An integrated workflow based on UAS, GIS, and BIM for building envelope maintenance management

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Abstract

The increasing volume and heterogeneity of data generated during building inspections pose significant challenges to maintenance management (MM). Although digital technologies are frequently discussed in the literature, their integrated application to support maintenance decision-making remains scarce. This study proposes an integrated data visualization workflow to support building MM by integrating information from inspections, UAS, BIM model data, and GIS geospatial information, and by leveraging analytical visualization in a BI (Business Intelligence) environment. A case study was conducted in a building of a Higher Education Institution (HEI) using real inspection data on facades and roofing systems. The results, presented through an interactive dashboard, demonstrate the potential of BI to integrate heterogeneous data sources and support the identification, location, and analysis of construction anomalies. Furthermore, the study highlights practical challenges in interoperability and data organization, and presents lessons learned that can support future applications of integrated digital environments for building maintenance management.

Keywords: Maintenance Management; BIM; GIS; UAS; Power BI; Dashboard; Business Intelligence.

Introduction

The increasing complexity of buildings has amplified the demand for more precise information management in maintenance processes [1,2]. In the work of Dompey et al. [3], it is noted that increases in operational costs and the growing volume of information to be managed highlight the limitations of traditional maintenance methods. This scenario becomes even more critical in exposed building envelope subsystems, such as roofs and facades, which are more susceptible to degradation and decline in building performance due to constant exposure to weather. Studies indicate that anomalies such as cracks, detachments, and surface wear serve as early indicators of failure and can compromise the building's performance, underscoring the importance of preventive strategies and periodic inspections [4, 5, 6, 7].

Sena et al. [2] identified that the main problems in building maintenance are related to the management and organization of processes, highlighting the absence of standardized procedures and a structured preventive maintenance plan. According to this study, there are also limitations in human, financial, and technological resources, as well as operational and informational deficiencies, which hinder efficient maintenance, access to up-to-date building data, and communication among the actors involved. In response to these demands, practices based on digital technologies have emerged to improve operational efficiency in building maintenance. The integration of BIM models, digital twins, and reality-capture systems has expanded monitoring and analysis capabilities, enabling greater precision and supporting informed decision-making [3,8]. Among these technologies, Unmanned Aerial Systems (UAS) have been employed for systematic inspections, providing a massive collection of visual data and supporting the construction of digital models [19]. However, expanding this volume of information reveals challenges in processing and organizing the collected data [7].

Therefore, recent studies highlight the role of Business Intelligence (BI) environments in structuring, integrating, and making large volumes of data accessible, thereby facilitating continuous, up-to-date analyses [9].

When combined with Geographic Information Systems (GIS), such platforms expand analytical capacity by associating spatial and non-spatial data. This feature has proven particularly relevant for projects involving multiple buildings distributed across different areas [10, 9].

Given these challenges, this study proposes an integrated workflow for visualizing building maintenance information that combines building envelope data from UAS-automated inspections, BIM models, and GIS in a Business Intelligence environment. Furthermore, this study aims to report the lessons learned during this integration process.

The novelty of this study lies in the structured integration of heterogeneous data sources into a unified, decision-oriented workflow. Unlike previous studies that focus on isolated integrations, such as BI–GIS [9] or BIM–GIS [10,7], this research proposes a reproducible data integration pipeline that connects data acquisition, organization, spatial contextualization, and analytical visualization within a single environment. This approach addresses the fragmentation of maintenance information by enabling the consolidation of inspection records, spatial data, and building components into an integrated and interactive system. As a result, it enhances the ability to interpret data and supports more informed decision-making in building maintenance management. This differentiates the proposed approach from prior studies that primarily focus on tool-level integration, rather than on structured workflows and decision-oriented data transformation.

This work contributes to the literature by: (i) proposing a structured workflow for integrating BIM, GIS, UAS, and BI data in building maintenance management; (ii) demonstrating the application of this workflow using real inspection data; and (iii) identifying practical challenges and lessons learned to support future implementations of integrated digital environments.

Application of digital technologies for Maintenance Management

Recent studies suggest that the adoption of digital technologies has enhanced the quality and reliability of information used in building maintenance management [2,6]. Thus, Building Information Modelling (BIM) serves as a central repository of information throughout the building lifecycle [11], while Business Intelligence (BI) tools, such as Power BI, are being explored for their potential for analysis, data integration, and decision-making support [1]. Recent studies investigate integrating Power BI with Python scripts, cloud services, and immersive technologies to support Facilities Management and the development of Digital Twin prototypes [12,13].

However, using BI tools alone has limitations for representing and analyzing spatial information, leading to their integration with Geographic Information Systems (GIS) to visualize dynamic, spatially referenced data [9]. Meanwhile, studies have examined the integration of BIM-GIS to support utilities management and the automated recording of inspections performed with UAS, emphasizing the technical feasibility of interoperability between these platforms [10,7]. During the operation and maintenance phases, BIM has served as a repository for inspection and maintenance data, with progress in data standardization through IFC and integration with UAS imagery and automated update systems [2,14,15].

Despite these advancements, the literature suggests that building maintenance management continues to face challenges related to information fragmentation and the lack of integrated data visualization and analysis workflows. In particular, there is a gap in interoperability between BIM models, GIS spatial data, and information from UAS inspections in Business Intelligence environments, especially during the operation and maintenance phases. Furthermore, many applications still rely on manual processes or ad hoc integrations, which limit the potential of these technologies to effectively support the location, documentation, and monitoring of anomalies. In this regard, the need for research focused on creating integrated, reproducible workflows that connect BIM, GIS, and BI to better manage building maintenance information is clear.

Research methodology

This study employed an exploratory case study strategy, which is suitable for investigations of complex and contemporary phenomena, where understanding data integration processes in their real-world application context is necessary [16]. The objective of the methodology was to establish a standardized workflow for collecting, preparing, integrating, and visualizing building maintenance data in a BI environment.

The research was conducted in two phases: a theoretical-practical investigation and a case study, including tool testing and the development of an integrated visualization environment (Figure 1).

Investigation of the theoretical and practical problem

The investigation of the problem was conducted through a literature review focused on identifying studies that address the integration of BI tools, GIS, BIM models, and UAS imagery. This stage aimed to understand how these technologies have been combined in previous research and to analyze the limits and challenges associated with the interoperability and visualization of building maintenance data. Meanwhile, secondary data were identified and analyzed, involving the collection and interpretation of records previously compiled by [6,2]. The goal was to confirm the nature, structure, and possible uses of this information. It is important to note that this initial analysis was not only about the problem's foundation but also served as the database for the later stages of the case study.

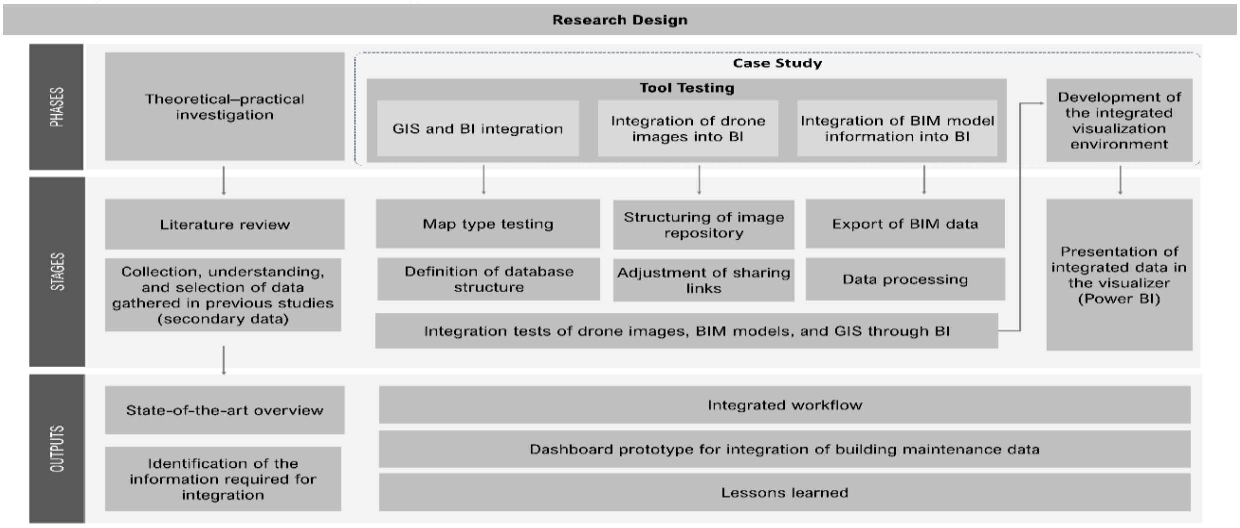

Figure 1: Protocol for developing information flow

Subject-of-Study Characterization

The selected building is in an unfinished state, with construction activities currently on hold, leading to deterioration, particularly of external components such as facades and roofing. The facades include areas with paint finishes, ceramic cladding, and incomplete sections. The roofing system has sections with fiber-cement sheets and exposed concrete slabs.

The building was selected as the only one with a consolidated BIM model and prior research data [6,2]. It is worth noting that the data related to roof inspections are organized separately, without a direct connection to the BIM model, which enabled the analysis of two complementary scenarios: the management of information integrated into the model and the processing of data outside it.

Assessment of digital tools

The tests covered the integration between GIS and BI tools, the incorporation of UAS imagery into the BI environment, and the integration of the BIM model into the analytical dashboard. Subsequently, tests were conducted on the integration process and the relationships among the datasets.

GIS-BI Integration

The tests were conducted using Power BI software, evaluating four native map viewers: Map, Azure Maps, Filled Map, and ArcGIS Maps for Power BI. This stage aimed to analyze the spatial representation capabilities of the building under study, focusing on how clearly its geographic location and placement in the urban environment can be identified. To this end, more detailed tests were performed with the Map viewer, which allowed publication of results online and met the requirements for displaying elements such as streets and neighborhood organization. Also, this viewer enabled integration of spatial information with data from other databases, such as spreadsheets containing building attributes, including name, built area, and year of construction.

Integration of UAS imagery and BI data

Tests focused on applying images collected by UAS in the Power BI environment were conducted using three distinct visualization strategies. The first involved making images available via external links; the second, presenting the images in a table arranged in a matrix; and the third, using the Simple Image visualization method. These approaches aimed to enable dynamic image access for users by integrating their queries into the analytical environment. During testing, the image file formats with the best platform compatibility were evaluated, along with the suitability of the links used to access images stored in cloud repositories.

Integration of BIM model and BI data

The tests for integrating the BIM model with Power BI were conducted in two complementary stages. Initially, the inspection data incorporated into the BIM model was exported from tests performed in Revit, where this information was associated with the building elements. In the next stage, the BIM model was integrated into the analytical dashboard, enabling both the visualization of data in tabular structures and the direct exploration of the three-dimensional model on the dashboard. To enable this integration, the Speckle plugin for Revit was utilized, along with the corresponding viewer in Power BI. This approach enabled interaction with the 3D model and the integrated analysis of inspection data, along with other information presented on the dashboard.

Development of the Integrated Visualization Environment

The development of the visualization environment involved preparing and organizing data for integration into Power BI. Inspection images were consolidated into a unified repository, using standardized nomenclature, file formats, and associated metadata. Accessible addresses were generated for each image via OneDrive shared links, allowing direct connection to dashboard visuals. Simultaneously, the buildings' geographic database was structured using their identifiers and coordinates, enabling their spatial representation in the analytical environment.

To support data integration, heterogeneous datasets were structured using a unified schema for both BIM-based and non-BIM-based information. When available, the BIM model generates two datasets: a tabular export (CSV BIM Data) and a geometry-based dataset via Speckle (BIM Data), which share attributes that enable integration. The CSV BIM Data structure was also adopted in scenarios without a BIM model, ensuring consistency and future compatibility. Inspection data are recorded following the same schema, including links to associated images.Data linkage is established through two identifiers: Building_ID, used for general building information, and Anomaly_ID, used to connect inspection records and images, and to associate them with BIM elements when available.

Based on this structure, a relational model (Figure 2) integrates building information, inspection data, images, and spatial data, supporting dashboard configuration and visualization.

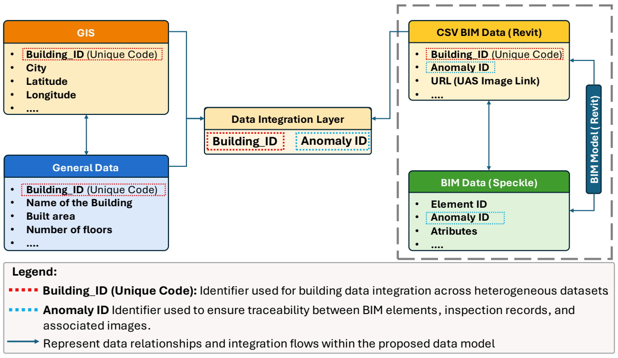

Figure 2: Data structure

Results

Integrated workflow

Figure 3 presents the interoperability flow among the various tools used in the study, demonstrating how data from facade and roof inspections, spreadsheets, geographic information systems (GIS), and the BIM project were integrated.

This process facilitated the organization and management of data within a single environment, enabling its visualization in Power BI dashboards and supporting the integration of information for the case study analysis.

The prototype developed in Power BI (Figure 4) shows the integration of the proposed data sources, featuring an interface with six main viewers and four dynamic filters (Buildings, Anomaly, Gravity, and Envelope). This structure enables the integrated analysis of maintenance data, thereby promoting a coordinated link between the databases. The integration of GIS and BI is evident in the location field, where map layers enable the visualization of buildings in their urban context.

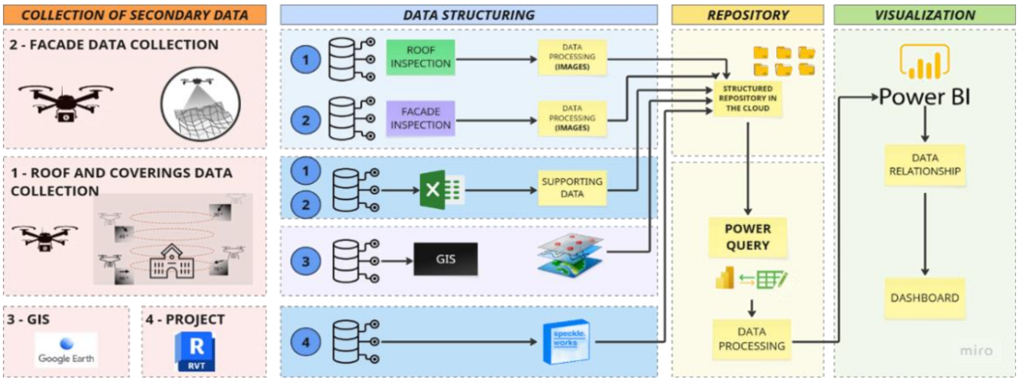

Figure 3: Integrated workflow

This feature links geographic coordinates to building attributes, allowing users to view information such as name, roof area (2,122 m²), and number of floors (3) by hovering over the building on the map. The chosen building is incomplete, with construction on hold, leading to deterioration, especially of its external parts, such as facades and roofing.

The building's geometric representation was incorporated into the panel via the BIM model using the Speckle plugin, enabling three-dimensional navigation directly on the dashboard. This integration linked inspection data to the model geometry, enabling the three-dimensional elements to respond to filters applied in the other sections of the panel. However, the automatic association between photographic records and model components is limited to the facade inspections documented by [2], whose images were already previously linked to the BIM elements.

Figure 4: Proposed Power BI dashboard

For roof inspections, data visualization occurred independently, without the corresponding automatic indication in the three-dimensional model. Even so, the panel maintains its functionality, as its architecture enables the presentation and analysis of inspection information autonomously, without reliance on linking to the BIM model. Thus, the dashboard provides an overview of the building's state of conservation at different levels of technical detail, preserving interface consistency and supporting analysis.

Functional Verification

Functional verifications were conducted during dashboard development to assess the consistency and reliability of the integrated workflow. Four aspects were evaluated. First, the building's geographic position matched its known location, confirming accurate spatial representation. Second, the number of anomalies in charts was consistent with the inspection records. Third, anomaly images and descriptions were validated against the source data, showing full consistency, with minor delays in image loading due to cloud-based storage.

Finally, BIM integration was tested: selecting an item in the table correctly highlighted the corresponding 3D element, while roof inspection anomalies did not affect the model, as expected, since they are not linked to BIM elements (Section 3). Overall, the dashboard performed consistently across all evaluated functions.

Lessons Learned

Despite the satisfactory results of the exploratory case study, integrating digital data into maintenance management poses challenges that require careful consideration, as summarized in Table 1.

Table 1: Challenges and lessons learned

Challenges	Lessons learned
Decentralized repositories	Organization of data from different sources into a centralized structure, with specific repositories defined for each type of information
BIM–BI data interoperability	Export of BIM model information to a CSV file, followed by data processing
GIS–BI data interoperability	The Map viewer was used due to its support for free web publishing and its adequate representation of georeferenced points. In contrast, ArcGIS Maps for Power BI presented restrictions on free publishing, and other map visuals showed limitations in spatial visualization
Integration of UAS imagery into BI	Development of workflows to adjust image sharing links for visualization
Visualization of UAS imagery using BI	Application of the Simple Image visual in Power BI for enhanced image visualization
Unrelated datasets	Use of Building_ID and Anomaly_ID as unique identifiers to ensure relational integration.

Discussions

Building on previous studies, this study advances by presenting the results of a Power BI dashboard that integrates real data on facade and roof maintenance, highlighting practical difficulties and lessons learned from an exploratory case study. While previous research explores, in isolation, the integration between BIM and Business Intelligence [17], the automation of maintenance data recording in BIM models [18], or the standardization and sharing of information through IFC schemas [15,14], this study focuses on the joint integration of data from BIM, GIS, and images obtained by UAS in a single visualization environment in Power BI.

In contrast to the work of Harode et al. [12], which integrates Power BI dashboards with HoloLens 2 for facility management using lifecycle data embedded in BIM models, this study does not rely on augmented reality technologies; instead, it emphasizes the interoperability between multiple spatial and visual data sources applied to building maintenance. Even so, the focus group validation adopted by these authors is identified as a potential strategy for future validation of the results presented here.

Regarding data analysis to support decision-making, Viveros et al. [13] demonstrate the potential of integrating Power BI and Python scripts for evaluating preventive maintenance policies. In contrast, this study prioritizes the organization, visualization, and interpretation of real inspection data, highlighting the technical and operational limitations of the integrated workflow. Compared to the work of Wang et al. [10] and Chen et al. [7], which explores BIM-GIS integration and UAS image registration, focusing on spatial modeling and urban networks, the role of GIS in this study was intentionally defined as a spatial context layer. This layer enables the geographic identification of buildings on campus and helps understand how location affects maintenance conditions. This complementary role aligns with the scope of the proposed workflow, which emphasizes data integration and visualization over complex spatial analysis. Nonetheless, the authors acknowledge that GIS could support more analytical functions in future iterations of this work, such as spatial prioritization of maintenance based on anomaly density, analysis of environmental exposure by facade orientation, or overlay with climatic and microclimate data [9,10].

Finally, this work builds on the findings of Sena et al. [2] and Silva et al. [6] by providing an integrated dashboard that displays the previously collected inspection data, making it easier to visualize, group, and analyze the information all in one place to support better decision-making. Therefore, the study contributes to advancing discussions on integrated data flows for building maintenance, highlighting, in an applied manner, the challenges of interoperability and opportunities for future research. Based on these findings, several implications and future directions can be highlighted. In this context, beyond identifying practical challenges, this study highlights the need to move from isolated integration efforts toward structured and scalable workflows. The lessons learned indicate that interoperability issues are both technical and organizational, requiring data standardization and consistent identifiers. In this context, future implementations should prioritize semi-automated pipelines and the incorporation of automated methods, such as the use of UAS and machine learning models for anomaly detection, thereby reducing manual effort and improving data reliability. Furthermore, expanding GIS functionalities to include spatial analysis can strengthen decision-making support. These findings are consistent with previous studies [7,2,6], reinforcing the importance of integrating digital technologies in maintenance management. Finally, the value of integrating BIM, GIS, UAS, and BI extends beyond data visualization, enabling a continuous data-to-decision workflow in which field-collected data are transformed into actionable insights for maintenance management. This positions the proposed approach as a step toward more integrated and intelligent maintenance management systems within the context of digital construction.

Conclusion

This study proposed an integrated digital data visualization workflow to support building maintenance management, combining data from UAS inspections, BIM models, GIS geospatial information, and BI tools. The application of the workflow was evaluated through an exploratory case study, using real data from facade and roof system inspections of an institutional building.

The results indicate that combining these data sources into a unified environment is practical and aids in identifying, locating, and analyzing anomalies, while enhancing data organization and accessibility. The use of an interactive dashboard in Power BI enabled integration among spatial analyses, analytical exploration, visualization of the 3D BIM model, and direct access to inspection images, thereby enhancing decision-making support during the operation and maintenance phase.

Limitations include the research's exploratory nature and the application of the workflow to a single object of study, both of which limit the generalizability of the results. Furthermore, the evaluation focused on the feasibility of data integration and visualization, and did not include quantitative metrics on performance, costs, or operational impacts.

Notably, although the proposed workflow was evaluated for technical feasibility and integration, no formal end-user usability testing was conducted. Aspects such as user experience, perceived ease of use, cognitive workload, and effectiveness, as experienced by facility managers and maintenance professionals, were not systematically measured. Therefore, the practical usability and user-centered performance of the developed environment still need empirical validation. Future research should address this gap by using structured usability assessment methods, such as standardized questionnaires and participatory evaluation approaches, to better understand how the system supports real operational decision-making in building maintenance contexts.

Future work recommends applying the proposed workflow to a broader range of buildings and incorporating performance indicators and criteria for prioritizing interventions. The adoption of participatory validation methods, such as focus groups with managers and specialists, can also help improve the developed environment and advance discussions on the integrated use of digital technologies in building maintenance. Furthermore, advancing the automation of UAS-related inputs represents a key opportunity for improving the workflow. Future implementations could incorporate automated flight planning with pre-defined waypoints for systematic envelope coverage, automatic image naming based on GPS coordinates and building component identifiers, and direct upload to cloud repositories upon flight completion. Integration with anomaly detection models, such as those based on deep learning architectures applied to roof damage detection, could further enable the automatic registration of defects in the dashboard without manual intervention, closing the data collection loop from UAS acquisition to maintenance decision-making. In parallel, expanding the analytical role of GIS by spatially prioritizing interventions and overlaying them with environmental exposure data would strengthen the methodological contribution of the integrated workflow. This reinforces the potential of integrated digital workflows as a foundation for more data-driven and proactive maintenance management practices.

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