Exploring the digital authentication of built asset information models at the object level

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Abstract

Building Information Modeling (BIM) provides a significant opportunity to enhance the performance of the asset building industry by enabling efficient collaboration and information exchange among stakeholders. Developed by buildingSMART, the Industry Foundation Classes (IFC) has been established as an open standard, facilitating data exchange and interoperability. The adoption of IFC offers several advantages for BIM data exchange. It promotes interoperability among different software platforms, allowing stakeholders to seamlessly exchange BIMs without format conversion issues. However, ensuring the authenticity and integrity of BIM data remains a critical concern. Various solutions and standards for exchanging and authenticating BIMs have been developed, yet certain flaws persist including limited support for object-level authentication, implementation complexity, and maintenance consideration like long-term verification. This research explores the potential of adding digital signatures to BIMs at the object level by investigating the IFC schema and highlights the existing challenges regarding IFC structure to implement a fully functional solution.

Keywords: BIM, IFC, digital signature, digital authentication

1 Introduction

One of the significant advantages of applying BIM in projects is the improvement in efficiency and productivity by facilitating collaboration among all multidisciplinary parties and stakeholders involved throughout project life cycle (Poirier et al., 2017; Song et al., 2021), In fact, BIM serves as a platform to improve collaboration (Zhang et al., 2021) providing the possibility of generating and managing data (Mohammad et al., 2019), as well as exchanging and sharing reliable information, which results in better decision-making (Zhang et al., 2021). However, there are many challenges in adopting BIM in practice, including lack of trust and transparency (Saini et al., 2019), Traceability (Celoza et al., 2023), Interoperability (Mohammadi et al., 2024), security and integrity of the shared information (Bodea, 2018), professional liability (Arshad et al., 2019), and Ownership and intellectual property (IP) rights (Hijazi et al., 2021).

Addressing the challenges mentioned above requires a solution ensuring authenticity and integrity of BIMs. Additionally, any solution should be compatible with existing (and emerging) processes and standards, aligned with regulatory and legal concerns, while supporting interoperability between software tools. One such approach, openBIM as an open standard which is “a collaborative process that is vendor neutral” (*openBIM Definition - buildingSMART International*, 2020) and its related concepts and standards, should be considered as a solution for regarding technical interoperability between software platforms as well as semantic and syntactic interoperability between business processes (Jiang et al., 2019). The research presented in this paper explores the possibility of applying data integrity techniques at the object level on BIMs in IFC format.

1.1 Research Methodology

The research begins with a literature review by exploring multiple academic databases like Scopus and Google Schoolar to understand BIM adaption challenges in context of legal concerns, digital delivery, data integrity, data integrity verification techniques, OpenBIM eco-system, and related standards particularly IFC standards, focusing on how digital signatures can be integrated within the BIMs. This involves examining required digital signature meta-data and mapping their components onto the IFC structure to ensure compatibility with existing BIM processes.

In order to understand the practical requirements of an ideal solution, workshops were conducted with Cybersecurity professionals and BIM experts. The next phase involves analyzing the IFC schema to identify suitable containers for digital signatures at the object level. This includes exploring the hierarchical structure and relationships within IFC data to determine the feasibility of embedding digital signatures without significant modifications, as well as identifying practical challenges and limitations.

1.2 Research Objective

This paper aims to explore the IFC schema to examine the possibility of adding digital signatures to BIMs at the object level by identifying the appropriate container and place in the IFC schema. It also highlights the challenges of exchanging information at the object level in BIMs using the IFC format. The research endeavors to contribute to the discourse on enhancing the integrity of BIM data through the integration of digital signature mechanisms within BIMs in IFC format. This serves as a conceptual foundation for developing a software toolkit, thereby facilitating reliable information exchange and collaboration in the building asset industry.

2 Background

The ideal solution for authenticating and verifying BIM data integrity should be interoperable, secure, open, and standardized (Maier, 2020). Additionally, based on professional opinion, it should ensure durability and long-term verification while being a standalone solution with minimal dependency on other tools and minimal intervention in existing tools and processes, to facilitate the adoption of the new solution in practice. Experts also emphasize the need for the ability to authenticate BIM objects in use cases where the model is created by multiple engineers, each responsible for their part as well as vouching other's work.

Current solutions mostly are based on standards that involves creating a memorandum file, either by converting the model to 2D pdf or by using a document as a cover that contains a list of files and attached files in a container (ARINC827-1· 827-1 Electronic Distribution of Software by Crate (EDS Crate), 2020; ARINC835-1· ARINC Report 835-1: Guidance for Security of Loadable Software Parts Using Digital Signatures, 2014; ISO 21597-1, 2020; PDF/A-3, PDF for Long-Term Preservation, Use of ISO 32000-1, With Embedded Files, 2020). Even BIM Common Data Environments (CDE) act as repositories for storing files. In fact, existing solutions support file-based authentication and would not support the mentioned cosigning or vouching scenarios.

Various techniques exist to verify data integrity, including digital signature algorithms and blockchain-based techniques, which are commonly employed. Block-chained solutions and their integration in BIM-based projects have received significant attention recently and there are some implemented solutions which support both file level (Pradeep et al., 2020) and object level (Xue & Lu, 2020) data integrity verification. Despite the various advantages of Block-chained solutions, including transparency (Hijazi et al., 2019; Holland et al., 2018), traceability (Hijazi et al., 2021; Yu, Zhang, et al., 2023), and non-repudiation for both the source and recipient (Fang et al., 2020) as well as providing a tamper-proof eco-system (Yu, Zhang, et al., 2023) to protect data, there are still many shortcomings, particularly in construction projects.

In fact, the adoption of Block-chained solutions in practice requires more thought in terms of regulatory and legal concerns (Li & Kassem, 2021). Moreover, the current technical complexity inherent in deploying block-chain makes them hard to implement and maintain (Nawari & Ravindran, 2019). More specifically, existing regulations and norms in construction projects require that any solution for authentication and data integrity support long-term validation (*Engineers Act*, 2024; Secretariat, 2021). This can be challenging to achieve using blockchain techniques, which consist of a decentralized network of blocks. In other words, blockchain solutions are more suitable for real-time data exchange and sharing and may be less suitable for digital authentication. Indeed, most frameworks and solutions in the literature point to the suitability of blockchain for ongoing construction projects or for data delivery within the construction supply chain (CSC) (Hijazi et al., 2021).

On the other hand, digital signatures are widely used to identify signatories and verify the integrity of digital documents (Lax et al., 2015). Digital signatures are accepted and used formally in many jurisdictions and industries. They are easier to implement and maintain compared to blockchain-based solutions. In fact, there are common standards, processes, and tools for applying digital signatures for digital documents and 2D drawings. Therefore, this paper focuses on digital signature and explores the possibility of integrating them in BIMs at the object level. It is worth noting that digital signatures do not create a tamper-proof eco-system. Instead, they allow the creation of a snapshot of the model at a specific date and time in order to detect any unauthorized modification afterwards. A summary of the high-level comparison between digital signatures and blockchain techniques in the context of this research is presented in Table 1.

Based on the preferred requirements of ideal solution and comparison presented, digital signatures emerge as a more promising solution compared to blockchain techniques for verifying data integrity in the built asset industry.

Table 1. High level comparison of Digital signature and Blockchain techniques.

Aspects	Digital Signatures	Blockchain
Legal Acceptance	Widely recognized	Requires more regulations
Complexity - Implementation & maintenance -	Relatively simple	Higher complexity
Long-Term Validation -LTV-	Support LTV	complex and costly solutions

2.1 Digital Signatures and their Required Meta-Data

A digital signature employs cryptographic methods to verify the authenticity and integrity of digital content (Goswami et al., 2021; Rai et al., 2023; Seetha, 2017). Adding a digital signature to digital content is done following two main processes: signing and verifying (Mulder et al., 2023, Chapter 15). The details of these processes, such as digital signature types, hashing and cryptographic algorithms, certificates, key management algorithms and their implementation are not within the scope of this research. The focus of the research is to highlight a mapping between the meta-data in the digital signature or certificate related to signatory and IFC data schema.

Table 2. Required meta-data for signing process.

Field	Sub-Field	Description	Source
Issuer	“**Labelling attribute types** (Common name, Surname, Given Name, Initials), **Geographical attribute type** (Country name, Locality Name, State or Province Name), **Organizational attribute types** (Organization Name, Organizational Unit Name, Title-Role-)”	The name of the entity issuing the certificate. The sub-fields are based on x.520(*X.520 : Information Technology - Open Systems Interconnection - The Directory: Selected Attribute Types*, 2019).	X.509
Subject	“**Labelling attribute types** (Common name, Surname, Given Name, Initials), **Geographical attribute types** (Country name, Locality Name, State or Province Name), **Organizational attribute types** (Organization Name, Organizational Unit Name, Title-Role-)”	The subject is the certificate owner’s name. The sub-fields are based on x.520 (*X.520 : Information Technology - Open Systems Interconnection - The Directory: Selected Attribute Types*, 2019).	X.509
Validity	valid from or valid after valid to or valid before	The validity period of the certificate.	X.509
Signing Time	---	the time the signer completed the signing process.	XAdES

Table 2 presents combination of partial structure of the X.509 certificate structure, as a common “public-key certificate framework”(*X.509 : Information Technology - Open Systems Interconnection - The Directory: Public-Key and Attribute Certificate Frameworks*, 2019) and XML Advanced Electronic Signatures (XAdES) (*ETSI TS 101 903: “Electronic Signatures and*

Infrastructures (ESI); XML Advanced Electronic Signatures (XAdES)," 2010) as a standard for specific type of digital signature, which are required for the signing process. The naming or detail of the parameters may vary in different standards; however, the selected parameters would fulfill the general requirements of this research.

2.2 openBIM overview

BIM is a "data-intensive process" (Xu et al., 2023) which covers various aspects of a construction project's life cycle including design and construction to operation and maintenance. Since various disciplines with multiple software tools are involved in the process, the "proprietary vendor data formats" (*openBIM Definition - buildingSMART International*, 2020) , and in general, system to system interoperability, emerges as a challenge. buildingSMART has developed the openBIM concept taking the form of international open standards and working procedures to create "common alignment and language" (*openBIM Definition - buildingSMART International*, 2020). The combination of these standards would support various aspects of projects in terms of people, processes, and tools. The summary of the buildingSMART (*buildingSMART International*, 2023) open standards and services is presented in Table 3.

Table 3. Summary of the buildingSMART openBIM standards and services

Name	**Type/Standard**	**Description**
IFC **-Industry Foundation Classes-**	ISO 16739-1:2024	As a data model schema, it provides a vendor-neutral digital description of project(*Industry Foundation Classes (IFC)*, 2024).
IDS **-Information Delivery Specification-**	buildingSMART Standard	Computer-interpretable XML standard to define and check information requirements from IFC model (*bSI Standards - buildingSMART International*, 2019; *buildingSMART/IDS*, 2020/2024).
IDM **-Information Delivery Manual-**	ISO 29481-1:2010	a methodology for collecting and defining information flow and procedures throughout the project lifecycle(*Information Delivery Manual (IDM)*, 2024).
BCF **-BIM Collaboration Format-**	buildingSMART Standard	It enables BIM apps to exchange model issues via shared IFC data, improving collaboration(*BIM Collaboration Format (BCF) - buildingSMART International*, 2019).
MVD **-Model View Definitions-**	buildingSMART Standard	a subset of IFC schema that fulfil one or more information exchange requirements(Jiang et al., 2019; *Model View Definitions (MVD)*, 2024).
bsDD **-buildingSMART Data Dictionary-**	buildingSMART Technical Service	collection of interconnected data dictionaries based on Information Framework for Dictionaries (IFD) standard (ISO 12006-3) to identify and validate the objects name and attributes(*buildingSMART Data Dictionary - buildingSMART International*, 2024).
IFC Validation service	buildingSMART Technical Service	Check the compliance of IFC file against IFC Standard(*IFC Validation Service*, 2024).
UCM-Use-Case Management service-	buildingSMART Technical Service	Developed based on IDM methodology to Capture, specify, exchange best practices(*Use Case Management*, 2024).

2.3 IFC Data Schema

IFC is defined by buildingSMART International and certified by the International Organization for Standardization (ISO) - ISO 16739-1 (*ISO 16739-1*, 2024) - as an international standard file format to facilitate BIM data exchange between and interoperability among software tools (Kim et al., 2020; Won et al., 2022). Architectural information within IFC files is represented through the "relationships between a building object and its property information" (Kim et al., 2020). IFC is a STEP physical file format -ISO 10303-21- and uses Express language -ISO 10303-1- for schema publication(*IFC4.3.2.0 Documentation*, 2023).

Based on (*IFC4.3.2.0 Documentation*, 2023), The architecture of the IFC data schema comprises four conceptual layers: Resource, Core, Interoperability, and Domain layers. Figure 1 illustrates an overview of the IFC architecture. At the lowest level, the Resource layer contains individual schemas base definitions. The definitions in Resource layer do not have a globally unique identifier (GUID), therefore they cannot be used independently. The next layer, the Core layer contains Kernel schema and core extensions. Entities defined at the core layer or above are assigned a GUID, and they can be initiated independently. The third layer, the Interoperability layer, encompasses schemas containing entity definitions customized for specific product, process, or resource specializations that cover various disciplines. The definitions in the Interoperability layer are usually employed for sharing and exchanging construction information between different domains. The top layer, the Domain layer, contains schemas related entity definitions specialized for products, processes, or resources within specific disciplines. The definitions are primarily utilized for sharing and exchanging information within the same domain. The IFC data schema architecture is a hierarchical structure in which entities and definitions in higher layers can reference and use those in the lower layers (Won et al., 2022).

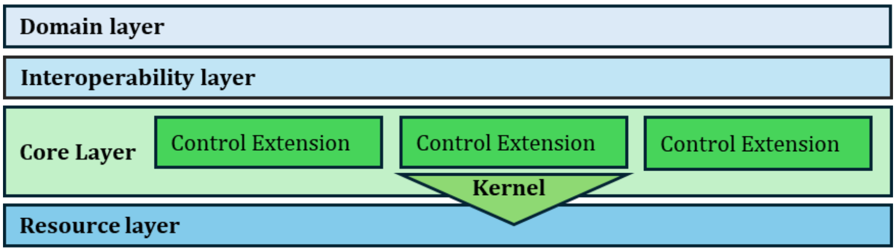

Figure 1. Overview of the IFC architecture (IFC4.3.2.0 Documentation, 2023).

3 Findings and Results

Various studies suggest different approaches to extend IFC Schema including creating a new entity or extending properties by adding new attributes to existing entities (Yu, Kim, et al., 2023). Another approach is reusing an existing entity in the IFC schema which holds all the necessary information for the specific purpose (Won et al., 2022). Since defining new entities or properties and adding them into the schema implies long and complex processes to become part of formal IFC standard, which them lead to modifications in existing tools, the research focuses on finding an existing entity in the schema to reuse it as a container for the digital signature.

3.1 Integrating digital signature into the IFC data schema

Integrating digital signature into IFC data schema involves ensuring that the signatures are embedded in a manner that is compatible with existing IFC data schema and common standards for digital signatures. As shown in Figure 2, the basic definitions of required meta-data for digital signatures can be found in the resource layer. The IfcActorResource schema represents persons or organizations and their relationships and the IfcDateTimeResource schema contains generic definitions of date and time (*IFC4.3.2.0 Documentation*, 2023).

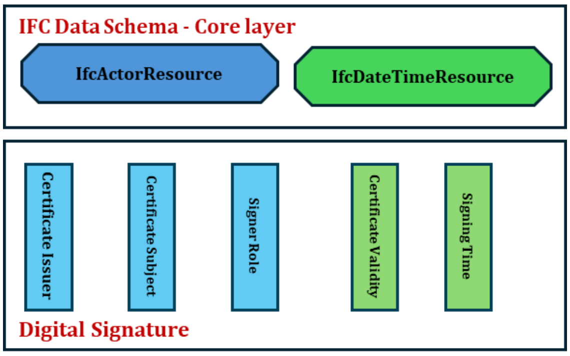

Figure 2. High-level mapping between IFC Data schema Core definitions and Digital signature Data parameters

To effectively utilize the inheritance structure in the IFC data schema, the digital signature container should be at the lowest possible level in the layered architecture. This ensures that the container can be accessed by the maximum number of entities within the schema in higher layers. Interoperability layer and Domain layer are not suitable because some definitions in these layers are specific to a particular concept which are unrelated to other entities, and they are placed in the section of the schema which cannot be inherited by higher levels. Moreover, some entities in lower layers need to have digital signature but they cannot inherit from definitions in higher layers. Consequently, using definitions in these layers requires repeating definition in various places in the IFC data schema. Therefore, the appropriate candidate for this placement would be the Core layer or Resource Layer.

As shown in Figure 2, IfcActorResource and IfcDateTimeResource cover the meta-data related to certificate issuer or signer and date and time of digital signature, however adding digital signature to an element requires a container which covers all meta-data together, including the digital signature. By exploring the IFC data schema in the resource layer, the IfcObjectReferenceSelect is found as a potential container for digital signature. Listing 1 illustrates the formal representation of IfcObjectReferenceSelect in Express language with highlighted required type values for the digital signature. “IfcObjectReferenceSelect is a select type, that holds a list of resource level entities that can be used as property values for an IfcPropertyReferenceValue being a property within an IfcPropertySet.”(*IfcObjectReferenceSelect - IFC 4.3.2 Documentation*, 2022). The IfcPropertySet is in the Kernel part of Core layer of IFC data schema and serves as a container for properties in property tree which ends in IfcRoot as illustrated in Figure 3. In fact, the relation of IfcObjectReferenceSelect with IfcPropertySet and consequently with IfcRoot, as the most abstract and foundational class for all entity definitions originating in the kernel or in higher layers of the IFC specification, ensure that IfcObjectReferenceSelect would be accessible by all entities in the IFC data schema.

IfcObjectReferenceSelect contains type values in relation with other entities and types in IFC data schema which supports adding more detailed meta-data for the digital signature. Additionally, calculated digital signature could be placed in IfcTable which supports having multiple digital signatures with customized table structure on specific object.

Listing 1. Representation of IfcObjectReferenceSelect
(IfcObjectReferenceSelect - IFC 4.3.2 Documentation, 2022)

```
“TYPE IfcObjectReferenceSelect =
 SELECT
          (IfcAddress
          ,IfcAppliedValue
          ,IfcExternalReference
          ,IfcMaterialDefinition
          ,IfcOrganization
          ,IfcPerson
          ,IfcPersonAndOrganization
          ,IfcTable
         ,IfcTimeSeries);
 END_TYPE;”
```

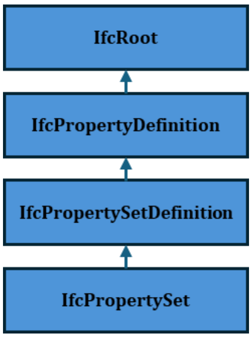

Figure 3. Entity inheritance of IfcProertySet
(IfcObjectReferenceSelect - IFC 4.3.2 Documentation, 2022)

3.2 Challenges of using the IFC data schema for Digital Signature of BIMs

Adding digital signatures to specific objects within IFC BIMs involves several significant challenges. In fact, similar to the signing process in the paper-based building models or digitalized 2D models, where the signatory would place the signature on a specific view of the model, this process requires the precise selection of specific objects and their related data in the model. The key challenges associated with this task and IFC Schema are highlighted as follows:

3.2.1 Backward and forward compatibility issue in the IFC Data Schema

Backward and forward compatibility refers to the capability of an exchange structure to function correctly with both previous and future versions of a specification (*IFC4.3.2.0 Documentation*, 2023). In the current version, IFC 4.3.2, there are new definitions that did not exist in previous versions, as well as definitions that are now obsolete or candidates for obsoletion in the next version. Therefore, using certain definitions in the schema carries the risk that they may not exist in previous or future versions of the IFC data schema. For instance, IfcObjectReferenceSelect, proposed as a container for digital signatures, is a new type in IFC 2.0, and IfcTable was added to its definition in IFC 4.0 (*IFC4.3.2.0 Documentation*, 2023).

3.2.2 Exchange of BIM data through the utilization of IFC MVD

MVDs can be considered as “IFC view definition”(Afsari et al., 2016) that are extracted from IFC schema to facilitate data exchange based on specific Exchange Requirement (ER)(Chipman et al., 2016). In practice, when the BIM model is developed in an authoring tool, it is exported to IFC format based on selected MVD (Afsari et al., 2016; Yu, Kim, et al., 2023). The MVDs and their related exchange requirements are presented by the buildingSMART standard mvdXML. This standard contains predefined templates for the sub-set of IFC schema as a graph, including all required entities and attributes (Chipman et al., 2016).

Whitin the scope of this research, two issues arise when using MVD IFC files to authenticate an object and its related entities: 1) There is a possibility of referencing entities that are not included in the files. This creates potential legal issues since an engineer might be responsible for an object that does not exist in the exported MVD IFC file. 2) predefining all possibilities for all entities and their combinations in the IFC schema is almost impossible.

3.2.3 Relationships in IFC schema

Relationships between entities play a significant role in IFC data structure in terms of consistency in definitions and creating flexible and extendable structures. However, the various types of relationships, including inverse relationships and objectified relationships along with related concepts attached to them including references, cardinality, make IFC BIMs complex for analyzing and navigation. In fact, this complexity creates challenges for "object-based use of IFC data"(van Berlo et al., 2021).

One approach to explore the issue of navigating IFC model starting from a selected object toward extracting all related objects is applying graph-based theories and methods to BIMs data because of IFC models object-oriented nature (Ismail et al., 2017; Tauscher & Crawford, 2018). By considering an IFC model as a graph, we need to find all possible path starting from specific object and ending with an object that has no related object. If the graph can be considered as a tree or directed acyclic graph, finding those paths is possible, however the relationships in the IFC schema implies that there are possibilities to have undirected circuits - loops - (van Berlo et al., 2021). Therefore, it seems that extracting related objects and data for a selected object in the IFC model is hard to achieve considering the current IFC data schema.

3.2.4 Redundant instances in IFC Models

IFC files produces by different software platforms often include considerable amount of redundant information from import and export processes (Du et al., 2020; Sun et al., 2015; Zheng et al., 2024). The direct consequence of redundant data in excessive file size and various studies focus on compressing the IFC file by eliminating redundant data. From an authentication point of view, duplicate instances could cause ambiguity in assigning responsibility.

3.2.5 Optional Data and elective implementation of the IFC Schema in Software tools

The IFC Schema contains various optional data elements, moreover, IFC authoring tools, whether native or proprietary, which convert models to IFC based on specific MVDs, may not always populate all required data. When integrating digital signatures into BIM objects, appropriate functionality can resolve this issue by automatically extracting necessary data from the signatory certificate and filling in the relevant properties.

4 Conclusion

This research explored the feasibility of integrating digital signatures at the object level within BIMs using the IFC data schema. The goal was to address the need for information exchange and collaboration in the built asset industry by ensuring the authenticity and integrity of BIM data. The investigation identified both promising opportunities and significant challenges associated with this approach.

One promising aspect is the potential for adding a digital signature to the IFC model through an existing entity, providing a foundational basis for incorporating necessary metadata related to digital signatures. However, the highlighted challenges, particularly the extraction of specific objects and their related objects and data in the model poses a critical barrier to integrating digital signature in the IFC model at the object-level. In fact, the current IFC data schema is designed to be optimized for file-based data exchange (van Berlo et al., 2021). There is an ongoing effort to address part of some of these issues by buildingSMART throughout the new version of IFC schema -IFC 5-. Until then, adopting an intermediary solution capable of authenticating objects in an IFC model, independent of the current IFC data schema, may be a more practical approach. The future work of this research will focus on proposing solution in which the digital signatures will add to the IFC file over a container within the file with reference to the selected objects in the model.

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References

Afsari, K., Eastman, C., & Shelden, D. (2016). *Data Transmission Opportunities for Collaborative Cloud-Based Building Information Modeling*. https://doi.org/10.5151/despro-sigradi2016-448

ARINC827-1· 827-1 Electronic Distribution of Software by Crate (EDS Crate). (2020). https://aviation-ia.sae-itc.com/standards/arinc827-1-827-1-electronic-distribution-software-crate-eds-crate

ARINC835-1· ARINC Report 835-1: Guidance for Security of Loadable Software Parts Using Digital Signatures. (2014). https://aviation-ia.sae-itc.com/standards/arinc835-1-arinc-report-835-1-guidance-security-loadable-software-parts-using-digital-signatures

Arshad, M. F., Thaheem, M. J., Nasir, A. R., & Malik, M. S. A. (2019). Contractual Risks of Building Information Modeling: Toward a Standardized Legal Framework for Design-Bid-Build Projects. *Journal of Construction Engineering and Management*, *145*(4), 04019010. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001617

BIM Collaboration Format (BCF)—buildingSMART International. (2019, April 23). https://www.buildingsmart.org/standards/bsi-standards/bim-collaboration-format-bcf/

Bodea, C.-N. (2018). *Legal implications of adopting Building Information Modeling (BIM)*.

bSI Standards—buildingSMART International. (2019, April 23). https://www.buildingsmart.org/standards/bsi-standards/

buildingSMART Data Dictionary—buildingSMART International. (2024, April 3). https://www.buildingsmart.org/users/services/buildingsmart-data-dictionary/

buildingSMART International. (2023, July 27). https://www.buildingsmart.org/

buildingSMART/IDS. (2024). [C#]. buildingSMART. https://github.com/buildingSMART/IDS (Original work published 2020)

Celoza, A., de Oliveira, D. P., & Leite, F. (2023). Role of BIM Contract Practices in Stakeholder BIM Implementation on AEC Projects. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction*, *15*(2), 04523002. https://doi.org/10.1061/JLADAH.LADR-916

Chipman, T., Liebich, T., & Thomas, M. (2016, February 15). *mvdXML- Specification of a standardized format to define and exchange Model View Definitions with Exchange Requirements and Validation Rules*. buildingSMART. https://standards.buildingsmart.org/MVD/RELEASE/mvdXML/v1-1/mvdXML_V1-1-Final.pdf

Du, X., Gu, Y., Yang, N., & Yang, F. (2020). IFC File Content Compression Based on Reference Relationships. *Journal of Computing in Civil Engineering*, *34*(3), 04020012. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000894

Engineers Act. (2024, February 20). https://www.legisquebec.gouv.qc.ca/en/document/cs/I-9

ETSI TS 101 903: "Electronic Signatures and Infrastructures (ESI); XML Advanced Electronic Signatures (XAdES)" (Version V1.4.2). (2010). [Technical Specification]. ETSI (European Telecommunications Standards Institute). https://portal.etsi.org/webapp/workprogram/Report_WorkItem.asp?WKI_ID=35243

Fang, W., Chen, W., Zhang, W., Pei, J., Gao, W., & Wang, G. (2020). Digital signature scheme for information non-repudiation in blockchain: A state of the art review. *EURASIP Journal on Wireless Communications and Networking*, *2020*(1), 56. https://doi.org/10.1186/s13638-020-01665-w

Goswami, P., Singh, M. M., & Rahman, K. T. (2021). Digital Signatures. *EAI/Springer Innovations in Communication and Computing*, 243–277. https://doi.org/10.1007/978-3-030-60890-3_14

Hijazi, A. A., Perera, S., Al-Ashwal, A. M., & Neves Calheiros, R. (2019). Enabling a single source of truth through BIM and blockchain integration. *Proceedings of the 2019 International Conference on Innovation, Technology, Enterprise and Entrepreneurship (ICITEE 2019), 24-25 November 2019, Kingdom of Bahrain*, 385–393. https://researchdirect.westernsydney.edu.au/islandora/object/uws%3A54569/

Hijazi, A. A., Perera, S., Calheiros, R. N., & Alashwal, A. (2021). Rationale for the Integration of BIM and Blockchain for the Construction Supply Chain Data Delivery: A Systematic Literature Review and Validation through Focus Group. *Journal of Construction Engineering and Management*, *147*(10), 03121005. https://doi.org/10.1061/(ASCE)CO.1943-7862.0002142

Holland, M., Stjepandić, J., & Nigischer, C. (2018). Intellectual Property Protection of 3D Print Supply Chain with Blockchain Technology. *2018 IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC)*, 1–8. https://doi.org/10.1109/ICE.2018.8436315

IFC Validation Service. (2024). buildingSMART Technical. https://technical.buildingsmart.org/services/validation-service/

IFC4.3.2.0 Documentation. (2023). https://standards.buildingsmart.org/IFC/RELEASE/IFC4_3/

IfcObjectReferenceSelect—IFC 4.3.2 Documentation. (2022). https://ifc43-docs.standards.buildingsmart.org/IFC/RELEASE/IFC4x3/HTML/lexical/IfcObjectReferenceSelect.htm

Industry Foundation Classes (IFC). (2024). buildingSMART Technical. https://technical.buildingsmart.org/standards/ifc/

Information Delivery Manual (IDM). (2024). buildingSMART Technical. https://technical.buildingsmart.org/standards/information-delivery-manual/

Ismail, A., Nahar, A., & Scherer, R. (2017, July 12). *Application of graph databases and graph theory concepts for advanced analysing of BIM models based on IFC standard*.

ISO 16739-1:2024. (2024). https://www.iso.org/standard/84123.html

ISO 21597-1:2020. (2020). https://www.iso.org/standard/74389.html

Jiang, S., Jiang, L., Han, Y., Wu, Z., & Wang, N. (2019). OpenBIM: An Enabling Solution for Information Interoperability. *Applied Sciences*, *9*(24), Article 24. https://doi.org/10.3390/app9245358

Kim, I., Lee, Y., Han, C.-H., Kim, G., & Choi, J. (2020). Validation of Support for Creation of License Drawings Using Application for openBIM-Based Automatic Generation of 2D Drawings. *Applied Sciences*, *10*(18), Article 18. https://doi.org/10.3390/app10186470

Lax, G., Buccafurri, F., & Caminiti, G. (2015). Digital Document Signing: Vulnerabilities and Solutions. *Information Security Journal: A Global Perspective*, *24*(1–3), 1–14. https://doi.org/10.1080/19393555.2014.998843

Li, J., & Kassem, M. (2021). Applications of distributed ledger technology (DLT) and Blockchain-enabled smart contracts in construction. *Automation in Construction*, *132*, 103955. https://doi.org/10.1016/j.autcon.2021.103955

Model View Definitions (MVD). (2024). buildingSMART Technical. https://technical.buildingsmart.org/standards/ifc/mvd/

Mohammad, W. N. S. W., Abdullah, M. R., Ismail, S., & Takim, R. (2019). Technology-organisation-environment framework for Building Information Modelling (BIM) adoption challenges for contractor's organisations in Malaysia. *Journal of Computational and Theoretical Nanoscience*, *16*(5–6), 2282–2288. https://doi.org/10.1166/jctn.2019.7885

Mohammadi, S., Aibinu, A. A., & Oraee, M. (2024). Legal and Contractual Risks and Challenges for BIM. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction*, *16*(1), 04523043. https://doi.org/10.1061/JLADAH.LADR-1040

Mulder, V., Mermoud, A., Lenders, V., & Tellenbach, B. (Eds.). (2023). *Trends in Data Protection and Encryption Technologies*. Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-33386-6

Nawari, N. O., & Ravindran, S. (2019). Blockchain and the built environment: Potentials and limitations. *Journal of Building Engineering*, *25*, 100832. https://doi.org/10.1016/j.jobe.2019.100832

openBIM Definition—buildingSMART International. (2020, March 19). https://www.buildingsmart.org/about/openbim/openbim-definition/

PDF/A-3, PDF for Long-term Preservation, Use of ISO 32000-1, With Embedded Files. (2020, October 12). [Web page]. https://www.loc.gov/preservation/digital/formats/fdd/fdd000360.shtml

Poirier, E. A., Forgues, D., & Staub-French, S. (2017). Understanding the impact of BIM on collaboration: A Canadian case study. *Building Research & Information*, *45*(6), 681–695. https://doi.org/10.1080/09613218.2017.1324724

Pradeep, A. S. E., Amor, R., & Yiu, T. W. (2020). *Blockchain Improving Trust in BIM Data Exchange: A Case Study on BIMCHAIN*. 1174–1183. https://doi.org/10.1061/9780784482865.124

Rai, A. K., Singh, M., Sudheendramouli, H. C., Panwar, V., Balaji, N. A., & Kukreti, R. (2023). *Digital Signature for Content Authentication*. Proceedings of the 2nd IEEE International Conference on Advances in Computing, Communication and Applied Informatics, ACCAI 2023. https://doi.org/10.1109/ACCAI58221.2023.10200472

Saini, M., Arif, M., & Kulonda, D. J. (2019). Challenges to transferring and sharing of tacit knowledge within a construction supply chain. *Construction Innovation*, *19*(1), 15–33. https://doi.org/10.1108/CI-03-2018-0015

Secretariat, T. B. of C. (2021, April 28). *Government of Canada Guidance on Using Electronic Signatures*. https://www.canada.ca/en/government/system/digital-government/online-security-privacy/government-canada-guidance-using-electronic-signatures.html

Seetha, R. (2017). An enhanced digital signature scheme. *International Journal of Applied Engineering Research*, *12*(22), 11878–11884.

Song, S., Zhang, C., & Marks, E. (2021). *Effectiveness and Practicability Analysis of BIM Adoption in the AEC Industry*. 530–537. https://doi.org/10.1061/9780784483893.066

Sun, J., Liu, Y.-S., Gao, G., & Han, X.-G. (2015). IFCCompressor: A content-based compression algorithm for optimizing Industry Foundation Classes files. *Automation in Construction*, *50*, 1–15. https://doi.org/10.1016/j.autcon.2014.10.015

Tauscher, H., & Crawford, J. (2018). Graph representations and methods for querying, examination, and analysis of IFC data. In J. Karlshøj & R. Scherer (Eds.), *eWork and eBusiness in Architecture, Engineering and Construction* (1st ed., pp. 421–428). CRC Press. https://doi.org/10.1201/9780429506215-53

Use Case Management. (2024). https://ucm.buildingsmart.org/?page=1&sort=language&direction=desc

van Berlo, L., Krijnen, T., Tauscher, H., Liebich, T., van Kranenburg, A., Paasiala, P., & Paasiala, P. (2021). *Future of the Industry Foundation Classes: Towards IFC 5*.

Won, J., Kim, T., Yu, J., & Choo, S. (2022). Development of the IFC Schema Extension Methodology for Integrated BIM. In Pak B., Wurzer G., & Stouffs R. (Eds.), *Proc. Int. Conf. Educ. Res. Comput. Aided. Archit. Des. Eur.* (Vol. 2, pp. 339–346). Education and research in Computer Aided Architectural Design in Europe. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85139252094&partnerID=40&md5=5b558ca39fa9e51ce8e312dc95d19e4b

X.509 : Information technology—Open Systems Interconnection—The Directory: Public-key and attribute certificate frameworks. (2019). https://www.itu.int/rec/T-REC-X.509-201910-I/en

X.520 : Information technology—Open Systems Interconnection—The Directory: Selected attribute types. (2019). https://www.itu.int/rec/T-REC-X.520-201910-I/en

Xu, Y., Tao, X., Das, M., Kwok, H. H. L., Liu, H., Wang, G., & Cheng, J. C. P. (2023). Suitability analysis of consensus protocols for blockchain-based applications in the construction industry. *Automation in Construction*, *145*, 104638. https://doi.org/10.1016/j.autcon.2022.104638

Xue, F., & Lu, W. (2020). A semantic differential transaction approach to minimizing information redundancy for BIM and blockchain integration. *Automation in Construction*, *118*, 103270. https://doi.org/10.1016/j.autcon.2020.103270

Yu, Y., Kim, S., Jeon, H., & Koo, B. (2023). A Systematic Review of the Trends and Advances in IFC Schema Extensions for BIM Interoperability. *Applied Sciences*, *13*(23), Article 23. https://doi.org/10.3390/app132312560

Yu, Y., Zhang, Y., Yu, J., & He, X. (2023). An overview of the application and development of data integrity verification techniques. *Second International Conference on Applied Statistics, Computational Mathematics, and Software Engineering (ASCMSE 2023)*, *12784*, 410–415. https://doi.org/10.1117/12.2691857

Zhang, L., Pan, Y., Wu, X., & Skibniewski, M. J. (2021). Process Mining. In L. Zhang, Y. Pan, X. Wu, & M. J. Skibniewski (Eds.), *Artificial Intelligence in Construction Engineering and Management* (pp. 147–172). Springer. https://doi.org/10.1007/978-981-16-2842-9_7

Zheng, Y., Shi, Y., & Wang, X. (2024). Research on Partial Model Extraction of Railway Infrastructure Based on the Industry Foundation Classes Files. *IEEE Access*, *12*, 94690–94701. IEEE Access. https://doi.org/10.1109/ACCESS.2024.3425898