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RELATIONAL DATABASES IN DIGITAL PLATFORMS FOR MONITORING: VERONA ARENA CASE STUDY

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Abstract

The increasing use of sensors and digital technologies in building management requires full integration of information into BIM models. However, few solutions exist that address this challenge organically using relational databases and open formats.

This work develops the study of a framework for real-time monitoring of the Verona Arena (Italy) by integrating SHM data from sensors within an IFC model using SQL databases.

The paper investigates how to relate different SQL databases of different building domains. Database integration provides a single environment for visualization and analysis of building conditions, improving maintenance and predictive management processes.

Introduction

Cultural heritage monitoring represents a critical challenge for the preservation and enhancement of historical and architectural heritage. The adoption of advanced technologies such as Building Information Modeling (BIM), Structural Health Monitoring (SHM), the Internet of Things (IoT), and others, offers new opportunities for integrated management and real-time monitoring of these structures. This technological synergy not only facilitates monitoring of the condition of the structures but also enhances the ability to detect critical events in a timely manner, supporting the planning of targeted maintenance interventions.

The literature review underscores the necessity of a more thorough exploration of information exchange management to ensure the effective integration of data originating from diverse sources and formats. Furthermore, it is crucial that this exchange is conducted in accordance with standardized and open protocols.

For this reason, the purpose of the article is to propose a framework that integrates real-time sensor data with BIM using the IFC standard. The research delves into the utilization of databases across different servers and platforms, focusing on how to facilitate their communication by employing the IFC communication standard as both the starting point and the endpoint for managing and visualizing information. The method has been applied to a case study of the Verona Arena.

This paper is organized as follows. First, it is presented a literature review on SHM, BIM and databases and the relationship between them. Then it is described the method proposed to integrate data from different origins and its appliance on the case study. Finally, are discussed implications, potentialities and limits for researchers and practitioners.

Literature review

SHM and databases

The infrastructure community is advancing toward seamless integration of IoT and real-time sensor data with the digital realm bringing together the latest advancements in SHM (Sakr and Sadhu, 2023). Effective data integration requires information organized and structured coherently. In cultural heritage monitoring, integrating data from heterogeneous sources necessitates adopting shared standards and protocols. For monitoring purposes, data collected from sensors or other sources is often stored in tabular databases in a structured format. Xu et al. (2023) used Microsoft SQL Server, while Valinejadshoubi et al. (2021) used MySQL to store monitoring data and table structure. This organizational approach supports the efficient management of large datasets, facilitating querying, analysis, and integration with other platforms.

BIM and sensor integration

The BIM environment facilitates the collection, organization, processing (including tasks such as cleaning, integrating, and analyzing), and visualization of large volumes of sensor data from monitoring systems. It enables the updating of relevant models and the execution of simulations to assess structural conditions and reliability in real time, as well as to predict the future health of the structures (Zhang and Bai, 2015).

Various solutions in the literature have demonstrated how the BIM environment can be integrated with sensor data of different kind. Corekci et al. (2019) and Suprabhas and Dib (2017) proposed real-time monitoring system that integrates BIM principles with wireless sensors. Cui et al. (2024) proposed a smart building construction management method based on BIM technology and actual construction conditions. Desogus et al. (2021) integrated BIM with IoT sensors through the use of Dynamo to observe the indoor comfort and energy consumption of a building.

Most of the articles have focused on integration within proprietary BIM software. Individual BIM applications often store information in proprietary formats, creating challenges for continuous data reuse in applications downstream in the workflow (Belsky et al., 2016).

The management and storage of sensor data is a topic widely discussed in the literature. Hu et al., (2016) and Tang et al. (2020) highlight that the IFC standard is commonly used for the representation and management of static data related to buildings and their components. However, IFC shows limitations in handling time-series data, such as those generated in real time by sensors. For this reason, the literature suggests integrating IFC with relational or time-series databases, which are more effective for storing, managing, and querying dynamic data.

IFC databases

Industry Foundation Classes (IFC) is an open standard for the exchange of information in BIM models, commonly used through the STEP format (STEP Physical File). This format allows data to be stored in text format, organized as a list of lines, each of which represents an entity of the model. IFC is developed by buildingSMART International and is characterized by neutrality, interoperability, and international recognition as the ISO 16739 standard ("Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries. Data schema," 2020). Adopting the IFC format is crucial to ensure interoperability between different software and systems used in the construction and architecture sectors, facilitating collaboration and information sharing among the various stakeholders in the design and construction process. IFC promotes transparent and standardized data exchange, serving as a fundamental tool to improve efficiency, reduce errors, and optimize processes within the BIM framework.

Several studies have addressed the issue of store IFC data within databases. The project by Adachi (2022) focuses on the development of an IFC Model Server platform for managing IFC information, overcoming the limitations related to the size of the source file that can make data sharing difficult. By using web technologies such as XML and Simple Object Access Protocol (SOAP), the need to reload files is reduced, enabling operations like partial model updates or data integration between different systems. In You and Yang (2004), the GTCIS2SQL system is used to facilitate the extraction of STEP data and transform it into relational tables. BIMServer is a widely used IFC model server that offers a Java-based interface for creating partial queries of BIM models, using Oracle Berkeley DB as the backend database (Beetz et al., 2010; Ying et al., 2016). The ifcSQL project, developed in 2019 (Bock and Eder, 2020a) addresses the issue of archiving the IFC file within an SQL relational database, including all buildingSMART International's IFC data model schemas.

Methodology and case-study

Artifact Production

The literature review highlights the need for a deeper investigation into the management of information exchange to enable the proper integration of data that come from different sources and different formats. The topic of databases is particularly relevant to this research, which aims to understand how to facilitate communication between them, using the IFC communication standard as both the starting point and the endpoint for managing and visualizing information. The methodology described in the paper is presented in Figure 1. All the scripts referenced later have been published on the following GitHub page: [SQL-Database-Integration] (Marcellino and Toldo, 2025).

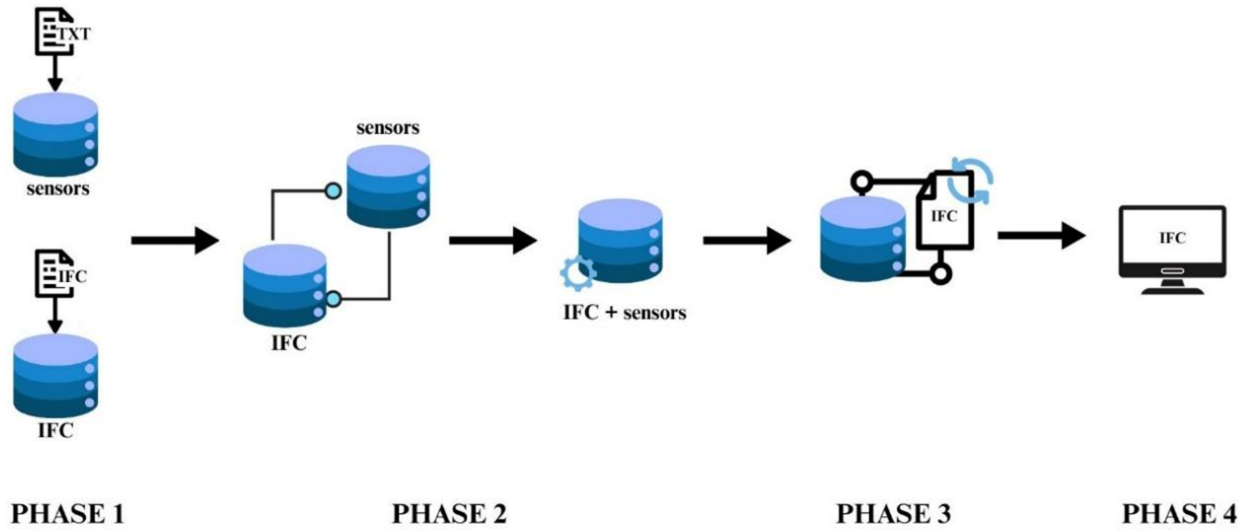

Figure 1: Methodology

The first phase begins with analyzing the input data. On one hand, the IFC model is converted into an SQL database, while on the other, the sensor database stores information related to the monitoring. In the second phase, queries are developed to integrate data from both databases. In the third phase, the updated IFC database is converted back into the IFC format. Finally, the updated model is visualized online.

Case study application

The research work has been applied to the case study of the Verona Arena. This amphitheater, constructed between the second and third decades of the first century AD, has over time become a symbol of Roman Verona. In recent decades, the municipality of Verona has shown a strong interest in understanding the Arena's structural response to various external stimuli, considering its significant usage. In the context of the monitoring addressed in this study, the system consists of four integrated sensors for measuring temperature and relative humidity and twenty linear potentiometers (displacement transducers), installed at the main surveyed cracks and lesions to monitor their behavior.

Phase 1: Database analysis

The databases analyzed, as mentioned in the previous sections, are relational SQL databases generated through scripts that are not part of this study. To provide a complete understanding of the work carried out, it is deemed important to briefly describe their structure.

IFC database

The IFC 4x3 (Building Smart, n.d.) model of the Arena was generated by exporting a version developed in a BIM software. It is is a simplified version of the amphitheatre, encompassing its primary structural components, including walls (IfcWall), columns (IfcColumn), floors (IfcSlab), arches (IfcBeam), arcovoli (IfcCovering), as well as the external steps and internal stairs (IfcStair).

Additionally, the model incorporates monitoring elements (IfcSensor), consisting of two distinct families: Static Sensor and Environmental Sensor. These sensor families share common properties, such as AssessmentDate (from Pset_Condition) and AssetIdentifier (from Pset_ConstructionOccurence). Additionally, each family has specific properties tailored to the type of data they collect. Static sensors feature the property SetPointMovement (from Pset_SensorTypeMovement-Sensor), while environmental sensors include properties such as SetPointHumidity (from Pset_SensorType-HumiditySensor) and SetPointTemperature (from Pset_SensorTypeTemperatureSensor). A list of the Psets and their relative properties is reported in Table 1. The AssetIdentifier property corresponds to the sensor names referenced in the monitoring data schematics.

Table 1: Psets and relative properties of IfcSensor

Property Set	Property
Condition	AssessmentDate
ConstructionOccurence	AssetIdentifier
SensorTypeMovementSensor	SetPointMovement
SensorTypeHumiditySensor	SetPointHumidity
SensorTypeTemperatureSensor	SetPointTemperature

The ifcSQL database, which contains the IFC file, was created following the GitHub guide (Bock and Eder, 2020a, 2020b).

ifcSQL is a database schema designed for storing IFC-based models, including all the data model schemas of buildingSMART International (Bock and Eder, 2020a). The method used to store the data involves creating separate tables for Entities and Attributes. One table is dedicated to Entities, and for each basic type, there is a corresponding table for Attributes, with rule checks implemented via triggers. Among the tables in the ifcSQL schema, those of particular interest to this study are IfcInstanceEntityAttributeOfString and IfcInstance-EntityAttributeOfFloat, as they store the attributes of an entity in string and float formats, respectively. Both tables are organized into four columns: GlobalEntityInstanceId, which represents a unique identifier within the database; OrdinalPosition, which corresponds to the attribute's position number within the IFC entity; TypeId, which is the identifier of an entity type based on EntityTypeId; Value, which represents the attribute's value.

Sensor database

The data collected by the sensors is stored in a MySQL database, which is updated every hour.

The database consists of four tables, all linked together by id automatically generated in the creation of each row: SENSOR_TYPES, for identification of typology of the sensors; SENSOR_TYPE_DATA, for the definition of parameters acquired by each sensor, including the name of the property, acronym and unit of measurement; SENSORS, for the identification of each individual sensor, recording its type and label; SENSOR_DATA, which collects all the values measured by the sensors. Each row corresponds to a value with the id of sensor that recorded it from SENSORS, the id of the type of data from SENSOR_TYPE_DATA, the date and time at which the data was collected (date_time).

Phase 2: Database integration

The integration of the two databases was carried out within the Microsoft SQL Server environment, where the ifcSQL database resides.

To establish a connection between the two databases, it is necessary to install an ODBC (Open Database Connectivity) driver specific for MySQL. This step is

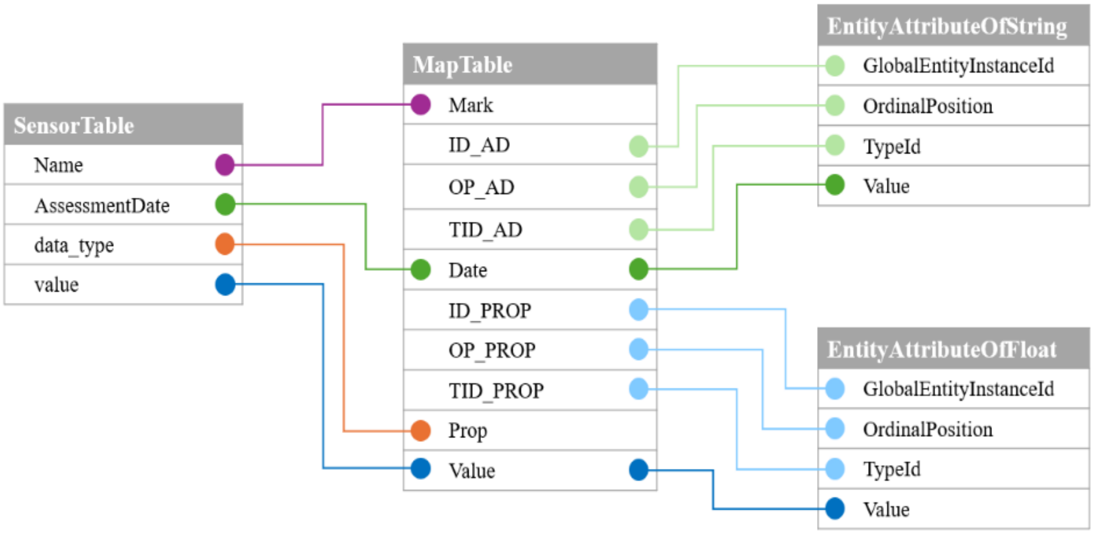

Figure 2: Connection between tables and databases

essential to ensure that the data can be read and processed by the database, regardless of the platform used. After installing the driver, the connection parameters are configured, including the address of the server hosting the database that collects sensor data, the access credentials (username and password), and the name of the MySQL database to be used. Once the connection to the MySQL server has been established via ODBC, the database can be linked to the MSSQL platform using the "Linked Server" functionality. Through this link, it is possible to access the information stored in the MySQL database for read operations and to execute update queries to modify the data stored in the IFC database.

This approach allows for seamless and efficient integration and synchronization of information between the two databases. To be able to do this, two different scripts have been written and runned into MicrosoftSQLserver: MapTable_Creation.sql and DatabaseUpdate.sql.

MapTable_Creation.sql

The script handles ifcSQL mapping, going on to create a consolidated "MapTable" table in which sensor values are collected from the IfcInstanceEntityAttributeOfString and IfcInstanceEntityAttributeOfFloat tables. The table is created only once, as the data remains the same at each iteration, so as to lighten and shorten the process.

Within the table, then, are the columns corresponding to the sensor mark, the Value, GlobalEntityInstanceId, OrdinalPosition, and TypeId of the AssessmentDate and sensor properties, for unique recognition of the data. For the construction of the table, we first go to search for IfcSensor class elements and unique GUIDs. Then we go on to search for property relationships and properties of interest (AssessmentDate, AssetIdentifier, SetPoint-Movement, SetPointHumidity, SetPointTemperature). Of these properties, for each sensor, we go to look up the actual Value, GlobalEntityInstanceId, OrdinalPosition, and TypeId of the AssessmentDate from the corresponding table.

DatabaseUpdate.sql

The purpose of the script is to update the IFC database with data from MYSQL.

To achieve this, a temporary table SENSORTABLE has been created. This table collects, for each sensor and its properties, the most recent measured value based on the latest AssessmentDate. The data from SENSORTABLE is then used to update the Date and Value columns in MapTable, matching records based on the same sensor name and property. Finally, for a unique substitution of these values, the script updates the corresponding values in tables in the IFC database (EntityAttributeOfFloat and EntityAttributeOfString) by comparing entries that share the same ID, OP, and TID as those mapped in the MapTable. The link between the different tables is shown in Figure 2.

Phase 3: IFC update

Once the update phase of ifcSQL is completed, the database is converted into the IFC format. This is achieved using the C# script provided on the GitHub page (Bock and Eder, 2020b).This process is then automated using the PC's Task Scheduler settings, which allow the creation of tasks that are triggered automatically at a user-defined interval.

To automate the entire data exchange process, a batch file is used. This file contains a series of commands executed sequentially, namely MapTable_Creation.sql, DatabaseUpdate.sql, and finally the C# script SQLtoIFC.

Phase 4: IFC visualization

To enable visualization of the updated IFC model and enhance the user experience, a web page has been created (ArenaSQL). This page includes an online viewer developed using the IFC.js libraries by That Open Company (That Open Company, n.d.). The web page updates automatically through the batch file, as explained previously. An example of visualization is shown in Figure 3. Users can navigate the model and select sensors.

Figure 3: Website visualization

Once selected, the updated sensor properties are displayed.

Results and discussion

This research proposed a framework to enable the integration of data between SQL databases from different platforms, such as Microsoft SQL Server (MSSQL) and MySQL, ensuring compatibility between systems and facilitating the exchange and synchronization of information.

The work presented in this paper considers IFC as a data model, a standardized container of information related to the Arena di Verona, which allows visualization of the current state of the building. The main purpose of the developed framework is to monitor the real-time condition of the structure, enabling prompt intervention when necessary. For this reason, IFC serves as the ideal container for storing the most recent data available from the sensors, while the historical data is stored in a dedicated MySQL database, which is more suitable for managing time-series data. So, it becomes easier to visualize the current state of the cultural heritage asset when needed, compared to accessing such information directly from a database.

An overview of the procedure is shown in Figure 4. In the figure, it can be observed how the value related to 'AssessmentDate', initially set by default as 'DataSA02', passes first from the IFC file to the STEP format (starting IFC), then to the SQL format (ifcSQL). Next, the database is updated with the values from the sensor database, specifically the date '2021-04-12 18:06:14:000000' (ifcSQL updated), followed by the subsequent conversion back to the STEP format.

Through this framework, the issue of compatibility between different database management systems is addressed, allowing them to easily exchange data with one another. Specifically, this research focused on analyzing the interoperability challenges between MSSQL and MySQL, which are databases with different architectures. The result is a tool that provides automated mechanisms for data mapping and conversion between different database formats. This system allows for smooth data management, regardless of its origin, minimizing the complexity of the integration process.

Importance is also given to the ifcSQL database, which faithfully reproduces the IFC model, an ISO standard, in tabular format, overcoming the limitations of a static file format (STEP) and enabling continuous and integrated information flow. The adoption of IFC as the database foundation also ensures global compatibility, allowing data exchange between different software and platforms without loss of information or the need for laborious conversions.

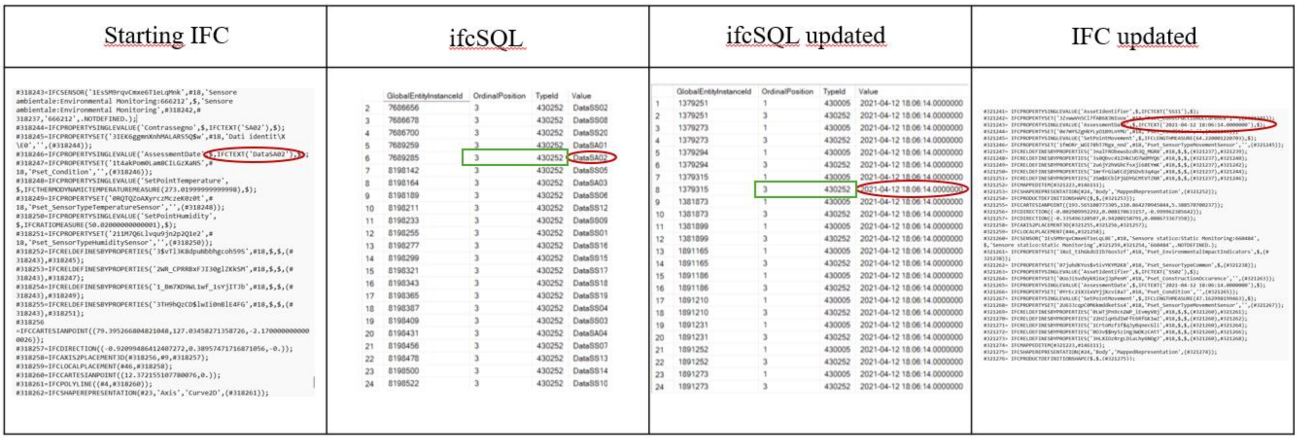

Figure 4: Entire process of IFC update through ifcSQL

This work proposed a solution to integrate and visualize SHM data in real-time within the BIM model maintaining open protocols. This integration provides several advantages for monitoring, including the ability to locate sensors within the structure, enabling better interpretation of the data collected. Real-time updates of monitoring data within the BIM model enhance decision-making by allowing engineers and stakeholders to respond quickly and effectively to maintenance needs or structural interventions.

Working with databases offers several advantages, such as enabling advanced analysis of collected data and facilitating integration with other domains. Many pieces of information are already stored in databases, making it easier to work with these tools due to their familiarity and accessibility.

The framework allows for the integration of any type of information into the IFC model, starting from relational databases. The procedure has been applied to the sensors and specific properties they have detected for this particular case study, so the provided scripts are specific. However, it can also be extended to other domains. In general, applying the framework to a new case would require minimal adjustments. A new IFC model can simply replace the existing one, from which a new database ifcSQL is generated. The relevant sensor database - or any other data source - can then be connected and then mapped. According to specific requirements, IFC classes and properties can be changed by modifying the scripts. Once the updated database is complete, it is reconverted into an IFC STEP file, ensuring a seamless integration of new information. The precise instructions on how to modify the scripts to use other Psets or attributes are defined on the GitHub page. The purpose of this paper is to provide an approach that is as standardized as possible, ensuring it becomes highly replicable and scalable. To demonstrate its replicability, additional case studies should be initiated, with different properties or databases

Despite the project's potential, several limitations emerged during the research, primarily related to the databases. Although MySQL and MSSQL are both relational SQL databases, they differ in syntax and functionality due to their proprietary characteristics. These differences hinder direct communication between the two systems. To address this, a specific driver is developed to enable interaction between the databases within the same platform, overcoming technical incompatibilities. Additionally, integrating data from two databases requires a thorough understanding of their structures, including tables, attributes, relationships, and data allocation. Without this knowledge, effective queries and conflict resolution would be impossible.

The presented research cames from the need to efficiently manage sensor data, previously collected and organized within a relational database structured according to specific functional criteria. This need arises from the goal of continuously monitoring a cultural heritage asset, ensuring its preservation and long-term usability through the analysis of environmental and structural parameters recorded by sensory devices. To meet this requirement, the ifcSQL project was adopted, proving to be a valuable tool for integrating sensor data into a broader information system, thus enabling a unified and continuously updated view of the monitored asset.

It is important to clarify that the main objective of this research is not to highlight the tools used or assess their effectiveness within the Internet of Things (IoT) context, but rather to propose an interoperable, scalable, and adaptable framework suitable for various application scenarios. It is also important to emphasize that this study is based on an already existing and operational sensor data storage database. As a result, the structure and choice of the initial database are not made by this research, but rather stem from decisions made previously, likely driven by different needs. This is often the case in monitoring contexts, where one deals with old, sometimes obsolete systems that are not well-structured or organized. In order to avoid making excessive changes to the existing database, this study focuses on optimizing the data management process that is already in place. One of the future developments of the research will focus on exploring how the management of sensor data can be further optimized, both in terms of the efficiency of data collection and storage processes, and in relation to data processing and analysis.

Conclusions

The use of SQL databases for information exchange leads to the creation of a framework that facilitates the communication of data from different environments and stages of the building lifecycle, significantly improving data management. In the case study of the Verona Arena, the BIM model transformed into a relational database is used for the structural monitoring of the cultural heritage site. The automatic transformation into IFC files ensures that the model remains up to date, thus creating a digital shadow of the Verona Arena. Thanks to this standard, an interoperable framework is developed, replicable in other contexts, overcoming barriers related to data formats.

IFC serves as the data model, and its main role is to represent and structure information related to the building, specifically the sensor data in this study. The use of the SQL format in this context arises from the main limitation, which is that the research is based on an already existing SQL database for managing sensor data. Therefore, to ensure integration with the pre-existing infrastructure, the decision was made to adopt the SQL format, leveraging the ifcSQL project. This approach allowed the research to work with the structure of the existing database, avoiding significant modifications to the current architecture.

However, the challenges related to the integration between MySQL and MSSQL systems highlight the need to further explore this topic to simplify integration processes.

Two different future developments can be highlighted: one related to the implementation of the work concerning the Arena and the other to the proposed framework. *Arena case study.* The work lays the foundation for future research on the use of the proposed framework, aimed at creating a digital platform capable of integrating information from different databases (in this specific case, monitoring sensors of the Verona Arena) with the IFC model. This implementation is crucial for the constant monitoring of the building's condition, allowing for timely interventions if necessary. In the future, there is also the plan to transition to a more performant database, which would allow for even more efficient management of the data collected from the sensors. *Framework.* The methodology adopted can be applied on a larger scale and across different sectors, including cultural heritage, structural health monitoring (SHM), building energy modeling (BEM), building management systems (BMS), and new constructions. The application to other case studies will allow for verifying the scalability, replicability and reliability of the proposed framework.

This work represents a significant contribution to research on interoperability and integrated data management, through the creation of a replicable and scalable solution.

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