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Integrating BIM and GIS for an Existing Infrastructure

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Abstract: Data-driven digital transformation is becoming increasingly relevant. Building information modelling (BIM) and geographic information systems (GIS) are two technologies specific to the construction industry. The two approaches are different, but complementary. In this article, BIM–GIS integration is approached from some of the most relevant aspects, such as standardization or level of detail, and a comparison between both approaches is presented with the aim of improving the operation and maintenance of urban infrastructure. By means of the Madrid Calle 30 ring road as a case study, the integration of the BIM model of the road in a GIS scenario using the IFC and SLPK formats is shown. The information is stored in an external database, which allows updates without modifying the 3D model and facilitates the inclusion of real-time data. The study highlights the challenges of interoperability between BIM and GIS, as well as the need for open standards and software tools that enable a wider implementation in the FM of this type of infrastructure.

Keywords: BIM; GIS; BIM-GIS integration; civil infrastructure; Facility Management

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1. Introduction

The integration of building information modelling (BIM) and geographic information systems (GIS) is one of the topics to be addressed in the digitalisation of the architecture, engineering, construction, and operation (AECO) sector. These two technological approaches are based on the organisation and analysis of information. However, their character is different. BIM works on specific infrastructure, while GIS covers large areas of land [1]. Digital transformation has enabled a greater volume and analysis of information that is available during the life cycle of an asset (LCA). This is where BIM–GIS integration becomes relevant, making it possible to understand the behaviour of an infrastructure in its environment.

Both BIM and GIS are used in the whole life cycle of the built environment, from the design and planning phase through to the management and maintenance of the infrastructure [2,3]. Thus, the combination of these two approaches can improve the decision-making process in all phases. This integration can be applied in the building sector, where an individual building is positioned within its location in the city, and in road infrastructure, where geospatial data is linked to the specific site [4]. The use of these technologies during the operation and maintenance (O&M) phase combines the information, thus enabling more reliable decision-making, allowing infrastructure managers to optimise the available resources [5,6]. However, BIM and GIS employ different approaches, leading to the technology and standards associated with them being different. The best example of this divergence is the standardisation, which is fundamental in both environments to facilitate collaboration among all project stakeholders, promoting interoperability and information exchange.

This article discusses how each of these two technologies is getting closer to standardisation, and specifically how standardisation could be an approach to a reliable BIM–GIS integration. Some of the main formats and international standards of each technology will be identified. The flow of information from GIS to BIM and from BIM to GIS is also discussed. This flow has been the subject of most of the recently published literature, focusing especially on the use of the standard IFC and CityGML formats for BIM and GIS, respectively. However, some authors have highlighted the complexity of the information transformation process between both formats [1,7].

Furthermore, success in the development of a model that includes the benefits of each technology involves the application of new enabling technologies that analyse information, i.e., the digital transformation of the AECO sector. Technologies based on big data, such as the Internet of Things (IoT) or artificial intelligence (AI) will be key in smart construction [5,8–12]. BIM and GIS are complementary technologies that together with enabling technologies will allow the development of digital twins (DTs) of infrastructure [7,10,13–17]. The use of proprietary applications focused on specific infrastructure requirements facilitates access to information, which is essential in the digitization of infrastructure. These applications allow not only access to the 3D model, regardless of the application used to develop it, but also access to the database (DB) and its analytics from adapted and intuitive interfaces [17–20]. It is therefore crucial to establish a quick and efficient information flow in order to extend the application of BIM–GIS integration in the AECO sector.

Lastly, a case study is presented that proposes a facility management (FM) system for an existing road. This is Madrid Calle 30, one of the main highways serving the city of Madrid (Spain). The O&M of this road is nowadays carried out using GIS technology supported by an external database The size of this urban infrastructure, more than 30 km long, demands a constant optimization of the resources available for its O&M. Therefore, BIM–GIS integration could be an option. Its implementation is addressed using open standards, and the link with the external database and access to information will be tackled.

2. Current State of BIM and GIS

2.1. BIM

BIM is a collaborative environment for the planning, design, construction, and management of building and infrastructure projects [21]. The collaboration takes a 3D model that contains all the information associated to the project. The most significant advances have been implemented over the last decade, although there is still a long way to go before full implementation in the AECO sector.

2.1.1. Regulations and Standardization of BIM

The benefits of BIM implementation have shown to be applicable for the entire life cycle, demonstrated throughout the LCA, mainly in the design and construction phases, given that all the stakeholders work on a single model, preventing duplication and improving the efficiency and quality of the projects. Therefore, governments have launched the implementation of BIM with the corresponding regulations. Stakeholders work on a single model, avoiding duplication and improving the efficiency and quality of projects, and public administrations have thus tried to implement BIM through regulations in this phase [22]. The European Directive on Public Procurement (2014/24/UE) [23] provides that public works contracts must specify the use of information and communications technology (ICT) in the design and execution phase of projects, including BIM. However, the implementation of BIM is often limited to the design phase of large projects and has not been extended to the sector as a whole [24], and each government has interpreted the directive differently [25].

There are several international standards dealing with BIM implementation. The International Organization for Standardization (ISO), in its committee ISO/TC 59/SC 13 [26], is responsible for the standardisation of information throughout the life cycle of buildings and infrastructure in the built environment, with the ISO 19650 [27] series comprising the standards regulating the implementation of BIM. The building SMART International consortium encourages standardisation in the sector. The Industry Foundation Classes (IFC) is the standard and open data model used in the construction industry. It defines the characteristics of data related to the design, construction, maintenance and operation of civil works, the most recent version being IFC4, the ISO international standard, published in ISO 16739 [28]. However, the adoption rate of these standards is still lower than the implementation rate of BIM [29].

Another standard in BIM is the Construction Operation Building information exchange (COBie), which focuses on FM using spreadsheets [30]. However, these standards, including the IFC, are very much focused on building models, leaving civil infrastructure to one side. The lack of standards dedicated to civil engineering and the complex transposition of building standards have led to more experimental use in the sector [31–33].

2.1.2. BIM Formats

The main advantage of BIM is the collaboration between all agents involved in the life cycle of a project. However, one of its main barriers is interoperability between files. In the last decade, a multitude of tools have been developed that can generate a 3D model and develop it with information. These applications are also focused on each operation type within the project drafting process. There are specific applications for installations, buildings, linear infrastructure, and structural calculations. However, each application hosts its own formats, with hardly any interoperability, even between different software packages from the main commercial companies [34]. Using standardisation, the IFC format can be operated by most of these applications. However, its use can lead to information leakage that is not defined in default parameters [33,35,36].

2.1.3. BIM Level of Development

Several levels of development (LOD) have been defined, being a term that indicates how reliable element data are. This term is different from level of detail (LoD), which indicates the degree of detail of the 3D object. Although sometimes these concepts have been used interchangeably, they do not mean the same thing, with LOD being more correct to talk about development in BIM. BIM Forum has published an update for the specification of each LOD in five levels. These levels range from 100 to 400 [37]. However, BIM projects have continued to increase in complexity as their implementation has increased [38]. As a result, different LODs are often adopted for each object in the BIM model according to the specific requirements at the time [39], trending towards progressively higher LODs as the project progresses [40].

2.2. GIS

A GIS is defined as an environment for organising, storing, and analysing data that, together with the science of geography, allows the visualisation of information on maps and 3D scenes. These systems have undergone strong development since the 90s [41,42]. They have traditionally been used in territorial planning and the management of infrastructure linked to territories, such as roads. Moreover, together with the advance of data science and satellite navigation systems, the use of these systems has become more popular, allowing the development of applications that permit citizens to access and visualise related data [43]. This is one of the reasons that justify the use of GIS by administrations to publish their data, a fundamental element in the development of the smart cities concept [7,44–46]. The development of this technology continues to the generation of more detailed models and 3D representations of the environment.

2.2.1. Regulations and Standardization of GIS

Regulations surrounding the use of GIS depend on the legal framework in a given country. They are essentially based on the management and privacy of spatial data. At the European level, the INSPIRE Directive (Infrastructure for Spatial Information in Europe) establishes a framework for the exchange of geospatial data between EU member countries [47]. This directive encourages the establishment and maintenance of thematic datasets, defining their metadata (detailed information on their content, quality, and conditions of use) and facilitating their open access [48].

At the international level, ISO has published some standards related to geospatial data and technologies that are relevant to the use and implementation of GIS in its ISO/TC 211 committee [49]. Some of these standards are ISO 19107 [50] for geographic data models, ISO 19111 [51] for the specification of coordinate representation and geospatial reference systems, ISO 19115 [52] for the specification of metadata, and ISO 19125 [53] for the encoding of geographic entities. Therefore, there are many public administrations and other organisations that are working together towards the collaboration and interoperability of data [3]. Many of these organisations are partners in the Open Geospatial Consortium (OGC). This is an international non-profit organisation committed to creating open and interoperable standards for the global geospatial community within the framework of GIS and the World Wide Web.

2.2.2. GIS Formats

When working with GIS data models, there are two types of data: the raster type data and the vector type data. Within each group there are a multitude of formats, but all of them are operable together using the main applications in the sector [3]. In the case of the raster model, the space is divided into a regular grid where each cell contains a single value, stored in a band with a specific wavelength in the electromagnetic spectrum. This leads to a wide variety of formats based on this data model, from more text delimited files such as ASCII to compressed image formats such as JPEG or ECW. However, in terms of open standards, the GeoTIFF format, which includes all the information necessary for a TIFF format image file to be positioned in a Coordinated Reference System (CRS), should be highlighted.

The vector format is defined by a simple object that defines the data. These have traditionally comprised points, lines, and polygons, i.e., 2D objects. The most recognised and widespread format is the Shapefile. This is a file format owned by ESRI, and is characterised as a set of files. Other relevant formats considered standards by the OGC are KML/KMZ and GeoJSON, which are closely linked to the development of web-mapping applications. However, we live in the era of data, and data-related technologies are becoming increasingly important. GIS is no exception to this trend, and spatial databases are becoming more relevant, especially when working with a high data volume. This is where the open coding standard GeoPackage emerges, to transfer geospatial information (both raster and vector) within an SQLite database. When the database is spatial, it is called Geodatabase and the GDB format is used to transfer the collection of files that make it up.

Regarding 3D, two main formats are commonly used. On the one hand, CityGML and derivates like CityJSON represent an OGC standard for representing urban objects in 3D. On the other hand, more recently, the leading company in the sector, ESRI, has developed the SLPK format, and ESRI's position as a member of the OGC has facilitated its publication by making it an open standard. The SLPK format goes further and focuses on packaging and distributing 3D scene layer data in general [54,55]. However, even though it is an open standard, only a few applications can operate with this format.

Finally, the OGC has defined several standards for publishing spatial data online, such as the Web Map Service (WMS) for maps in image format, the Web Feature Service (WFS) for entities, or Indexed 3D Scene Layers (I3S) for the visualisation of complete 3D scenes, among others.

2.2.3. GIS Levels of Detail

The representation of data in GIS depends on its data model, i.e., whether it is a raster model or a vector model. The detail in a raster data model will depend on its resolution, mainly the cell size, and the number of bands that compose it. For a vector data model, a distinction must be made between 2D and 3D. In 2D, there are three basic symbols: point, line, and polygon. All the information is represented by means of these types of geometries, and the adoption of one or another geometry will depend on the scale being worked with. For example, if a building is represented on the plan of a large city block, a polygon will be used to represent the contours of its front, but if it is represented on the plan of a city, a point will be used, containing the same associated information in both cases. In the case of 3D scenes, five LoD were defined for the representation of buildings in the CityGML 3.0 format. These levels range from LoD 0, representing the footprint of the building, to LoD 4, representing the building with interior and exterior details [56]. These levels have been updated to LoD 0 to 3 in CityGML 3.0 [57]. On the other hand, the SLPK format includes multiple LoDs for the same object [58], by modifying the LoD of the elements that compose the scene according to the display scale, allowing the performance of the device to be adjusted and improving user experience.

3. Interoperability Issues

The integration between BIM and GIS is becoming increasingly relevant in the AECO sector, with public administrations having a significant influence. However, this integration presents some difficulties and incompatibilities. The main challenge is the definition of the uses of the model. Thus, before proceeding with BIM–GIS integration, it is essential to define the objective of this integration and its minimum requirements.

The widespread implementation of BIM is in progress, supported by new regulations [23] that impose its use in public contracts. However, this implementation is occurring as part of a technological race, with many different applications and formats being developed concurrently, which makes interoperability more difficult. In contrast, GIS have undertaken the opposite approach; these systems have a greater technological background and have been committed to collaboration and standardisation from their beginning. Although there are some very powerful commercial applications, free applications are capable of carrying out the main required tasks in any of their formats.

The following sections address the main challenges and incompatibilities in BIM–GIS integration as discussed by some authors. These problems have been corroborated in the development of the case study presented in Section 5.

3.1. The Data Integration Problem

The main challenge in BIM–GIS integration is the transfer of data between these domains. The main issue is the difference in the geometric models used in these systems. GIS uses boundary representation (B-Rep), while BIM uses construction solid geometry (CSG) representation. This difference makes it difficult to compare the two models and to map the data between them. On the other hand, both BIM and GIS have their own schemes and languages in the semantic field. The information is ordered and stored differently, which makes the mapping between the two domains at metadata level difficult [59,60].

Most studies to date have focused on the 3D representation of buildings in GIS. This interoperability has mainly been realised through the open formats IFC and CityGML [1,7,58,61]. This leads to a loss of information, which is even more acute in the case of civil infrastructure. Firstly, the use of the IFC format implies the assumption of predefined parameters, focused on building. The conversion from IFC to CityGML format presents two main problems. First, the IFC format does not fully support the 3D representation of civil infrastructure. Second, the CityGML format is not designed to store all the information that is contained in the IFC format. This can lead to a loss of information during the conversion process. The mapping of information in the semantic field between BIM and GIS has been the subject of many studies [1,7]. However, there is still no agreed-upon standard for these mappings, and different authors have used different approaches. This can make it difficult to integrate BIM and GIS models that have been created using different software applications. Although there have been significant improvements in this area, integration ultimately requires the simplification of the model [62].

3.2. Scale-Level of Detail Problem

Another challenge is the problem of scale. BIM focuses on detail, i.e., it tries to provide the stakeholders in the LCA with all available documentation. Therefore, the higher the LOD of its 3D model, the more information that will be received by the user. Furthermore, its scope of work is focused on infrastructure, such as a building or a bridge, and is limited to its component elements. Therefore, it works on a scale of tenths of a metre.

In contrast, GIS focus on the study of the environment and are closely linked to geographical science. Therefore, the greatest potential of GIS is the collection and analysis of spatial data. The landscape has a fundamental role in contextualising these data within its environment, which means that scales of hundreds of metres are used. The use of spatial data has become widespread among citizens. The use of navigation systems and the representation of data in cartographic environments has made it possible to give free access to information to any user using most any device. The irruption of well-known applications has facilitated great advances in society; however, there has been a loss in the conception of scale [63]. The entities appear and disappear as discrete objects using icons depending on the zoom in and out of the visualization.

3.3. Georeferencing

All information in the AECO sector has coordinates defined by CRS. The most popular geographic CRS is the WGS 84, used in GIS tools and by the Global Positioning System (GPS). However, in the AECO sector, relative Cartesian coordinates are used, defined by a XY plane, adding the Z coordinate for three-dimensional cases. The 1989 European Terrestrial Reference System (ETRS89) was established as an official system in Europe. There is a good correlation between the two CRSs, with ETRS89 being more precise. Although the main BIM and GIS tools operate with these CRSs, it is essential to know at all points in the process which CRS is being used and to work with correctly located BIM models, that is, the point of origin (0, 0, 0) must be georeferenced to be able to carry out a good BIM–GIS integration.

3.4. BIM-GIS Incompatibilities

BIM–GIS integration has some incompatibilities and limitations. Firstly, they are two technologies that utilise different approaches, languages, and common data environments (CDEs). Most GIS applications, formats, and tools are 2D based, but BIM–GIS integration is associated with 3D modelling of infrastructure. Therefore, much GIS data and analyses do not have a counterpart in BIM.

Standardization in GIS has aimed at the transmission of information by means of service models, facilitating use through open standards and online formats. However, in BIM, there is no equivalent concept; this approach is in opposition to the concept of collaboration in BIM. BIM collaboration within cloud environments is restricted to project members, enhanced by defining CDEs. This collaboration is defined as access to information through the so-called Exchange of Information Requirements (EIR) or the uses established for the BIM model in the BIM Execution Plan (BEP). In the GIS domain, free access to information is provided through the services derived from the model, whereas in the BIM domain, access to the model is restricted.

On the other hand, the information in GIS is stored in databases, so it is possible to access the information using query languages, without the need for the geometric model. This is not possible in the BIM domain without intermediate programming.

4. Interoperability Opportunities

BIM–GIS integration facilitates a joint vision of a project in its environment. This is because these technologies are complementary and make it possible to increase the quality and volume of information available for each technology. BIM–GIS integration is part of the information flow throughout the project lifecycle [1]. Figure 1 shows the flow of information through an integrated BIM–GIS model linked to an external database containing all the information and accessible from an external web application dedicated to the FM of the infrastructure.

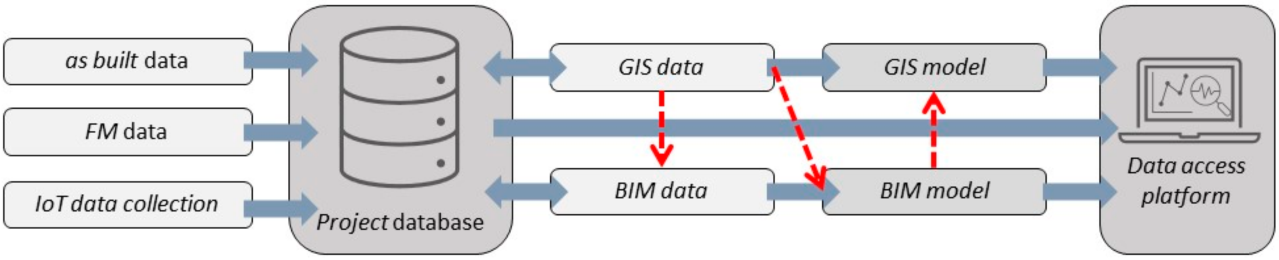

Figure 1. Information flow for a BIM–GIS integration for infrastructure FM.

4.1. Interoperation: GIS to BIM

The analysis of the environment using GIS tools allows the information contained in a project in the AECO sector to be improved. Understanding BIM as a methodology, the organisation and spatial analysis of the territory that is carried out in GIS increases the CDE that makes up BIM. Therefore, the integration in the GIS to BIM direction is from a semantic point of view.

4.2. Interoperation: BIM to GIS

Furthermore, the use of BIM models makes it possible to increase the quality and LoD in 3D GIS scenes. This requires the use of viewers that can process the huge data load associated with the change from CSG to B-Rep representations. In this sense, the integration in the BIM to GIS direction is from a geometric point of view. Furthermore, the adoption of the BIM methodology in the GIS domain facilitates the organisation and clarity of processes within the project lifecycle.

4.3. BIM–GIS Interoperability with External Databases

Both BIM and GIS are information management models whose main value is data, which represent the main asset nowadays. Therefore, both BIM and GIS are directly related to the new technologies derived from big data. The AECO sector has always been reluctant to implement change. However, the joint implementation of BIM, GIS, and ICTs provides more control over all information within the LCA. This requires the storage of information in databases that allow fast and reliable access, with both BIM and GIS serving as a visual tool for accessing this information.

In the case of GIS, the formats are conceived to operate as spatial databases, so the connection to external databases is inherent to this technology. However, in the case of BIM, the information is stored within the model itself. This means that, together with the use of formats specific to each software, the information is only accessible through the software itself. Then, the information must be stored in the model itself or some kind of linkage must be established that allows each object in the BIM model with its information to be stored in the external database, requiring intermediate programming.

4.4. Applications of BIM–GIS

Some applications where BIM–GIS integration has proved to be efficient in improving asset FM are presented below. For example, for the management of urban subway pipelines [6], a management platform has been developed with real-time monitoring that improves efficiency compared to traditional management, providing more accurate information on the condition and location of the pipelines.

In the case of infrastructure management, studies have been carried out to monitor in real-time the quality of pavement construction on a highway [64] or the design of airport infrastructure [65]. In both cases, no real integration of BIM data and GIS data is detailed. Of note is the research by Zhou D. et al. [66] on the application of BIM methodology in the design and construction of a road infrastructure in China. A BIM+GIS based cloud management platform was used, offering a substantial improvement in project communication and management. However, the study recognizes some limitations such as integration with other information technologies and standardization.

BIM–GIS integration has been mostly explored in the literature related to the concept of smart cities [12,14]. Shi J. [7] explored an ontological framework for a coherent semantic and geometric data structure, but focused on building concepts, leaving aside urban infrastructures such as roads or pipelines. On the other hand, Meschini S. [17] approached the implementation of a BIM–GIS asset management system through a platform based on a flexible and centralized database that improved the user experience of a university campus.

In all these cases, one of the main challenges is the conversion of data between the two technologies. Tan Y. et al. [59] discussed the current status of this conversion using the IFC-CityGML standards, Zhu J. et al. [62] addressed the simplification of IFC models for ease of use in the GIS data environment using the SLPK standard, reducing the file size by up to 97.3% in the case of the door and window model. Zhu J. et al. [60] proposed a methodology for the transformation of IFC geometry to SHP.

5. Case Study: Madrid, Calle 30

This article proposes a BIM–GIS integration method applied to Calle 30. This is a ring road infrastructure located in Madrid, Spain. To improve the efficiency of its O&M, the application of BIM methodology was applied to this existing urban infrastructure. This road is characterised by its great length of more than 30 kilometres, over which numerous structures such as bridges, footbridges, walls, and several kilometres of tunnels are located. Each of these could be considered BIM projects. In addition, all the facilities and road equipment required by the road for its operation must be considered.

The FM of this infrastructure was performed using GIS methods, so the starting information was in these formats. The development of a BIM model from GIS data was therefore sought post-FM. The road was subdivided into sections in order to facilitate operation with each three-dimensional model from a conventional computer due to the large volume of data. This was due to the extent of the infrastructure and the large volume of information available in the city's public administration in GIS formats. Each of the models generated was added to a scene to establish a global approach to the infrastructure in its environment, and the complementary city data allowed for the evaluation of its behaviour and the optimisation of the resources available for its conservation and operation. Figure 2 identifies the file formats used in each phase to achieve a GIS viewer hosted in a web application focused on the FM of the infrastructure. Red colours identify proprietary formats, and green colours identify open formats.

5.1. BIM Model from GIS Data

The input data to generate a BIM model of Calle 30 were provided by the infrastructure management company in GDB and SHP formats. First, this information was processed. All the information was unified to CRS ETRS89, obtaining all the coordinates. This work was carried out using the open application QGIS. On the other hand, a library of BIM objects was developed for each element of the infrastructure, such as road markings, road equipment, safety barriers, or facilities. Based on the XYZ coordinates, several programs were developed in Dynamo to automate the modelling of the roadway and the positioning of all the elements that make up the road [67]. This BIM model was developed in Revit 2023 software with a LOD of 200, as can be seen in Figure 3.

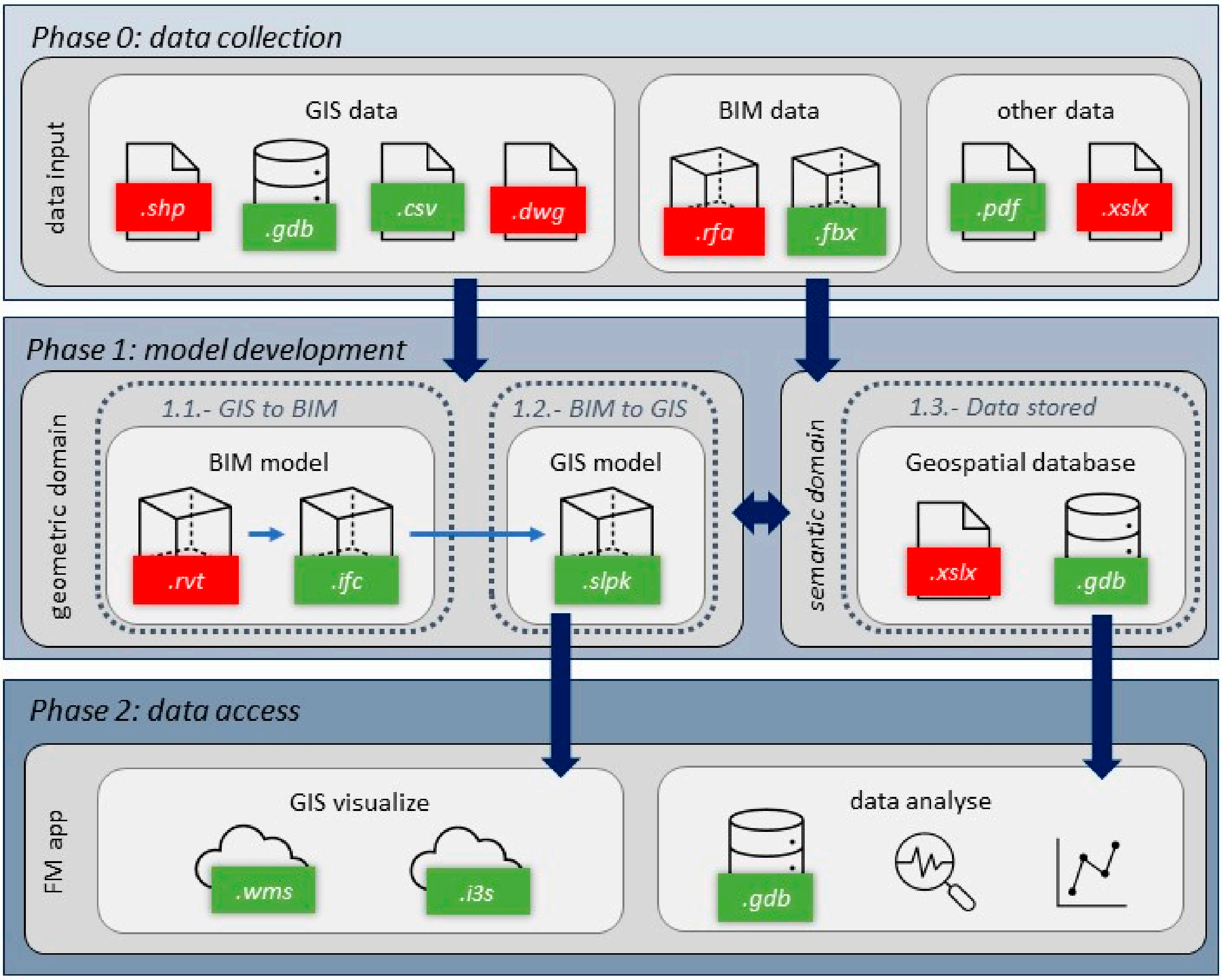

Figure 2. Main formats used to develop the BIM–GIS model for the development of an FM app.

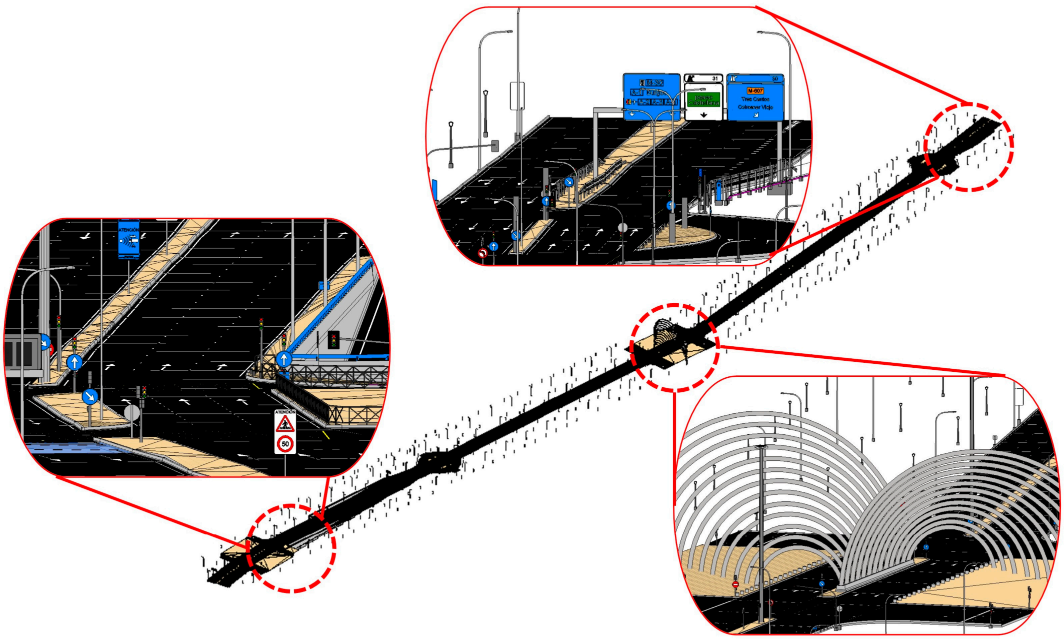

Figure 3. Infrastructure BIM model.

All the available data from the original documentation, the information generated from it, the information generated by the BIM methodology, and the complementary information to the O&M were structured in an external relational database (SQL). For this purpose, the open-source database manager PostgreSQL was used, as it allowed the management of spatial data. All the elements that make up the model were uniquely identified using the existing real coding used by the infrastructure manager. This coding was defined as a new ID parameter in the BIM model. Figure 4 shows the ID parameter with the DB linked for an element and other information that has been input from the GIS data, such as UTM coordinates.

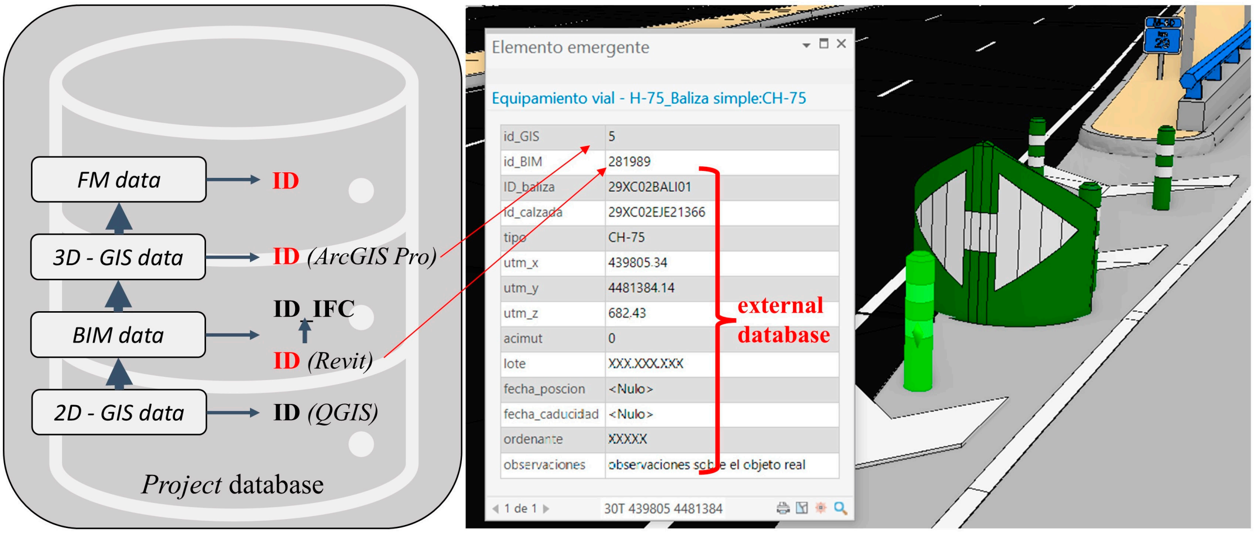

Figure 4. External database linked for an element by ID.

5.2. GIS Scene with BIM Models

Once the BIM model was developed, the GIS scene was developed with the BIM model and its environment. The advanced software ArcGIS Pro version 2.9 was used for this purpose. However, due to the use of educational licences in the indicated versions, it is not possible to use the BIM model in RVT format in this ArcGIS Pro version. It should be noted that compatibility between other versions is possible. To solve this problem, the open standard IFC4, which is readable by GIS software, was chosen. However, the use of the IFC format leads to the loss of associated information, as well as the incorrect georeferencing of the model. It is therefore necessary to correct this error using the application's projection tools.

This model was then transformed into the open SLPK format for use in a 3D scene. This new layer had a level of detail equivalent to LoD 3 of the CityGML 3.0 format in GIS. This 3D scene was developed in the free software ArcGIS Online, composed of the sections modelled up to the model, the 3D terrain base layer, and additional information such as the buildings of the city of Madrid. Figure 5 shows a capture of the published scene.

5.3. Calle 30 Management System

All the information required for the FM of the infrastructure was stored and organized in the database. This was crucial for the use of the integrated BIM–GIS model. On the one hand, the problem of information loss in the intermediate step when using the IFC standard was solved by keeping all the information in this database and not the model. In addition, all BIM and GIS applications automatically generate internal codes to identify each modelled element, and these codes are always accessible in their respective applications. As many fields must be reserved in the database as there are applications used, so that at any point in the process the information can be accessed from the corresponding ID.

Figure 5. Infrastructure scene.

Keeping all the documentation associated with each element in an external database has some advantages. First, it lightens the three-dimensional models and makes them easier to operate from any device. Second, all the information is accessible and can be updated, allowing a historical record to be kept. If a parameter within the model needs to be updated, the entire model would have to be updated, which would defeat the purpose of the methodology. For example, if road equipment was replaced after an accident, the same object in the 3D model would represent both the initial element and its replacement, while the database would maintain the information about both elements, such as the date of replacement and the manufacturer of each piece of equipment.

Lastly, access to this database was made possible thanks to the implementation of a web management application. This application also allowed the visualization of the 3D scene or just the BIM models, as well as the visualization of the data in an intuitive way. This makes it easier for the technical staff responsible for O&M to use these models, even if they do not have knowledge of the BIM or GIS applications used, from any connected device. In addition, the database can grow and host new information. This information can come from IoT devices that link real-time data to road management and vice versa, from the model to the real environment.

The BIM–GIS integration provided a detailed model of Calle 30 in its urban environment. This complex infrastructure has an annual budget of more than €30 M for maintenance, and its complexity causes difficult and time-consuming implementation. Therefore, the evaluation of quantitative metrics comparing possibilities with the existing management system, such as cost and time savings, is critical. The developments presented in this paper are limited to the integration of the BIM model in a GIS environment using standards. However, this is one of the current lines of research.

6. Discussion

Vast areas of industry are undergoing a period of digital transformation, supported by the development of ICT. The AECO sector is usually more reticent when it comes to applying new technologies, but it is no stranger to this transformation. Both BIM and GIS are part of these data-driven technologies, and in both cases, information management and visualisation play a key role [1]. However, their approaches to dealing with data are different.

On the one hand, GIS were born from geographic science, being more technologically mature than BIM. Traditionally, these systems have been used for territorial analysis, so the scope of work has been 2D at large scales. More recently, 3D GIS has begun to develop thanks to the development of applications that can represent three-dimensional environments, which has been quickly adopted in the representation of cities [42,45]. On the other hand, BIM was developed as a way of unifying all the documentation available on a project [21]. One of its greatest virtues is access to information through a 3D model, through which the greatest possible level of detail could be obtained. In terms of standardisation, GIS has consistently been characterised by its open-source aspect. This has meant that, although there are a multitude of formats associated with GIS, most of them are standard. Furthermore, most of these formats are operable by a few applications. Although the main technological advances in GIS, such as the implementation of 3D, are found in a few commercial applications, there are free applications capable of performing most GIS functions [3,48,54]. This has led many public administrations to publish their data under this framework. However, there is hardly any legislation on the implementation of GIS, limited to the regulation of data transfer.

On the other hand, BIM has been characterised by a technological race in which numerous commercial applications have been developed, each with their own formats [34]. Great efforts have been made towards standardisation, and the IFC format has become the most important one for the transfer of models. However, the use of this open format implies a loss of semantic information [33,35,36]. Nevertheless, governments have started to propose and regulate the use of BIM in public contracts.

BIM–GIS integration in the AECO sector brings with it several opportunities. Both technologies are data-driven, and this is one of the critical links between the two technologies, which can be complemented by an external DB. The DB holds all up-to-date and accessible information, including data that do not necessarily need to be included in the 3D model. This makes it possible to lighten the content of the model, facilitating its use from any device and avoiding the modification of the model for non-geometric updates. On the other hand, it is possible to apply technologies such as IoT or AI by keeping the information segregated and organised in the DB, favouring the efficiency of the infrastructure management systems and easing the FM of the infrastructure through its DT. In this case, access to the DB and the model must be accomplished with proprietary management applications, which allows implementing the functionalities required for each infrastructure. These applications can be designed and adapted to each of the needs by providing simple and intuitive interfaces that can be used by the technical staff dedicated to the O&M of the infrastructure.

Another linking point is 3D integration. Most authors have assessed BIM–GIS interoperability using the IFC–CityGML formula. This implies a loss of semantic information due to the use of both formats. Moreover, there is a loss of geometric information [1,7,61]. This is where the level of detail comes in. This is a common concept in both technologies, but with a different meaning. The way in which the 3D element is modelled is key. The geometry in GIS is defined by surfaces (B-Rep), while in BIM, the object is defined as a solid (CSG) with the information contained in it [59,60]. For this reason, the concept has evolved at the level of development in BIM.

From a geometrical point of view, 3D BIM models are suitable for buildings or specific civil infrastructure such as bridges where all three XYZ dimensions are equally important, compared to the two-dimensional XY dimensionality of GIS. Therefore, linear infrastructure, where the XY dimension is predominant as opposed to the Z coordinate, has traditionally been managed using GIS tools. 3D GIS offers complete integration of BIM, covering buildings in a city, civil infrastructure across the landscape, and the structures and equipment contained therein. This allows managers to achieve an overall view of the infrastructure in an environment, facilitating decision-making and optimising available resources.

This BIM–GIS integration has occurred mainly in the building industry, linked to the development of environments for smart cities, with very few cases for civil infrastructure. This may be due to the fact that the development of BIM in civil engineering is a step behind. In addition, applications focused on the modelling of linear infrastructure consider the terrain on which they are built, although they cannot carry out analysis of the environment in the same manner as GIS applications. Each technology has its own scale: micro in BIM and macro in GIS [1,44]. The combined use of these two technologies enables a joint vision of the two domains, whether it is, for example, the urban environment for a building, or the landscape for infrastructure. The BIM–GIS integration will be useful in those phases of the LCA where this joint vision is necessary.

BIM–GIS integration therefore involves developing a model to store, visualise, and analyse all available data on an asset and its environment. Semantic information is as important as, or more important than, geometric information, especially for the FM of the infrastructure. For this, it is necessary to maintain the full flow of information as much as possible. In addition, the efficiency of the management system depends on access to data outside modelling applications. The development of an application that meets the needs of infrastructure management, with access from any mobile device, is essential. The use of formats optimised for online access is also essential. Therefore, the use of the I3S format can be a good option for the development of a viewer that gives the user access to the entire scene surrounding the infrastructure. This can be generated from the corresponding scene layer package (SLPK) format, which can be generated from BIM models while maintaining the geographic and semantic information.

The use of the I3S and SLPK formats represents a qualitative leap compared to the workflow used until now, i.e., the IFC to CityGML transformation. Although the I3S and SLPK formats are defined as standards, for now it is only possible to use them in the commercial applications of their developer company, with this being the great impediment to generalising their use. However, they are optimized formats for storing and sharing 3D GIS data from any device, either on the web or as local files [54,55]. This is especially useful in the FM of assets, as it eliminates the dependence on specialized BIM software and facilitates the development of specific applications for each case. Therefore, research should delve deeper into the creation of these packages and scene services in the specifications of these standards.

This article has shown a process of data integration for an existing road to optimise the resources available for its O&M. BIM and GIS technologies have been integrated to develop, together with a database, a web application focused on its FM. The aim was to generate a viewer using open standards to facilitate the interoperability of the data. Following the workflow shown in Figure 1, a 3D BIM model was developed from the available GIS data. For the authors, it was essential to implement this flow using standards, so the BIM model was exported to IFC to continue the IFC–SLPK–I3S flow using ESRI's commercial applications. It has been possible to verify that this process can be carried out by using standards in the key steps of the integration, without prejudice in the quality of the model or information it contains. In addition, all the models developed in each of the steps are reflected in the external database allowing access to the information.

In the case of Madrid Calle 30, the BIM–GIS provided a detailed model of the road in its urban environment. This joint model increases knowledge about the infrastructure status for its administrators, who can apply it in areas such as city traffic affections, incident management, or interaction with other city infrastructure.

7. Conclusions and Future Developments

The AECO sector is in an era of digital transformation, marked by the ongoing advent of the use of data-driven technologies. BIM and GIS are two of these technologies, with each employing a different but complementary approach, providing a global view of infrastructure and the surrounding environment. With this in mind, collaboration and access to information from any device through proprietary applications that meet the needs of each project becomes essential. These must be linked to information, data analytics, and virtual representations of infrastructure, enabling the use of BIM viewers, GIS viewers, or joint viewers to provide global models with all the detail of BIM in large GIS environments.

The use of open standards allows integration from BIM to GIS. However, further research is needed to achieve a stronger link in this interoperability, being necessary to strengthen the semantic linkage, as the geometric linkage seems to have been overcome. Each project is unique, and the associated information needs to be organized and structured according to a project's specific needs. The use of external DBs compensates for the shortcomings of the use of these standards and facilitates the implementation of other data technologies such as IoT or AI.

In the development of the case study in the present research, some limitations have been identified for future lines of research. Firstly, the use of the standard SLPK format may generate certain shortcomings and uncertainty since its usability is presently restricted to certain commercially licensed software. Therefore, the use of this standard in open-source applications should be addressed. The integration of a BIM model into a GIS environment has been explored here, so the inverse direction should be investigated, i.e., from a data model in the SLPK standard to the IFC. Finally, another line of research should be to assess the efficiency of the BIM–GIS management application versus traditional management methods in the O&M of this road.

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Abbreviations

AECO	Architecture, Engineering, Construction, and Operation
AI	Artificial Intelligence
BEP	BIM Execution Plan
BIM	Building Information Modelling
B-Rep	Boundary Representation
CDE	Common Data Environment
CityGML	City Geography Markup Language (format)
COBie	Construction Operation Building information exchange
CSG	Construction Solid Geometry
CRS	Coordinated Reference System
DB	Database
DT	Digital Twin
EIR	Exchange of Information Requirements
ETRS89	1989 European Terrestrial Reference System
FM	Facility Management
GIS	Geographic Information System
GPS	Global Positioning System
I3S	Indexed 3D Scene Layers
ICT	Information and Communications Technology
IFC	Industry Foundation Classes
INSPIRE	Infrastructure for Spatial Information in Europe
IoT	Internet of Things
ISO	International Organization for Standardization
LCA	Life Cycle of an Asset

LoD	Level of Detail
LOD	Levels Of Development
OGC	Open Geospatial Consortium
O&M	Operation and Maintenance
SHP	Shapefile (format)
SLPK	Scene Layer Package (format)
SQL	Structured Query Language
WMS	Web Map Service
WFS	Web Feature Service

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