

Review

Prospective Directions in the Computer Systems Industry Foundation Classes (IFC) for Shaping Data Exchange in the Sustainability and Resilience of Cities

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Abstract: Sustainability and resilience in addressing construction's environmental, social, and economic challenges rely on interoperability. A model-centred approach using standardised information structures like industry foundation classes (IFC) is essential for data sharing in architecture, engineering, construction, and facility management. Achieving complete interoperability across domains requires further research. This review paper focuses on IFC schema, highlighting upcoming developments like IFC 5 and "IFC x", with a core emphasis on modularisation to enhance domain interoperability, improved links between building information modelling (BIM) and geographic information systems (GIS), along with IoT integration into BIM, cloud-based collaboration, and support for other advanced technologies such as augmented reality (AR), virtual reality (VR), artificial intelligence (AI), and digital twins. Through a critical examination of the IFC and an outlook towards its future enhancements, the research has the potential to offer valuable insights into shaping the trajectory of future advancements within the AEC and facility management sectors. The study's discoveries could aid in establishing standardised data exchange protocols in these industries, promoting uniformity across projects, facilitating smoother communication, and mitigating errors and inefficiencies. Anticipating enhancements in the IFC could catalyse innovation, fostering the adoption of emerging technologies and methodologies. Consequently, this could drive the creation of more sophisticated tools and procedures, ultimately enhancing project outcomes and operational effectiveness.

Keywords: industry foundation classes (IFC); building information modelling (BIM); sustainability; resilience; IFC 5; geographic information systems (GIS); internet of things (IoT)



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1. Introduction

Cities are becoming increasingly complex systems of social, economic, and environmental concerns [1,2]. They are, however, extremely susceptible if any of their subsystems is damaged or fails to adapt to new problems [3]. This situation might result in a deadly crisis or catastrophe [4]. Natural disasters, climate change, energy crises, political insecurity, financial crises, food security, and terrorist attacks pose significant risks to urban growth [5].

While these ideas of sustainability and resilience vary in their underlying concepts, various scholars have explored their relationships [6–10]. Nevertheless, the questions of whether resilience and sustainability are essentially synonymous, if resilience plays the primary role in determining sustainability [11–13], or if sustainability represents a broad societal objective while resilience focuses on its practical implementation [10,14] remain open. Derissen et al. [15] characterise their distinction as sustainability maintaining resource levels above normative secure thresholds. In contrast, resilience strategies adapt to change by building capacities to return to a desired state after a disturbance. In the face of urban development's existential threat, the precise definition of these concepts becomes less crucial, given their substantial impact on social, economic, and environmental

factors. Sustainability and resilience are large, multifaceted, and crucial systemic issues that both rely on interoperability (i.e., the capacity for programs to share any data) to deal with problems around the built environment [16] and improve the accessibility of environmentally relevant data [17], as well as intensifying the sharing and reuse of these data during all lifecycles of a building [18].

The demand for interoperability across multiple software systems in the architecture, engineering, construction, and facility management (AEC/FM) industry has increased [19]. Interoperability has been seen to provide Effective asset management [20] and support standardised procedures for verifying the association of cost to geometric objects, addressing the wasting of time, inaccuracy, and human errors in cost estimates [21]. Berlo et al.'s [22] "late binding" approach to modularisation provided interoperability between domains, providing a solution that easily supports incremental updates in software implementations. Interoperability has allowed integrating BIM and F.M. systems, underpinned by a performance information model, to help with performance assessment and maintenance management [23]. Also, access and interaction with a BIM model are granted through functionalities for measurement, data consultation, collaboration, visualisation, and integration of information from sensors [24]. Integrating BIM with remote sensing [25], visual programming [26], and generative and algorithmic design [27] further enhances interoperability in the design process. Interoperability in AEC/FM industries allows for the easier management of buildings, from design to decommissioning [28].

The widespread utilisation of the BIM platform has heightened the need for straightforward and reliable data exchange methods that preserve data and their quality [29]. Moreover, integrating the numerous disciplines within the AEC sector has become essential [30–32]. Comprehensive interoperability becomes essential when users use different software packages and interact with local or national authorities. The industry foundation classes were introduced to establish a standard for data exchange [33]. However, areas like IFC modularisation, normalisation of IFC trees and relationships, and ensuring language neutrality in the foundational data structure require additional research and enhancements to attain complete interoperability solutions across various domains. Interoperability is one of those vital improvements expected of the IFC 5 and future release cycles (referred to as "IFC x" in this paper). The study aims to critically review the IFC and future improvements expected of this international standard for building information model (BIM) data schema used in the AEC and facility management industries. While the paper seeks to emphasise sustainability and resilience within construction, highlighting the importance of interoperability in addressing environmental, social, and economic challenges through the IFC is the core of the study.

The significance of the study lies in its relevance to ongoing discussions surrounding the industry foundation classes (IFC) and their future trajectory. This trajectory anticipates improvements in BIM and GIS, BIM and IoT integrations, enhancing the model view definition (MVD) concept, cloud-based collaboration, and supporting advanced technologies like AR, VR, AI, and digital twins within the IFC schema. By critically reviewing the IFC and anticipating their future improvements, the study can provide valuable insights that shape the direction of future developments within the AEC and facility management industries. The study's findings can contribute to standardising data exchange practices within these sectors, fostering consistency across projects, enhancing communication, and reducing errors and inefficiencies. This standardisation ensures that stakeholders, including architects, engineers, contractors, and facility managers, can effectively exchange information and collaborate on projects regardless of the software they use. Anticipating future improvements in the IFC can stimulate innovation by encouraging the adoption of emerging technologies and methodologies. This can lead to the development of more advanced tools and practices that improve project outcomes and operational efficiency. Enhanced interoperability through advancements in IFC facilitates greater collaboration among stakeholders, resulting in better-designed, constructed, and managed buildings and infrastructure. It is essential to note that while the study makes bold predictions for the future of the IFC, it

is also saddled with some limitations; for example, the study's focus on interoperability may not fully address the practical challenges of achieving seamless data exchange in diverse real-world scenarios. Furthermore, the study's exploration of various technologies might not cover all potential advancements comprehensively, limiting its applicability to newer innovations. As the AEC and facility management industries become increasingly globalised, adherence to international standards like IFC is crucial. The study's insights can enhance the competitiveness of organisations by ensuring they remain aligned with global best practices. Additionally, future improvements in IFC can better support the integration of sustainability parameters into BIM data, enabling more informed decision making regarding energy efficiency, environmental impact, and lifecycle analysis.

2. IFC—Industry Foundation Classes

The industry foundation classes (IFC) are a widely adopted open data transfer standard within building information modelling (BIM). This standard facilitates the seamless exchange of information across various software platforms within the BIM industry. The IFC file format, denoted by the ".ifc" extension, is the conduit through which these data are transferred. Its versatility enables the transfer of diverse information encompassing attributes spanning many domains, including mechanical and physical properties, cost data, construction timelines, and other relevant factors. This expanded scope of information is not confined solely to geometric data. Still, it encompasses a comprehensive range of attributes associated with different components within a building, such as walls, beams, and columns.

The inception of the IFC dates back to 1996, when the inaugural data model standard, IFC 1.0, was introduced. Since its inception, BuildingSMART, an international consortium dedicated to improving the efficiency and interoperability of the construction industry, has taken an active role in refining the architecture of the IFC. Before 1996, BuildingSMART was formerly the International Alliance for Interoperability (IAI) and started in 1994 as an industry consortium of twelve (12) United States companies [34]. BuildingSMART's ongoing effort is geared towards enhancing the standard's efficacy in facilitating collaboration, data sharing, and integration across diverse software systems. The foundation upon which IFC is built finds its roots in the standard for the Exchange of Product model data (STEP), specifically adhering to the structure outlined in ISO 10303-21: 2016. STEP, a comprehensive and globally recognised standard for representing product data across various industries, is the framework for IFC's architecture [35]. This foundation ensures IFC's reliability, consistency, and compatibility with other standards and systems, contributing to its widespread adoption within the BIM community.

The domain, interoperability, core, and resource levels of the IFC data model describe the core structure of the IFC data model. The essential limitation of the layers' rigid reference hierarchies is that referencing can only take place at the hierarchy's lower levels. As a result, the resource layer's data must be self-contained and independent of the classes above it. On the other hand, the data from the resource layer and any layers below it may all be related to the different levels. For the resource layer, only references inside the same layer are allowed [36].

The resource layer comprises the resource schema, which includes the basic guidelines for classifying items in the levels above. The core layer is composed of the kernel and extension modules. The kernel provides the model's structure and breakdown, which defines key terms like objects, relationships, types, traits, and roles. Kernel-defined classes are specialised in core extensions. The interoperability layer acts as an exchange mechanism to facilitate cross-domain interoperability and serves as the interface for domain models. The sector section encompasses domain models of processes within specific AEC fields or categories of applications, like architecture, structural engineering, and HVAC [37–39].

3. Previous and Current Status of the IFC

Over the years, several proposed releases have been made. The IFC 4.3.0 is the most recent, released on 7 March 2022, with continuous documentation updates and minor changes to the specification and schema expected. Figure 1 clearly shows a descriptive style of the timelines of the different versions of IFC over the years.

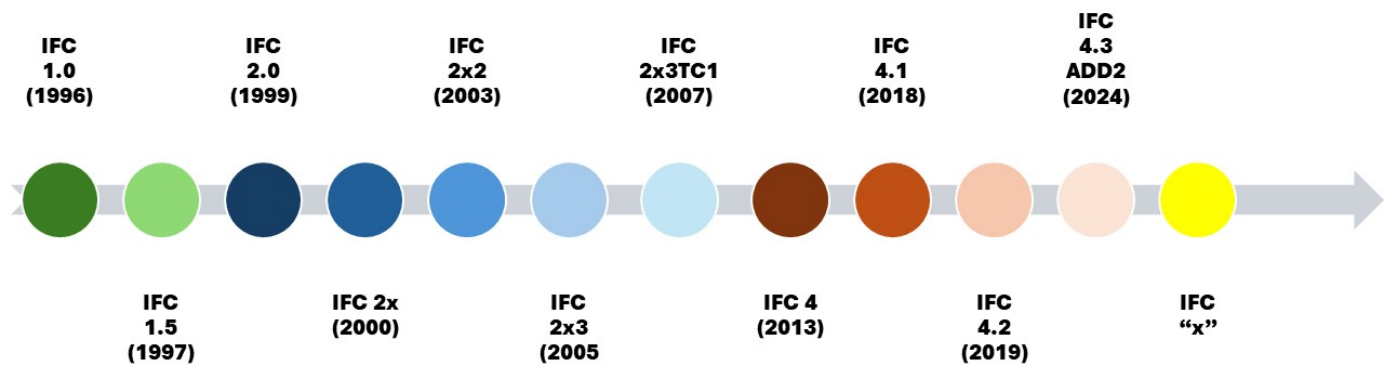


Figure 1. The timelines of the different names of the IFC (IFC “x” represents future developments). Source: created by the authors.

From the first release of the IFC in June 1996, the IFC has undergone tremendous developments. The IFC 1.0 had a limited scope, focusing mainly on the architectural component of the building model, containing five architectural procedures, two HVAC design processes, two construction management processes, and one facilities management process. The scope of IFC 1.5 included implementer feedback, model architectural refinement, plug-in extensions, and better development tools. The demo implementations of IFC 1.5 revealed the necessity for several models and documentation modifications. Parallel to the development of IFC 2.0, the upgraded version of IFC 1.5.1 was produced [40].

3.1. IFC 2.0-IFC 2x3 TC1

IFC 2.0 included coverage for HVAC systems, general-purpose networks, cost calculation, code checking, occupancy management for facilities management (FM), property management, and external document references. The notion of a core model and domain extensions was invented by IFC 2x. It was the first version of the IFC with a broader base of implementations, and implementations were accredited under an antiquated certification method. IFC 2x3 mainly updated IFC 2x2’s quality and included some new features. It quickly established itself as the standard for IFC implementations, combining previous IFC2x and IFC 2x2 implementation threads. The goal of the IFC 2x3 TC 1 was to improve the documentation generally and address some minor technical issues that were found after the release of the IFC2x Edition 3 specification, including the deletion, modification, or addition of several rules in the EXPRESS schema [40]. IFC 2.0-2x3 possessed four similar vital features, which are “Define Types”, “Enumerations”, “Select Types”, and “Entities”. The defined types serve as a CAD data exchange data schema to describe architectural, building and construction industry data [41,42]. Enumerations serve as a collection of simple or measure values that define a prescribed set of alternatives from which “enumeration values” are selected [43]. It is also known as property enumeration. Select types are based on value, with an IFC Value used for selecting between more specialised select types: IFC Simple Value (for basic defined types of simple data type), IFC Measure Value (for basic measure types of ISO 10303-41) and IFC Derived Measure Value (for derived measure types) [44]. However, each feature possesses upgrades with each version of IFC developed, as displayed in Table 1.

Table 1. IFC version 2 series and upgrades.

Listings	IFC Version		
	2.0	2x2	2x3
Define Types	89	110	117
Enumerations	117	159	164
Select Types	23	42	46
Entities	370	623	653
Total Listings	4	4	4
DIAGRAMS	2.0	2.2	2.3
Domains	5	9	9
Elements	5	5	5
Extension	3	3	3
Kernel	1	1	1
Resources	20	26	26

Source: compiled by authors from [45].

Examining the architectural diagrammatic component of each iteration of the IFC demonstrates an improvement in the domains (which define the permissible data kinds and limitations, guaranteeing data representation consistency) [46]. The elements are the non-physical entities like spaces or zones, as well as the building components or objects represented in a BIM, such as walls, floors and roofs [47]. The extensions allow standards to be customised by adding data attributes or functionality beyond the defined core IFC schema [48]. Resources that incorporate all the elements, entities, and data that describe a building or construction project within a kernel consist of basic entities and relationships necessary for portraying building information within the IFC framework [49].

3.2. IFC 4-IFC 4.3 ADD2

The IFC format has enabled new BIM processes, such as the interchange of 4D and 5D models, manufacturer and product libraries, BIM to GIS interoperability, improved thermal simulations, and sustainability assessments. Complete integration with the new mvdXML technology makes it simple to develop data validation services for IFC4 data submissions, allowing IFC to be expanded to include infrastructure and other built-environment elements, among other things. IFC4.1's principal objective was to provide a base for the numerous infrastructure domain extensions (e.g., rail, roads, tunnels, ports and waterways). At the same time, IFC4.2's primary objective was to enlarge IFC4.1 to include details of bridge building. IFC4.3 ADD2 primary objective is to expand the IFC schema's application to describe infrastructure builds in the realms of roads, railways, ports, and waterways, as well as the features standard to all four domains [40,50]. IFC 4.0-4.2 was an upgrade from the IFC 2 series with an addition of five more components: "Functions", "Rules", "Property Set", "Quantity Set", and "Individual Properties" [35]. The functions aid in creating, modifying, and querying building information within a software application [51,52]. Rules were incorporated to ensure consistency and interoperability among software applications implementing the IFC standard [23,53]. Property sets were created to interpret each property and classify information associated with an entity in BIM [52]. At the same time, each quantity set interprets quantities according to their name attribute and is classified according to their measure type [46,54]. The individual property is a subset of the property set where each property has a significant name string [55]. The IFC 4.3 ADD2 upgrade, however, was limited to only seven instead of nine. Each feature possesses upgrades, and each version of the IFC was developed, as displayed in Table 2.

The IFC 4.0-4.3 ADD2 architecture diagram is complicated and cannot be captured in a single flow diagram. Nonetheless, the software's architecture diagram consists of an instance diagram, domain-specific data schemas, shared element data schemas, core data schemas, and resource definition data schemas. Only the instance diagram—206 and 213 for IFC 4.0 and 4.1, respectively—varies. The remaining elements—four core data schemas, five shared element data schemas, eight domain-specific data schemas, and twenty-one

resource definition data schemas—are the same. The IFC 4.3 ADD2 architectural diagram has 846 components and is perhaps two to three times more efficient than earlier IFC versions, although it has not yet been fully separated.

Table 2. IFC version 4 series and upgrades.

Listings	IFC Version		
	4.0	4.1	4.3 ADD2
Define Types	126	130	X
Enumerations	206	210	348
Select Types	59	60	436
Entities	766	801	1255
Functions	42	47	48
Rules	2	2	2
Property Set	408	413	760
Quantity Set	91	93	X
Individual Properties	1691	1694	2513
Total Listings	9	9	7
Diagrams	244	251	846

Source: compiled by authors from [45].

3.3. Similarities and Differences between IFC 2 and IFC 4

Highlighting the significant differences between the IFC 2 and 4 series is crucial, with IFC 2x3 and IFC 4.0 sharing much in common [54]. Their considerable similarities and differences are highlighted in Tables 3 and 4. Table 3 highlights the fundamental similarities between IFC 2 and IFC 4, emphasising their commonalities in various aspects. Firstly, both standards are products of international collaborations involving specialists and organisations, reflecting a shared commitment to meeting global criteria within the construction industry. Secondly, using standardised naming conventions in both IFC versions enhances consistency and facilitates user comprehension and analysis of data within building information modelling (BIM) models. Thirdly, IFC 2x3 and IFC 4 support three-dimensional building element geometry, contributing to construction information and architectural visualisation.

Additionally, the semantic structure is a shared feature, allowing the portrayal of significant relationships between architectural elements through spatial linkages and data connectivity. Furthermore, interoperability is a common goal, as both versions employ a similar framework for data interchange to enhance collaboration. Finally, IFC 2x3 and IFC 4 adhere to core concepts, emphasising a uniform manner of exchanging and representing building information.

Table 4 outlines the notable differences between IFC 2 and IFC 4, emphasising advancements in the latter. Firstly, IFC4 exhibits a richer data model, offering a more comprehensive representation of building elements and characteristics, enabling more detail and accuracy in modelling construction projects. Secondly, IFC4 expands its scope to include infrastructure and urban planning support, allowing the representation of a broader range of projects related to utilities, transportation, and other infrastructure activities. Thirdly, the improvement in interoperability support in IFC4 is achieved through precise definitions, enhanced entity connections, and improved software implementation instructions. Fourthly, the geometry representation in IFC4 is enhanced, enabling a more accurate depiction of complex geometric shapes and topological relationships for intricate structural and architectural details. Furthermore, IFC4 introduces semantic expressiveness, allowing for more fully and accurately defined data in the model and facilitating informed decision-making during the building process. Lastly, the introduction of quantity sets in IFC4 is highlighted, providing a valuable tool for cost estimation and quantity take-off in construction projects.

Table 3. Similarities between IFC 2 and IFC 4.

Similarities	Discussion
International collaborations	To achieve the necessary criteria for the global community, all IFC are established through international collaborative efforts and approaches among diverse specialists and organisations [36,56].
Use of standardised naming conventions	This makes consistency possible and makes it easier for users to comprehend and analyse the data contained in BIM models [57].
Geometry representation	IFC 2x3 and 4 support three-dimensional building element geometry in construction information and architectural visualisation [30,58].
Semantic structure	The portrayal of significant relationships between architectural elements is made possible by both versions' maintenance of a semantic framework through spatial linkages, connectedness, and other data [59,60].
Interoperability	IFC 2x3 and IFC4 have similar data interchange frameworks intended to improve collaboration [23,53].
Core concepts	IFC 2x3 and IFC4 both adhere to the same basic ideas and precepts. Both are intended to interchange and uniformly portray building information [61].

Source: created by the authors.

Table 4. Differences between IFC 2 and IFC 4.

Differences	Discussion
Richer data model	IFC4 boasts a more sophisticated and all-encompassing data model than IFC 2x3. It has improvements to represent a greater variety of building elements and characteristics, making it possible to model construction projects in more detail and with higher accuracy [62].
Infrastructure and urban planning support	IFC4 includes infrastructure and urban planning in addition to building construction. Thanks to this development, a more comprehensive range of projects can now be represented, such as those about utilities, transportation, and other infrastructure-related activities [63].
Improved interoperability support	Through the introduction of more precise definitions, the improvement of entity connections, and the provision of improved software implementation instructions, the goal of IFC4 is to promote interoperability [54].
Enhanced geometry	With IFC4, 3D geometry is represented more accurately, allowing for more complex geometric shapes and topological relationships to be implemented. This makes it possible to represent intricate structural and architectural details more accurately [41].
Semantic expressiveness	This implies that the data in the model can be more fully and accurately defined, resulting in more informed choices being made during the building process.
Introduction of quantity sets	Quantity sets, which enable the depiction of measurable quantities connected to entities, are introduced in IFC4. For construction projects, this is useful for cost estimation and quantity take-off [46].

Source: compiled by the authors from [54,58].

4. Industry Foundation Classes (IFC) 5 and IFC x Future Directions

IFC 5 is in an early planning phase under BuildingSMART, and several changes will be anticipated for the subsequent and future release cycles. These changes must include the ones that will be discussed below.

4.1. Infrastructure BIM and GIS Model Integration

Because infrastructure developments such as roads, tunnels, bridges, and trains typically need the consideration of widely varying scales, expertise from both fields is required. As BIM and geographic information systems (GIS) use several types of data modelling standards [64], converting the data models will result in data loss, inconsistencies, and a

failure to accurately preserve the intricate relationships that exist between various project elements [65,66]. The concept of linked data offers a potential solution to this challenge. Linked data connect datasets from multiple sources while retaining their original context and relationships [67]. In integrating BIM and GIS, linked data act as a bridge, facilitating seamless data exchange between the domains [64,68]. By employing linked data, the original data from BIM and GIS can coexist without needing direct conversion, thereby avoiding the pitfalls of potential data loss. Linked data ensure that references and relationships between entities in both standards—such as industry foundation classes (IFC) for BIM and City Geography Markup Language (CityGML) for GIS—are maintained [69]. This approach guarantees data coherence and integrity as information flows between the BIM and GIS systems. The anticipated release of IFC 5 should promise to significantly enhance support for various infrastructure domains. IFC 5 is expected to incorporate specialised features, data structures, and relationships tailored to infrastructure elements like roads, tunnels, bridges, and railways [22,70]. This advancement will simplify the integration of BIM and GIS technologies, enabling professionals to collaborate effectively and make informed decisions throughout the infrastructure project lifecycle. IFC5 is anticipated to substantially assist several infrastructure areas (e.g., IFC road, IFC tunnel, IFC rail, etc.).

4.2. Model View Definition (MDV)

Model view definition (MVD), also referred to as an IFC view definition, serves as a targeted subset of the complete industry foundation classes (IFC) schema, designed to facilitate data exchange for specific purposes or processes. This approach narrows down the scope of data based on the recipient's requirements [71,72]. Often labelled as an IFC-filtered view, it enables users to extract specific segments of model information that cater to distinct needs [73,74]. Rather than exporting the entire model, users can select a preconfigured IFC export, such as the Energy Analysis MVD, when providing their model for tasks like energy analysis. This focused export contains only the pertinent information necessary for the designated purpose. The concept of MVD offers three fundamental capabilities. First, it involves selecting a subset of the IFC schema relevant to achieving a specific objective, somewhat akin to Information Delivery Specifications (IDS) [75]. Second, MVDs allow additional constraints on this chosen subset, enhancing its applicability and relevance. Third, MVDs encompass defining an anticipated level of software implementation required to support the chosen subset of schema [58,71]. This system, while practical, introduces challenges that make the current approach to MVDs unsustainable.

Users frequently encounter confusion since an IFC dataset is fundamentally built upon an MVD. This confusion arises from the inability to seamlessly interchange datasets constructed from different MVDs. The interoperability between various MVDs cannot be guaranteed, hindering seamless collaboration between diverse software applications. Each MVD necessitates separate implementation as a distinct feature within software tools, which can limit the scalability and versatility of this approach. Moreover, the monolithic structure of IFC means that consensus must be reached across all stakeholders before a new version of IFC can be introduced, which can impede swift progress.

To address these challenges, the IFC model must be made modular. Modularisation will make it easier to separate and coordinate the three functions the MVD now performs by introducing a standard (interoperability) layer in the schema as a foundation for the modules. It depicts the Interoperability layer, which comprises the three green layers in the image. The dark green layer represents the IFC resource layer [22]. Modules are extensions that define extra categorisation and attributes on top of the standard layer when the shared base is applied. When the repercussions are not too severe, the split might be performed on all specialisations from *IfcBuiltElement* or possibly on *IfcProduct*. Other branches, such as the tree beneath *IfcControl* and *IfcProcess*, must also be evaluated [22]. From Figure 2, interoperability across domains will be assured when the green interoperability layers are fully implemented, regardless of whatever module the software supports. The strict application of this shared foundation is critical.

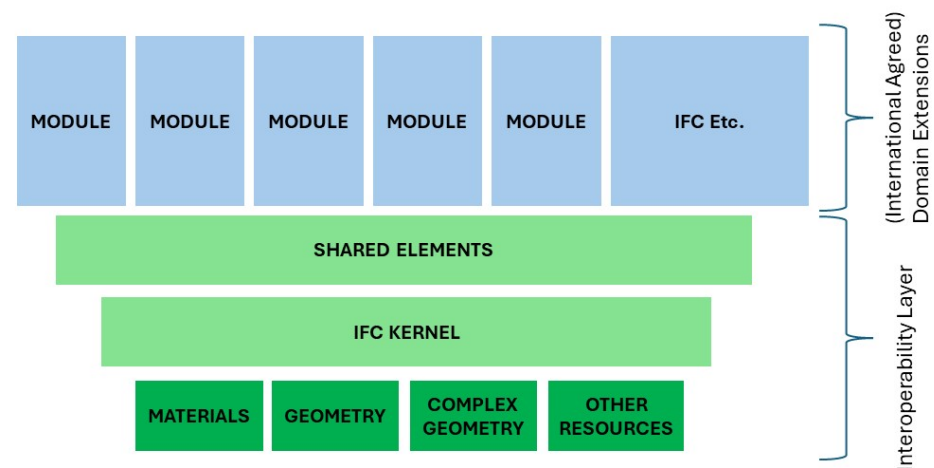


Figure 2. Modules (blue) on a shared base (green layers) for domain interoperability. Source: compiled by the authors from Berlo et al. [22].

4.3. IFC x and Internet of Things (IoT) Integration

Integrating internet of things (IoT) technologies into building information modelling (BIM) stands poised to bring substantial advantages, particularly in contemporary concepts like intelligent buildings and cities. There have been several attempts to integrate BIM and IoT data by several authors [76–78]. The IFC4 schema, a foundation for data exchange in BIM, has successfully represented various building elements such as doors, windows, walls, and furniture. However, as the focus shifts towards IoT, certain critical aspects are notably absent in the IFC4 schema, particularly when describing dynamic environments [79]. For instance, let us consider the entity of a door in IFC4, represented as *IfcDoor* or *IfcDoorStandardCase* (different types and subtypes). While attributes like colour, size, and description are well defined, there is a noticeable lack of attributes related to the operational status of the door (whether it is open or closed).

Similarly, IFC4 introduces the entity *IfcSensor* to represent sensors. Still, it falls short of providing crucial details about sensor interaction, such as communication protocols or the information the sensor offers [79]. To bridge these gaps, future updates to the IFC schema must facilitate the seamless integration and modelling of IoT-related components while also considering security requirements for elements like Things, Locations, Networks, State, and Security. This integration stands to revolutionise various stages of a building's lifecycle. It can enhance processes such as cost estimation, bolster facility management practices, foster collaboration, and simplify tasks for developers and programmers through integration with Building Information Systems (BIS), Building Automation Systems (BAS), and Building Control Systems (BCS), and enable more comprehensive management of IoT infrastructure [79]. In their research, Ruiz-Zafra, Benghazi, and Noguera [79] explored the promising potential of incorporating IoT into BIM during the early design phases. Their work showcases the myriad possibilities such integrations can offer and underscores the significance of these advancements for future iterations of the IFC schema. This convergence of BIM and IoT has the potential to reshape the landscape of design, construction, and facility management in profound ways, paving the way for smarter and more interconnected built environments. Integrating IoT technologies into BIM presents significant challenges, including representing dynamic environments effectively, ensuring interoperability and standardisation, addressing security concerns, managing modelling complexity, handling lifecycle management, providing necessary skills and training, and adhering to regulatory compliance. Bridging these gaps requires comprehensive solutions to enable seamless integration, data exchange, and collaboration across various systems while ensuring the security, privacy, and compliance of building infrastructure data. Overcoming these challenges is essential for leveraging the potential of IoT-BIM integration to revolutionise

design, construction, and facility management practices, leading to more intelligent and interconnected built environments.

Integrating sensor data with building information modelling (BIM) systems can significantly enhance building monitoring and management, but this integration comes with several challenges. This process can be categorised into one-way data transfer and two-way telemetry, each presenting unique difficulties. One-way data transfer involves collecting sensor data and integrating it into the BIM model for analysis and visualisation. This unidirectional flow of data presents specific challenges such as data interoperability, handling real-time data within BIM models and managing the volume and frequency of data generated by sensors. An example approach to address these challenges is discussed by the authors of [80], who propose a methodology for integrating sensor data into BIM models. The research employs a cost-effective NodeMCU microcontroller along with a temperature and pressure sensor to examine the comfort level of residents in a standalone household.

Two-way telemetry involves not only sending sensor data to the BIM model but also enabling the BIM model to send commands or adjustments back to the sensors or control systems. This bidirectional flow of data allows for more dynamic and responsive building management systems, but it also introduces additional challenges. System integration is a significant hurdle, as establishing seamless interaction between BIM models and sensor/control systems requires sophisticated platforms capable of handling bidirectional communication. An approach to tackle these challenges is presented by [81], developed a prototype system based on this framework that demonstrates the feasibility and effectiveness of integrating BIM, IoT, and intelligent compaction (I.C.) for real-time road construction quality monitoring. The case study conducted shows how the system can visualise compaction quality and provide timely adjustments to construction processes, ensuring that the final quality meets specified requirements.

4.4. Cloud-Based Collaboration

Cloud-based collaboration revolutionises how project stakeholders in the architecture, engineering, and construction (AEC) industry communicate, share data, and collaborate in real-time [82]. To further support this aspect, industry foundation classes (IFC) can be developed to support cloud-based collaborations [83] further. Standards and protocols must be designed to ensure seamless integration between IFC and various cloud-based collaboration platforms such as BIM 360, Trimble Connect, and Aconex. This involves defining data exchange formats and APIs to enable interoperability [83]. Implementing features within IFC that will allow real-time collaboration among project participants is essential. This includes enabling concurrent editing of models, incorporating chat functionality, and implementing version control. Such features would allow stakeholders to work together efficiently regardless of location. Addressing data security and privacy concerns associated with cloud-based collaboration is crucial [84]. Robust security measures, encryption protocols, and access controls must be implemented within the IFC standard to protect sensitive project data during transmission and storage [85]. Optimising IFC for cloud environments ensures scalability and performance. Large building models should be processed and accessed efficiently by distributed teams across different regions [86]. Also, integrating cloud-based collaboration features with BIM Execution Planning processes streamlines project management tasks within the IFC framework [83]. This includes task assignments, progress tracking, and issue resolution.

4.5. Support for Other Advanced Technologies

The future trajectory of IFC 5 is poised for modernisation and integration of diverse standards and building smart solutions, as highlighted by [22]. This evolution should bring about significant enhancements in various processes, such as lifecycle assessment for integral planning, computer-integrated facility management, cyberinfrastructure crucial for engineering management, and knowledge dissemination across different fields, as noted by [62,87–89], respectively. The potential for streamlining these processes further

underscores the promising capabilities of IFC 5. However, achieving this vision may necessitate active cooperation and the incorporation of emerging technologies like virtual reality and artificial intelligence into the development of IFC, as suggested by [90–92]. By embracing these technological advancements, IFC 5 is expected to offer a more straightforward and efficient foundation for process implementation, ultimately improving the model's overall quality, as emphasised in Taray's statement [6]. Integrating cutting-edge technologies reflects a forward-looking approach, positioning IFC 5 at the forefront of innovation in the construction and building information modelling domain. Extending the IFC schema to include data structures and attributes that support integrating AR and VR technologies enables stakeholders to visualise building designs in immersive environments and conduct virtual walkthroughs for design review and stakeholder engagement [93]. Also, incorporating AI and ML capabilities into IFC enables tasks such as automated clash detection, energy performance analysis, and predictive maintenance [94]. This involves defining standardised data formats for AI/ML models and integrating them with the IFC schema. Furthermore, developing guidelines for creating digital twins using IFC data allows stakeholders to create digital replicas of physical assets for monitoring, simulation, and optimisation purposes [95]. This includes defining data exchange protocols between IFC and digital twin platforms and supporting bidirectional data synchronisation. Other advanced technologies will consist of the exploration of the use of blockchain technology to enhance data security, provenance, and traceability within the IFC ecosystem, which involves investigating how blockchain can be integrated with IFC to create immutable audit trails for changes made to building models and project data [96,97]. Extending the IFC schema to support advanced simulation and analysis tools for structural, thermal, acoustic, and lighting performance enables stakeholders to perform detailed analysis and optimise building designs using IFC-compatible software applications such as REVIT, Blender, etc.

5. Conclusions

In conclusion, the industry foundation classes (IFC) are pivotal in addressing the complex challenges of sustainability and resilience in the built environment through interoperability. As cities become more intricate systems of interconnected social, economic, and environmental factors, the demand for efficient data sharing and exchange standards intensifies. IFC's evolution has been significant, from its inception in 1996 to the latest IFC 4.3 ADD2 version, which has enabled advancements like 4D and 5D modelling, some aspects of BIM to GIS interoperability, and improved sustainability assessments. Looking ahead, the upcoming IFC 5 release should hold the promise of addressing crucial aspects that require further research and enhancement. Integrating infrastructure BIM and GIS is critical for addressing the varying scales and expertise needed for projects such as roads, tunnels, bridges, and railways. The concept of linked data emerges as a solution to data loss and inconsistencies when converting data models between BIM and GIS. IFC 5's expected features tailored to infrastructure domains will facilitate seamless data exchange between BIM and GIS, enhancing collaboration and informed decision-making across infrastructure projects. The concept of model view definition (MVD) within the IFC schema should provide targeted data subsets for specific purposes, but the current approach has limitations. A shift towards modularisation is necessary to address these limitations, allowing for more streamlined implementation, maintenance, and scalability of MVDs. This modularisation will establish a shared foundation that supports interoperability across domains and ensures the coherent evolution of IFC.

Furthermore, integrating internet of things (IoT) technologies into BIM represents a transformative frontier. While IFC has successfully represented various building elements, there is a need to incorporate IoT-related attributes to address dynamic environments. Integrating IoT elements like sensors and devices and robust security considerations can significantly enhance cost estimation, facility management, collaboration, and IoT infrastructure management. Cloud-based collaboration offers unprecedented opportunities for real-time communication and data sharing among project stakeholders. Optimising IFC for

cloud environments and implementing robust security measures will ensure the integrity and privacy of project data while enhancing scalability and performance. Furthermore, supporting advanced technologies like AR, VR, AI, and digital twins within the IFC schema will empower stakeholders to perform detailed analysis, visualisation, and optimisation of building designs, leading to more sustainable and efficient built environments. The evolution of industry foundation classes reflects the ongoing efforts to standardise and enhance data exchange in the construction industry. By embracing emerging technologies and addressing industry challenges, IFC is poised to play a central role in shaping the future of design, construction, and facility management, ultimately leading to smarter, more interconnected, and sustainable built environments.

The study's ambitious predictions regarding the future of the IFC are noteworthy, but it is important to recognise that these forecasts come with certain limitations. One such limitation is that while the study focuses on the concept of interoperability, which is crucial for seamless data exchange, it may not fully delve into the practical challenges that arise in real-world scenarios. In other words, achieving interoperability in diverse contexts outside controlled environments may present unique hurdles that the study might not fully address. Moreover, the study's exploration of various technologies related to IFC may not cover all potential advancements comprehensively. This means that while it may provide insights into existing technologies and their potential improvements, it might overlook emerging innovations that could significantly impact the future of IFC. As a result, the study's findings may not be as applicable or relevant to these newer developments, thereby limiting its scope and applicability in predicting the future landscape of IFC and its impact on industries like AEC and facility management.

This study is significant due to its relevance to the ongoing development and future direction of industry foundation classes (IFC). By critically evaluating the current state of IFC and predicting its future advancements, the research provides valuable insights that can influence the trajectory of future developments in the architecture, engineering, and construction (AEC) and facility management industries. The study's outcomes will contribute to the standardisation of data exchange practices within these fields, fostering consistency across projects, improving communication, and minimising errors and inefficiencies. The study can inspire innovation through the adoption of new technologies and methodologies. This can lead to the creation of more sophisticated tools and practices, enhancing project outcomes and operational efficiency. Improved interoperability through IFC advancements will facilitate greater collaboration among stakeholders, resulting in better-designed, constructed, and managed buildings and infrastructure.

The IFC standard has evolved to address the ever-growing demands of the AEC and facilities management industries, focusing on interoperability to tackle sustainability and resilience challenges. The future directions of IFC, including the forthcoming IFC 5 release and integration of IoT, should reflect the commitment to enhancing data exchange standards to support a more connected and sustainable built environment. As cities continue to evolve, the evolution of IFC remains pivotal in shaping a more intelligent, resilient, and efficient urban landscape.

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