Level of Integration (LoInt): A Conceptual Framework for BIM-GIS Data Integration

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Abstract

Building Information Modelling (BIM) – Geographic information System (GIS) data integration constitutes a crucial component in the development of urban digital twins. This integration can be achieved through a variety of techniques and methodologies; however, numerous challenges arise during the integration process that hinder seamless interoperability. Although several attempts have been made to address these challenges, prior studies tend to address these challenges in isolation, and the literature stills lacks from a standardized approach to perform the integration. This paper proposes a conceptual framework designed to support standardizing the integration practices by synthesizing these challenges into a progressive, structured model. The framework consists of four Levels of Integration (LoInt) that are designed from LoInt100 to LoInt400, each level identifies and categorizes integration challenges into distinct classes and provides a literature-based approach to address the challenges. Moreover, each level corresponding to the degree of interoperability between BIM and GIS systems. The framework can be utilized as a guideline and as a decision-making support system in applications that require BIM-GIS data integration.

1. Introduction

A digital replica of a physical system is called a digital twin (Grieves & Vickers, 2002). When a digital twin is created for a city or a built environment, it is called an urban digital twin (Weil et al., 2023). Since the built environment is composed of a variety of entities, an efficient urban digital twin requires the integration of various types of data representing each entity. In that sense, the integration of Building Information Modelling (BIM) and Geographic Information Systems (GIS) data constitutes a crucial component in the development of urban digital twins (Kang, 2023; Pan et al., 2020). BIM can provide detailed information about an entity in the built environment, while GIS offers information about the environment surrounding the entity (Ma & Ren, 2017; Wang et al., 2019a). Moreover, GIS can be utilized to analyze, store, and present data collected from heterogeneous disciplines (Goyal et al., 2017). Due to the unique characteristics of BIM and GIS, the integration of data from these two systems provides essential techniques for advancing digitalization and the creation of urban development of digital twins (Zhu & Wu, 2021).

Despite the fact that BIM and GIS data are complementary, integrating data from these two domains is a difficult task and remains under study (Herle et al., 2020; Noardo et al., 2020). Several factors contribute to this challenge. Karimi & Iordanova (2021) mention that due to the nature of the focus of each system, the integration of BIM and GIS is complicated. Similarly, Zhu & Wu (2022) claim that the integration between BIM and GIS data is hard since both systems are quite different and are developed for various purposes. Sani & Rahman (2018) argued that BIM-GIS data integration causes a loss of information that makes integration a cumbersome task. Donkers et al. (2016) argue that due to differences in the data models, the integration between the two systems is difficult. Wang et al. (2019) highlighted that the existence of a variety of techniques for performing the integration without a unified standard method is one more aspect that makes the integration to be challenging. Thus, it is obvious that since each system has unique characteristics and is developed for specific purposes, the data integration between these two systems is still a cumbersome task.

In addition to the unique characteristics of BIM and GIS, several technical challenges hinder achieving seamless integration between the two systems as well: Tobiáš (2015) claimed that the main challenges to a seamless integration between BIM and GIS include different geometry representations of the 3D models in each system, different semantic terminology and the usage of different coordinate systems. Similarly, Zhu et al. (2018) showed that scope of interest, coordinate system difference, and data storage methodology are challenges to efficient BIM-GIS integration. Zhu & Wu (2022) mention that the difference in the geometric representation of models in the two systems hinders full BIM-GIS data integration. Liu & Zhong (2021) argued that the most noticeable challenges in integration between BIM and GIS include mismatch of information, geometric transformation, semantic loss, the matching process between BIM and GIS, information overload, and lack of a unified technical standard. Therefore, it can be stated that the quality of integration is largely based on addressing different technical challenges in the integration process.

An efficient BIM-GIS data integration process involves addressing various challenges. Numerous techniques have been developed to address the challenges in the context of BIM-GIS.

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Nevertheless, the categorization of these techniques is a difficult task due to the diverse range of study objectives, research methods, and data models employed in developing each technique (Zhu & Wu, 2022). Moreover, since the existing research on BIM-GIS data integration is fragmented and composed of isolated individual studies (Shkundalov & Vilutienė, 2021), it is difficult to categorize the challenges addressed by each technique. In order to make the integration process easier to manage, this study presents a framework that categorizes these challenges into different levels of integration and provides literature-based approaches to address each integration challenge.

2. Methodology

In order to develop the framework in this study, a five-step methodology was implemented (Figure 1).

In the first step, a literature review was conducted to discover the relevant papers on BIM-GIS data integration. The utilized databases include Web of Science Core Collection, Scopus, and Google Scholar. Various types of publications, including journal papers, review papers, and conference papers, were retrieved and subsequently analysed. The search was conducted using a combination of specific keywords, namely "BIM," "GIS," and "Integration," with the operator "AND" between each keyword. The search was restricted to publications between 2010 and 2024, and the language of the publications was limited to English. As it is expected, a huge number of papers were retrieved from each database. After filtering and removing irrelevant and duplicated papers by checking the title and/or reading the abstract and/or examining the content, the final number of papers was reduced to 148 including 14 literature review papers.

In the second step, the papers that involved introducing integration techniques were further filtered. Simultaneously, the integration challenges from each technique were identified. The third step involved categorization of the techniques and challenges into distinct classes. In the fourth step, the literature is used to find approaches to address challenges from each integration technique. Finally, in the fifth step, the categorized challenges, associated with integration aspects, were structured into a Level of Integration (LoInt) framework.

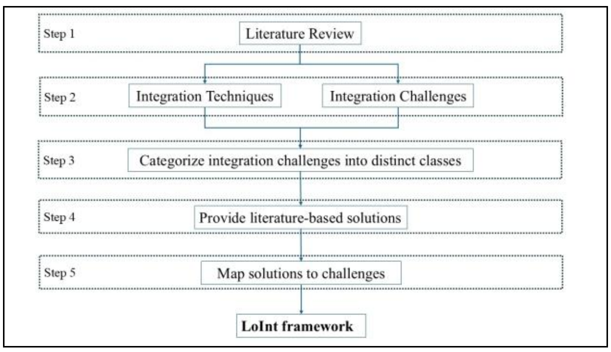

Figure 1. LoInt Development Methodology

3. Literature Review

2.1 BIM-GIS Data Integration Techniques

In recent years, several studies have been conducted on categorizing the BIM-GIS data integration techniques. Xia et al. (2022) categorized the techniques into three distinct categories: data merging, standard extension, and ontology-based integration. In contrast, Wang et al. (2019) identified three modes of integration: BIM leading with GIS support, GIS leading with BIM support, and equal involvement of BIM and GIS. In another study, Herle et al. (2020) proposed a classification system comprising of four techniques, which include transformation and conversion, linked models, unified models, and integrated models. Similarly, Kang & Hong (2015) classified the integration into five categories: Schema, Service, Ontology, Process, and System-based classification. In a seminal study, Amirebrahimi et al. (2016) classified BIM-GIS data integration into three distinct levels, namely application level, process level, and data level. Since other studies widely reference the categorization suggested by Amirebrahimi et al. (2016) and provide a simple and efficient approach for classifying BIM-GIS data integration techniques, this categorization approach was adopted with a focus on the data level only.

2.2 BIM-GIS Integration techniques at Data level

At the data level, the integration between BIM and GIS is achieved by directly performing operations on the data models from each domain. However, regardless of the operation conducted at the data level, the data flow is the factor that determines the efficiency of the integration. Ma & Ren (2017) identified three patterns of data flow: data extraction from GIS to BIM, from BIM to GIS, and from BIM/GIS to third-party software. Since GIS web service is considered a third-party software by itself, Zhu & Wu (2022) enhanced this flow by combining the second and third patterns. Moreover, they introduced a unified semantic model between the two systems as well. The challenges faced in the integration process are largely impacted by the direction of information. Thus, in the scope of BIM-GIS data integration, it is imperative to decide on the appropriate direction based on the intended application.

It is noticeable from the literature that open data standards are frequently utilized for BIM-GIS data integration to increase interoperability. The most popular open standard models in BIM and GIS domains are IFC and CityGML (Liu et al., 2017). Moreover, it is evident from the literature that, in general, three main techniques that can be utilized for achieving integration at the data level are **Conversion/ Transformation, Unification,** and **Linked data techniques**.

2.2.1 Conversion/ Transformation

In this technique, a model is converted/transformed from a format in the source domain into a format compatible with the specifications of the target domain. The conversion process is usually associated with geometric conversion and semantic mapping of the model to be converted to the target model.

Several studies can be identified that attempted to achieve complete integration between BIM and GIS through IFC and CityGML open data standard conversion/transformation. One of the initial theoretical efforts in this regard is the study by Isikdag & Zlatanova (2009) that provided a conceptual framework for transforming IFC files into CityGML with different LoDs considering both geometrical and semantical aspects of data models. The framework can be utilized as guidance for conducting the conversion. At the same time, one of the noticeable practical attempts in the IFC/CityGML conversion is the study by de Laat & van Berlo (2011). In this study, GeoBIM IDE extension was suggested to CityGML utilizing an open-source BIM server (BIMserver). While these studies are significant contributions to BIM-GIS data integration through conversion techniques, several drawbacks and limitations can be noticed from each attempt. Thus, this motivated researchers to introduce new techniques to overcome these limitations by inventing more efficient techniques and methodologies. In general, these conversion attempts can be divided into two main categories: **utilizing existing tools and producing custom tools**.

2.2.1.1 Utilizing existing tools

Due to the numerous benefits of converting IFC models into CityGML, several tools, both commercial and open source, have been developed. These tools provide practical and semi-automated methodologies to perform the conversion.

It is evident from the literature that utilizing commercial software packages for converting IFC to CityGML is the dominant technique for converting IFC into CityGML: Dore & Murphy (2012) presented a workflow for IFC to CityGML conversion based on the CityGML plugin in SketchUp. In a very similar attempt, Tashakkori et al. (2015) utilized BIM commercial software packages to create and export BIM models into IFC. Then, they utilized interoperability tools in the ArcGIS geospatial package (which is based on FME) to convert IFC into ArcGIS Geodatabase format. Similarly, Jusuf et al. (2017) utilized ArchiCAD and Autodesk Revit to create and export BIM models and employed FME to convert them into CityGML. Floros et al. (2018) presented a workflow to convert the IFC BIM model into CityGML LoD4 utilizing FME and Trimble SketchUp. It is obvious from these studies that it is possible to employ various commercial platforms to create and convert IFC models into CityGML.

Regarding open-source tools, Janisio-Pawłowska & Pawłowski (2024) utilized the FZK viewer to convert IFC to CityGML. FZK viewer was developed by Karlsruhe Institute of Technology (KIT) and offers the capability to read and export IFC models into CityGML models. However, it is noticeable from this tool that the conversion is not perfect, and the loss of geometric and semantic data is frequent.

One open-source tool that allows for the automatic conversion of IFC models into 3D GIS models without user involvement is the IFC2CityGML tool developed by Donkers et al. (2016). One drawback of utilizing this tool is that it does not support direct conversion from IFC to CityGML. Rather, IFC must be converted in CityJSON, which necessitates employing an additional tool. Moreover, geometric and semantic data loss is another drawback associated with implementing this tool for performing the conversion.

2.2.1.2 Producing custom tools

Another approach for achieving conversion from BIM to GIS is the development of customized tools. For instance, Ohori et al. (2018) developed a custom script utilizing IfcOpenShell (with its Open CASCADE kernel) to export IFC entities into 3D model format (.obj). The CGAL library was utilized to parse the produced model. Finally, the geometries were validated before converting to CityGML. Similarly, Sani et al. (2021) utilized custom scripts for converting IFC models into LoD2 CityGML models. In this study, Affine transformations were employed to accomplish georeferencing in the conversion process. Thus, it is noticeable that developing custom scripts is an effective approach to accomplishing the IFC to CityGML conversion. Nevertheless, similar to other conversion methods, several drawbacks can be realized by adopting this approach, and it is mostly beneficial when addressing a specific aspect of integration only.

It is obvious from the previous sections that employing conversion techniques for achieving BIM-GIS data integration is associated with several advantages and drawbacks. The advantages include the pragmatic nature of the technique and the availability of the necessary tools for accomplishing the integration. These two factors make conversion a preferred technique for many academic researchers and industry practitioners when it comes to BIM-GIS data integration. However, conversion techniques are also associated with several drawbacks as well that could significantly impact the integration process. For example, currently, conversion techniques allow only for unidirectional transformation of data when there should be a two-way flow of data (Zhu & Wu, 2022). The second drawback revolves around the idea that extending CityGML formats to accommodate missing entities causes interoperability issues and limits the readability of the model by software packages. This limitation makes the converted model to be beneficial only locally within an organization. Moreover, introducing extensions makes the conversion process more complicated and results in huge CityGML file sizes (Floros et al., 2018).

2.2.2 Unification

The second technique for achieving BIM-GIS data integration is known as unification, in which a new model is created that encompasses the unique characteristics of the models from both systems. El-Mekawy & Östman (2010) and El-Mekawy et al. (2012) are among the noticeable attempts to create a unified model based on IFC and CityGML data models. In these studies, a new model is presented, named the “Unified Building Model (UBM),” and it utilizes information from the IFC and CityGML models. Since the unified model contains information from both domains, the information loss in the integration process is minimal, which is a positive aspect of this technique. However, the created unified model contains huge amounts of information obtained from both systems, which increases file size and makes implementation more complicated. Moreover, this unification process creates new file format which might not be supported by software vendors (Herle et al., 2020). Thus, this technique might not be the best option for improving interoperability and sharing data between BIM and GIS domains.

2.2.3 Linked data

Linked data is a technique to integrate the BIM and GIS data models without editing or modifying the structure of the data models. Semantic web technologies are the common application of a linking approach. The semantic web can be described as a set of technologies that can be utilized for the representation, publication and browsing of structural data on the Web (Hor et al., 2016). This technology is composed of four fundamental components (Hor et al., 2016):

- URIs (Uniform Resource Identifiers) as object identifiers.
- RDF (Resource Description Framework) as a means of representing data in a graphical format.
- Ontology Web Language (OWL) as a representation of conceptual schema.
- SPARQL, a SQL-type language for querying graph data using RDF.

Several studies presented the benefits of utilizing linked data and semantic web technologies in the context of integrating BIM-GIS data compared to other integration techniques. Usmani et al. (2020) concluded that semantic web technology makes the integration between BIM and GIS more flexible and allows for seamless integration without modifying the format and structure of the data. Liu et al. (2017) claimed that the semantic web for BIM and GIS data integration allows for bidirectional exchange of data. Karan & Irizarry (2015) argued that since semantic technologies allow for associating meaning to concepts, it is considered the highest level of interoperability.

Despite many advantages of employing linked data for integrating BIM and GIS data, this technique is associated with some drawbacks as well. One of these drawbacks is related to the utilization of domain-specific ontology, which makes the implementation a slow process (Karan & Irizarry, 2015; Zhu et al., 2018; Usmani et al., 2020). Moreover, Zhu & Wu (2022) argued that the primary focus of linked data is on semantic transfer with limited consideration for geometric transfer. One more disadvantage of linked data is related to difficulty in retrieving and querying the data due to the extensive information contained in RDF files (Karan & Irizarry, 2015).

It can be noticed from previous sections that different integration techniques have been introduced to address the variety of challenges in the BIM-GIS data integration. Nevertheless, each technique is associated with several drawbacks and is usually developed for addressing specific challenges. The proposed framework in this study is an attempt to categorize the challenges and make integration techniques more efficient through suggesting literature-based workflows.

4. Level of Integration (LoInt)

It is apparent from the literature review that integrating BIM-GIS data is a complex process associated with various challenges. Therefore, to streamline the process and achieve more seamless integration, the Level of Integration (LoInt) framework is proposed that categorizes the challenges into four main classes arranged into 4 levels (LoInt100 – LoInt400); each level focuses on addressing specific aspect of integration related to the main challenge at that level. LoInt100 addresses the validation of BIM and 3D GIS models accordance to international specifications. LoInt200 focuses on geometric aspects of the models, while LoInt300 deals with semantic aspects. Finally, LoInt400 considers other aspects of integration that affect the overall quality and efficiency of the BIM/GIS data integration but does not fall into a specific category. The following section describes the rationale for introducing levels in LoInt and presents literature-based approaches to achieve the aims at each stage. Moreover, the challenges and future research directions associated with each level are presented in detail.

LoInt100

The main aim of this level is to address the quality validation aspects of the BIM and 3D GIS open standards in accordance with existing international specifications. Since validation is fundamental to interoperability, it is imperative to use this level as a reference at all stages of the integration process, including during creation of BIM and GIS models within their authoring environment, following their conversion into open standards, and both prior to and after the integration.

This level encompasses two main tasks related to validation of IFC and CityGML models. The first task involves identifying the relevant quality elements required for validation (Wagner et al., 2013: Sun et al., 2020; Biljecki & Tauscher, 2019). The second task is related to performing the actual validation. Regarding IFC models, the validation can be performed manually (Hajji et al., 2021) or semi-automatically (Broekhuizen, 2021) using tools such as IfcValidator developed by BuildingSMART. For CityGML, semi-automatic approaches can be employed (Alam et al., 2013), using tools such as CityDoctor (developed by Stuttgart University of Applied Sciences) and val3dity (Ledoux, 2018).

This level is associated with several challenges that require further investigation. Existing validation processes are manual, complex, and prone to error (Solihin et al., 2015; Olsson et al., 2018). therefore, there is a need for an automatic validation process (Zhu & Wu, 2021). Moreover, it is essential to develop a validation approach that addresses all aspects of BIM and 3D GIS open standard models (Colucci et al., 2020).

LoInt200

The main objective of this level is to achieve geometrically accurate models based on BIM/GIS data integration.

This level encompasses several tasks related to addressing geometric aspects in the integration process. The first task, which must be performed prior to intgeration, involves assessing and performing IFC georeferencing (Clemen & Görne, 2019; Jaud et al., 2020; Uggla & Horemuz, 2018). The second task is related to establishing mapping between IFC and CityGML entities (Hijazi et al., 2009; Liu and Issa, 2012; Irizarry et al., 2013; Laat and van Berlo, 2011). Third task involves performing the actual IFC and CityGML geometric integration utilizing either commercial tools (Dore & Murphy ,2012; Yu & Teo, 2014; Tashakkori et al., 2015; Jusuf et al., 2017; Floros et al., 2018), open-source solutions (Janisio-Pawłowska & Pawłowski, 2024; Donkers et al. (2016), or custom-developed scripts (Ohori et al., 2018; Sani et al., 2021). The final task involves validating the integrated model using the validation procedure presented in LoInt100.

Several challenges hinder an efficient geometric integration at this level that require further investigation. Sun et al. (2020) indicate that further research is required regarding conducting geometric accuracy comparison between georeferenced BIM model against 3D GIS. Uggla & Horemuz (2018) and Zhu & Wu (2022) note that further research is required on georeferencing BIM models for infrastructure BIM projects. Guler et al. (2022) outline that further research should be conducted on the georeferencing of open-source BIM data by implementing geoinformation-based software and using survey control points. Similarly, Tan et al. (2023) highlight that there is a need for further improvement of georeferencing in the context of BIM and GIS data integration. Bartonek et al. (2023) argue that more research is required regarding local to global coordinate system transformation in the BIM environment. Zhu & Wu (2021) demonstrate that generating 3D GIS models using solid modelling instead of currently applied surface models must be further investigated. Finally, Sani & Rahman (2018) highlight that aligning the level of details in the BIM-GIS data integration is one more geometrical challenge that needs further investigation.

LoInt300

This level aims to address the semantic characteristics and attributes in BIM and GIS data integration process.

The approach at this level involves employing ontology-based techniques to maintain the semantics of BIM and GIS datasets (Deng et al., 2016; Karan & Irizarry, 2015; Usmani et al., 2021). Additionally, the validation of the converted model must be performed using the approach presented in LoInt100.

This level introduces several challenges that hinder achieving a seamless semantic integration between BIM and GIS. In this regard, Donkers et al. (2016) mention that more study is required on semantic mapping techniques when converting BIM models into 3D GIS open-source models. Floros et al. (2018) highlight that future research should focus on enriching the BIM model with different types of semantic information depending on intended applications. Zhu & Wu (2022) argue that semantic challenges in BIM-GIS data integration are only partially solved, and more research is required on that aspect.

LoInt400

The main objective at this level of integration is to achieve complete and seamless integration between BIM and GIS. This level represents the highest level of integration that encompasses addressing integration aspects which do not fall into a specific category. Nevertheless, these aspects contribute to achieving complete interoperability between BIM and GIS domains.

The suggested approach at this level involves minimizing data loss by implementing a semantic web application as presented in Stouffs et al. (2018) and Adouane et al. (2020). Moreover, at this level, effective visualization of BIM and 3D GIS digital models must be considered, an aspect of integration shown by Dursun et al. (2022) and Zhao et al. (2022). Furthermore, efforts should be made to achieve a bidirectional integration between both domains as outlined in Donkers et al. (2016) and Celeste et al. (2022). Finally, the produced models must be validated using the approach presented in LoInt100.

The level is associated with several challenges that require further investigation. In this regard, Sani & Rahman (2018) outline that there is a need to develop a general data model in BIM-GIS data integration. Wang et al. (2019) highlight that it is essential to develop easy-to-adapt workflows for BIM-GIS data integration. Carrasco et al. (2022) mention that more research must be conducted on minimizing information loss in BIM-GIS data integration.

The LoInt framework is depicted in Figure (2), in which the levels of integration (LoInt100 – LoInt400) associated with the main challenges to be addressed at each level are illustrated.

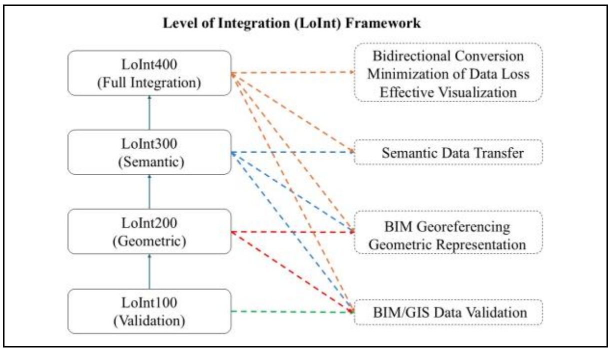

Figure 2. Level of Integration (LoInt)

5. Discussion

The proposed LoInt framework in this study contributes to establishing more standardized methodologies for integrating BIM-GIS data. Previous studies often focus on addressing specific challenges and aspects of BIM-GIS data integration. This introduces uncertainty regarding the methodology to follow to achieve scientifically approved, high quality and effective integration. LoInt framework fills this gap by providing a structured hierarchical pathway (LoInt100-LoInt400) that categorizes the challenges into distinct categories and covers all aspects of BIM-GIS data integration.

The framework is particularly valuable for applications that require integrating BIM and GIS data, such as the development of urban digital twins. In such cases, after determining the purpose of developing urban digital twin, LoInt can be applied to identify the appropriate level of integration, the primary aspect of integration to be addressed, the relevant tasks to that aspect, and the challenges related to addressing each task. For example, if the purpose of developing the urban digital twin is to be used as a reliable source for geospatial data and measurements, then based on LoInt framework, LoInt200 is the most appropriate level of integration. According to the framework, when addressing LoInt200, LoInt100 must be considered as well. In that sense, validation and geometric aspects must be addressed. The relevant tasks include BIM/ GIS data validation, ensuring data accuracy, performing georeferencing and dealing with geometric representations. Based on that, the approaches suggested at LoInt100 and LoInt200 can be utilized as a guideline to address achieve the integration. Finally, special care must be given to challenges identified for each LoInt in the framework.

LoInt framework has some limitations that hinder its complete applicability. Firstly, the framework remains conceptual and require empirical validation across diverse case studies and applications. Secondly, although the framework is designed in a progressive structure, the levels could be mixed or skipped depending on the purpose of integration and intended application. For example, if the project requires addressing geometric challenges only but with high quality visualization, then LoInt200 and LoIn400 must be addressed skipping LoInt300. Finally, some projects have unique requirements that might not be present in the current framework. In such cases, enhancement of the framework might be necessary to include extra challenges associated with the unique requirements.

6. Conclusion

The process of BIM-GIS data integration for the development of urban digital twins is a complex task and is still under investigation. Several integration techniques are available to achieve the integration including conversion, unification and linked data approaches. These techniques can be implemented by utilizing commercial or open-source tools and software packages; each with its own set of advantages and limitations. Moreover, each technique is associated with range of challenges that hinder the achievement of complete and seamless integration. It is noticeable form the literature that these challenges have been addressed in isolation without following a standardized approach. This study explored these challenges and produced a conceptual framework, named the Level of Integration (LoInt), that systematically categorizes these challenges into different classes and suggest a literature-based approach to address each challenge. The LoInt framework can be utilized both as a guideline to perform more effective integration and as a base for establishing more standardized methodology for BIM-GIS data integration. In addition, it can be used as a reference for identifying future research directions in the field of BIM-GIS data integration. Nevertheless, the framework's conceptual nature remains its main limitation. To assess its practical applicability, future research should focus on implementing the framework in various empirical and real-world projects.

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