applied sciences

Article

Integration of BIM and GIS for the Digitization of the Built Environment

Giuseppe Piras *, Francesco Muzi and Claudia Zylka

Department of Astronautics, Electrical and Energy Engineering (DIAEE), Sapienza University of Rome, 00184 Rome, Italy; francesco.muzi@uniroma1.it (F.M.); claudia.zylka@uniroma1.it (C.Z.)
* Correspondence: giuseppe.piras@uniroma1.it

Abstract: The integration of Building Information Modelling (BIM) and Geographic Information Systems (GIS) is a growing reality in the building production sector. Through this integration, it is possible to improve the efficiency of management, maintenance, use and planning of conservation operations, providing an integrated and dynamic vision of the built environment. Simultaneous exchange of BIM-GIS elements in a shared environment facilitates information access and optimizes processes like requalification, activity planning, safety and sustainable urban design. Two alternative strategies are proposed for the multidisciplinary approach, using advanced technologies to acquire, process and manage detailed and georeferenced data. The first one is an open-source environment to guarantee flexibility, customization and accessibility. The second option, in a closed-source environment, provides advanced functionalities and dedicated support. Both require careful planning, detailed analysis and collaboration between the disciplines of architecture, engineering and geoinformatics. The study transcends theoretical analysis by exploring practical implications for real-world systems integration, examining their advantages, limitations and potential synergies in terms of flexibility, security and sustainability. This will enable a more efficient and comprehensive management of the architectural heritage and the built environment, contributing to its preservation and enhancement in the context of the digital transition in a future perspective of smart cities.

Keywords: digital transition; building production; digital methodology; digital management; BIM-GIS integration; built environment

Citation: Piras, G.; Muzi, F.; Zylka, C. Integration of BIM and GIS for the Digitization of the Built Environment. *Appl. Sci.* **2024**, *14*, 11171. https://doi.org/10.3390/app142311171

Academic Editor: Asterios Bakolas

Received: 1 November 2024
Revised: 23 November 2024
Accepted: 27 November 2024
Published: 29 November 2024

1. Introduction

The end of 2019 and the beginning of 2020 were characterized by the emergence of a viral epidemic belonging to the SARS-COVID family, known as COVID-19. The virus originated in Wuhan, China and quickly spread worldwide [1,2]. The pandemic had a more significant impact on the Italian economy than on other European countries [3]. In 2020, the Italian Gross Domestic Product (GDP) contracted by 8.9%, compared to an average decline of 6.2% for the European Union (EU). The country was already facing economic, social and environmental fragilities when this occurred [4]. The Italian economy's struggle to compete with other European countries is due in part to a significantly slower pace of productivity growth than in the rest of Europe; other reasons include the inability to seize the opportunities offered by the digital transition [5]. The delay in innovation can be attributed to the lack of adequate infrastructure and the composition of the production fabric, which is dominated by small and medium-sized enterprises that are reluctant to adopt new technologies and move to high value-added production [6]. The public sector also lacks familiarity with digital technologies. Before the pandemic, 98.9% of public administration employees in Italy had never used agile working [7]. The decrease in both public and private investment, which has slowed down the necessary modernization of public administration, infrastructure and production chains, is also partly to blame. In response to the pandemic crisis, the EU introduced the Next Generation EU (NGEU) plan [8]. This instrument aims to aid the socio-economic recovery of member states from the effects of the pandemic by allocating a fund of over EUR 800 billion to the economic, health, and public administration sectors, including infrastructure, social policies, and foreign policy [9].

The plan aims to target investments and promote initiatives to facilitate the transition to a greener and digital economy, enhance workers' skills, and foster gender, territorial, and generational equality of opportunities. Italy is one of the principal recipients of the Recovery and Resilience Facility (RRF) and the Recovery Assistance Package for Cohesion and European Territories (REACT-EU) [10]. The RRF requires Member States to develop a comprehensive investment and reform plan, the National Recovery and Resilience Plan (PNRR) [4], which details investment priorities of EUR 191.5 billion for 2021–2026, divided into six missions [11–16]. The PNRR outlines objectives and measures across various sectors, including tourism, culture, agriculture, logistics, education, the labor market, health services, and public administration digitalization. A unifying theme is digital innovation, seen as crucial for productivity and employment growth. The first mission focuses on digital transition, aiming to implement integrated digital services to simplify administrative processes for citizens, businesses, and institutions [17]. The digitization theme permeates all six missions of the Plan.

The phenomenon of rapid global urbanization presents urban centers with a multitude of complex challenges, including traffic congestion, environmental pollution and resource inefficiency. In such circumstances, the concept of the smart city emerges as a solution, employing a range of innovative information technologies to maximize the use of available resources and to create new ones. An example could be the following:

- Intelligent urban transport networks;
- Improvement of waste management facilities;
- Optimization of air-conditioning and lighting systems in buildings;
- More interactive local public administration;
- Real-time monitoring of the urban environment, leading to improved safety in public places;
- Integration with digital, networked, modular and multifunctional technologies for street-furniture components;
- Use of different intelligent mobility options such as electric cars, public transport, service vehicles powered by renewable energy and connected through dedicated digital systems to a management system for recharging, maintenance, emergency situations and traffic conditions;
- The ability to plan, book and pay for different types of mobility services through digital tools and pay-per-use or pay-as-you-go payment models.

The integration of BIM-GIS within smart city initiatives is a key strategy for achieving the multiple objectives of modern urban development. By leveraging the complementary strengths of this holistic approach, cities can foster innovation, optimize resource allocation, and improve the efficiency and safety of urban systems, contributing to the creation of more robust and reliable digital infrastructures. Such integration is particularly important in the context of digital transformation. It facilitates the development of flexible, scalable and interoperable solutions capable of addressing the dynamic and evolving challenges of urban environments. Through these paradigms, smart cities can create an ecosystem that balances openness with control, enabling seamless integration of diverse technologies and stakeholders. This approach supports a wide range of applications, including real-time data analytics, intelligent transport systems, energy management and citizen engagement platforms. Ultimately, the BIM-GIS integration underpins the transition to sustainable and citizen-centric urban models, improving the overall quality of life and resilience of modern cities.

The field of Architecture, Engineering, Construction and Operations (AECO) is undergoing constant technological development due to the increasing digital innovation and integration of BIM approaches and methods, which are significantly impacting the entire construction life cycle [18]. The pervasive adoption of Building Information Modelling (BIM) and the digitization of building production are profoundly revolutionizing the way buildings are conceived, constructed and managed over time. In this context, this research work proposes to identify a synergy between two digital systems, BIM and the Geographical Information System (GIS), with the aim of improving the management of information in the AECO sector. BIM is a process that involves the creation and exchange of digital representations of the physical and functional characteristics of buildings and infrastructures [19].

GIS uses Geographic Markup Language (GML) [20] to illustrate events in specific areas by collecting diverse data. GIS and BIM methodologies [21–23] have been used separately in data digitization for planning and management. The integration of BIM with thematic GIS data is crucial to address the loss of information during building processes, which is a key challenge in the digital transition of the AECO sector [24]. This integration is essential during the transition from planning to diagnosis and management phases, facilitating the exchange of parametric information among various operators using different software. Often, software only recognizes its own data format, necessitating data conversion and diminishing its completeness and value. It is therefore possible to recognize the importance of enhancement of information data as a central element of the entire process.

BIM-GIS integration leverages the synergetic harmonization of their respective strengths, fostering fruitful collaboration. While BIM excels in parametric information modeling, GIS is adept at using data in the spatial domain. A significant advantage of this integration is evident when incorporating time information (BIM 4D), allowing stakeholders to visualize and understand decision outcomes before construction through simulation tools. Accurate predictions require a data volume commensurate with the analysis type. Additionally, real-world contextual information, such as environmental and demographic conditions, can enrich BIM models. For instance, GIS data on flood-prone areas can assist designers in selecting the optimal location, orientation, and materials for the structure's spatial context.

The availability of shared and easily accessible data opens the door to a number of significant and transformative benefits, facilitating the simultaneous exchange of parametric information on elements and helping to improve the quality and consistency of processes. This leads to a number of benefits, including improved safety on construction sites, where timely and accurate information sharing can prevent accidents and improve working practices; more efficient supply chain management in the construction sector, through more timely planning/coordination of resources; and sustainable urban design, with more accurate and informed planning of urban infrastructure and resources, with long-term benefits for the environment and the quality of life of communities [25,26]. In fact, this integration is efficient in the post-construction phase, enabling more effective management of structures through a unified database that facilitates information retrieval for maintenance or diagnosis. In facilities management, where constant data use is necessary, an integrated BIM-GIS model ensures access to all required information during operation. Planners can utilize these solutions to retrieve and reuse key data at every stage of a building or property complex's lifecycle. GIS data are crucial for planning operations, especially for infrastructure such as airports, rail networks, bridges, and highways, allowing optimal placement in their environment. BIM-GIS integration overlays the BIM model with geospatial information layers, providing designers with precise details about construction areas. This enables designers to make informed decisions about building materials or foundation types in advance, ensuring the stability and durability of structures over time.

The BIM-GIS systems integration promotes sustainability and resilience in infrastructure and land construction [27,28]. Addressing climate change adaptation, energy transition, and emissions reduction requires innovative information management solutions that enable scenario assessment, multidisciplinary collaboration, and information sharing. These goals are closely tied to the interoperability of GIS and BIM technologies [29,30]. Parametric data's semantic richness allows BIM to be used in designing new buildings and rehabilitating existing ones, ensuring efficient interventions [31]. GIS's advanced spatial analysis capabilities make it essential for solving environmental conservation issues, and are used in urban planning, mapping geological and seismic hazards, environmental monitoring, and traffic management. These systems are fundamental for ecosystem protection and sustainable natural resource management, enabling detailed analyses of large data sets to identify environmentally favorable strategies [32]. Advanced data processing and simulation of energy and environmental flows allow for assessing projects' environmental and social impacts and identifying strategies to mitigate negative environmental impacts [33].

The functionalities resulting from the combined use of BIM and GIS are numerous and diverse, encompassing a range of applications, including emergency and risk management, support with climate change and energy management, and the monitoring of FM operations. In other instances, the combined use of BIM and GIS encompasses landscape planning, facility management, environmental simulations, pedestrian road design, and spatial control for national security. The development of GIS and BIM platforms has been driven by a variety of factors, but with the evolution of the AECO sector and the emergence of smart cities, the integration of BIM in the geospatial context has become increasingly strategic. Despite the evident advantages, this paradigm is confronted with a number of challenges, including the management of spatial scale, the definition of data layers, the representation of geometry, and the storage and access of data. Another challenge is the semantic discrepancy between BIM and GIS. Based on the available literature, it reveals that one of the principal challenges is the adaptation of standards, given that the structure and information in the two schemes differ considerably [31].

Literature Review

Several studies have been conducted in the field of BIM-GIS integration, with the objective of examining the potential benefits of combining these two technologies [34]. Ohori et al. [35] identify three use-case scenarios for this integration. Firstly, the examination of the 3D Industry Foundation Classes (IFC) model of a building or structure is conducted in comparison with the existing physical environment, which is represented by a 3D city model and in comparison with the specific type of zoning in the area. This process entails the generation of a continuously updated 3D city model. Furthermore, they investigate the use of urban area information and data in BIM, such as geospatial data, in the early design phase, particularly for infrastructure projects. This approach aims to provide a continuous flow of information that would eventually be combined with BIM data and used for maintenance purposes. Finally, the following research considers the integration of subsurface data in the initial BIM design phase. Congiu et al. [36] develop a multiscale approach based on a bi-directional integration between the two information systems, relating them appropriately and allowing easy switching between the databases of the two systems, mainly using open source (OS) tools (QGIS 3.20.3 and Dynamo 3.0.3). Kang et al. [37] present a new method to integrate scanning data with BIM in a three-dimensional GIS. Using point cloud data from airborne laser scanning, detailed building information is automatically generated in the GIS. This approach offers benefits for urban planning, facilitating the management of buildings and improving visualization and analysis. The proposed process is flexible and algorithmic, with prototypes demonstrating its effectiveness in automatically generating BIM on three-dimensional GIS platforms, reducing manual effort. Janisio-Pawlowska et al. [38] focus on developing a strategy for combining different data sources, including the use of BIM in CityGML within an existing GIS system. The process of converting BIM files into CityGML and transferring the data to the GIS software is analyzed. According to [38], the growing demand for digital tools in the field of spatial and urban analysis is highlighted, suggesting prospects for improving spatial data integration through the use of OS programs. Cao et al. [39] analyze, through a systematic review, the capabilities of BIM-GIS integration in post-disaster prevention, response and recovery, to improve urban disaster management. Data acquisition, interoperability, data use and analysis are examined, and future directions of integrated BIM-GIS use are discussed. Yoon et al. [40]

propose a decision framework that combines a GIS-based routing model and a genetic algorithm in a BIM environment to improve the planning of sporting events. They develop a framework that evaluates environmental variables in GIS routing models to consider the urban impact of sporting events and which allows route selection priorities to be modified according to user needs. By integrating data into BIM, models can be created and analyzed to assess urban impacts. Celeste et al. highlight the current phase of development and expansion of BIM-GIS integration, attributing this growth to the constant exploration and research in the field [41,42].

The aim of this study is to provide an innovative strategy that can be applied in any BIM-GIS integration process, regardless of the specific requirements or intended uses. For this reason, two different methodologies are developed: one in the open-source environment (OSE), characterized by the possibility of access to the source code and the possibility of customization and modification by the developers, and the other in the closed-source environment (CSE), which requires the purchase of licenses to obtain a single shared environment that can host both building data and spatial data.

In the OSE, interoperability between the two systems will be examined through the use of QGIS software. The process, which is complex and laborious, requires the intervention of an additional application beyond those managing BIM and GIS for the final visualizations. In contrast, in the CSE, ArcGIS software 3.4 is used, which guarantees a remarkable integration process due to its readability of BIM geometries/information that eliminates dependence on external platforms for visualization. As anticipated, this will allow us to examine the solutions available in both the OS and proprietary software domains. OS technologies often offer greater flexibility and customization possibilities, while proprietary software can offer advanced functionalities.

2. Materials and Methods

The AECO sector is undergoing a digital transition driven by the necessity to enhance the efficiency, sustainability, and quality of operations in the built and to-be-built environment, which is a crucial aspect of the sector's development. In this context, the integration of tools such as BIM and GIS emerge as a strategic priority in spatial management processes, including those of public institutions. The adoption of digital systems is of paramount importance for the improvement of operational efficiency and the optimization of resources. The implementation of BIM solutions enables organizations to create three-dimensional virtual models that accurately and comprehensively represent the physical and functional characteristics of a project. These models enable more accurate planning and design, reducing the risk of errors and discrepancies during the construction and management phases. Another key point is the ability to manage all information related to a project in an integrated and centralized manner, even taking advantage of cloud platforms. BIM systems make it possible to create a shared database that includes not only the architectural and structural elements of a building, but also information on materials, costs, schedules and energy performance. By integrating this information with the geographic and topographical data provided by GIS, organizations can gain a holistic and detailed view of their environment, facilitating planning and informed decision-making. Through online platforms and data sharing tools, everyone involved in the building process can collaborate in real time, exchanging information, comments and updates on project progress.

The adoption of this approach is conducive to enhanced transparency, expedited response times, and greater cohesion among team members. Moreover, the implementation of these systems plays a pivotal role in fostering sustainability and resilience in the construction industry. By means of advanced data analysis and the simulation of energy and environmental flows, it is possible to assess the environmental and social impact of a project and to identify solutions to reduce the negative impact on the environment. The integration of BIM and GIS is an increasingly relevant area of interest for the management and development of the built environment. This synergy offers considerable potential for enhancing the planning, design, construction, operation, maintenance and preservation of infrastructure and buildings.

In recent decades, as part of the information technology revolution, GIS has played a major role in map management and production. These systems represent a major innovation because they combine two fundamental pillars of information technology: computer-aided drafting (CAD) and relational databases (DBMS), the latter being one of the first computer creations. This integration has made it possible to overcome the inherent limitations of traditional cartographic representations, which usually have a symbolic nature and a predefined scale of values. GIS offers the possibility of analyzing geographical entities not only from a geometric point of view, but also from an information point of view, associating each mapped entity with a corresponding record in the database. This synergy makes it possible to explore additional details and information on geographical entities, opening up a vast potential of applications, especially in the field of safety and environmental impact analysis, especially with regard to industrial projects. However, in fields such as AECO, where the consideration of specific construction details is essential, GIS often assumes only a contextual function. In these circumstances, BIM becomes essential, also taking advantage of the advances of the IT revolution to provide a more detailed and integrated view of construction projects.

The advancement of integrated BIM-GIS management is an ever-growing field, driven by technological innovation and continuous research. In recent years, several emerging technologies have shown tremendous potential to improve the interoperability and efficiency of infrastructure design, construction and management processes. One of the most promising trends is the application of machine learning and artificial intelligence (AI) techniques [43,44] to BIM-GIS integration. AI makes it possible to analyze large numbers of data from both domains, identify hidden patterns and relationships, and generate useful insights for urban planning, resource management and infrastructure maintenance. For example, machine learning algorithms can be used to predict the energy needs of a building based on BIM data and geospatial information on solar orientation and geographic location. Another important development is the use of augmented reality (AR) and virtual reality (VR) technologies for visualization and collaboration based on BIM models and GIS data [45]. These technologies allow users to explore and interact with 3D models in an immersive way, facilitating communication and information sharing between different stakeholders. For example, developers and planners can use AR devices to visualize BIM models of new infrastructure in the existing geospatial context in real time to assess visual and environmental impacts and make informed decisions.

IoT is revolutionizing the way data are collected, processed and used in BIM-GIS integration [46]. Intelligent sensors embedded in buildings and the urban environment can collect a wide range of real-time information, such as air quality for occupant comfort, automatic monitoring of security cameras with computer vision systems, users' behavior for automation customization, monitoring of energy produced by renewable energy systems and life cycle assessment of sources, control of vehicle traffic, and much more [47–50]. The collected data can be interpolated in a single working environment to improve the accuracy of analyses and predictions. Cloud computing is becoming increasingly important in information management, storage and sharing, including in the supply chain of integrated BIM-GIS systems, enabling flexible and scalable data storage, processing and access. Cloud platforms offer the ability to collaborate in real time on shared models and data, overcoming the limitations of geographical distribution and local computing capacity. The adoption of these technologies holds great promise for improving the efficiency, sustainability and resilience of cities and infrastructure, enabling smarter, data-driven management of the built environment.

3. Methodology

The following sections illustrate two methodologies, one for the OSE [51] and one for the CSE [52]. The OSE concept is based on community collaboration and knowledge sharing.

Software is developed collectively by a team of developers, who collaborate to create a freely accessible, modifiable, and redistributable product. This model fosters innovation and flexibility, enabling users to adapt software to their specific requirements. The OSE is frequently underpinned by principles of peer production and mass collaboration, which facilitate the creation of a sustainable development environment. Organizations such as the Free Software Foundation (FSF) [53] and the Open Source Initiative (OSI) [54] promote and protect these values through a variety of graphical software licenses, including the MIT License [55], the GNU General Public License (GPL) [56], the Apache License [57] and numerous others. On the other hand, the CSE is proprietary and not freely distributed to the public. The authors retain exclusive control over the source code and impose restrictions on the use and modification of the software by end users. This model presents limitations in terms of flexibility and accessibility of software, but can offer greater control and security for developers. The integration of the OSS and CSS into the built environment offers several advantages and opportunities. The OSS fosters innovation and collaboration in an open and adaptable environment, while the CSS can offer greater control and data security through the use of more advanced blockchain systems. Nevertheless, both approaches present specific challenges and considerations that must be taken into account during the decision-making process.

The novelty of this research lies in the comparative and integrative approach adopted to evaluate two different methodologies, the OSE and CSE, to address specific problems in the context of the built environment, demonstrating both the value of the two approaches and their potential synergies. The study explores the advantages and limitations of two opposing paradigms in the AECO sector, taking into account aspects such as flexibility, safety and sustainability. This comparison is not limited to a theoretical analysis, but also highlights practical implications for integration into real systems. The illustration of the methodology through concrete case studies is an important contribution that is not always found in the literature. Not all research succeeds in translating theoretical concepts into practical and well-documented applications.

The application of the methodology is illustrated below, step by step, through a series of figures showing its application to two different case studies.

3.1. Open-Source Methodology

In the field of information technology, the term "OS" refers to a specific type of software that is released under certain licenses that allow access to the source code for potential developers. During the 1980s, as the computer industry underwent a period of rapid expansion, there was a shift from a free approach to restrictions imposed by proprietary software, with all its implications. The advent of the OS concept in 1998 represented an attempt to reverse the prevailing trend by promoting the free circulation of program information. Access to the source code enables programmers and advanced users to modify software according to their specific requirements. This feature serves to distinguish OS programs from freeware programs, which, although freely usable, remain the property of their creators and cannot be modified by others. The OS approach should therefore be considered not only as an alternative to avoid the purchase of proprietary software, but also as a choice aimed at fostering the free circulation of information and the exchange of ideas, thereby promoting inclusive and participative growth. In this context, the Italian Ministry for Innovation and Technology issued a directive in December 2003 inviting public administrations to consider the use of OSS as a new way of development and diffusion. This was done with the aim of promoting interoperability between public administration IT systems and preventing dependence on a single supplier and/or proprietary technology [58].

In the building production sector, it is of paramount importance that the various stakeholders collaborate and share information, utilizing cloud platforms, in order to ensure the success of projects throughout the construction lifecycle. Consequently, the use of common standards and protocols is of paramount importance. These tools provide a common basis for communication and data exchange, thereby enhancing interoperability between the various systems and applications employed in the construction sector. The collective endeavors of the principal actors in the sector have resulted in the development of software platforms and tools such as the IFC [59] and the Construction Operations Building Information Exchange (COBie) [60]. The IFC represents an open standard file format utilized for the exchange of BIM information between disparate software applications. It provides a standard digital description of the built environment, including buildings and building infrastructure. Such platforms permit the exchange of parametric three-dimensional models, design data and information on the geometry and properties of building components in an interoperable manner.

The IFC (which was originally created as an open and interoperable interchange file format) is able to fulfil various needs, but it should be noted that it represents a specific data structure. The IFC schema may be conceptualized as a "storage system" for organizing and transporting digital data, which must be usable by several operators over a fairly long period of time. It follows that the IFC format is accessible to any user, regardless of the software employed and its version. In addition to the aforementioned preservation requirements, the storage of the IFC file must also ensure that it is easily accessible for consultation. This necessitates the structured storage of the model data and the identification of the models themselves, according to their intended use and function. In summary, it is possible to state the following points:

- IFC models contain geometric and non-geometric entities;
- IFC models contain the geometry of the building and the data associated with its elements;
- Exporting the data of a project carried out using the BIM methodology by means of an IFC file transfers the data from one application to another;
- The IFC format is open, free, and contains a large amount of information.

The provision of an IFC-compliant interface for export and import enables software application providers to guarantee interoperability with a multitude of other tools. Ji et al. [61], in their discussion of BIM-GIS integration for the purpose of enhancing urban management, highlight the role of standards such as the IFC and City Geography Markup Language (CityGML) [62]. However, this study identifies a significant challenge in the transformation of these standards, namely the discrepancy between them in terms of geometry and semantics. In order to address this issue, an ontology-based-rule mapping approach has been developed, which enables the transformation from IFC to CityGML through coordinate system conversion. Jaud et al. [63] address the complexity of the problem of georeferencing BIM models and the need for a comprehensive solution by focusing on the open BIM data format of IFC. Although the IFC already encompasses some of the concepts, an extension of the IFC schema is proposed to address any inadequacies. The proposal consists of two new entities: one supporting geographic reference systems (GIS) and the other allowing a rigid transformation of BIM geometries.

The tools used for the integration process between BIM and GIS in OSE are illustrated below (Figure 1).

For the GIS environment, QGIS 3.20.3 software was chosen (Figure 2), which permits the identification of various real-world assets such as land, roads, or other features [64]. QGIS is a software designed for the management, analysis, and visualization of spatial data. QGIS's flexibility, versatility and extensive toolset make it an invaluable resource for scientific research and project implementation across a range of fields, including urban planning, environmental management, precision agriculture and natural resource monitoring. The software is compatible with a multitude of spatial data formats, including vector formats (such as shapefiles, GeoJSON and GPKG) and raster formats (such as GeoTIFF and satellite images), thereby ensuring broad interoperability with other platforms and data sources. The software enables sophisticated spatial analysis operations, including layer overlay, buffer calculation, proximity analysis and raster modelling, rendering it particularly well-suited to multidisciplinary studies and complex geospatial applications.

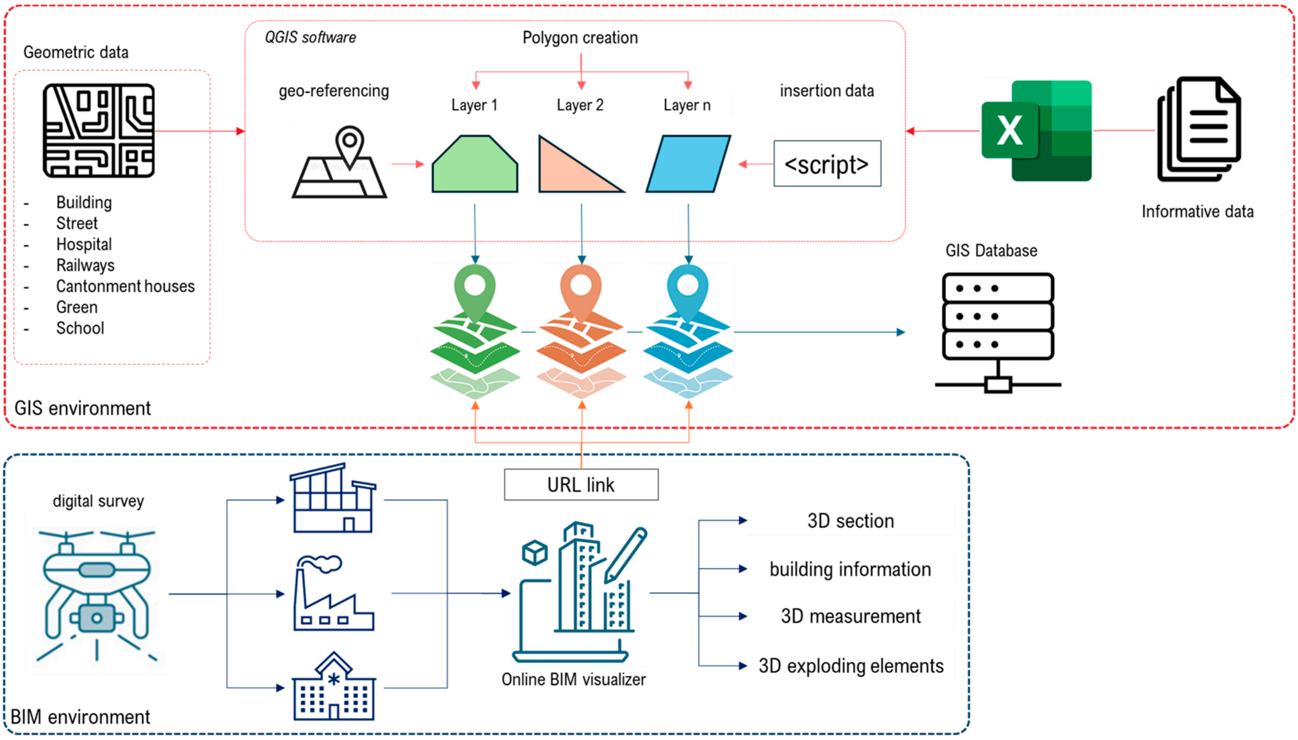

Figure 1. OS methodology chart.

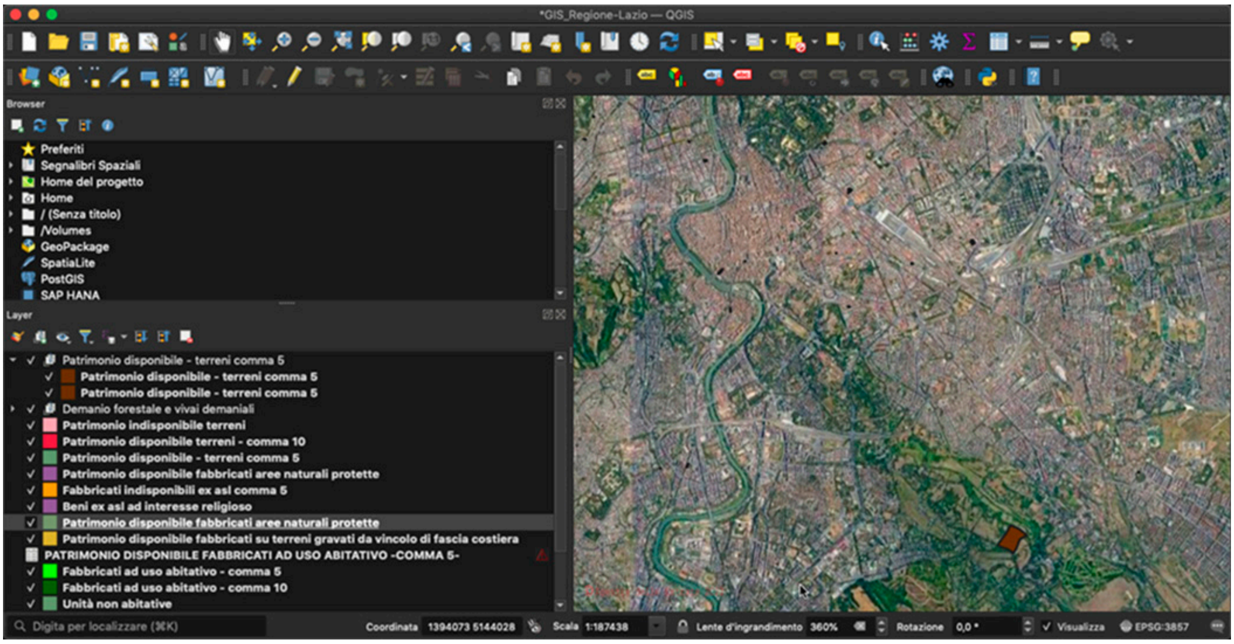

Figure 2. QGIS interface, layer and geospatial map.

This is done using information derived from cadastral data and other documentation. The initial stage of the process requires the configuration of certain software settings, including the loading of the base map to serve as a reference for the assets. A new connection can be created through the "Data Source Manager" function using the "XYZ Tile" option. This procedure enables the loading of Google Satellite and cadastral maps.

Subsequently, the location and identification of real estate and land can be undertaken. To facilitate this process, three plug-ins have been identified:

- OSM Place Search 1.4.5 is a QGIS plug-in designed to simplify the search for places using OpenStreetMap (OSM) data [65]. It allows you to quickly locate and center your map view on a place, address or point of interest. Key features of the plug-in include the ability to search for cities, addresses, monuments or other geographical locations using the OpenStreetMap database. It integrates seamlessly into the QGIS interface and presents itself as an easy-to-use search bar or dialogue box. Once the desired location is selected, the map is automatically centered on the search result, making navigation fast and intuitive. The plug-in also supports place names in different languages, depending on the information available on OSM. Its intuitive interface makes it suitable for both beginners and advanced QGIS users. The installation involves opening QGIS, go to Plugins > Manage and Install Plugins, search for OSM Place Search in the search bar, select the plugin and click Install. Once installed, the plug-in will be available in the QGIS toolbar.
- MMQGIS 2.99 is a plug-in that provides a wide range of tools for analyzing, managing and manipulating geographic data, with a particular focus on vector data [66]. This tool is appreciated for its flexibility and ability to extend the basic functionality of QGIS, making it an essential element for those who regularly work with spatial data. Key features of MMQGIS include tools for geocoding and reverse geocoding, allowing addresses to be converted to geographic coordinates and vice versa, using external services such as OpenStreetMap or Google Maps. It also offers a wide range of options for managing and manipulating vector data, such as merging, splitting, dissolving layers or creating buffers, regular grids and random points. The plug-in supports advanced operations such as merging tables, splitting layers based on attribute values and calculating new fields. Other useful tools include the ability to manage labels, create thematic maps and export data in a variety of formats including CSV, KML and GPX for easy use on other platforms such as Google Earth or GPS devices. Installation follows the same procedure as above.
- QuickMapServices 3.22 is a plug-in that simplifies access to base maps and map web services, making it an essential tool for anyone working on GIS projects [67]. Its intuitive interface allows you to quickly integrate online maps into your projects without complex configuration. It offers pre-configured base maps from popular providers such as OpenStreetMap, Google Maps, Bing Maps and Esri, as well as thematic maps such as satellite imagery, topographic surveys and street maps. It also supports online map services (WMS, WMTS, TMS), allowing custom maps to be added and managed via URL. The plug-in has a search function to quickly find available maps and offers the ability to cache maps for faster access, which is useful in contexts with limited connectivity. The installation process is identical to that described above.

The support of these plug-ins enables the creation of a database of georeferenced elements comprising multiple layers, which are associated with the typology of the asset, as well as the generation of a two-dimensional graphic representation, which may represent a building, infrastructure or terrain (Figure 3). The contribution of these innovative functions makes it possible to optimize BIM-GIS integration, providing support both at the level of geographic maps and at the level of simplifying the search for different assets on the territory. Each asset is classified according to the aforementioned typologies, and is placed in the reference layer, which is distinguished by color. An MMQGIS script can be employed to automatically insert the available documentation of an asset into the table of its characteristics. Consequently, once the assets under discussion have been georeferenced, it is possible to enter all the necessary information with reference to the polygon.

The set of all documents entered into the software constitutes a GIS database, subdivided into layers, which can be consulted and exported in different formats (Figure 4). The database enables the management of assets at the territorial level, thereby permitting the analysis of the territory for urban planning or restoration projects.

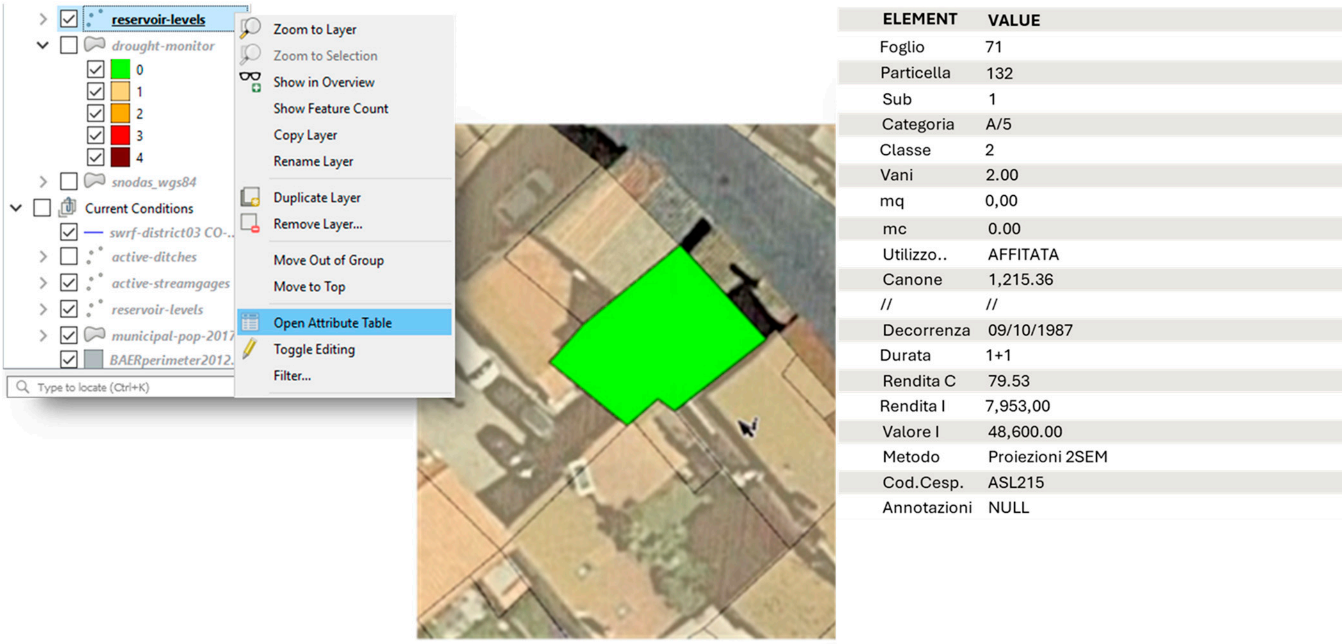

Figure 3. Creation of polygon process in QGIS.

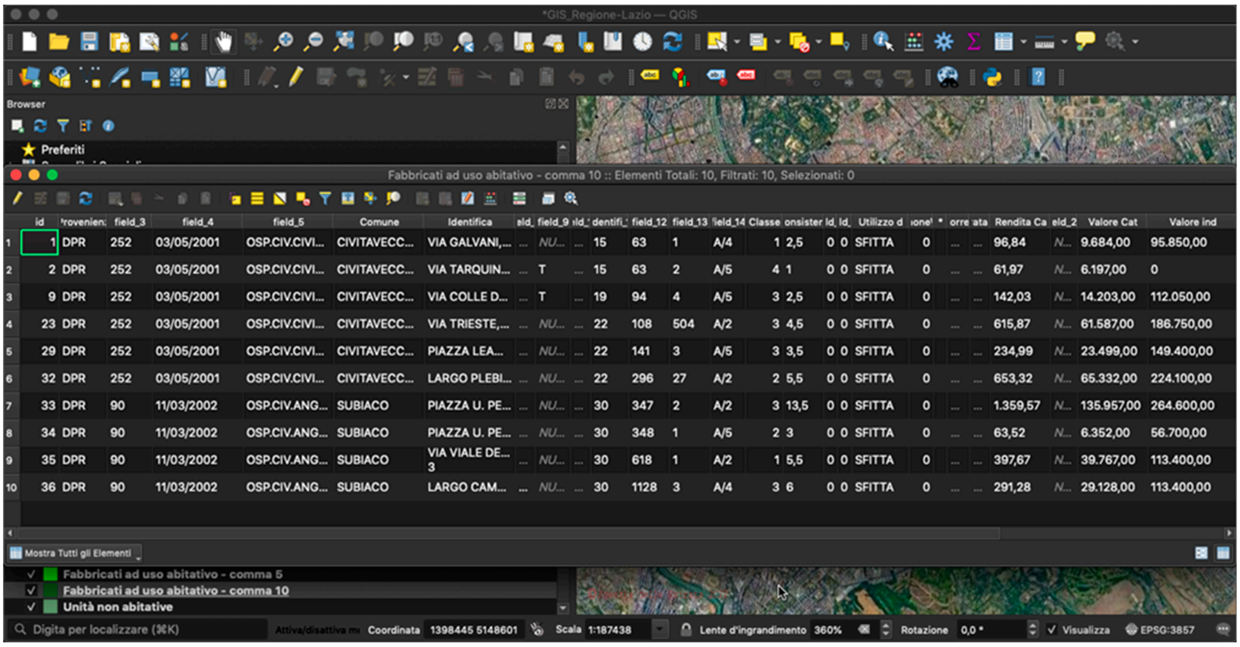

Figure 4. Database DBMS property visualization in QGIS.

On the other hand, it is also necessary to have a BIM model of a building or infrastructure in order to operate at a more detailed level. The digital model represents the informational contribution related to the characteristics of the building work. The creation of a model of an existing building can be achieved in two ways:

1. A digital survey of a work can be conducted through the use of drones or laser scanners [68].
2. The creation of a model of an existing building can also be initiated from available documentation, even if it is not in digital format [69].

It is well established that the fidelity of a model derived from a point cloud is superior to that of a recalculation of design drawings. Kim et al. [70] discuss the adoption of 3D laser sensing technology in the monitoring and analysis of construction-related phenomena as part of intelligent construction technologies. This approach is posited to facilitate a more rapid and precise measurement of construction progress, thereby enhancing the efficiency of process management and the realization of sustainable construction management. In any case, once the digital information model has been acquired, the geographic coordinates of the depicted property must be set to ensure a correspondence of information in the database. Following the initial configuration, an export in IFC format is scheduled for implementation, which will then be uploaded into an online viewer compatible with the OS.

This online visualization tool enables both informative and geometric queries on the building, such as reading the properties of a building element (Figure 5), creating interactive sections and measuring elements in 3D (Figure 6).

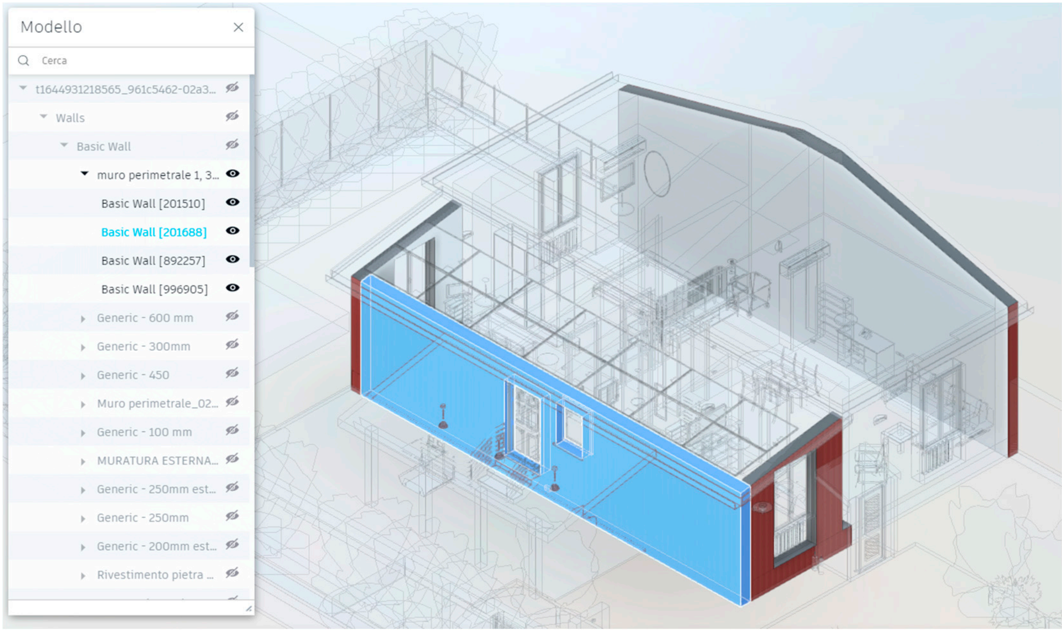

Figure 5. Interactive view, property of building element in OS viewer.

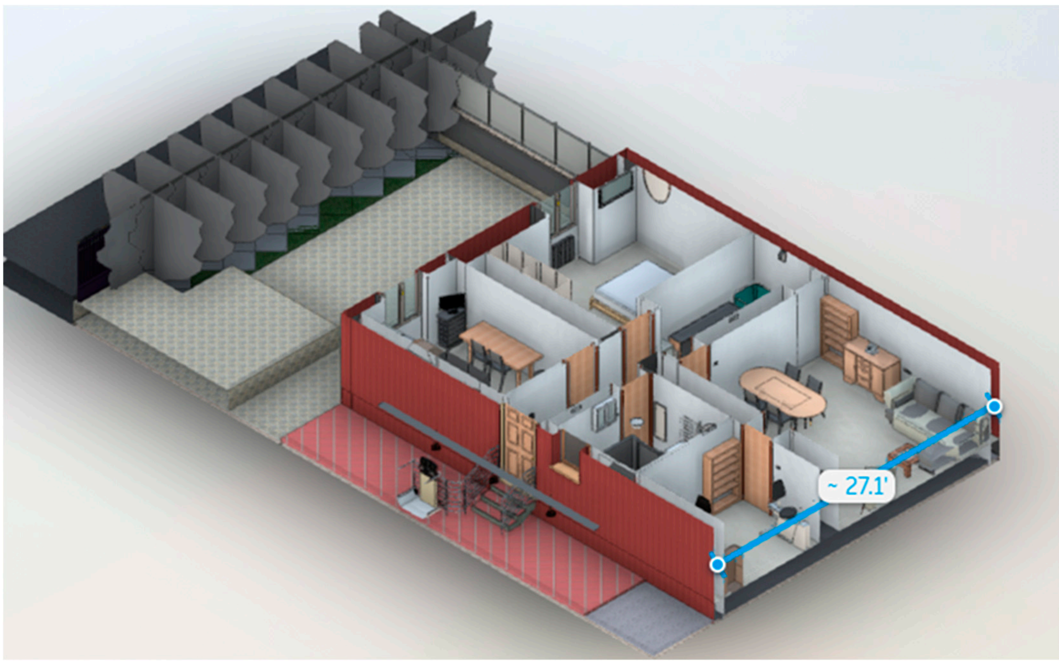

Figure 6. Interactive view, 3D measurement in OS viewer.

Subsequently, the URL of the web page of the building viewer is entered into the attribute table of the reference object in the QGIS software. In this manner, once the object has been located on the map and its information has been opened, it is possible to identify and open the link to access and view the digital information model of the object. The methodology incorporates this step, as it is not possible for the QGIS software to provide a three-dimensional visual characterization of any object.

3.2. Closed-Source Methodology

CSE is a type of software whose use is permitted only under certain conditions specified in the license, restricting activities such as study, modification, sharing, distribution or analysis. These restrictions are imposed by the holder of the economic rights, which may be the author himself or the assignee of the rights, through legal means such as clauses in the license agreement or restrictions on sources or patents in countries where this is permitted. Restrictions may also include technical elements, such as distributing software only in binary code without making the source code available. This practice makes it impossible to study and modify the software, which would require advanced computer skills and considerable effort to obtain information. The Free Software Foundation (FSF) employs the term "proprietary software" to designate software that is not free or only partially free. However, technically, the term encompasses any software that is controlled by a single entity, so it could be applied to any software that is not in the public domain [71]. Proprietary software is developed with the intention of offering a service against payment, whereas free software is developed with the objective of guaranteeing the freedom customization of software from users, without any kind of limits. The AECO sector is represented in the market by a number of large companies that are leading providers of BIM and GIS software, such as Autodesk, Graphisoft, ESRI and ACCA [72–75].

Hu et al. [76] propose an innovative process for transforming a motorway model based on a GIS into a well-structured BIM platform using the visual programming tool Dynamo. The developed process involves the conversion of poly-curves from the GIS model into BIM-compatible model curves, the classification of attributes into shape families, and the integration of traffic data from traffic detection and recording stations. The finalized multi-dimensional BIM platform, which extends from three to eight dimensions, incorporates essential project details and traffic data. To guarantee interoperability, an Open BIM process is employed, which involves the generation of an IFC file, enabling efficient data exchange between different software and stakeholders.

The CS methodology is illustrated as follows (Figure 7), with the relevant tools and software used during the development process.

The initial development phase of the CS methodology can be outlined as follows. Firstly, the GIS software environment is established, in this case ESRI's ArcGIS Pro 3.4 [77]. Esri (the Environmental System Research Institute) is one of the leading producers of GIS software systems and applications for the management of geospatial databases. ArcGIS is a geographic information system that is employed for the creation, analysis, and technical use of maps, the compilation of geographic data, and the sharing and management of geographic information within a database. This phase encompasses the definition of the standardized coordinate system to be employed, the selection of the graphical display mode of the model and the background map, and, finally, the specification of the nomenclature for the Common Data Environment (CDE) repository to be followed and the final destination of the project file [78].

The selection of the coordinate system to be used as the basis for georeferencing is a crucial step in ensuring the interoperability of the systems (Figure 8). A terrestrial coordinate system is defined by a set of parameters that enable the unique identification of objects on the Earth's surface. The WGS84 (World Geodetic System 1984, also known as EPSG:4326) has been employed as the coordinate system. This is a geodetic, worldwide, ellipsoid-based geographic coordinate system that was developed in 1984 [79]. It represents the Earth from a geometrical and gravitational perspective, and was constructed on the foundation of measurements and scientific and technological knowledge available in 1984. Geodesy data can be classified as either local or regional, with the former approximating the geoid with greater accuracy in a limited area around the emanation point. In contrast, the WGS84 global datum employs the EGM96 standard, which provides a more comprehensive approximation of the geoid, and is applicable globally.

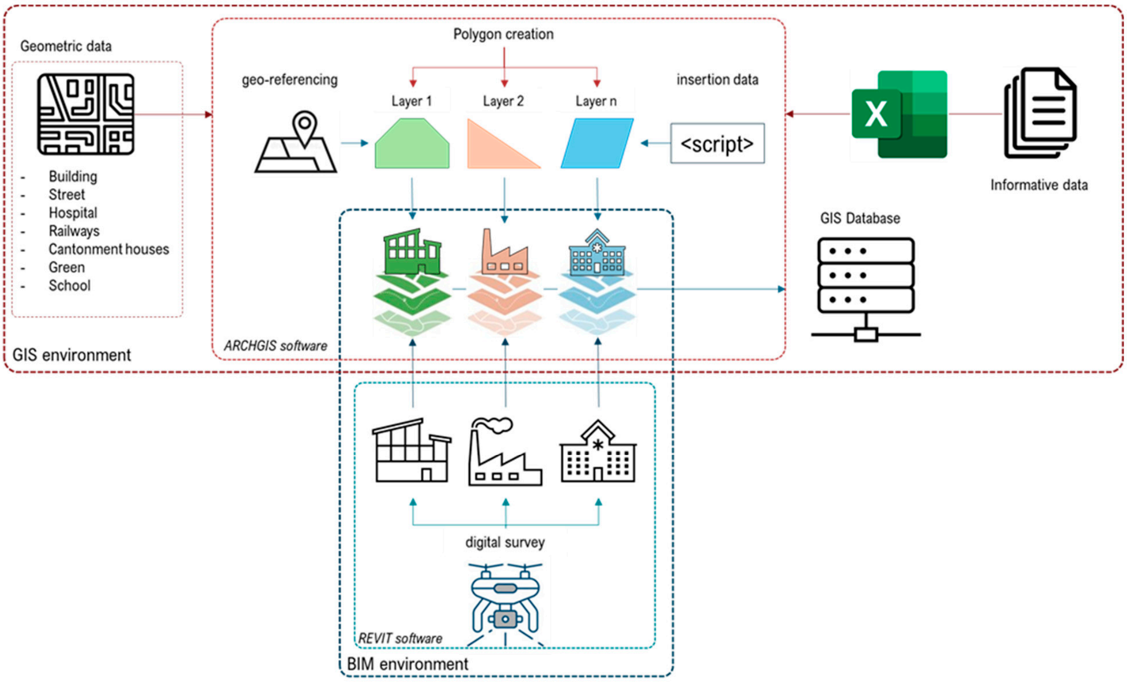

Figure 7. Closed-source methodology chart.

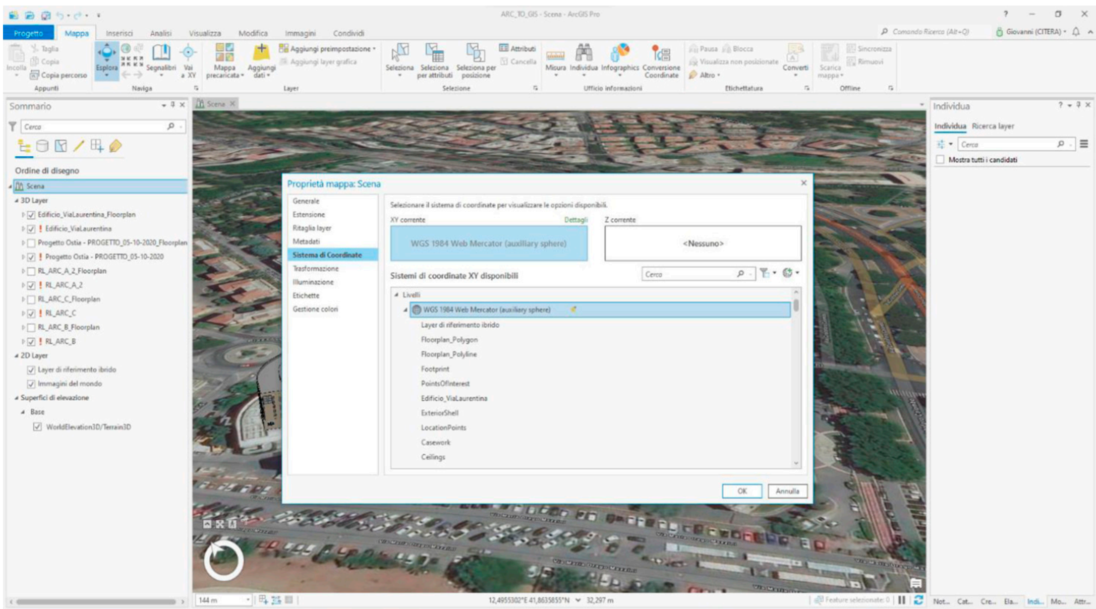

Figure 8. Application of the WGS84 coordinate system in ArcGIS Pro.

Regarding the BIM environment, the same considerations apply as for the OS methodology. It is therefore recommended that the built environment be digitized through digital surveying. However, the use of specific software for the CS approach, determined in Autodesk Revit, allows the BIM model to be geo-referenced with maximum precision in the previously identified coordinate system (Figure 9) [80]. Revit is capable of importing, exporting and linking data in the most commonly used file formats in the industry, including IFC, DWG and DGN. Furthermore, the solution allows multiple project coordinators to manage centrally shared tasks and models, thereby facilitating simplified collaboration. Furthermore, it facilitates the communication and expression of ideas in a clear and effective manner to all players involved in the construction process.

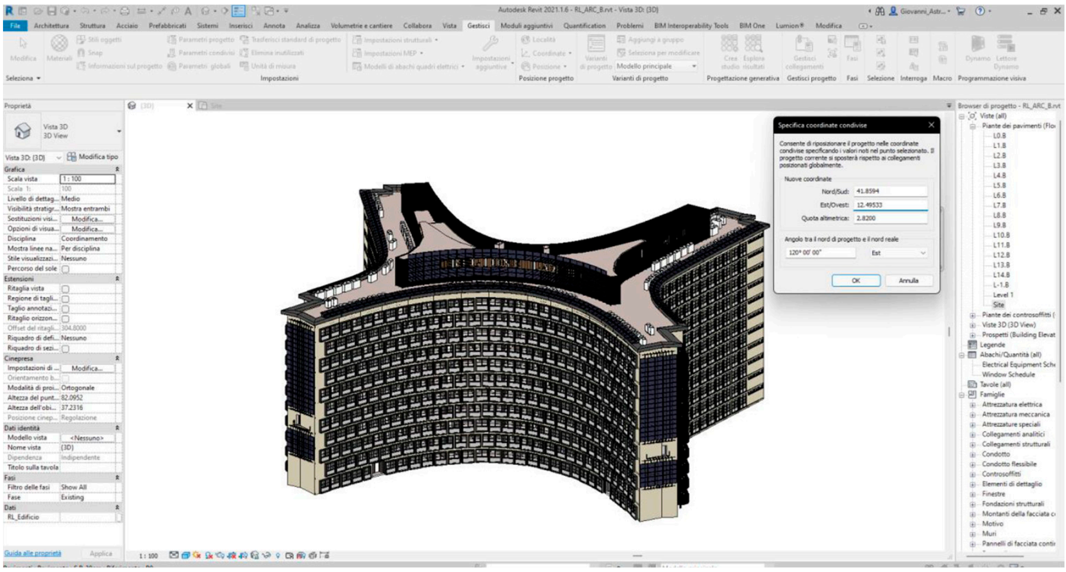

Figure 9. Application of the coordinate system in the Revit (BIM) environment.

The Revit model can then be imported into Esri ArcGIS. Following a brief interval, during which the software processes the data, the model is loaded into the GIS environment at the specified coordinates. In this manner, it is possible to graphically display the three-dimensional geometry of the building information model BIM on the GIS environment (Figure 10). The integration of CS enables the analysis of building information on a small scale, while simultaneously allowing for the examination of spatial information on a large scale.

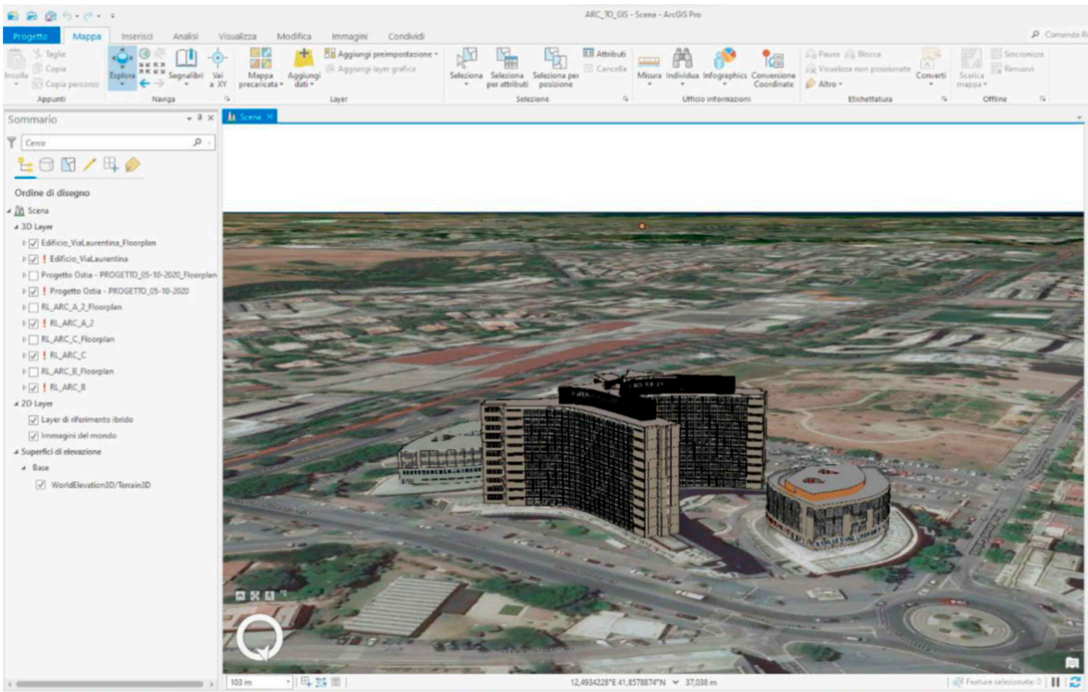

Figure 10. Visualization interface of BIM-GIS integration into the CS, 3D BIM model in a GIS environment.

4. Results and Discussion

The BIM-GIS integration presents a number of challenges, including those related to spatial scale, granularity level, geometric representation methods, archiving and access methods, and semantic discrepancies between the two systems. One of the principal challenges identified in the literature is the significant divergence in the information and data structures between standards developed with originally disparate purposes. It is evident that the integration of BIM methodology with data from thematic GIS maps becomes crucial to address the progressive loss of essential information and data in engineering, architecture and construction. BIM, on the other hand, is focused on infrastructure development and management, with a strong emphasis on object relationships. In contrast, GIS models the current geospatial context, where georeferencing plays a crucial role. Another significant challenge concerns the representation of geometric data, with different approaches between BIM and GIS. While BIM offers several methodologies for the three-dimensional representation of geometry, including CSG, B-rep and sweep, GIS primarily relies on the B-rep approach, with boundaries derived from straight lines and flat surfaces. The two-way transformation between the two standards remains problematic, particularly when converting from B-rep to sweep or CSG. Furthermore, the level of detail (LOD) definition differs between BIM and GIS, necessitating accurate mapping for proper conversion:

- In the GIS environment, the concept of LOD in a tiling scheme defines the value of the zoom level for a map or scene view. This scale ranges from 0 to 23, with lower values indicating views further from the Earth and higher values indicating closer, more detailed views. A higher zoom level corresponds to more detailed geographic information, and a conversion tool is available to convert zoom levels to map scales, representing the relationship between map measurements and real-world measurements. The default zoom levels vary, depending on the type of layer used (vector raster layers vs. image raster layers), with vector raster layers typically having zoom levels one level lower than map raster layers. Understanding and correctly applying zoom levels and scales is essential for the accurate display of geographic information, increasing the precision and detail of map views for effective geospatial analysis and visualization.
- In the BIM environment, LOD definitions act as the user's parameter set, to ensure that all parties involved in the BIM process build the model with a consistent level of content definition throughout all phases of the project design and execution. BIM processes can be categorized based on the level of detail of the information contained within the model, known as LOD. The American Institute of Architects (AIA) has established guidelines for levels of detail in the AIA G202-2013 BIM Protocol [81]. Recognizing that an element may appear visually detailed, but in reality remain generic, the term LOD refers to the "level of development" of model elements rather than their "level of detail". According to American standards, the level of development is divided into five distinct levels, from LOD 100 (Symbolic Representation), which is the elementary level of the project, represented graphically by a symbol or other generic schematic representation, to LOD 500 (As-Built), where elements are field-verified representations in terms of size, shape, location, quantity and orientation. Definitive non-graphic information is associated with geometric elements. These standards ensure a common understanding and consistency in the level of detail required at each stage of the BIM process, facilitating effective communication and collaboration among all project stakeholders.

It is known that the discrepancies in LOD scales between BIM and GIS can be attributed to the intrinsic characteristics of the file format. Nevertheless, in order to attain an equivalent level of detail between the two systems, a standardized mapping model could be devised that translates BIM LODs into GIS equivalents, and vice versa. The model should be based on a comprehensive analysis of the characteristics and requirements of both systems. Zhu et al. highlight the potential of graph-based technologies, in particular the Resource Description Framework (RDF) and the Labelled Property Graph (LPG), by undertaking a systematic investigation of these technologies to determine the most suitable for LOD conversion between BIM and GIS [82]. The choice between RDF and LPG depends on the specific use case, as these technologies perform differently in different scenarios. For example, LPG outperforms RDF in the context of linked data for smart homes, while RDF performs better when searching for the glycan substructure [82].

A further obstacle to the integration of the two standards is the use of divergent coordinate systems. In the context of BIM, absolute coordinates have limited relevance, as they are based on the World Coordinate System, a local rectangular coordinate system specific to drawing, without correlation to the global spatial reference system typical of GIS. The latter employs the Geographic Coordinate System (GCS) to represent cities, regions and the world in general. Each object is positioned by means of latitude, longitude and elevation, or by means of coordinated Universal Transverse Mercator (UTM) such as Northing, Easting and height. To resolve this discrepancy, Wu et al. proposed a matrix transformation [83]. The IFC contains a greater number of defined classes than CityGML. Despite the assistance of the application domain extension (ADE), CityGML is unable to provide the requisite additions to guarantee a correct transformation of all objects and classes from the IFC. To illustrate, when considering the CityGML class "Building Installation", which encompasses columns, stairs and beams, each object of this class must be associated with the appropriate IFC class during the transformation to IFC [84]. The semantic distinction between IFC and GIS represents a final challenge. Whereas BIM places particular emphasis on the relationships between objects, GIS does not necessarily adopt the same approach, which can give rise to difficulties in integrating the two standards. One proposed solution to this discrepancy is matrix transformation. The semantic differences between the two standards present a significant challenge. BIM places a strong emphasis on the relationships between objects, whereas GIS does not consider these parameters. One potential solution to this problem is semantic mapping, which aims to ensure proper integration between the two standards by addressing the semantic differences between them.

4.1. Open-Source Environment

The analysis of trends in methodology development examined the evolution of practices from closed-code to open-source models. It turns out that in the 1960s, with the advent of mainframe computers, companies sold integrated hardware and software. Due to the limited availability of commercial software, researchers turned to the open exchange of source code [85]. The introduction of email around 1969 further supported this free exchange of ideas. Subsequently, the unbundling of hardware and software by IBM, which began around 1969, made software an autonomous and increasingly sought-after product. In 1981, changes in patent law in the United States, combined with the advent of the PC, led to the source code of the UNIX operating system being closed. In September 1983, Richard Stallman started the GNU project to create a UNIX-like operating system and introduced copyleft licenses such as the GNU General Public License [86]. OS later found a place among hackers, programming enthusiasts or software developers, with motivations ranging from the quest for freedom of choice to the desire to contribute to the good of society. The definition of open-source software development (OSSD) has been outlined by evidencing its distributed nature and the wide participation of contributors communicating through the Internet. Communities such as the Open Source Observatory (OSOR) [87] support the improvement of code quality and usability; the Software quality observatory for open source software (SQO-OSS) [88], which is flexible and accessible through different user interfaces, facilitates the effective inspection of OSS.

In the event of collaboration difficulties, it is imperative that communication between developers be maintained at a high level in software development. In OS, however, this only happens over the Internet, which means that geographical distance and distributed collaboration can lead to a decrease in communication between developers. Another problem is getting users to contribute to the project to the end, as there is no obligation to do so, and they are completely free to decide whether or not to continue. Release management can be problematic, as the guidelines for managing releases are informal from the start of the project. In addition, the lack of suitable developers or interested users in OS projects can have a negative effect on the motivation of volunteers to maintain the project. In addition, all patches submitted to the project must pass the peer review process, which assesses code style, overall quality and interoperability with other parts of the application.

There are also disadvantages to the use of OSS in business, which including version proliferation, complexity and the necessity for numerous licenses, implementation problems where there is no one person responsible for developing and solving software problems, and high short-term costs for OSS compared to lower long-term costs than those of the traditional model. Moreover, the economic challenge of OS in motivating volunteers to participate without remuneration is considerable. Furthermore, it is possible that for an extended period of time, there will be no updates to the system, forcing users to work with an older version of the software, as there is no guarantee that regular updates will be provided. A comparable issue arises with regard to support; in fact, there is no support for OS, in contrast to CS. In large OS projects, the contributions of developers may take longer to be exhausted, which can be problematic for volunteer developers.

As shown in the proposal study, in the OS context, interoperability was achieved through the use of QGIS software. To integrate BIM models within this software, it was essential to use an external platform capable of generating a sharing link to be inserted into the attribute table of the polygon created. Only after this operation was it possible to view the BIM model within QGIS. Specifically, the Autodesk Online Viewer was used, both to visualize the 3D geometry and to query the database that makes up the BIM model. It is obvious that this approach is complex and cumbersome from a usability point of view, since the transition from GIS to BIM is not direct and requires the intervention of a third software. Ideologically, it goes against the philosophy of the BIM methodology, which is to reduce human error and man-hours. In the context of software houses, the limitation of having to use multiple software platforms to achieve such a goal is overcome.

4.2. Closed-Source Environment

The CSS is characterized by the exclusive protection of rights that prevents users from accessing and freely modifying the source code. The use of CSS is contingent upon the purchase of a license by users. One of the principal implications of CSS is its non-competitive nature. As it is exclusively controlled and managed by the owner or company that developed it, there is no direct competition from other developers. This can result in constrained progress and innovation, dependent entirely on the decisions and investments of the proprietor. Furthermore, CSS tends to have limited interoperability with other systems and applications, making software integration with other platforms or external management systems difficult. This can restrict the potential for collaboration and the effectiveness of software use in complex or heterogeneous environments. Another noteworthy attribute of closed-source software is the necessity to await the release of subsequent versions in order to address bugs or deficiencies, or to advance the development of new functionalities. As users are unable to modify the source code directly, they must rely on the manufacturer to address any errors or implement improvements.

CSS also offers benefits such as support and services provided by the developer. Users can receive technical support and regular updates to ensure the proper functioning of the software, which is often associated with high security standards as its development takes place in a controlled and managed environment. In the CSS, using the GIS software ArcGIS, there is a significant improvement due to its more advanced interoperability component. BIM models can be integrated directly within the project file, eliminating the need for external platforms for visualization. This applies both to the visualization of 3D geometries and to querying the database of BIM model information and parameters. However, this does not mean that there are no operational challenges: the transition from GIS to BIM can still be complex, although less so than using QGIS. The real limitation of the Software House option is that the platform is only accessible through the purchase of a user license, thus limiting its accessibility. This procedure imposes the constraint of having to choose a particular software, compromising interoperability and the idea behind the IFC format, which aims to facilitate the exchange of information between different operators and software.

4.3. Open-Source and Closed-Source Comparison

When choosing software, the most important question is whether it is free or not. Unfortunately, the decision is not so clear-cut, and depends on the needs of the end user. The following is a comparison of the strengths and weaknesses of closed-source software (CSS) and open-source software (OSS). In the traditional development model, software is copyrighted and sold to users to make money, whereas in the OS paradigm, software is freely available to users to use and modify.

In the traditional way, software development is systematic and formal work done by experienced developers to improve quality; a centralized management team helps them to improve the software in new versions, whereas in the OSS development model there are frequent releases in which the software is improved by users and developers worldwide. There are no specific people or places for physical discussion. In the OS development model, the improvement of code quality may depend on the personality of everyone who participates by registering on host sites, and it remains the responsibility of each person to ensure that the system works better and improves quality.

The quality success of closed software is related to its central management, whereas in OSS the quality comes from its openness, because many programmers can examine it and find bugs, even though this may lead to iterative corrections and some developers may correct the same thing. In addition, quality is improved in the OSS development model compared to closed software because the development processes of OSS, such as review, testing and maintenance, take place in parallel. Openness in OS helps to identify user requirements better than in CSS, because in this type of software, users themselves can contribute and intervene, even as developers. The number of teams working on quality assurance is an effective way of assessing quality, and this issue is maintained by companies in closed software, whereas in OS it can be deduced from commitment logs and the source code itself. The goal of CSS is to develop software that can be released to the public for market penetration and profit. The objective of CSS is the development of software to be presented to the public in order to gain market penetration and profit, while OS is a personal idea that can spread and receive contributions from users all over the world to implement and develop it, bearing in mind that coordinating a large number of contributions requires the use of standardization platforms to manage all processes.

The main differences between OSE and CSE are summarized below.

- Development models:
    - CSS: software is copyrighted and sold for profit. Development is systematic and formal, managed by a central team;
    - OSS: software is freely available for use and modification. It is continuously improved by a global community of users and developers.
- Software quality:
    - CSS: quality is guaranteed by a central team that releases new versions;
    - OSS: quality is improved by many programmers examining the code and finding/fixing bugs, as well as continuous iterative corrections, parallel revisions and dedicated testing.
- User involvement:
    - CSS: users do not contribute to software development;
    - OSS: users can actively contribute to the development and definition of software requirements.
- Main objectives:

- CSS: the goal is market penetration and profit;
- OSS: the objective is collaborative sharing and evolution, with the support of standardization platforms to manage developer contributions.

- Community:
    - CSS: Smaller community, often limited to users and the organization's development team;
    - OSS: Strong community of developers and users who actively participate in the development and improvement of software.
- Security:
    - CSS: Security depends on the policies and resources of the company developing the software;
    - OSS: Security tends to be based on the principle of "security through transparency". Many users check the code for vulnerabilities.
- Flexibility:
    - CSS: Flexibility limited by restrictions imposed by licenses and company policies;
    - OSS: High flexibility due to the ability to modify and customize the software.
- Implications for the built environment:
    - CSS: May limit adoption of open standards, increase costs, reduce transparency and slow innovation;
    - OSS: Encourages the development of open standards, reduces costs, increases transparency and could accelerate innovation.

The choice between OSS and CSS depends on a number of factors, including the specific requirements of the project, the available budget, the need for customization and the desired level of control. Both types of software have advantages and disadvantages, and the optimal choice will depend on the specific context.

5. Conclusions

BIM-GIS integration provides the ability to create robust contextual models that fuse geographic information and infrastructure design data to better understand asset interactions in real-world geographic contexts. To meet current macro-economic challenges and deliver more sustainable and flexible infrastructure, it is essential to simplify the exchange of data between BIM design processes and GIS systems. This will enable better planning and management of urban areas and infrastructure investments with less negative social, economic and environmental impacts. One of the most striking innovations in information technology in recent years has been the gradual emergence of OSS. In the field of geoinformatics and GIS, OSS has also played an important role, thanks to the possibility of revising and improving the source code, according to individual needs. QGIS is one of the most articulated Free Software projects in the world, offering versatility and potential in dealing with different environmental issues. In an era of digitization of construction and interoperability of data, the use of OSS is also becoming important in public administration, allowing data to be shared, processed and improved in virtually unlimited ways. However, it is important to recognize the importance of proprietary software such as ArcGIS, as vendors of such solutions can offer advanced spatial planning and control functionality. In a free market, each construction professional has the freedom to use his or her preferred application, while retaining the ability to read data on different platforms.

Despite the progress made, there are still some limitations in BIM-GIS integration that require further attention; e.g., for discrepancies in LOD definitions between BIM and GIS, the development of standardized and automated mapping templates would be useful. The research involved the development and evaluation of two methodologies for the integration of BIM-GIS in the AECO sector. One, employed in OSE, uses QGIS and an online visualizer, whereas the other, adopted in CSE, employs Revit and ArcGIS for advanced visualization of BIM models in a GIS environment. The CSE platform is notable for its enhanced usability, enabled by its capacity to visualize 3D models and represents an advancement over the OSE approach, but, on the other hand, requires payment of a user license.

Geo-DT represents a significant and natural development of this research in the digital transformation of the AECO sector, with highly efficient and sustainable management of smart cities and smart buildings.

The Geo-Digital Twin (Geo-DT) concept represents a significant advancement in the synergistic integration of BIM models and GIS data, offering an unprecedented opportunity for intelligent and dynamic management of infrastructure and the built environment. A Geo-Digital Twin is a digital entity that can realistically replicate a physical environment or infrastructure by integrating geospatial data, information from BIM models and real-time data from IoT devices. This enables real-time simulation, analysis and management. The implementation of Geo-DT offers new avenues for enhancing urban planning, infrastructure design, and city management. It integrates real-time data from a multitude of detailed sources on infrastructure components to provide a comprehensive and dynamic view of the built environment. DT thus permits stakeholders to explore and monitor the urban environment through a virtual interface, thereby enabling complex data to be visualized and analyzed in an intuitive and accessible way. Furthermore, it is possible to perform simulations and predictive analysis to assess the impact of different decisions and scenarios on the infrastructure and the surrounding environment. From the perspective of infrastructure management and maintenance, Geo-DT could provide an advanced monitoring and control system, enabling the real-time detection of anomalies or problems and the timely implementation of corrective actions. This would result in the continuous and proactive monitoring of the state of infrastructure, the optimization of maintenance processes and the assurance of reliable operation over time.

Author Contributions: Conceptualization, G.P. and F.M.; methodology, G.P., F.M. and C.Z.; software, G.P., F.M. and C.Z.; validation, G.P., F.M. and C.Z.; formal analysis, G.P., F.M. and C.Z.; investigation, G.P., F.M. and C.Z.; resources, G.P., F.M. and C.Z.; data curation, G.P., F.M. and C.Z.; writing—original draft preparation, G.P., F.M. and C.Z.; writing—review and editing, G.P. and F.M.; visualization, G.P., F.M. and C.Z.; supervision, G.P.; project administration, G.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in this study are included in the article, further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

American Institute of Architects	AIA
Application domain extensions	ADE
Architecture, Engineering, Construction and Operations	AECO
Artificial intelligence	AI
Augmented reality	AR
Building Information Modelling	BIM
City Geography Markup Language	CityGML
Closed-source environment	CSE
Closed-source software	CSS
Common Data Environment	CDE
Computer-aided drafting	CAD
Construction Operations Building Information Exchange	COBie
Environmental System Research Institute	ESRI
European Union	EU
Free Software Foundation	FSF
General Public License	GPL
Geo-Digital Twin	Geo-DT

Geographic Coordinate System	GCS
Geographic Information Systems	GIS
Geographic Markup Language	GML
Gross Domestic Product	GDP
Industry Foundation Classes	IFC
Labelled Property Graph	LPG
Level of detail	LOD
National Recovery and Resilience Plan	PNRR
Open source	OS
Open-source environment	OSE
Open-Source Initiative	OSI
Open-Source Observatory	OSOR
Open-source software	OSS
Open-source software development	OSSD
OpenStreetMap	OSM
Recovery and Resilience Facility	RRF
Recovery Assistance Package for Cohesion and European Territories	REACT-EU
Resource Description Framework	RDF
Software quality observatory for open source software	SQO-OSS
Universal Transverse Mercator	UTM
World Geodetic System 1984	WGS84

References

1. CONSOB. Crisis COVID-19. Available online: https://www.consob.it/web/investor-education/crisi-covid-19 (accessed on 4 June 2024).
2. Di Girolamo, P.; Piras, G.; Pini, F. The effect of COVID-19 on the distribution of PM10 pollution classes of vehicles: Comparison between 2020 and 2018. *Sci. Total Environ.* **2022**, *811*, 152036. [CrossRef] [PubMed]
3. Viesti, G. The Italian Economy: From the Effects of COVID-19 to a Possible Recovery? L'economia Italiana: Dagli Effetti Della Pandemia Ad Una Possibile Ripresa? *Industria* **2020**, *41*, 629–654. [CrossRef]
4. Ministero delle Imprese e del Made in Italy, GOV, PNRR—Piano Nazionale di Ripresa e Resilienza. Available online: https://www.mimit.gov.it/it/pnrr/piano (accessed on 4 June 2024).
5. Digitalizzazione e PNRR—Sviluppare una Capacità Progettuale e Strategica Trasversale. Available online: https://mondointernazionale.org/focus-allegati/digitalizzazione-e-pnrr (accessed on 4 June 2024).
6. ISTAT. Transizione Digitale, Analytics and AI. Available online: https://www.corrierecomunicazioni.it/digital-economy/transizione-digitale-imprese-italiane-al-palo-pmi-penalizzate-analytics-e-ai/ (accessed on 4 June 2024).
7. Smart Working in Public Administration. Available online: https://www.diritto.it/il-lavoro-agile-nella-pubblica-amministrazione (accessed on 4 June 2024).
8. European Commission. Recovery Plan. Available online: https://commission.europa.eu/strategy-and-policy/recovery-plan-europe_it#:~:text=NextGenerationEU%20%C3%A8%20uno%20strumento%20temporaneo,alle%20sfide%20presenti%20e%20future (accessed on 4 June 2024).
9. Ceron, M.; Palermo, C.M. COVID-19, National Responses and NGEU: Uniting a Divided Europe? *SSRN Electron. J.* 2020. Available online: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3758172 (accessed on 24 November 2024).
10. Europe Direct Trieste, NextGenerationEU: All'Italia 24,9 Miliardi di Euro Dalla Commissione. Available online: https://europedirect.comune.trieste.it/nextgenerationeu-allitalia-249-miliardi-di-dalla-commissione/ (accessed on 4 June 2024).
11. Orsini, G.; Piras, G. Digital Construction and Management the Public's Infrastructures. In *Technological Imagination in the Green and Digital Transition*; CONF.ITECH 2022; The Urban Book Series; Springer: Cham, Switzerland, 2023. [CrossRef]
12. Vallati, A.; Muzi, F.; Fiorini, C.V.; di Matteo, M.; Sundararajan, M. Development of an Energy Community through semi-dynamic simulation of a urban social housing. *J. Phys. Conf. Ser.* **2023**, *2648*, 012040. [CrossRef]
13. Vallati, A.; Morganti, M.; Causone, F.; Mannucci, S.; Fiorini, C.V.; di Matteo, M.; Muzi, F. Building archetype characterization for mass-housing energy efficiency through a UBEM approach. *J. Phys. Conf. Ser.* **2023**, *2600*, 082030. [CrossRef]
14. Cumo, F.; Pennacchia, E.; Zylka, C. Energy-Efficient Solutions: A Multi-Criteria Decision Aid Tool to Achieve the Targets of the European EPDB Directive. *Energies* **2023**, *16*, 6245. [CrossRef]
15. Cumo, F.; Giustini, F.; Pennacchia, E.; Romeo, C. The "D2P" Approach: Digitalisation, Production and Performance in the Standardised Sustainable Deep Renovation of Buildings. *Energies* **2022**, *15*, 6689. [CrossRef]
16. Vallati, A.; Di Matteo, M.; Sundararajan, M.; Muzi, F.; Fiorini, C.V. Development and Optimization of an Energy Saving Strategy for Social Housing Applications by Water Source-Heat Pump Integrating Photovoltaic-Thermal Panels. *Energy* **2024**, *301*, 131531. [CrossRef]
17. UNIFE. Missione 1—Digitalizzazione, Innovazione, Competitività, Cultura e Turismo. Available online: https://www.unife.it/it/fondi/pnrr/m1 (accessed on 4 June 2024).

18. Cumo, F. Innovation for the Digitization Process of the AECO Sector. In *Technological Imagination in the Green and Digital Transition, Proceedings of the CONF.ITECH 2022, Rome, Italy, 30 June 2022–2 July 2022*; The Urban Book Series; Springer: Cham, Switzerland, 2023. [CrossRef]
19. Dalir, A.H. A Framework and Methods for BIM Contract Management and Monitoring. In Proceedings of the 4th International Law Conference, Tehran, Iran, 31 February 2024.
20. Amirebrahimi, S.; Rajabifard, A.; Mendis, P.; Ngo, T.D. A data model for integrating GIS and BIM for assessment and 3D visualization of flood damage to building. *Locate* **2015**, *15*, 10–12.
21. Muzi, F.; Marzo, R.; Nardi, F. Digital Information Management in the Built Environment: Data-Driven Approaches for Building Process Optimization. In Proceedings of the International Conference on Technological Imagination in the Green and Digital Transition, Rome, Italy, 30 June–2 July 2022; Springer International Publishing: Cham, Switzerland, 2023; pp. 123–132. [CrossRef]
22. Di Matteo, M.; Pastore, L.M.; Pompei, L. A Critical Overview of BIM (Building Information Modeling) and DT (Digital Twin): Challenges and Potentialities in Energy and Sustainability of Buildings. In *Sustainability in Energy and Buildings 2023*; Littlewood, J.R., Jain, L., Howlett, R.J., Eds.; Smart Innovation, Systems and Technologies; Springer: Singapore, 2024; Volume 378. [CrossRef]
23. Cumo, F.; Piras, G.; Pennacchia, E.; Cinquepalmi, F. Optimization of Design and Management of a Hydroponic Greenhouse by Using BIM Application Software. *Int. J. Sustain. Dev. Plan.* **2020**, *15*, 157–163. [CrossRef]
24. Mangon, N. VP Autodesk-IT. Available online: https://www.autodesk.com/it/design-make/articles/integrazione-gis-e-bim (accessed on 4 June 2024).
25. Agostinelli, S.; Cumo, F.; Marzo, R.; Muzi, F. Digital construction strategy for project management optimization in a building renovation site: Machine learning and big data analysis. In Proceedings of the International Conference on Trends on Construction in the Post-Digital Era, Guimarães, Portugal, 7–9 September 2022; Springer International Publishing: Cham, Switzerland, 2022. [CrossRef]
26. Guyo, E.D.; Hartmann, T.; Ungureanu, L.C. Interoperability between BIM and GIS through open data standards: An overview of current literature. *Sign* **2021**, *3*, 5–9.
27. Piras, G.; Muzi, F. Energy Transition: Semi-Automatic BIM Tool Approach for Elevating Sustainability in the Maputo Natural History Museum. *Energies* **2024**, *17*, 775. [CrossRef]
28. Basir, W.N.F.W.A.; Ujang, U.; Majid, Z. Adaptation 4D and 5D BIM for BIM/GIS data integration in construction project management. *IOP Conf. Ser. Earth Environ. Sci.* **2023**, *1274*, 012002. [CrossRef]
29. Piras, G.; Agostinelli, S.; Muzi, F. Digital Twin Framework for Built Environment: A Review of Key Enablers. *Energies* **2024**, *17*, 436. [CrossRef]
30. GIS Infrastructure. Available online: https://www.gisinfrastrutture.it/2022/01/la-sostenibilita-delle-infrastrutture-richiede-lintegrazione-tra-bim-e-gis/ (accessed on 4 June 2024).
31. Borkowski, A.S. Integration of BIM and GIS data of a heritage building using FME. *Civ. Environ. Eng. Rep.* **2024**, *2*. [CrossRef]
32. ESRI. Environmental Sustainability. Available online: https://www.esri.com/it-it/industries/roads-highways/business-areas/environmental (accessed on 4 June 2024).
33. Romano, G.; Margani, P.; Mancini, F.; Battisti, A. Building a Renewable Energy Community for the Tor Sapienza district in Rome. *J. Phys. Conf. Ser.* **2023**, *2648*, 012037. [CrossRef]
34. Sani, M.J.; Abdul Rahman, A. GIS and BIM integration at data level: A review. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2018**, *42*, 299–306. [CrossRef]
35. Ohori, K.A.; Biljecki, F.; Diakité, A.; Krijnen, T.; Ledoux, H.; Stoter, J. Towards an integration of GIS and BIM data: What are the geometric and topological issues? *ISPRS Ann. Photogramm. Remote. Sens. Spat. Inf. Sci.* **2017**, *IV-4/W5*, 1–8. [CrossRef]
36. Congiu, E.; Quaquero, E.; Rubiu, G.; Vacca, G. BIM-GIS Integrated Framework in Support of Facility Management (FM). *Buildings* **2024**, *14*, 610. [CrossRef]
37. Kang, T. Scan to BIM Mapping Process Description for Building Representation in 3D GIS. *Appl. Sci.* **2023**, *13*, 9986. [CrossRef]
38. Janisio-Pawłowska, D.; Pawłowski, W. Implementation of BIM Data in CityGML—Research and Perspectives for Creating a QGIS Plugin for Spatial Analysis: Experience from Poland. *Sustainability* **2024**, *16*, 642. [CrossRef]
39. Cao, Y.; Xu, C.; Aziz, N.M.; Kamaruzzaman, S.N. BIM–GIS Integrated Utilization in Urban Disaster Management: The Contributions, Challenges, and Future Directions. *Remote Sens.* **2023**, *15*, 1331. [CrossRef]
40. Yoon, Y.-J.; Kim, S.-Y.; Lee, Y.-K.; Ham, N.; Kim, J.-H.; Kim, J.-J. GIS-Based Multi-Objective Routing Approach for Street-Based Sporting-Event Routing. *Appl. Sci.* **2023**, *13*, 8453. [CrossRef]
41. Celeste, G.; Lazoi, M.; Mangia, M.; Mangialardi, G. Innovating the Construction Life Cycle through BIM/GIS Integration: A Review. *Sustainability* **2022**, *14*, 766. [CrossRef]
42. Zhu, J.; Wright, G.; Wang, J.; Wang, X. A Critical Review of the Integration of Geographic Information System and Building information Modelling at the Data Level. *ISPRS Int. J. Geo-Inf.* **2018**, *7*, 66. [CrossRef]
43. Romano, G.; Mancini, F. Transformation of a historical building into a Nearly Zero Energy Building (nZEB). *J. Phys. Conf. Ser.* **2022**, *2385*, 012008. [CrossRef]
44. Lamagna, M.; Groppi, D.; Nezhad, M.M.; Piras, G. A comprehensive review on Digital twins for Smart energy management system. *Int. J. Energy Prod. Manag.* **2021**, *6*, 323–334. [CrossRef]

45. Paolella, L.; Ochmanski, M.; Modoni, G. An Innovative Holistic GIS-BIM and Artificial Intelligence Based Approach to Manage Mechanized Tunneling: The Back-Analysis of the Budapest Metro Line4. In *Geotechnical Engineering in the Digital and Technological Innovation Era*; Springer: Cham, Switzerland, 2023. [CrossRef]
46. Tayeh, R.; Bademosi, F.; Issa, R.R.A. BIM-GIS Integration in HoloLens. In Proceedings of the 18th International Conference on Computing in Civil and Building Engineering, São Paulo, Brazil, 18–20 August 2020; Springer: Cham, Switzerland, 2021. [CrossRef]
47. Piras, G.; Sferra, A.S. Environmental Product Declarations as a Data Source for the Assessment of Environmental Impacts during the Use Phase of Photovoltaic Modules: Critical Issues and Potential. *Energies* **2024**, *17*, 482. [CrossRef]
48. Huang, T.; Kou, S.; Liu, D.; Li, D.; Xing, F. A BIM-GIS-IoT-Based System for Excavated Soil Recycling. *Buildings* **2022**, *12*, 457. [CrossRef]
49. Pennacchia, E.; Romeo, C.; Zylka, C. Towards High-Efficiency Buildings for Sustainable Energy Transition: Standardized Prefabricated Solutions for Roof Retrofitting. *Sustainability* **2024**, *16*, 3850. [CrossRef]
50. Zareba, M.; Cogiel, S.; Danek, T.; Weglinska, E. Machine Learning Techniques for Spatio-Temporal Air Pollution Prediction to Drive Sustainable Urban Development in the Era of Energy and Data Transformation. *Energies* **2024**, *17*, 2738. [CrossRef]
51. Amyx, S. Internet of Things Open-Source Systems. In *Internet of Things and Data Analytics Handbook*; Geng, H., Ed.; John Wiley & Sons: Hoboken, NJ, USA, 2017. [CrossRef]
52. Khanjani, A.; Sulaiman, R. The aspects of choosing open source versus cloed source. In Proceedings of the 2011 IEEE Symposium on Computers & Informatics, Kuala Lumpur, Malaysia, 20–23 March 2011; pp. 646–649. [CrossRef]
53. Free Software Foundation (FSF). Available online: https://www.fsf.org (accessed on 4 June 2024).
54. Open Source, Defining Oper Source AI, About the Open-Source Initiative. Available online: https://opensource.org (accessed on 4 June 2024).
55. TLO. Exploring the MIT Open-Source License: A Comprehensive Guide. Available online: https://tlo.mit.edu/understand-ip/exploring-mit-open-source-license-comprehensive-guide (accessed on 4 June 2024).
56. GNU. General Public Licence. Available online: https://www.gnu.org/licenses/gpl-3.0.html (accessed on 4 June 2024).
57. Apache, Apache Licence. Available online: https://www.apache.org/licenses/LICENSE-2.0 (accessed on 4 June 2024).
58. Gazzetta Ufficiale, Direttiva 19 dicembre 2003. Available online: https://www.gazzettaufficiale.it/atto/serie_generale/caricaDettaglioAtto/originario?atto.dataPubblicazioneGazzetta=2004-02-07&atto.codiceRedazionale=04A01079&elenco30giorni=true (accessed on 4 June 2024).
59. Building Smart, Industry Foundation Classes (IFC). Available online: https://www.buildingsmart.org/standards/bsi-standards/industry-foundation-classes/ (accessed on 4 June 2024).
60. NIBS. National BIM Standard. Available online: https://www.nibs.org/nbims/ (accessed on 4 June 2024).
61. Ji, Y.; Wieng, Y.; Wie, Y.; Wang, J.; Yan, W. An ontology-based rule mapping approach for integrating IFC and CityGML. *Trans. GIS* **2024**, *28*, 675–696. [CrossRef]
62. OGC. CityGML. Available online: https://www.ogc.org/standard/citygml/ (accessed on 4 June 2024).
63. Jaud, Š.; Clemen, C.; Muhič, S.; Borrmann, A. Georeferencing in Ifc: Meeting the Requirements of Infrastructure and building industries. *ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci.* **2022**, *X-4/W2-2022*, 145–152. [CrossRef]
64. Qgis Home Page. Available online: https://www.qgis.org/ (accessed on 20 November 2024).
65. OSM Place Search. Available online: https://plugins.qgis.org/plugins/nominatim/ (accessed on 20 November 2024).
66. MMQGIS. Available online: https://plugins.qgis.org/plugins/mmqgis/ (accessed on 20 November 2024).
67. QuickMapServices. Available online: https://plugins.qgis.org/plugins/quick_map_services/ (accessed on 20 November 2024).
68. Savu, C.; Pescaru, A.-H.; Zsak, I.-G.; Durgheu, A.-M.; Frent, A.-P.; Suba, N.-S.; Buda, A.S.; Nistor, S. Analysis on Using 3D Scanning and BIM to Reduce the Physical and Non-Physical Construction Waste for Sustainable Fireproofing of Steel Trusses. *Sustainability* **2024**, *16*, 1832. [CrossRef]
69. Yang, F.; Pan, Y.; Zhang, F.; Feng, F.; Liu, Z.; Zhang, J.; Liu, Y.; Li, L. Geometry and Topology Reconstruction of BIM Wall Objects from Photogrammetric Meshes and Laser Point Clouds. *Remote Sens.* **2023**, *15*, 2856. [CrossRef]
70. GEOMAP. Available online: https://www.geomap.it/it/cose-una-nuvola-di-punti-e-a-cosa-serve.html (accessed on 4 June 2024).
71. FSF. About Free Software Foundation. Available online: https://www.fsf.org/about/ (accessed on 4 June 2024).
72. Autodesk. Available online: https://www.autodesk.com (accessed on 4 June 2024).
73. Graphisoft. Available online: https://graphisoft.com (accessed on 4 June 2024).
74. ESRI. Available online: https://www.esri.com/en-us/home (accessed on 4 June 2024).
75. ACCA. Available online: https://www.acca.it (accessed on 4 June 2024).
76. Hu, X.; Jiang, Y.; Li, S. Innovative Approach to Convert Geographic Information System-Based Highway Models into Multidimensional Building Information Modeling Platforms Using Dynamo. *Transp. Res. Rec.* **2024**, *2678*, 637–659. [CrossRef]
77. ESRI. ArcGIS Pro. Available online: https://www.esri.com/en-us/arcgis/products/arcgis-pro/overview (accessed on 4 June 2024).
78. Jaskula, K.; Kifokeris, D.; Papadonikolaki, E.; Rovas, D. Common data environments in construction: State-of-the-art and challenges for practical implementation. *Constr. Innov.* 2024, *ahead of print*. [CrossRef]

79. Crocetti, L.; Schartner, M.; Soja, B. Discontinuity Detection in GNSS Station Coordinate Time Series Using Machine Learning. *Remote Sens.* **2021**, *13*, 3906. [CrossRef]
80. AUTODESK. Key Features of Autodesk Revit. Available online: https://www.autodesk.eu/products/revit/features (accessed on 4 June 2024).
81. American Institute of Architects, AIA G202-2013 BIM Protocol. Available online: https://shop.aiacontracts.com/contract-documents/19016-project-bim-protocol (accessed on 4 June 2024).
82. Zhu, J.; Chong, H.-Y.; Zhao, H.; Wu, J.; Tan, Y.; Xu, H. The Application of Graph in BIM/GIS Integration. *Buildings* **2022**, *12*, 2162. [CrossRef]
83. Alocci, D.; Mariethoz, J.; Horlacher, O.; Bolleman, J.T.; Campbell, M.P.; Lisacek, F. Property graph vs. RDF triple store: A comparison on glycan substructure search. *PLoS ONE* **2015**, *10*, e0144578. [CrossRef]
84. Wu, I.; Hsieh, S. Transformation from IFC data model to GML data model: Methodology and tool development. *J. Chin. Inst. Eng.* **2007**, *30*, 1085–1090. [CrossRef]
85. Hertel, G.; Niedner, S.; Herrmann, S. Motivation of software developers in Open-Source projects: An Internet-based survey of contributors to the Linux kernel. *Res. Policy* **2003**, *32*, 1159–1177. [CrossRef]
86. Steiniger, S.; Hay, G.J. Free and open-source geographic information tools for landscape ecology. *Ecol. Inform.* **2009**, *4*, 183–195. [CrossRef]
87. European Commission. Oper Source Observatory (OSOR): OSOR Mission. Available online: https://joinup.ec.europa.eu/collection/open-source-observatory-osor (accessed on 4 June 2024).
88. European Commission. Software Quality Observatory for Open Source Software (SQO-OSS). Available online: https://cordis.europa.eu/project/id/033331 (accessed on 30 October 2024).