		ISO 19650-5	2020	Organization and digitization of information about buildings and civil engineering works, including BIM - Information management using BIM - Part 5: Security-minded approach to information management	Implicit	No
		ISO 19650-3	2020	Organization and digitization of information about buildings and civil engineering works, including BIM - Information management using BIM - Part 3: Operational phase of the assets	Implicit	No
		ISO 1291	2023	Organization and digitization of information about buildings and civil engineering works, including building	Implicit	No

(continued on next page)

Table 8 (*continued*)

Committee	Committee Domain	Standard Number	Year	Standard Title	References to Interoperability	Procedures to Enable Interoperability
				information modelling (BIM) - Framework for specification of BIM implementation		
BEPS Domain						
ISO/TC 59/ SC 17	Sustainability in buildings and civil engineering works	ISO 22057	2022	Sustainability in buildings and civil engineering works - Data templates for the use of environmental product declarations (EPDs) for construction products in building information modelling (BIM)	Implicit	Yes
		ISO 20887	2020	Sustainability in buildings and civil engineering works - Design for disassembly and adaptability - Principles, requirements and guidance	Implicit	No
ISO/TC 205	Building environment design	ISO 16484-1	2024	Building automation and control systems (BACS) - Part 1: Project specification and implementation	Explicit	Yes
		ISO 16484-5	2022	Building automation and control systems (BACS) - Part 5: Data communication protocol	Implicit	Yes
		ISO 16484-2	2025	Building automation and control systems (BACS) - Part 2: Hardware	Implicit	No
		ISO 16484-6	2020	Building automation and control systems (BACS) - Part 6: Data communication conformance testing	Implicit	Yes
		ISO 16484-3	2005	Building automation and control systems (BACS) - Part 3: Functions	Implicit	Yes
ISO/TC 59/ SC 14	Service life planning	ISO 15686-4	2014	Building Construction - Service Life Planning - Part 4: Service Life Planning using Building Information Modelling	Implicit	Yes
		ISO 15686-10	2010	Buildings and constructed assets - Service life planning - Part 10: When to assess functional performance	Implicit	Yes

projects [61]. It primarily addresses business processes and does not provide detailed mechanisms for interoperability. In the *BEPS domain*, ISO 15686–4:2014 [62] and ISO 15686–10:2010 [63] provide guidelines to support service life planning and the assessment of building operational performance for stakeholders. Both rely on the use of IFC (IFCXML) to enable interoperability.

4.2.2. Semantic interoperability

In the context of *Digital Twin*, ISO/IEC TR 30172:2023 [49] states that the primary goal of interoperability is to reduce or eliminate redundant handling or translation of data between systems. ISO 23247–4:2021 [64] provides detailed guidelines and examples for information exchange within Digital Twin systems. However, a limitation is that the standard focuses on the manufacturing domain, a more controlled and constrained environment compared to the AECO sector. The standard defines four types of networks in Digital Twin architecture: user network (connection between the user and the Digital Twin), service network (connections between sub-entities), access network (communication between devices, user, and Digital Twin), and proximity network (interactions between devices and manufacturing elements). For information exchange, the standard acknowledges the use of standardized methods and protocols such as REST, HTTP, and OpenAPI. For connectivity between entities, the MQTT protocol and communication methods PULL, PUSH, and PUBLISH. To ensure data security, the standard refers to IEC 62443. For semantic and syntactic verification, it references STEP and QIF schemas. In terms of geometry, the standard recommends CAD/CAM models, which are mainly relevant to manufacturing, and file formats such as STL, FBX, and COLLADA for 3D data. To describe a Digital Twin model, the Asset Administration Shell (AAS) is recommended, which can also describe assets in XML, JSON, or RDF.

In the *BIM domain*, ISO 21597–1:2020 [65] provides guidelines for exchanging building-related information via a container format that allows packaging different file types, including the relationships between them. The data remains in its native format and is not converted. The standard relies on RDF/OWL and includes specifications for converting RDF/OWL to and from XML. Geometric data are not explicitly discussed, likely because they are expected to remain in their original formats. For metadata, Dublin Core is used. ISO 29481–3:2022 [66] provides a data schema to support machine readability of the IDM. It uses XML schema (idmXML) to store, exchange, and interpret information. The standard does not assume direct file translation.

ISO/TR 23262:2021 [35] represents an initial step to align the GIS and BIM domains. According to the report, the key barriers to interoperability between domains include:

- Conceptual barriers: 1) different concepts for entity representation, including inconsistencies in geometry, semantics, and syntax. 2) variations in how items are expressed, defined, and understood.

Table 9
Content analysis: terminology, geometry, and semantics.

Standard Number	Term	Terminology Cluster	Referenced Standard	Geometry Considered	Semantic Considered
Digital Twin Domain					
ISO/IEC 20924	Interoperability	Identical	ISO/IEC 22123–1:2023 "Information technology - Cloud computing. Part 1: Vocabulary"	N/D	N/D
	Transport interoperability	Synonymous	ISO/IEC 19941:2017 "Information technology - Cloud computing - Interoperability and portability"	N/D	N/D
ISO/IEC TR 30172	Interoperability	Identical	ISO/TS 27790:2009 "Health informatics - Document registry framework"	Yes	Yes
ISO/IEC 30173	Interoperability	Identical	ISO/TS 27790:2009 "Health informatics - Document registry framework"	Yes	N/D
ISO 23247-2	Interoperability support FE (Functional Entities)	Unique	N/A	N/D	N/D
ISO 23247-4	N/D	N/A	N/A	Yes	N/D
BIM Domain					
ISO/TR 23262	Interoperability	Synonymous	ISO/IEC 2382:2015 "Information technology - Vocabulary"	Yes	Yes
	Semantic interoperability	Contradict	ISO 18308:2011 "Health informatics - Requirements for an electronic health record architecture"	Yes	Yes
ISO 21597-1	N/D	N/A	N/A	N/D	Yes
ISO 19650-4	N/D	N/A	N/A	N/D	Yes
ISO 29481-1	N/D	N/A	N/A	Yes	Yes
ISO 29481-2	N/D	N/A	N/A	Yes	Yes
ISO 29481-3	N/D	N/A	N/A	Yes	Yes
ISO 19650-2	N/D	N/A	N/A	Yes	Yes
ISO 12911	N/D	N/A	N/A	Yes	N/D
BEPS Domain					
ISO 16484-1	Interoperability	Unique	N/A	N/D	N/D
ISO 15686-4	N/D	N/A	N/A	N/D	Yes

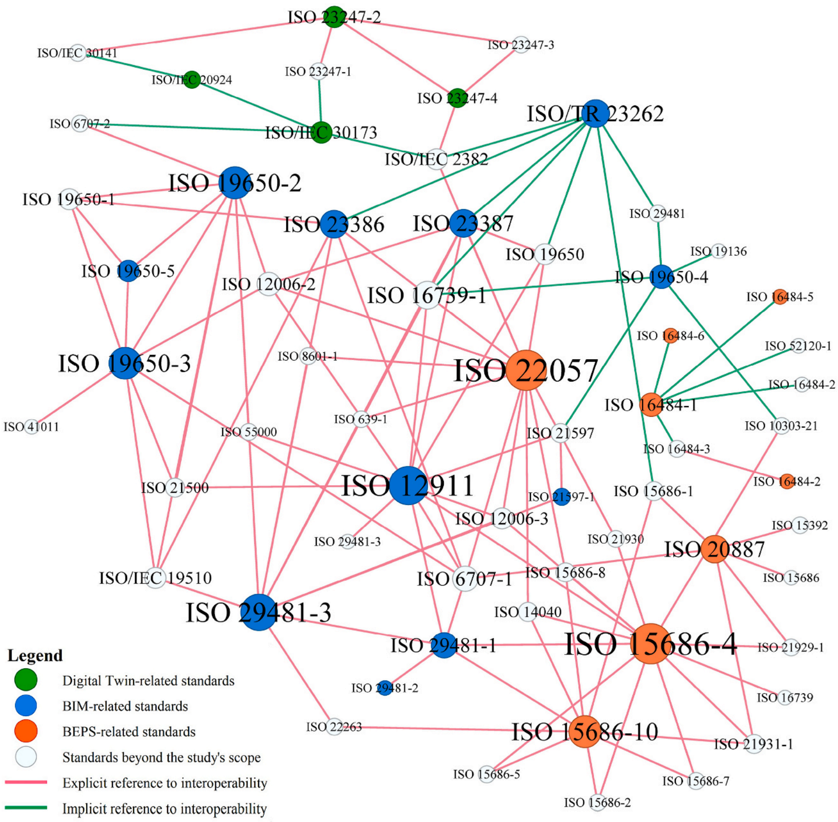

Fig. 7. Network graph of interconnections among ISO standards.

Table 10
Frequently referenced ISO standards outside the study scope.

Standard Number	Standard Title	Comment
ISO 16739–1:2024	Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries - Part 1: Data schema	
ISO 6707–1:2017	Buildings and civil engineering works – Vocabulary - Part 1: General terms	*Withdrawn. New version: ISO 6707-1:2020 Buildings and civil engineering works – Vocabulary - Part 1: General terms*
ISO 12006–2:2015	Building construction - Organization of information about construction works - Part 2: Framework for classification	*Expected to be replaced. New version: ISO/DIS 12006-2 Building construction - Organization of information about construction works - Part 2: Framework for classification and breakdown structures*
ISO 12006–3:2022	Building construction - Organization of information about construction works - Part 3: Framework for object-oriented information	
ISO 19650–1:2018	Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM) - Information management using building information modelling - Part 1: Concepts and principles	*Expected to be replaced. New version: ISO/CD 19650-1 Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM) - Information management using building information modelling - Part 1: Concepts and principles*
ISO/IEC 19510:2013	Information technology - Object Management Group Business Process Model and Notation	
ISO/IEC 2382:2015	Information technology - Vocabulary	

- Technological barriers: 1) incompatible interfaces, exchange protocols, and data storage systems. 2) misalignment of standards and their implementation.

Since both domains have evolved in parallel, aligning them is a non-trivial task. Standards for GIS are primarily developed by the Open Geospatial Consortium (OGC) and regulated within the European Union by the INSPIRE Directive. Domains use different modeling languages: UML is often used for designing GIS data models, and EXPRESS is used for defining BIM data schemas (for IFC). In terms of geometry, GIS uses Boundary Representation (B-Rep) for vector data, while BIM (IFC) primarily uses Constructive Solid Geometry (CSG), though it also supports B-Rep for more complex shapes. The report highlights main directions to enable interoperability, but smooth integration between domains has yet to be achieved. Harmonizing core principles, abstract concepts, geometry, and metadata is an ongoing work.

In the *BEPS domain*, ISO 22057:2022 [67] provides guidelines for machine readability of Environmental Product Declarations (EPDs) in the context of Life Cycle Assessment. It specifies information modules for each stage of the product life cycle, including data types and units. XML is defined as the primary data schema.

4.2.3. Technical interoperability

Enabling interoperability in the Digital Twins goes beyond data exchange; it also involves managing device networks and incorporating devices of different generations and manufacturers. Within our dataset, the issue of technical interoperability is primarily addressed in BEPS-related standards. The ISO 16484 series focus mainly on technical interoperability of Building Automation and

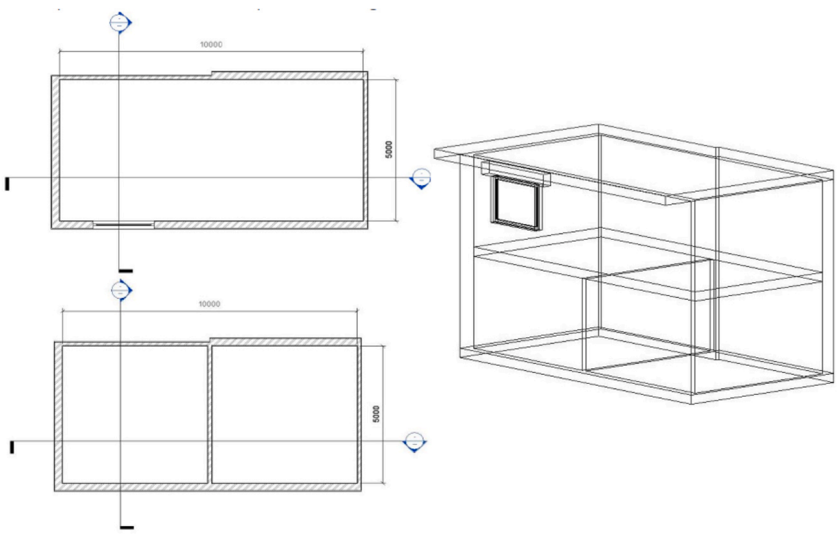

Fig. 8. Test building model: floor plans and 3D view.

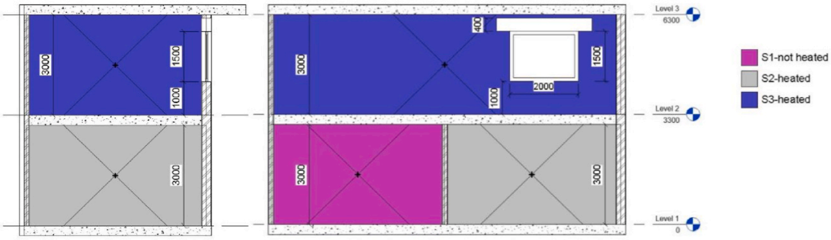

Fig. 9. Test building model: thermal zones.

Table 11
Building model: surface areas, volumes, and heights.

	Unit	Space 1 (not heated)	Space 2 (heated)	Space 3 (heated)	Total (heated)
Net surface area	m^2	24.60	24.60	50.00	74.60
Gross surface area	m^2	28.35	29.27	57.62	86.89
Height net	m	3.00	3.00	3.00	6.00
Height gross	m	3.30	3.45	3.45	6.75
Net volume	m^3	73.80	73.80	150.00	223.80
Gross volume	m^3	93.54	100.97	198.80	299.77

Control Systems (BACS). ISO 16484–1:2024 [56] provides guidelines for the design, engineering, installation, and commissioning of BACS. While procedures for enabling interoperability are not stated explicitly, the standard acknowledges that interoperability should be considered in terms of data sharing, device integration, and network management. The subsequent standards, ISO 16484–2:2025 [58], ISO 16484–3:2005 [68], ISO 16484–5:2022 [69], and ISO 16484–6:2020 [70], address specific technical aspects, including: requirements for BACS software (e.g., configuration, functions, and interfaces), communication protocols, and testing methods for ensuring compatibility across systems. Another relevant standard, ISO/IEC 19941:2017 [53], provides detailed guidelines to support interoperability across different system layers. However, it is specific to cloud computing and falls outside the study's domains.

5. Experimental assessment of interoperability in the BIM-to-BEPS process

A simplified building model was created in Autodesk Revit to evaluate interoperability in the BIM-to-BEPS process. The test model is a two-story structure with a rectangular footprint and a flat roof (Fig. 8). It includes geometry and the thermal properties of the materials but excludes HVAC details and operation schedules. The model has two types of external walls and one internal wall, each with different thicknesses (Fig. 9). It also includes a ground floor, an internal slab, a flat roof with a consistent layer composition, and a window fitted with a roller shutter box. Geometrical characteristics of the test model (surface areas, heights, and volumes for heated and unheated spaces) are provided in Table 11. The materials' thermal properties and the building elements' layer compositions are detailed in Tables 12 and 13, respectively.

5.1. *Procedure 1: Autodesk Revit → Autodesk Green Building Studio/Insight → SketchUp → EnergyPlus*

In the first procedure, building data was transferred from BIM to BEPS as shown in Fig. 10. The process included the following steps:

1. Retrieval of data from the BIM model: an "Energy Model" was created using Autodesk Revit's Energy Optimization panel.
2. Export to IDF: the simplified model was exported to Autodesk Green Building Studio and processed through Insight to create an IDF file compatible with EnergyPlus.
3. Import into SketchUp: the IDF file was imported into SketchUp via the Euclid plugin (OpenStudio) to check the geometry visually. Manual corrections of geometry and spatial zones were made.

Table 12
Building model: thermal properties of materials.

	Unit	Plaster	Brick	Concrete	Wooden frame[a]	Roller shutter box[a]
Thickness	mm	20	250	300	60	290
Thermal conductivity	W/(m·K)	0.72	0.54	1.046	0.21	1.74
Specific heat capacity	J/(g·°C)	0.84	0.84	0.657	0.19	0.10
Density	kg/m^3	1860	1550	2300	496	21.72
Emissivity	–	0.90	0.95	0.95	0.85	0.85
Permeability	$ng/Pa{\cdot}s{\cdot}m^2$	216.6	182.4	182.4	0	0

[a] *Equivalent materials selected to achieve a frame U-value* = 2.2 W/m2K *and a roller shutter box U-value* = 6 W/m2K, *excluding surface resistances.*

Table 13
Building model: layer composition of building components.

Building Components	Layer	Thickness [m]	Total Thickness [m]	Thermal Transmittance U-value [W/m^{2}K]
External Wall_EW01	Plaster	0.02		
	Brick	0.25		
	Plaster	0.02	0.29	1.45
External Wall_EW02	Brick	0.12		
	Plaster	0.02	0.16	2.23
Internal Wall_IW01	Plaster	0.02		
	Brick	0.12		
	Plaster	0.02	0.16	1.86
Ground floor_GF01	Concrete slab	0.30	0.30	2.01
Roof_RF01	Concrete slab	0.30	0.30	2.34
Internal Floor_IF01	Concrete slab	0.30	0.30	1.60
Roller shutter box	Wood panel	0.29	0.29	2.97

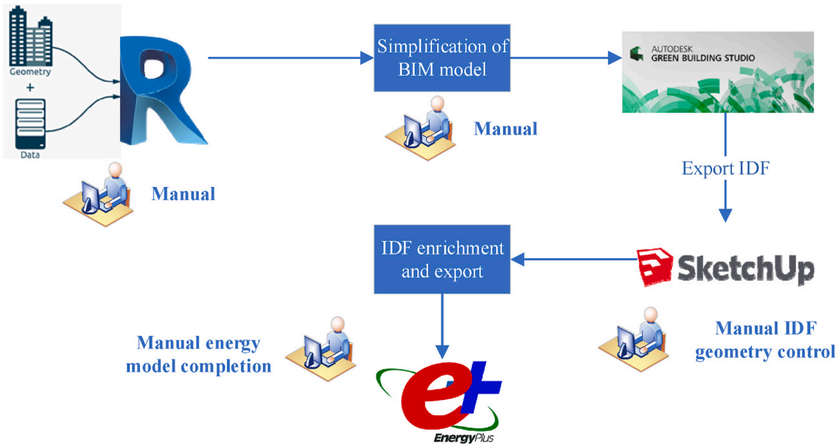

Fig. 10. Workflow of procedure 1.

Table 14
Procedure 1: geometric and semantic errors.

Workflow Step	Step Description	Step Output	Errors Identified		Corrective Effort	Process Support
			Geometric	Semantic		
1. Retrieval of data from the BIM model	Creation of an “Energy model” via Autodesk Revit’s Energy Optimization panel. Exported via Green Building Studio and Insight	Intermediate IDF file	Geometry simplification	Semantic errors are not detected	Visual check of geometry	Semi-automatic
2. Transformation and evaluation of the exported model	Evaluation of the model using a GUI. Import of IDF into SketchUp via Euclid (OpenStudio)	Corrected IDF file	Inverted or overlapping surfaces. Zoning misalignments. Glazing areas misplaced	Loss of original object naming	Correction of geometry and spatial zones	Manual
3. Configuration of the simulation model	Import of corrected IDF into EnergyPlus. Verification of the model in the simulation engine	IDF for enrichment	Presence of “noise” objects. Incorrect zone boundaries	Missing or incorrect material thermal properties. Schedule mismatches. Internal loads are not transferred	Cleaning and filtering of the objects. Manual reentry of material properties, internal loads	Manual
4. Finalization of the energy model	Entry of HVAC system data, operational loads, and weather files via IDF Editor	Simulation-ready IDF file	Geometric errors are not detected	Missing HVAC components and operational schedules. Incomplete weather/location input	Input of HVAC settings and operational schedules. Weather file upload	Manual

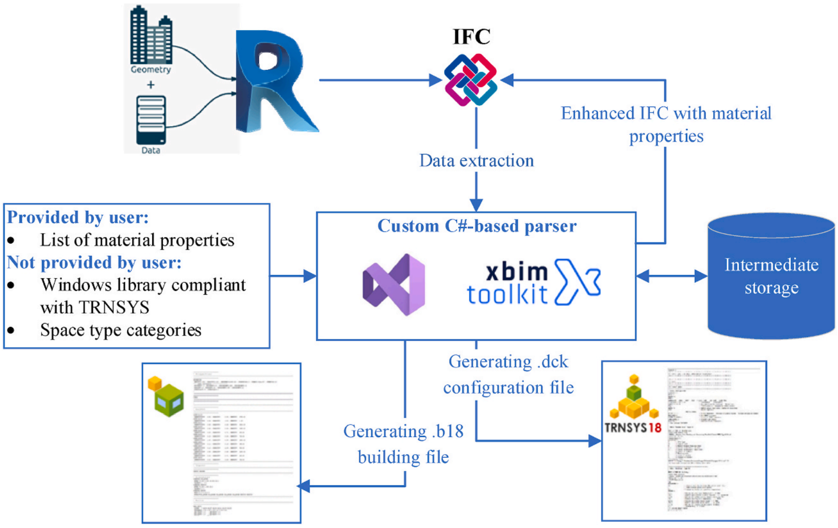

Fig. 11. Workflow of procedure 2.

Table 15
Procedure 2: geometric and semantic errors.

Workflow Step	Step Description	Step Output	Errors Identified		Corrective Effort	Process Support
			Geometric	Semantic		
1. Retrieval of data from the BIM model	Modification of material properties and energy-related settings in Autodesk Revit to ensure TRNSYS compatibility. Export using IFC4 Design Transfer View	IFC file	Geometry simplification. Misrepresentation of wall orientations. Volume discrepancies	Incomplete or missing thermal properties	Editing in Revit to match export requirements	Manual
2. Transformation and evaluation of the exported model	Parsing of IFC with xBIM Toolkit and a custom C# parser to extract geometry, space boundaries, zones, and materials	Intermediate structure	Discrepancies in surface areas, volumes, and zone boundaries	Incomplete transfer of material thermal properties	Manual recalculation of missing volumes, reassignment of zones, filling in missing material values	Semi-automatic
3. Configuration of the simulation model	Generation of simulation input files. From the intermediate structure, .b18 (geometry, materials) and.dck (simulation configuration) files are generated for input to TRNSYS Type56	.b18 and.dck files	Geometry inconsistencies from previous stages	Missing window definitions, material thermal properties, schedules, and zone-specific internal loads	Manual completion using predefined libraries and standard values	Semi-automatic to manual
4. Finalization of the energy model	Manual input and correction in TRNSYS Type56: HVAC details, weather data, simulation time steps	Simulation-ready TRNSYS model	Geometric errors are not detected	Lack of TRNSYS-compliant window libraries	Configuration in Type56	Manual

4. Import to EnergyPlus: the final IDF was run in EnergyPlus, where additional parameters (HVAC system, schedules, operational loads, and weather data) were configured using IDF Editor.

Table 14 provides a detailed description of the workflow and the errors identified at each step.

5.2. Procedure 2: Autodesk Revit → IFC4 Design Transfer View → custom C# parser (xBIM Toolkit) → TRNSYS

The second procedure used a custom-developed parser built in C#, utilizing the xBIM Toolkit to export the IFC file and generate TRNSYS-compatible input as shown in Fig. 11. The workflow included the following steps:

Table 16
Differences between procedures.

Aspect	Procedure 1	Procedure 2
File format	IDF	IFC to.b18/.dck
Geometry verification	Manual via SketchUp	Automated parsing; manual review only
Semantic verification	Manual via IDF Editor	Partially automated parsing
Software	Disconnected tools with standard export-import workflows	Custom-built parser for direct generation of TRNSYS input files; bypasses GUIs
Automation level	Low	Moderate
Manual workload focuses on	Geometry corrections	Semantic enrichment

1. Export from Autodesk Revit to IFC: BIM model was exported as an IFC4 Design Transfer View, ensuring that geometry, space boundaries, and material data are included.
2. IFC parsing using xBIM Toolkit: automated extraction of geometry, materials, zoning, and space boundaries. Data was parsed into an intermediate structure formatted to meet TRNSYS Type56 requirements. Basic checks were performed for volume and area consistency.
3. Generation of. b18 (building geometry and material data) and. dck (simulation configuration) files.
4. Manual edits: list of material thermal properties, TRNSYS-compliant window types, space type categories. Additional editing of building geometry, material layers, and HVAC details in Type56.

Table 15 provides a detailed description of the workflow and the errors identified at each step.

An overview of the main differences between the two procedures is presented in Table 16. The main distinction lies in the partial automation implemented in procedure 2, which allows direct extraction of geometry from the IFC and generation of files compatible with TRNSYS. As a result, procedure 2 provides a more optimized processing of geometric data, but still requires significant manual input to complete or correct semantic information. On the other hand, procedure 1 relies on the manual verification of the geometry through an intermediate GUI, as well as manual input and editing of semantic data.

6. Verification and validation

6.1. Support for standardized data exchange formats

Current practice: both procedures rely on a standardized data exchange format for information transfer. *Identified gap:* despite the use of a standardized format, errors still frequently occur. This highlights the limitations of file-based information exchange and shows that the syntactic aspect of interoperability is not fully implemented. Each time data is translated from one format to another, or into a temporary intermediate structure, there is a risk of misinterpretation or loss of information. *Pathways:* 1) reduce dependence on file-based data exchange by using API-based integrations between tools and supporting "partial" data transitions; 2) improve the extensibility of current data schemas to allow for easier integration of new or evolving data.

6.2. Provision of a semantic structure

Current practice: in both procedures, semantic data are either only partially transferred, misinterpreted, or entirely missing. As a result, extensive manual intervention is required. *Identified gap:* the inconsistent data schemas across different software. Each tool relies on its own data model, leading to misinterpretation or loss of object relationships and properties. *Pathways:* a promising solution is to shift from traditional file-based data exchange toward semantic web and linked data principles. This would support dynamic updates from distributed sources without the need to regenerate or re-import entire models. However, this shift faces technical, organizational, and industry-specific challenges that should be acknowledged, as the infrastructure for full linked data interoperability is not yet widespread.

6.3. Accurate geometric data translation

Current practice: procedure 2 demonstrates a higher level of accuracy in geometric data transfer by using automated parsing. This approach slightly reduces the need for manual corrections of geometry. *Identified gap:* numerous geometric errors were observed, especially in procedure 1, when an intermediate GUI was used. The effectiveness of automated parsing depends on the quality of the algorithm and data. *Pathways:* interoperability for geometric data remains a major challenge. While graph-based models are well-suited for representing semantic relationships, they are not optimized for handling detailed geometric representations. Geometry is typically better managed using parametric models and native file formats. A potential solution is to maintain geometric data in its original format while using ontologies to represent semantics. However, accurately linking the two remains challenging. A general recommendation is to use URIs or other unique identifiers for the connection. Semantic data can be stored in graph databases such as Neo4j, with references to geometric data stored in external files. However, EnergyPlus and TRNSYS are both file-based and rely on structured, well-defined inputs; they do not natively support linked data, meaning a transformation layer for direct data input or API integration remains necessary.

The limitations of the study can be categorized into several aspects: 1) The study focuses only on ISO standards and may overlook other relevant standardizations that impact interoperability in the BIM-to-BEPS processes. 2) Due to the access restrictions of ISO standards, a manual and limited search was conducted. Consequently, the analysis followed a scoping review approach rather than a systematic one. 3) A simplified building model was used in the experimental phase. Real-world buildings are more complex, which may uncover additional interoperability issues not captured in the study. 4) The experimental results are constrained by specific combinations of software and procedures. The use of different tools and procedures may lead to the identification of additional errors. 5) Although interoperability is a broad concept, this study ultimately focused only on semantic and syntactic aspects. Other aspects, such as technical or organizational interoperability, are not addressed. 6) While real-time data integration in Digital Twins was acknowledged, the study did not incorporate these elements into the experimental analysis.

7. Conclusions

This study shows that both conceptual and technological fragmentation cause ongoing interoperability problems in the BIM-to-BEPS process. First, terminology harmonization would help create a shared understanding across different domains. Currently, many sources define interoperability types, layers, and related concepts differently, which leads to inconsistency and makes it harder to establish a clear understanding.

Second, while most of the standards we reviewed focus on organizational interoperability, many of the actual problems in the BIM-to-BEPS process are due to weak semantic interoperability. Unfortunately, current standards do not offer enough support in this area. Most of the guidance is either too broad or not directly relevant to the BIM-to-BEPS context.

Another important point is that BIM-to-BEPS workflows still rely heavily on file-based data exchange. Our experimental analysis confirmed the results reported in previous studies: even when standardized formats such as IFC are used, recurring problems in geometry and semantics remain. To move toward more dynamic Digital Twin systems, there is a need for more adaptive data transfer, ideally partial, rather than requiring the transfer of the entire model. Ontology-based modeling and linked data principles offer promising alternatives, as they align better with the dynamic, cross-domain nature of Digital Twins. However, as long as simulation tools require structured, rigid input formats, some level of data transformation will remain necessary.

In conclusion, paraphrasing Turk's (2020) question *"Is interoperability in construction possible?"* to *"Is interoperability in the BIM-to-BEPS process possible?"*, the answer remains the same: *"Yes, but"*. As Turk (2020) states, *"Research and development will continue to offer solutions to improve the interoperability of the systems, but perfectly interoperable integrated systems will never be achieved. It is therefore important to study how to design, build, and operate in such partially integrated environments"* [14].

CRediT authorship contribution statement

Iryna Osadcha: Writing – original draft, Software, Investigation. **Egle Klumbyte:** Software, Formal analysis, Data curation. **Andrius Jurelionis:** Writing – original draft, Validation, Conceptualization. **Paulius Spudys:** Writing – original draft, Software, Investigation. **Timo Hartmann:** Validation, Supervision. **Shayan Saket:** Writing – original draft, Visualization, Software. **Damian Harasymczuk:** Visualization, Validation, Software. **Paris Fokaides:** Writing – review & editing, Supervision, Resources, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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