GEOMETRIC AND SEMANTIC INTEGRATION OF BIM AND GIS FOR THE PROTECTION OF CULTURAL HERITAGE ASSETS AGAINST NATURAL DISASTERS

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This master's thesis is publicly available.

This master's thesis has been carried out in accordance with the rules of the TU/e Code of Scientific Integrity.

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Preface

This master's thesis is a result of my exploration into the world of using digital technologies for protecting the cultural heritage buildings. Throughout this work, I have explored the concepts of Building Information Modeling (BIM), Geometric Information System (GIS), and Semantic Web technologies.

I want to express my gratitude to my supervisors Pieter Pawels and Dujuan Yangwho guided me along this path. Their support has been invaluable, and I couldn't have reached this point without them.

Thank you for joining me on this journey.

Loizos Georgiou

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Table of Contents

Contents

Summary 7

Abstract 9

List of Abbreviations 10

1.Introduction 14

1.1. Problem definition 14

1.2. Research question(s) 15

1.3. Research design 15

2. Literature review 17

2.1. Introduction 17

2.2. Heritage Building Information Modelling (HBIM) 17

2.2.1. Scan to BIM 18

2.3. Fundamentals of BIM 19

2.3.1. Industry Foundation Classes (IFC) 19

2.3.2. BIM Benefits in Cultural Heritage Conversation 20

2.4. Semantic Web technologies and Linked Data 20

2.4.1. Semantic Web Technologies in Heritage BIM 21

2.4.2. Existing ontologies for the Building Damages and Cultural Heritage 22

2.5. Geospatial Information Systems for Cultural Heritage 24

2.6. Integration of BIM and GIS 25

2.7. Integrating BIM and GIS Data Using the Semantic Web Technologies. 30

2.8 Literature review summary 32

3. Development Approach: Building a holistic connection of BIM and GIS 34

3.1. Introduction 34

3.2. Integration Approach 34

3.2.1. Conversion of the IFC model to CityGML with FME 36

3.2.2. Summary 41

4. Project Implementation 43

4.1. Case study – Karmiotissa Church 43

4.2. Transformation of Karmiotissa church BIM model to CityGML with FME 44

4.2. Positioning of 3D Models for CityGML 46

4.3. GIS Data 47

4.3.1. Flood Risk GML data 47

4.3.2. Earthquake Hazard Zones GML data 48

4.3.3. Wind GML data 49
4.3.4 Conclusion 51
5. Semantic Data Management 52
5.1. IFC to Linked Building Data Converter 54
5.2. Building data Semantic-Enrichment 55
5.3. Query Data in Stardog Studio 62
5.4. Python in QGIS 65
5.5. Query Data with SPARQL language in QGIS 66
5.6. Conclusion 68
6. Discussion and Conclusion 71
6.1. Introduction 71
6.2. Research questions 71
6.3. Drawbacks 76
6.4. Conclusions and future works 77
Bibliography 78

Summary

Natural disasters always have been a threat to cultural heritage buildings. Floods, earthquakes, soil loss landslides and wind effects cause irreversible damage for vulnerable historical buildings (Drdacky et al., 2007). Protection of cultural heritage can become feasible using real time environmental data for monitoring and assessing the building's performance against the natural forces. The goal of this project is to link the environmental elements with the building characteristics, allowing a constant monitoring of heritage buildings against natural disasters in a user-friendly environment. The assessment of building damages and deterioration mechanisms will be tracked and documented so that a structural failure can be foreseen and prevented. The challenge of this thesis is to introduce the heterogeneous environmental data to the historic buildings and associate them with the existing damages that will allow the engineers to retrieve information about the origin and the nature of the damage, while at the same time both buildings and environmental elements can be visualised in an interactive environment.

The project aims to bring together different data related to the geometric aspects of the buildings and the environmental elements to allow a holistic representation of the building along with environmental threats in a digital cartographic environment. Building Information Modelling (BIM) provides a modelling environment where geometric information and architectural properties can be structured in a coherent database. Geographic Information Systems (GIS) facilitates the storage, management, and analysis of spatial and non-spatial hazards. A BIM model of a historic church was transformed into a GIS readable model to be visualised in a GIS map along with the environmental layers. The BIM model was transferred into GIS by transforming the Industry Foundation Classes (IFC) file of the building into CityGML using the FME workflow. The CityGML format supports the storage, representation and exchange of virtual 3D city models.

To support the non-geometric data and to provide the opportunity to users to query and link the environmental data with the damages, semantic web technologies were used. These technologies were used to describe the building damages and their environmental root of cause. Firstly, an ontology was constructed to describe the environmental threats to cultural heritage buildings from wind, flooding, rain and earthquake in Protégé. Resource Description Framework (RDF) is the standard model for representing information in the Semantic Web. An RDF graph represents all the information using triples. The next step was to apply semantic web technologies to describe the types of damages that can be found on the building and can be associated with their natural origin. To do this the IFC structure of the building model was converted into an RDF graph. IFC to Linked Building Data (LBD) conversion method was used to create an RDF graph of the building from the IFC file of the BIM model that was exported from Revit. IFC to LBD converter is an open-source project available on Github. Then, the damages were assigned to the corresponding elements along with the environmental root of cause directly on the RDF graph database of the building by following a semantic enrichment process. The semantic integration of the building elements, types of damages and natural forces allow engineers to query information and

retrieve details regarding the origin of the crack formation and the impact of the damage on the buildings.

The goal of this project is to provide an information system at architectural and topographical scale to enable the management of semantically enriched three-dimensional models in a GIS environment. For this reason, a QGIS software was selected as a hosting platform. The next step was to load the semantic data to QGIS to allow queries in QGIS platform. QGIS includes a Python application program interface (API) for extending its functionality and a Python console/editor. The query process was executed in Python and hosted in QGIS via the Python console/editor. Stardog graph database was selected to allow the query of RDF database with Python scripts. Pystardog was used to connect Python to Stardog databases. Pystardog warks as a wrapper for Python that provides communication with the Stardog HTTP server. It wraps all the functionality of the external database for the Stardog Knowledge Graph and allows access to a complete set of functions such as executing SPARQL queries (Pystardog Documentation (2019).

The enriched RDF of the building with the damages was then imported in QGIS and in addition to geometry the semantic information was queried. The integration of building damages and natural elements allowed the user to interact with the model and assign on it risk indicators and vulnerability parameters in a user-friendly environment. For the implementation of the proposed method of integrating building, environmental and damaging related data in GIS, a BIM model a historic church in Cyprus was selected as a case study. The building was assessed based on the environmental characteristics of the region where it is located and based on the damages that were recorded and documented with a laser scanner during a building survey.

The purpose of this project is to help engineers that participate in renovation to assess the nature of the damages on a heritage building and their natural root of caused. Because renovation is a multidiscipline process a common platform is needed that can support both building data and environmental data. A centralized platform for sharing data and information between different stakeholders can improve collaboration and decision-making. QGIS was selected to host the building model along with the damages that were observed during survey. QGIS provides advanced spatial analysis tools that can be used to analyse and visualise the relationship between the building and its surrounding environment. Advanced visualization tools that QGIS provides can create interactive maps and 3D models of the building and its surrounding environment, improving communication and understanding of the building and its context. By semantically enriching the building model with observed damages, it becomes possible to analyse and understand the relationship between damages and other relevant factors, such as the nature of the damage and the location of the damage. This information can be used to prioritize repairs, improve construction management, and enhance the overall maintenance of the building, preserving its heritage value.

Abstract

Natural disasters have a catastrophic impact on cultural heritage structures. To preserve heritage buildings, digitalization plays a crucial role. Building Information Modeling (BIM), Geometric Information System (GIS), and Semantic Web (SW) technologies offer promising solutions in this context. BIM, specifically Heritage Building Information Modeling (HBIM), enables the parametric representation of historic buildings. GIS technology allows for the analysis of the surrounding environment and the visualization of 3D building models on a map, incorporating environmental parameters. This project aims to present a semantically enriched HBIM model within a GIS platform. By doing so, the model can be visualized in a GIS environment where environmental data can be associated with building damages. Semantic web technologies and linked data provide the means to link and query the building data and damages. The project utilizes IFC for the BIM model and CityGML for GIS data, with IFC representing building information and CityGML serving spatial analysis purposes. The project focuses on a historic church as a case study to assess damages resulting from natural phenomena. The digital BIM model, obtained from point cloud data, is transferred to a GIS environment for investigating environmental characteristics and detected damages from building surveys. GIS cartographic environmental data is sourced from regional geoportals. The transformation of the BIM model to GIS format is achieved by converting the IFC file into CityGML using the FME workflow. Information regarding building damages and environmental elements is added to a semantically enriched RDF model of the church, requiring manual work. The conversion of BIM data to GIS data presents challenges due to differences in reference systems, spatial scale, level of detail, geometric representation methods, storage, access methods, and semantic mismatches between BIM and GIS data models. The final RDF graph is queried in GIS using Pystardog, a Python wrapper library that facilitates communication with the Stardog Knowledge Graph and allowed the Stardog knowledge graph to be hosted in QGIS python console. By transferring the HBIM model to a GIS platform and enriching it with the observed damages, a comprehensive understanding of the building and its context is achieved. This facilitates improved decision-making regarding the preservation of cultural heritage buildings.

List of Abbreviations

ADEs	Application Domain Extensions
AEC	Architecture, Engineering & Construction
BEO	Building Element Ontology
BIM	Building Information Modelling
Brep	Boundary Representation
CityGML	City Geography Markup Language
CSG	Constructive Solid Geometry
DOT	Damage Topology Ontology
FME	Feature Manipulation Engine
GCS	Geographic Coordinates System
GeoJSON	Geographic JavaScript Object Notation
GFM	General Feature Model (as defined in ISO 19109)
GIS	Geographic Information System
GML	Geography Markup Language
HBIM	Heritage Building Information Modelling
HEX	Hexademical
IDE	Integrated Development Environment
IFC	Industry Foundation Classes
IT	Information Technology
IRI	Internationalized Resource Identifier
KML	Keyhole Markup Language
LBD	Linked Building Data
LODs	Levels of Development
MONDIS	Monument Damage Information System
NDT	Non-Destructive Testing
OGC	Open Geospatial Consortium
OWL	Web Ontology Language
RCC	Region Connection Calculus
RDF	Resource Description Framework

RDFS	RDF Schema
RIF	Rule Interchange Format
SPARQL	Protocol and RDF Query Language
SHP	Shapefile
STEP	Standard for the Exchange of Product model data
SW	Semantic Web
TLS	Terrestrial Laser Scanner
URL	Uniform Resource Locator
WDR	Wind-Driven Rain
W3C	World Wide Web Consortium
XML	Extensible Markup Language
3D	3 Dimensional

List of figures

Figure 1: The development approach of the project

Figure 2: Scan to BIM workflow (Rocha et al., 2020).

Figure 3: The main structure of an RDF triple. (Vinasco-Alvarez et al., 2020).

Figure 4: The conceptualization of HBIM Model with the integration of the BIM and the knowledge base. (Simeone et al., 2014).

Figure 5: Topological classes and object properties defined by DOT. (Hamdan et al., 2019)

Figure 6: The semantic representation of the BIMserver and GIS architecture. (De Laat and Van Berlo., 2011)

Figure 7: IFC object file is processed independently with a modified version of IfcOpenShell (Arroyo et al., 2018)

Figure 8: The example of an FME workflow of transforming the IfcWindow to CityGML. (Colucci et al., 2020)

Figure 9: Architecture of the proposed methodology.

Figure 10: Create parent/child lookup

Figure 11: The VariableSetter Output

Figure 12: ConvertGeometry custom transformer.

Figure 13: Geometric and Data Structure Representation

Figure 14: Get grandparent ID custom transformer.

Figure 15: CityGMLGeometrySetter custom transformer.

Figure 16: Shows the example of the FME conversion of the IFC file to CityGML giving the example of the window.

Figure 17: The medieval church of Panagia Karmiotissa, Pano Polemidia, Limassol, Cyprus

Figure 18: Point Cloud Model of Panagia Karmiotissa (Autodesk Recap)

Figure 19: Building Information Model of Panagia Karmiotissa (Autodesk Revit)

Figure 20: FME workflow for the transformation of the IFC file to CityGML

Figure 21: Visualisation of the CityGML model of the structure in FZKviewer.

Figure 22: The 3D model of the building can be visualised in the QGIS map from 3D map window with coordinates based on ESPG:3857

Figure 23: Flood Risk Maps acquired from the Department of Water Development of Cyprus.

Figure 24: Map of Earthquake Hazard Zones and Other Geological Hazards (INSPIRE)

Figure 25: GML layer shows the areas with a wind speed larger than 4m/s.

Figure 26: 2D visualisation of the building in QGIS where the local natural risks are located.

Figure 27: The construction of the OWL ontology in Protégé for the environmental elements.

Figure 28: Earthquake class annotated with historic earthquakes.

Figure 29: The nature class with four subclasses of Rain, Flooding, Wind and earthquake visualised in GraphDB.

Figure 30: The semantically enrichment process on the turtle file using Notepad.

Figure 31: Cracks and Erosion patterns on the building were manually added on the model during semantic enrichment process.

Figure 32: *Structuring IFC and cracks as liked data.* The biggest circles are the parent classes and the nested ones are their children

Figure 33: The gutter of the southwest of the building with crack visualised in Autodesk Revit.

Figure 34: RDF graph data model of the part of the wall that was associated with a crack.

Figure 35: Nature element is added as an extra node that is linked with the type of crack.

Figure 36: Stardog's features are used with the Stardog Studio platform in the browser.

Figure 37: This triple pattern matched all the triples in the graph that have "hasWind" as the predicate and Crack as the object.

Figure 38: Ask query returns a true/false result.

Figure 39: Pystardog database connection.

Figure 40: Execution of the query process with the Pystardog command.

Figure 41: Query the enriched heritage building database in QGIS software.

List of Tables

Table 1: Query of the database with SPARQL.

1.Introduction

This chapter gives a brief introduction of the goals of this thesis and the problem that it aims to solve. By providing the research question, it is stated what is needed to be covered through the thesis and what are the main limitations that are needed to be overcome. Through the research design the strategy of the proposed methods is provided in a structured and comprehensive way and it will be used as the core guideline for this project.

1.1. Problem definition

Historical buildings are tangible remains of our cultural past. The European Union has set a clear path on protecting the cultural heritage with policies and funds. The EU states in Article 3.3 of the Lisbon Treaty: “The Union shall respect its rich cultural and linguistic diversity, and [...] ensure that Europe’s cultural heritage is safeguarded and enhanced”. Natural disasters represent one of the greatest threats to cultural heritage.

Damage to cultural heritage buildings can be result of flooding, wind effects, fire and earthquake. Soil loss has been long characterized as one of the main threats with possible impact to natural and cultural heritage (UNESCO report 2006). The slow degradation of building materials is accelerated with wind erosion, salt cycles, capillary rising damp, etc. (Mattei et al., 2019). It is well understood that cultural heritage needs to be shielded and protected against the natural threats. This study aims to provide a process for documenting and analysing cultural assets using current digital technologies, ICT and open data.

In this thesis, the documentation of heritage buildings and their surrounding environment relies on various information sources, including building data, geospatial data, and surveying data. A key focus of this study is to address the challenge of providing engineers with a formula and user-friendly tools to assess historic buildings and propose remediation works when necessary. As operators in the Cultural Heritage field may not be comfortable to working with databases, 3D models, and information systems, the development of a user-friendly system for Cultural Heritage management becomes crucial. By working collaboratively on a common platform, engineers and stakeholders in the field can easily access and interact with the data, facilitating the preservation and conservation efforts of these invaluable historic buildings. The integration of digital technologies, such as BIM and GIS, can enhance the documentation process, while the use of open data sources enriches the analysis. Ultimately, the aim is to empower Cultural Heritage professionals to make informed decisions and formulate effective preservation strategies for these historic assets.

Environmental data are available in GIS format from governmental portals and independent organisations. A BIM model can provide a digital representation of the building with all its structural and material properties accompanied with architectural characteristics. For BIM and GIS, a data level and geometric integration is needed. This can be implemented by transforming data from the BIM system to the GIS system and the opposite, or host both in the same interface. The data transformation from BIM system to GIS system is difficult for many reasons. Among them, data incompatibility is the most significant, because BIM and

GIS data are created, stored, analyzed, managed, and visualized in different ways in terms of the scope of interest, coordinate systems, and data structures.

Digital cultural heritage preservation is a field that requires strict measurements regarding the conservation of information between the different phases. Alongside with the digital representation of the building the assessment of building damages and their relationship with the environmental elements should be implemented as well. By incorporating heterogeneous datasets (technical reports, photographs, documents, etc.), 3D digital models can be semantically enriched, making them extremely useful for management and conservation (Saygi and Remondino, 2013). Degradation occurs during the entire life-cycle of a building and the digital representation of damages can benefit engineers to forecast and prevent further failure (Hamdan, et al., 2019).

1.2. Research question(s)

The principal research question is:

How can digital technologies be effectively utilized to document, analyse, and assess historic buildings, their environmental context, and damages caused by natural phenomena, while providing user-friendly systems for cultural heritage management and an effective restoration planning?

While the sub questions below need to be satisfied.

1. What are the challenges and solutions for integrating building and cartographic data, considering data incompatibility, differences in coordinate systems, and data structures?
2. How can GIS technology be employed to analyse and visualize the environmental context of historic buildings, incorporating geospatial data?
3. How can heterogeneous data generated from building surveying methods, such as laser scanning to be incorporated and semantically enriched in 3D digital models to support management and conservation efforts?
4. How can digital technologies aid in assessing and predicting damages to historic buildings caused by natural phenomena, enabling engineers to forecast and prevent further failures?

1.3. Research design

This research study is divided into four separate phases. (a) Literature Review, (b) Development Approach, (c) Project Implementation, (d) Semantic Data Management. In the literature review, the impact of environmental threats to heritage buildings will be discussed, followed by a discussion on the benefits of BIM and semantic web technologies. The existing tools in the industry, and how BIM and GIS could be integrated are discussed as well. Furthermore, the literature review covers current methodologies of integrating BIM and GIS on a geometric and semantic level and existing ontologies for damages in heritage buildings are investigated.

The development approach discusses the methodology towards the implementation of the integrated BIM-GIS tool. Project Implementation is the execution of the project with real

data from a case study and then in the Semantic Data Management section, the result of the final product is presented to allow the semantic enrichment of the model and the query of information. BIM and GIS are integrated in a GIS platform where building, environmental and damage related data can be queried while a geometric presentation is supported. Lastly, the Conclusion discusses a short overview of the steps taken throughout the research with recommendations for future researchers.

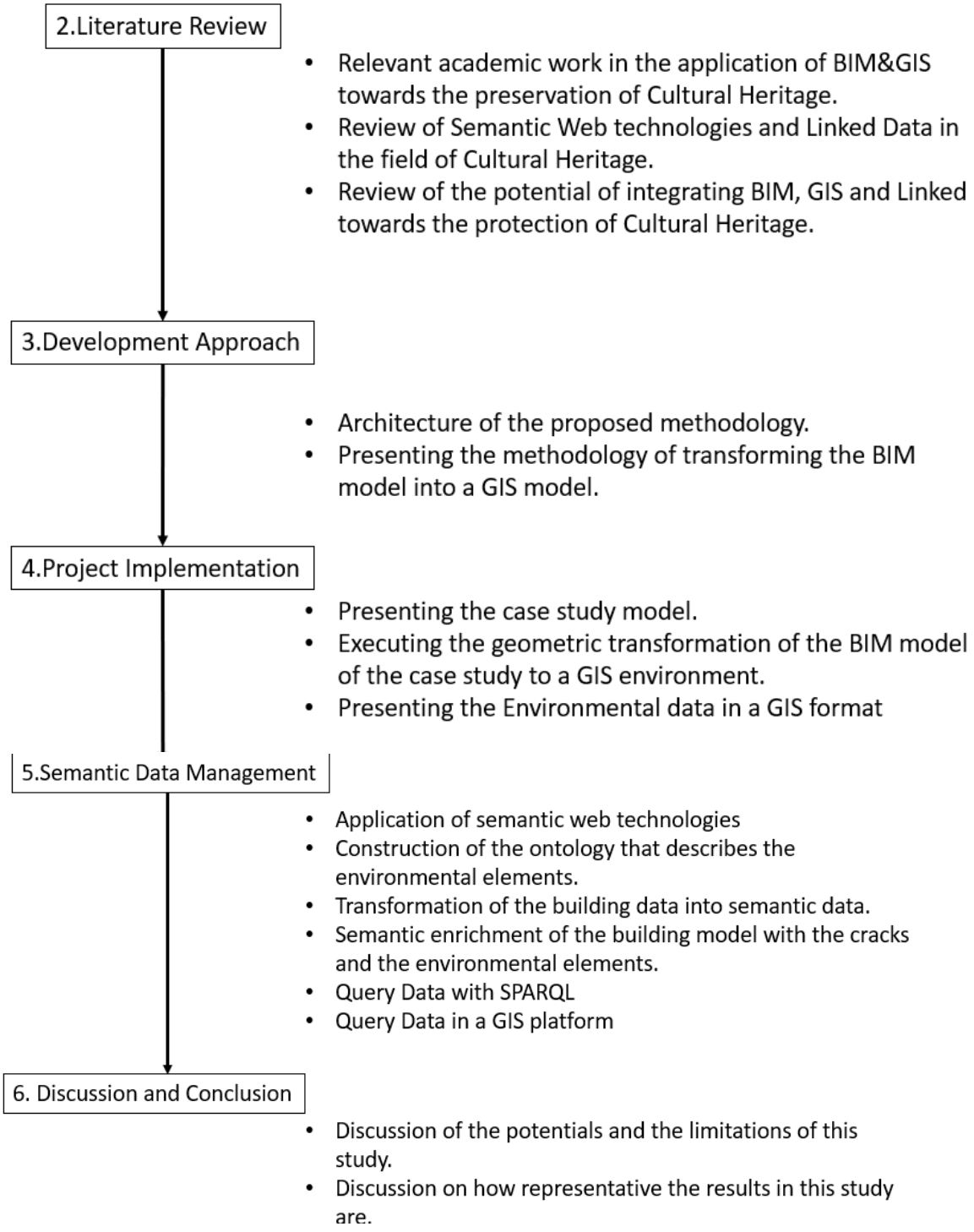

Figure 1: *The development approach of the project*

2. Literature review

2.1. Introduction

The literature review covers a comprehensive review of academic research conducted in the field of cultural heritage preservation and the utilization of heterogeneous data. It begins by introducing the concept of Heritage Building Information Modelling (HBIM) and discussing the significant contributions of BIM technology to the preservation of cultural heritage. The workflow involved in creating a BIM model from 3D laser scanning survey data is also outlined. Semantic Web technologies and Linked Data technologies are explored, emphasizing their relevance and impact on cultural heritage. Existing ontologies related to cultural heritage are assessed, providing insights into their applicability and effectiveness. The review further explores Geospatial Information Systems (GIS) fundamentals, emphasizing the integration of BIM and GIS. Various approaches to integrating BIM and GIS are discussed and evaluated. Finally, the review focuses on the combination of BIM, GIS data, and Semantic Web Technologies. It examines projects that aim to achieve a comprehensive representation of BIM models within a GIS environment, where semantic data can be effectively supported and utilized.

2.2. Heritage Building Information Modelling (HBIM)

The concept of Heritage Building Information Modeling (HBIM) was introduced by Murphy et al., (2009) as a digital approach aimed at documenting and preserving historic buildings. HBIM involves the creation of a 3D model that serves as a repository for parametric objects and systems specific to heritage contexts. This model can be enriched with survey data and images to support various tasks related to cultural heritage. While BIM technology is commonly utilized in new construction projects, its applicability extends to existing buildings that require intervention or management, making it well-suited for cultural heritage purposes. BIM's capacity to store attributes, model objects, and establish relationships between them provides significant value for the digital documentation and restoration of cultural heritage structures. HBIM harnesses the power of BIM technology to assist architects, operators, and structural engineers in various tasks, including diagnostic analysis, construction site management, cost analysis, project management, construction tendering, and restoration efforts. It involves the establishment of a digital multidisciplinary workflow that integrates BIM tools with survey data, such as point clouds or images, to facilitate the mapping of parametric objects and enhance the comprehension and management of historic buildings.

Murphy et al., (2009) explored the potential of digital worlds as collaborative environments for heritage education and research. The HBIM process begins with onsite surveys conducted using Non-Destructive Techniques (NDT) such as terrestrial laser scanning or digital photogrammetric modelling. These surveys are crucial for capturing the accurate condition of historic buildings, which often exhibit irregularities and damages. The

integration of semantic attributes and 3D geometric models forms the foundation of HBIM, enabling the creation of semantic 3D reconstructions of heritage buildings and sites. Additionally, various documents and information, including photographs, maps, literature, and intangible data, are incorporated into the models.

HBIM for historic buildings poses unique challenges due to their complex architectural structures and the limited availability of existing drawings and data. The irregularity and uniqueness of these buildings make the HBIM process more complex compared to traditional BIM models. A key step in HBIM is the creation of BIM parametric models from point clouds, which can be further enriched with conservation-related data (Khan et al., 2022). The final HBIM model combines both geometric and non-geometric data, making it suitable for documentation and engineering applications. This comprehensive model serves as an open platform for stakeholders involved in restoration projects. During the restoration phase, the HBIM model facilitates various tasks. According to (Brumana et al., 2020), the impact assessment of the building is conducted, followed by a diagnostic analysis within the BIM environment. This analysis involves assessing surface decay, analysing materials, and applying Finite Element Analysis (FEA) techniques to evaluate the structural behaviour of the building. The HBIM model plays a crucial role in supporting these restoration activities and informing decision-making processes.

2.2.1. Scan to BIM

Surveying techniques are crucial for conducting thorough inspections and preserving cultural heritage assets in heritage buildings. According to (Brumana et al., 2020), modern non-destructive testing (NDT) equipment and technologies provide powerful tools for digitalizing buildings and obtaining detailed geometric information. These advanced surveying techniques, such as Terrestrial Laser Scanning (TLS) and 3D photogrammetry, offer the ability to capture accurate data and generate point clouds that can be used to create 3D parametric Building Information Modeling (BIM) models. This process, known as Scan to BIM, enables the creation of detailed digital models that facilitate evaluation, planning, and knowledge management for the conservation and maintenance of historic buildings. The Scan to BIM process begins with the use of a Terrestrial Laser Scanner (TLS) as the primary tool for capturing precise base geometry data for modeling 3D heritage buildings. This data serves as the foundation for the final BIM model.

By employing modern surveying techniques and the Scan to BIM process, it becomes possible to create comprehensive BIM models that offer significant potential for evaluating and planning the conservation and maintenance of heritage buildings (Rocha et al., 2020) These digital models serve as valuable resources for documenting, analyzing, and managing the intricate details of historic structures, as shown in Figure 2.

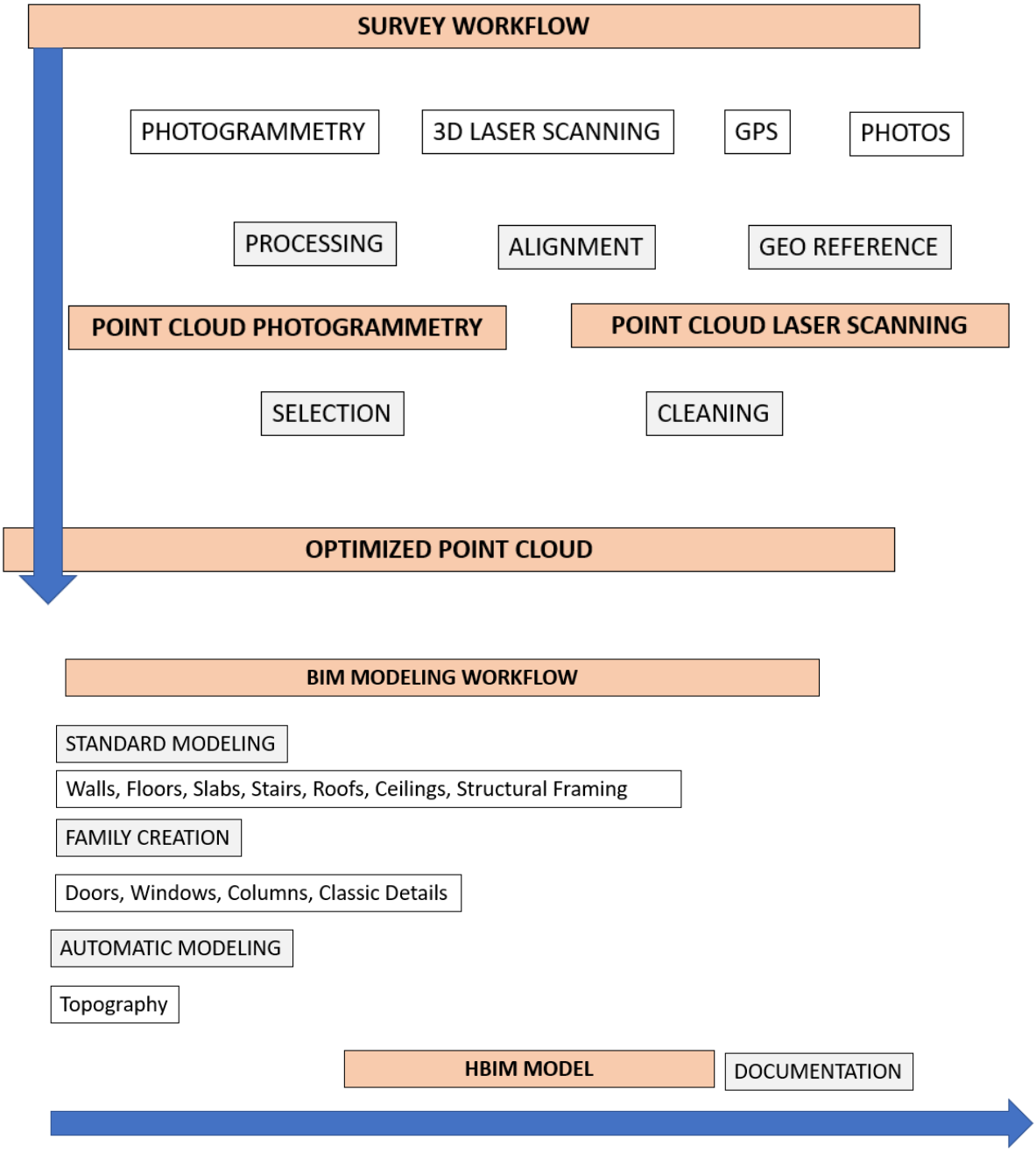

Figure 2: Scan to BIM workflow (Rocha et al., 2020).

2.3. Fundamentals of BIM

2.3.1. Industry Foundation Classes (IFC)

The Industry Foundation Classes (IFC) stand as the representative data formats for BIM. IFC is an open, impartial, object-oriented data format designed to represent building components, construction tasks, and information throughout the building's life cycle

(BuildingSMART). IFC is typically used to exchange information from one party to another in the building sector and provides an interoperability platform for standardization and data exchange in a BIM environment.

IFC data can be encoded in different formats, including XML (Extensible Markup Language) and STEP (Standard for the Exchange of Product model data). The development of IFC aimed to enhance productivity and communication while reducing delivery time, construction costs, and maintenance expenses associated with buildings. IFC was developed to provide a common language for building industry technology. IFC schema can be complex and they usually include a large number of classes and properties. This leads to inflexibility and complexity. Other BIM data exchange formats that can also be used in HBIM are the .rvt and .dwg file formats. The software tools corresponding to these native proprietary file formats, AutoCAD and Revit easily support point cloud generated geometries (Colucci. E et al., 2020).

2.3.2. BIM Benefits in Cultural Heritage Conversation

BIM technology offers significant advantages for the renovation and documentation of historic structures. By providing detailed 3D models, BIM allows for a better understanding of the complex nature of historic buildings and facilitates the scheduling of conservation work. It enables the sharing of data across various applications and supports more efficient and sustainable retrofits and renovations. With a 3D parametric model of the building, decision-making becomes more reliable and faster. The integration of semantics and parametric BIM elements enables the 3D reconstruction of historic buildings (Cheng et al,. 2015).

2.4. Semantic Web technologies and Linked Data

The concept of the "Semantic Web" follows a W3C's vision of a connected and data-driven Web. Semantic Web technologies enable individuals to establish data repositories, develop vocabularies, and define guidelines for data management. These technologies, such as RDF, SPARQL, JSON-LD, OWL, SHACL, and SKOS, empower the utilization of linked data World (Wide Web Consortium 2023). Ontology Web Language (OWL) is commonly used as the formalization language for ontologies, while RDF serves as a standard model for data interchange on the Web. RDF is a standard model used for data interchange on the Web. It provides features that enable the merging of data from different sources, even when the underlying schemas differ. In RDF, the linking structure of the Web is extended by using URIs to name the relationships between entities, as well as the two endpoints of the link.

This relationship is represented as a "triple," which consists of a subject, a predicate, and an object (W3C. n.d.). By employing this simple model, RDF allows for the mixing, exposure, and sharing of structured and semi-structured data across various applications. An RDF graph represents all the information using triples as it can be seen in Figure 3.

RDF is, among other things, a data model based on edge-node "graphs."

- Subject (start node, instance, entity, feature)

- Predicate (verb, property, attribute, relation, member, link, reference)
- Object (value, end node, non-literal values can be used as a Subject) (Open Geospatial Consortium. n.d.).

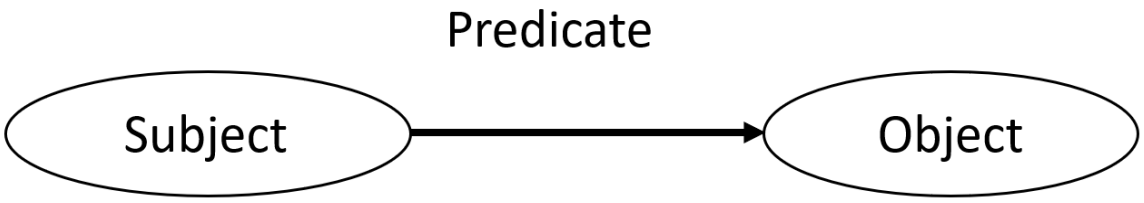

Figure 3: *The main structure of an RDF triple.*

RDF Syntax

The node-and-link syntax is a straightforward and accessible way to represent and visualize graphs. Turtle is the textual syntax for RDF and can be the basis of the SPARQL query language by providing the triple pattern syntax (W3C).

SPARQL

SPARQL is a collection of specifications that define languages and protocols used for querying and manipulating RDF graph data. Its purpose is to enable the retrieval and manipulation of information stored in RDF data sources. The SPARQL Query Language allows for formulating queries ranging from simple graph pattern matching to complex queries involving union, optional parts, filters, aggregation, and grouping. It supports SELECT queries for retrieving variable bindings, ASK queries for boolean results, and CONSTRUCT queries for constructing new RDF graphs (W3C. n.d.).

2.4.1. Semantic Web Technologies in Heritage BIM

The HBIM process aims for a holistic digital reconstruction of the historic assets. In the cultural heritage sector, BIM models require enrichment with additional information that pertains to the complexicity of architectural elements as well as the present condition of the buildings. To support the HBIM process, the utilization of semantic web technologies can be employed to host the relevant information and facilitate its integration within the models. (Werbrouck et al., 2020) have emphasised the necessity to apply semantic web technologies to describe the attributes in a standardised way in the field of heritage building management.

Semantic web technologies offer a valuable opportunity to connect and describe available information related to historic buildings. By enriching 3D building models with semantic information, it becomes possible to effectively incorporate additional documents, such as images, maps, literature, and non-geometric data, into the representations. (Werbrouck et al., 2020) introduced the Scan to Graph framework, which aims to annotate 3D shapes with semantic meaning. Building on this work, (Simeone et al., 2014) proposed an extension of H-BIM that focuses on enhancing information management during investigation and

restoration activities for historic buildings. In (Simeone et al., 2014) project, a BIM-based modeling environment is integrated with a knowledge base built using ontologies, enabling the representation of essential semantics for a comprehensive portrayal of the historical artifact. Figure 4 provides a visual depiction of the HBIM model, illustrating the integration of the BIM environment and the knowledge base to effectively represent the data gathered during the archaeological survey phase. When a BIM element is associated with a class, it helps stakeholders understand the information they need to collect from the site and identify any missing data. Additionally, BIM provides a shared database where stakeholders can contribute and edit data collected during the investigation process. As a result, the modelled information remains up-to-date, and the BIM model itself serves as a record of the investigation and interpretation outcomes.

Figure 4: *The conceptualization of HBIM Model with the integration of the BIM and the knowledge base. (Simeone et al., 2014).*

2.4.2. Existing ontologies for the Building Damages and Cultural Heritage

The development of the MONDIS ontology by (Blaško et al., 2012) and (Cacciotti et al., 2013) aimed to support the computerized documentation of damages to cultural heritage objects. This ontology model was specifically designed to capture and organize knowledge in the field of cultural heritage conservation, focusing on representing causal relationships between identified factors. The MONDIS ontology serves as the foundation for a knowledge-based system that facilitates data sharing, access, and integration across existing digital systems. Its potential applications include a portable version of the system, which could assist in the on-site assessment of building conditions based on predefined assessment standards. Additionally, a visualization tool was developed to enhance knowledge searching for users with less experience, such as students and monument owners. The MONDIS ontology enables the input and search of various entries related to object description, structural evolution, location characteristics and risk assessment, component and material properties, surveys and measurements, damage typology, damage triggers, and potential interventions.

The Damage Topology Ontology (DOT) is an ontology designed to describe damages related to construction and their spatial relationships. It also captures how these damages are connected to the affected construction components and spatial regions. It includes classes and properties for documentation management and basic structural assessment. DOT

serves as a core ontology within the Linked Building Data framework, allowing for the addition of modules focused on detailed damage classification, damage assessment, mechanical degradation, and other specific applications. The ontology separates geometrical representations of damages from the topology, enabling the initial recording of damages without geometrical properties and later linking them using terminology from geometry-related ontologies. By using DOT, damages can be represented in a machine-interpretable format, replacing traditional recording methods. It provides a generic terminology capable of accommodating different types of damage and can be extended with domain-specific information. DOT is suitable for the BIM modelling process and is recommended to be used alongside other ontologies as extensions to incorporate specific information, such as taxonomies for different damage types or national assessment standards.

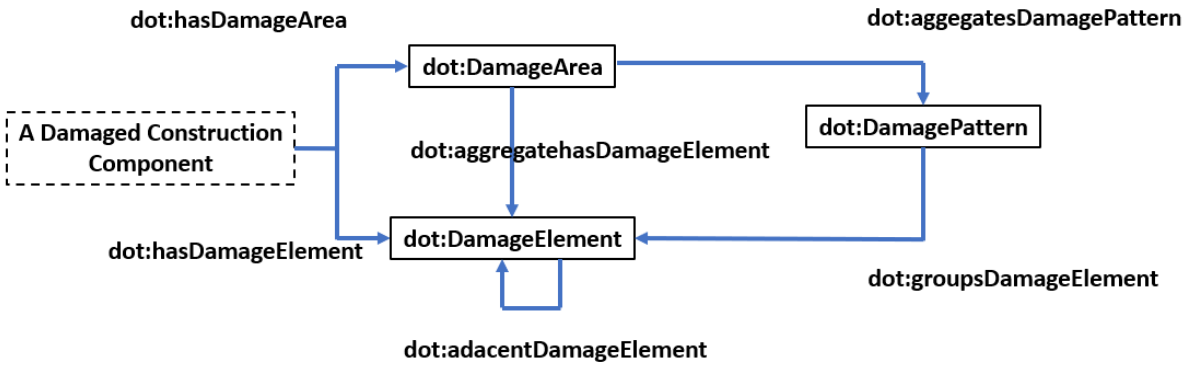

Figure 5: *Topological classes and object properties defined by DOT. (Hamdan et al., 2019)*

RDF stores

An RDF store, specifically an RDF triplestore, is a graph database that utilizes the RDF model to store and manage data. It organizes data as a network of interconnected objects represented by triples, which consist of subject-predicate-object statements. RDF triplestores are specifically designed to handle complex and interconnected data, offering flexibility, adaptability, and the ability to connect diverse information. These triplestores play a crucial role in constructing extensive knowledge graphs by establishing links and indexing data, allowing for semantic search and enriching the information through text analysis. They enable powerful semantic queries and inference, facilitating the discovery of new insights from existing relationships. A fundamental concept within RDF triplestores is the Uniform Resource Identifier (URI), which serves as a unique identifier for web resources. Notably, Linked Open Data datasets like DBPedia and GeoNames heavily rely on RDF triplestores, benefiting from their interconnected nature and enabling efficient querying and federated searches across a wide range of evolving data sources (Ontotext. n.d.).

According to Bellini and Nesi (2018), RDF stores such as Virtuoso, GraphDB, Oracle, and Stardog are commonly utilized in web and mobile applications for the purpose of integrating diverse data. Stardog, a commercial RDF quadruple store, provides extensive features including support for SPARQL 1.1, OWL2 inference, full-text indexing and search, and spatial

indexing and search. It has the capacity to store up to 10 billion triples on a single node, with a limitation of 25 million triples in the community version. GraphDB SE 7.0.1, formerly known as OWLIM store, is another commercial solution that offers a SPARQL 1.1 endpoint and supports spatial indexing and full-text indexing using Lucene and Apache. It also enables inference capabilities during load/indexing and supports horizontal scaling through master-slave nodes. Virtuoso and GraphDB exhibit different performance characteristics: Virtuoso performs better for less selective queries, yielding a larger number of results, while GraphDB excels in searching for specific results with fewer matches. Despite some minor issues that may exist with Virtuoso, these RDF stores provide valuable solutions for the management and querying of RDF data (Bellini & Nesi, 2018).

2.5. Geospatial Information Systems for Cultural Heritage

Geographic Information System (GIS) has long been acknowledged as a reliable tool for modelling the environment and conducting 2D spatial analyses of different regions. As the field has progressed, GIS models have evolved to encompass more detailed representations of buildings, with the aim of achieving 3D city modelling. BIM plays a crucial role in this endeavour, as the domains of GIS and BIM intersect when it comes to modelling cities and buildings (Liu et al., 2017). However, it should be noted that GIS and BIM datasets exhibit significant differences in terms of geometry, semantics, and level of detail. Consequently, there is no singular optimal or standardized method for converting between these two heterogeneous information models.

GIS play a significant role in the field of cultural heritage management, offering robust capabilities for managing, analysing, and querying spatial, attribute, and relationship data among elements. It serves as a valuable tool for creating comprehensive databases of archaeological sites and monuments, thereby facilitating effective heritage site management. GIS empowers users with querying tools, preservation capabilities, and the ability to conduct advanced analyses (Yang et al., 2020). Moreover, GIS systems can be leveraged to monitor cultural heritage sites and safeguard them against natural threats. By considering the surrounding environment of historic buildings, which directly influences their condition, GIS incorporates pertinent geographical, hydrological, and seismological information. In the realm of GIS, City Geography Markup Language (CityGML) and Shapefile (SHP) emerge as representative data formats, offering standardized means of storing and managing geospatial data.

CityGML is an open standard data model and exchange format designed to represent 3D models of cities and landscapes based on Geography Markup Language (GML) defined by the Open Geospatial Consortium (OGC) and is expressed in XML format. Similar to other XML-based data models, CityGML provides a standardized framework for describing 3D objects and their relationship with geometry, spatial properties, semantics, hierarchy and topology. (Jusuf et al., 2017). It was developed in 2002 under the initiative of the Special Interest Group 3D (SIG3D) and it was officially adopted by the OGC in 2008 as the standard for modelling and exchanging of 3D city and landscape models. CityGML supports different Levels of Detail (LoDs) to represent the varying degrees of detail in city models. LoD 0

represents a landscape-level view, LoD 1 captures the regional context, LoD 2 depicts districts and urban environments, LoD 3 introduces exterior architectural models and landmarks, and LoD 4 represents detailed interior architectural models (Tolmer et al., 2013). In the GIS environment, CityGML models with LoDs 0-1 can be visualized and queried in 2D or 2.5D utilizing various cartographic data sources from spatial data infrastructures (SDIs), regional and national geoportals, such as orthophotos and shapefiles.

The shapefile format is extensively utilized for data exchange in GIS and can be seamlessly displayed in multiple modeling software. It supports the representation of 3D geometry, making it a crucial format in the integration of BIM and GIS (Zhu et al., 2019). Unlike CityGML, shapefile does not entail the challenges associated with inflexible Level of Detail (LOD) transformations (Kyzirakos et al., 2018). Shapefile serves as a format for storing location, shape, and attribute information of geographic features in vector data. Developed as an open specification by ESRI, it allows for the representation of spatial features as points, lines, surfaces, or multipatches (ESRI, Shapefile Technical Description). Along with spatial attributes, shapefiles can also store non-spatial attributes of geographic features. Similar to IFC, shapefiles can employ Brep (boundary representation) to store 3D geometry. The prevalence of shapefile usage in regional databases worldwide further enhances its significance as a widely adopted format for data exchange in GIS. Its compatibility with various modelling software, support for 3D geometry, and ease of exchange make shapefile a pivotal element in the integration of BIM and GIS (Zhu et al., 2019).

2.6. Integration of BIM and GIS

According to Jusuf et al., (2017), the integration of BIM and GIS faces challenges due to the distinct spatial representations used by each system. This integration is essential for assessing the performance of building models within their surrounding environments. IFC and CityGML have emerged as two formats that provide a shared platform for bridging the differences between BIM and GIS, facilitating the creation of a unified 3D city environment. GIS and BIM data exchange formats differ significantly in terms of semantics, geometry, and level of detail. The inherent disparities between the two models make it challenging to find a single optimal and uniform conversion method. Therefore, linking and managing information from diverse sources becomes crucial, particularly in the cultural heritage context, where GIS-derived environmental data can be effectively integrated with an HBIM model. However, integrating BIM and GIS data presents its own set of challenges due to the use of different data formats, structures, and schemas in the two domains. While BIM and GIS data have distinct purposes, the integration of their information can create a more holistic understanding of buildings within their geographic context, providing better decision-making.

In a 3D GIS environment, various approaches exist for transferring BIM data into a GIS platform. One commercial approach involves using ArcGIS Pro, which allows for direct insertion of .rvt files into a GIS context without the need for intermediate data format transformations. On the other hand, a non-commercial method involves integrating BIM and GIS through standard formats and model solutions. This can be achieved by converting

the object-oriented IFC model into the standard GML format. Currently, many methods tend to convert BIM models to CityGML, considering both the geometric and semantic aspects. This process involves mapping IFC semantic classes to the corresponding CityGML classes.

The integration of BIM and GIS focuses on the essential exchange of data between these heterogeneous systems. The main challenge lies in achieving efficient and effective data exchange to prevent compatibility issues. Particularly when dealing with existing buildings, it is crucial to consider not only the integration between standards but also the accurate georeferencing of the building within the 3D GIS environment. By utilizing standard formats and model solutions, the integration can be achieved by converting the object-oriented IFC model to the standardized GML format, ensuring the preservation of both geometry and semantic information. To achieve integration at both the geometric and semantic levels, BIM models are commonly converted to CityGML, with IFC semantic classes being mapped to the corresponding CityGML classes (Jusuf, 2017).

Feature Manipulation Engine (FME) was developed by Safe Software and serves as a platform for translating spatial data between geometry and digital formats. FME allows for data extraction from its original source and facilitates the transformation of data into the required format for its destination FME supports a variety of file formats and databases. FME is mainly used for transforming and combining data from 3D models and GIS, enabling seamless integration between different file formats. It can provide comprehensive support for various 3D models, including Autodesk 3DS, Collada, and CityGML. Additionally, FME is compatible with popular GIS file formats such as shapefiles and Google KML. FME can facilitate data interoperability and enhance the integration of diverse mapping software (Jusuf, 2017).

A recent methodology was developed to convert the IFC geometries and their related parameters in a GIS environment through the FME software. In addition, FME has a free plug-in (FME Exporter for Revit) for Autodesk Revit, which allows to export BIM models into a ".rvz" format. By using FME, it is possible to create a workflow that reconfigures the data model (IFC) and converts it into the desired destination data format (CityGML). Regarding the transformation of BIM geometry into a shapefile, similar methods have been developed. Two of them are the data interoperability extension for ArcGIS (DIA) and FME. Different attempts of converting IFC models to CityGML were made. (Hijazi et al., 2010) developed an open-source web-GIS that allows IFC objects to be imported after having been converted to b-rep models. The limitation was that only sweep-volume objects can be converted and all the geometries were kept resulting in non-manifold building models.

According to Liu et al. (2017), the integration of BIM and GIS relies on aligning the semantics and geometry of the data. This integration can involve converting data from both systems into a unified model or adhering to the specific standards of each system. The conversion process can be bi-directional, allowing for data flow between BIM and GIS, or it can be one-way, with data converted from one system to the other. In a study by Donkers et al., (2016), a specific approach was implemented to convert IFC models into CityGML LOD3 models. The researchers identified subsets of objects and applied a series of 3D Boolean set operations to extract the exterior envelopes of these objects. The algorithm used in this process

successfully generated CityGML models without any instances of missing or overlapping geometry.

(Dore & Murphy, 2012) presented a design framework for the integration of HBIM and CityGML in 3D GIS environment using the CityGML framework for the purpose of cultural heritage modeling. Similarly, (Jayakody et al., 2013). In this paper authors present an approach to merge both BIM and GIS. This paper properties the development of a CityGML extension called GeoBIM to get semantic IFC data into a GIS context. The proposed solution is integrating these two (BIM & GIS) technologies. For achieving the above task, the authors have used the open-source BIM server. For defining CityGML object types it is using IFC Classes.

The GeoBIM project, a collaborative research effort between TU Eindhoven and TU Delft, has made significant progress in integrating BIM and GIS. The project focused on achieving integration at both the data level and application level. An approach of integrating BIM and GIS was presented by (De Laat & Van Berlo, 2011) for the development of the CityGML GeoBIM extension that gets semantic IFC data into a GIS context. The transformation of IFC to CityGML with the GeoBIM extension was implemented in the open source BIM server. (De Laat and Van Berlo, 2011) presented the development of a CityGML as it can be shown in Figure 6. The process involves converting IFC data, including the GeoBIM extension, into CityGML format through the use of the open source Building Information Modelserver (BIMserver). The implementation of this conversion takes place within the BIMserver, offering a practical environment for both theoretical model testing and software implementation.

Arroyo et al., (2018) presented an experimental GeoBIM project that aimed to develop an interface between IFC and CityGML for the seamless exchange of BIM data in the GIS domain and vice versa. The experiment utilized IFC files from the City of The Hague, and an interface based on IfcOpenShell and CGAL was created. CGAL is a pair of libraries used for processing BIM and GIS models. The modified version of IfcOpenShell attempted to process each IFC object file independently, as it is illustrated in Figure 7. The goal was to apply spatial analysis algorithms from the GIS domain, including Boolean set operations, to address various use cases. (Bieri & Nef, 1988), (Nef, 1978) and (Hachenberger, 2006). The Boolean set operations were performed using CGAL. CGAL primary purpose is to provide a comprehensive toolkit for manipulating and analyzing geometric shapes and structures on computers. CGAL serves as a versatile toolbox equipped with a variety of tools capable of performing calculations with a high degree of accuracy and efficiency. Because of those capabilities for analysing shapes CGAL found fertile ground in GIS projects. (CGAL. n.d.).

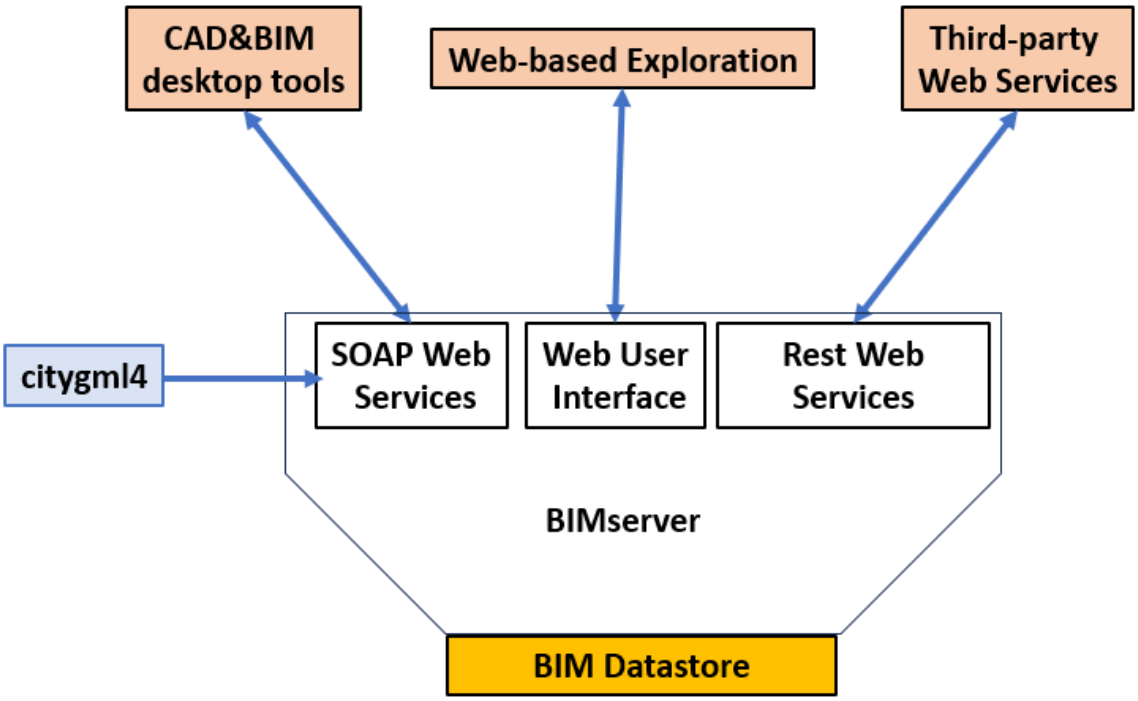

Figure 6: *The semantic representation of the BIMserver and GIS architecture. (De Laat and Van Berlo., 2011)*

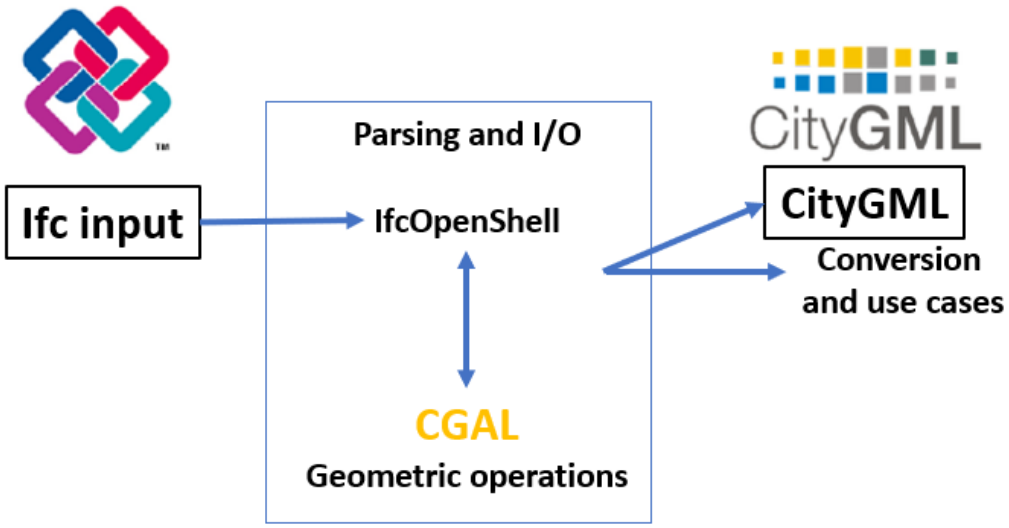

Figure 7*: IFC object file is processed independently with a modified version of IfcOpenShell (Arroyo et al., 2018)*

The results of GeoBIM project showed many errors that seem to be pervasive in IFC models. Those errors make the automated processing of complex architectural models very hard and automatic repair algorithms were needed. It was also found that the available features of CGAL are not cable enough to support all the complex features of IFC.

To support the documentation and conservation of culturally significant buildings exposed to natural risks, Colucci et al., (2020) conducted a research project that integrated an HBIM (Historic Building Information Modeling) model into a 3D GIS (Geographic Information System) environment. The focus of their study was the San Lorenzo Church in Norcia, Italy, which had suffered extensive damages due to earthquakes. The authors aimed to convert the HBIM model into a GIS format, transferring both geometry and semantic information between the two domains. The study compared two integration methods: a commercial method using ArcGIS Pro 2019 software, which allowed for the direct insertion of the BIM model as a .rvt file into a GIS context, and a data-level method using the FME data integration platform. FME platform can be used to convert the IFC data format into the GML format, enabling the creation of a unified model and vocabulary for the 3D GIS project based on the various levels of detail specified in the CityGML standard. The research investigated potential data loss, both in terms of geometric and semantic information, during the conversion process from BIM to GIS data formats. Technical and semantic interoperability levels were assessed to analyze the impact on geometric and informative data, and the results of converting the HBIM model into a LoD (Level of Detail) 4 CityGML model were evaluated.

An example of the FME workflow is illustrated in Figure 8, illustrating the transformation process of an IfcWindow into a GML format window. The IFC solid geometry was converted into a multisurface geometry of CityGML using the "Transform Geometry" transformer within the workspace. The resulting output file in .gml format was visualized in the FME Data Inspector and subsequently imported into the FZK viewer, a software developed by KIT (Karlsruher University of Technology) that supports 3D CityGML models. The FZK viewer allows for both graphical visualization and textual representation of properties and relationships between objects, as well as the ability to query 3D CityGML models. The generated GML file was then imported into QGIS, where the georeferencing information was successfully maintained in both standards using the proposed solutions. Within the GIS environment, the BIM model and its associated data could be linked to environmental parameters, enabling risk analyses by comparing entities with raster data and risk maps. However, it should be noted that there was a lack of an automated workflow to manage and maintain the attributes of the BIM model after the conversion. Nevertheless, the transformation of IFC to GML format using FME was able to preserve all the geometry and semantic information throughout the process.

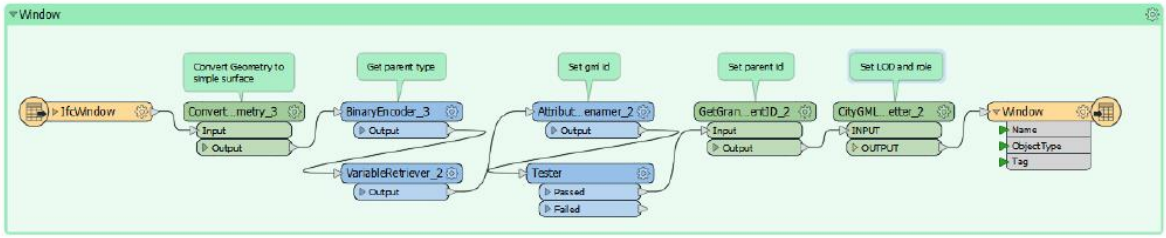

Figure 8: *The example of an FME workflow of transforming the IfcWindow to CityGML. (Colucci et al., 2020)*

(Tan et al., 2023) implemented a state-of-the-art analysis of the current challenges and opportunities for the role of CityGML in the Integration of BIM and the GIS. It was mentioned that CityGML cannot fully support the semantic information of all IFC classes, leading to data loss during mapping. The adoption of Application Domain Extensions (ADEs) can be a very promising method to integrate the two heterogenous environments. ADEs are specialized extensions that can be integrated into standards or models to customize them for particular application domains or industries. Regarding GIS and data modeling, ADEs serve to expand existing standards like CityGML by introducing supplementary attributes, entities, and connections that are pertinent to specific domains. ADEs are added through XML Schema Definition (XSD) files, introducing new objects or properties to enhance semantic information. ADEs allow users to define and incorporate domain-specific concepts and information into the standard data model. For instance, if an application requires detailed information about historical buildings, cultural heritage, or environmental factors, an ADE can be developed to extend CityGML to include attributes, objects, and relationships that are pertinent to those domains.

2.7. Integrating BIM and GIS Data Using the Semantic Web Technologies.

Semantic web technology is used to describe and support the geospatial data and metadata. A popular method is the development of GeoTriples by Open Geospatial Consortium (OCC). Geotriples is a semi-automated tool that enables the transformation of geospatial data into RDF graphs using state of the art vocabularies like GeoSPARQL (Kyzirakos et al., 2018). At the geometry level, the main focus is on geometry transformation, and semantics usually get lost. However, this does not necessarily mean that all the semantic information would be lost after translation. Some of the IFC attributes would remain, such as Global ID, Name, Description and Tag. The main loss of semantic information is the relationship between objects, or the hierarchy structure of the building model. This is the main reason that a semantic integration of the two data formats is needed to support the geometric integration efficiency by mitigating the semantic information loss (Zhu et al., 2018). Especially in cultural heritage conservation BIM and GIS applications require both 3D geometry and complex semantic information in different scales and domains. Using semantic web technologies, the semantic knowledge about historic buildings and environment can be supported with a semantic integration of GIS and BIM. The first process is the development of new data models that are usually ontology-based using semantic web technology. The second methodology is the modification of existing schema including schema simplification and extension. These two strategies have one thing in common that they both rely on existing schemas of IFC, shapefile or CityGML.

The process of semantic integration involves merging information from different domains into a unified data structure that facilitates querying, planning, data exchange, and documentation. Ontologies play a crucial role in providing precise descriptions of entities and their relationships, enabling semantic integration. This integration enhances reasoning capabilities, ensuring logical consistency among different statements. Graph data structures are well-suited for solving data-related issues and are easily understood. Leveraging

semantic web technologies, such as RDF graphs, allows for flexible access and processing of datasets from both HBIM and GIS domains.

In a study conducted by Felicetti et al., (2010), an approach was proposed to integrate 3D archaeological models within a GIS environment at both geometric and semantic levels. The integration involved providing semantic descriptions of the geometric elements and annotating them with semantic information. GML and CityGML formats were used to represent the 3D archaeological models, while the CIDOC-CRM cultural heritage ontology was employed for semantic enrichment of the CityGML model. The software environment utilized for this integration was QGIS, which offers support for Python through its Python bindings (PyQGIS). The researchers developed a CIDOC-CRM Python plugin for QGIS, enabling the implementation of semantic functionalities within the software. QGIS, primarily coded in C++, provides a Python interface that allows users to create plugins, execute commands, and develop customized applications using the QGIS API (Rossetto et al., 2018).

(Simeone et al., 2014) presented a model for the integration of a BIM-based modelling environment and a knowledge base developed by means of ontologies, in order to represent all the semantics needed for a comprehensive representation of the historical artefact. It is a proposal for the extension of BIM for built heritage to enhance information management during the investigation and restoration activities. To test its features, the model has been applied to the real archaeological investigation process of the Castor and Pollux temple at Cori, Italy. BIM environment of Autodesk Revit. For each component identified on site, a set of properties and values has been implemented in order to enrich the artefact representation with not-geometrical data (i.e. material, historical period, degradation level. BIM was integrated with a knowledge management system based on ontologies. A building component modelled by means of the ontology-editor “protégé”.

The case of sharing information after a natural disaster event in the field of cultural heritage was proposed by (Colucci et al., 2018). Using linked data in a web-based technology it was developed. A framework and a supporting decision tool to evaluate the risk of damage to cultural heritage. The aim of this work was to represent the architectural elements of a 3D historic building connected with their damage mechanisms. The damages created from the earthquakes on a historical medieval church. Deterioration mechanisms were linked to the building elements in a QGIS environment. The CityGML 3D building was visualised and queried in QGIS. Created a database that connects the cultural heritage building data with the hazard and risk analysis. The ontology used in this study was the MONDIS. Mondis is a Linked Open Data model, therefore OWL.

(Simeone, Cursi, & Acierno, 2019) proposed a methodology designed to enrich BIM with semantic details, aimed at meeting the presentation requirements of architectural heritage by employing Semantic Web technologies. This strategy entails the integration of a BIM framework with a knowledge repository established on information ontologies. The model exhibits adaptability to diverse documentation and intervention needs in the field of built heritage, and it supports the entire conservation process. Unlike previous studies, this model seamlessly combines investigation, planning, and management activities, facilitating

the smooth flow and integration of information across different disciplines. In another study conducted by (Tchouangouem et al., 2019), semantic web technologies, particularly Linked Data, were combined with BIM tools to promote building sustainability. The researchers developed ontologies based on Linked Building Data (LBD) vocabularies and environmental data, representing them as RDF graphs. They created a database access plugin that was integrated into a BIM tool, enabling the LBD to reference the environmental assessment of each product stored in a triplestore. Using a Java API, multiple RDF graphs containing environmental data for various products were generated. This framework not only demonstrates the availability of environmental data as RDF graphs but also showcases their successful integration into a BIM tool.

(Malinverni et al., 2020), analysed methods to convert a CityGML model along with an Indoor GML model and Shapefiles in an ontological domain. The aim of this work was to use Indoor GML ontology to create connections between buildings and a linkage between outdoor and indoor spaces. The model was semantically enriched, based on connections of different urban model elements in a GIS environment, and queries were possible based on these relations. All data were transferred and filled a graph database in a semantic web environment, while all its features remain interconnected with ontological relationships. The database created defined the connections between models in the same information system. Shapefiles were transformed to CityGML using the FME (Feature Manipulation Engine). Python script was used to transform CityGML and IndoorGML models into JSON data to be available in a NoSQL graph database the ArangoDB. The created graph database represented all kind of data, converted in JSON formats and created RDF triples that connect all the elements with their attributes.

(Vinasco Alvarez et al., 2020) proposed a methodology to generate an ontology for geospatial data from GIS by converting the CityGML application schema into an OWL by creating an XSLT-based pipeline. A method that transforms CityGML and GML instances to RDF from their application schemas. The workflow of this processes was divided into two steps, an instance transformation and a model transformation. OWL ontology describes the CityGML instances from GML and CityGML application schema. The ontology was tested in Protégé. This study analysed the conversion of city data into linked data formats. A methodology that reads and converts CityGML instances into geospatial RDF data.

2.8 Literature review summary

The literature review covered various topics, including the use of BIM and laser scanning technology for digitizing heritage buildings, the application of GIS in assessing environmental impacts, and the utilization of semantic web technologies for effective data management. HBIM, which stands for Historic Building Information Modeling, is a methodology that leverages BIM technology to digitally document and safeguard historical structures. It involves the collection of survey data through non-destructive techniques like laser scanning or photogrammetry, which is then used to create a BIM model. HBIM models are particularly valuable for professionals such as architects, operators, and structural

engineers involved in the preservation and management of cultural heritage sites. Given the unique and irregular characteristics of historical buildings, HBIM models can be more intricate than conventional BIM models. Nevertheless, they offer substantial benefits in conservation efforts as they can incorporate both geometric and non-geometric information about the building. HBIM models play a crucial role in the restoration process by enabling impact assessments and diagnostic analyses to gain a deeper understanding of the building's condition and identify potential issues. These models provide an open platform that allows all stakeholders in a restoration project to access and utilize the data and models, fostering collaboration and facilitating informed decision-making.

Different approaches for transforming BIM data to GIS were investigated. Most of the current methods tend to convert BIM models to CityGML in a geometric level and a semantic level, where for the latter the IFC semantic classes are mapped to the relevant CityGML classes. Many of the above-described methods result in the loss of semantics, limitations in geometric conversion and sole focus on the larger building elements. The main loss of semantic information is the relationship between objects, or the hierarchy structure of the building model. This is the main reason that a semantic integration of the two data formats is needed to support the geometric integration efficiency by mitigating the semantic information loss (Zhu et al., 2018). The transformation of IFC to CityGML format with the FME was able to keep all the information related to geometry.

Using semantic web technologies to integrate BIM building data with external databases is fundamental in this thesis. The semantic integration involves incorporating the information from the different domains into a new data structure that allows querying of information for the purpose of heritage protection. Literature review showed that is a powerful tool for building heritage documentation and conservation. Semantic integration of the domains will provide more flexibility to access and process datasets from both HBIM and GIS through RDF graphs. Different vocabularies were presented that are related building damages like the Building Topology ontology (BOT) or ontologies related to geospatial data like GeoSPARQL.

Various RDF stores were investigated to establish knowledge bases that integrate building, environmental, and damage-related data, enabling efficient information retrieval. The examined RDF stores encompassed Stardog, Virtuoso, and GraphDB. These stores possess the capability to map relational data to RDF and demonstrate rapid query execution. Notably, when combining spatial and text search queries, GraphDB and Stardog exhibited superior performance. Moreover, the ability to execute Stardog queries as Python commands presents opportunities for seamless integration with applications such as QGIS or Revit.

A final observation from the literature review is the absence of a unified platform that combines the visualization of building and environmental elements with the utilization of damage-related data for building preservation and collapse forecasting. Bridging the BIM, GIS, and semantic domains within a shared environment has the potential to address this gap and provide a comprehensive platform to serve these objectives.

3. Development Approach: Building a holistic connection of BIM and GIS

3.1. Introduction

The objective is to introduce a semantically enriched HBIM model into QGIS, enabling the visualization of the model within a GIS environment where environmental data can be associated with building damages. Through the utilization of semantic web technologies and linked data, it becomes possible to query both the building data and the building damages within a GIS platform. This integration is crucial for the preservation of historic buildings as it allows for the inclusion of damages and deterioration mechanisms alongside environmental elements. Environmental data, available in GIS formats such as shapefile and GML layers from open data portals, are regularly updated. By monitoring the performance of the surrounding environment, it becomes feasible to forecast the building's response to external factors and take preventative actions.

3.2. Integration Approach

The methodology employed in this thesis revolves around establishing a connection between the heterogeneous platforms of BIM and GIS, with a focus on supporting semantic information. The case study selected for this research involves a historic church, where an assessment of its damages caused by natural phenomena is conducted. The digital BIM model derived from point cloud data needs to be transferred to a GIS environment, where the environmental characteristics can be examined alongside the damages identified during the building surveying process.

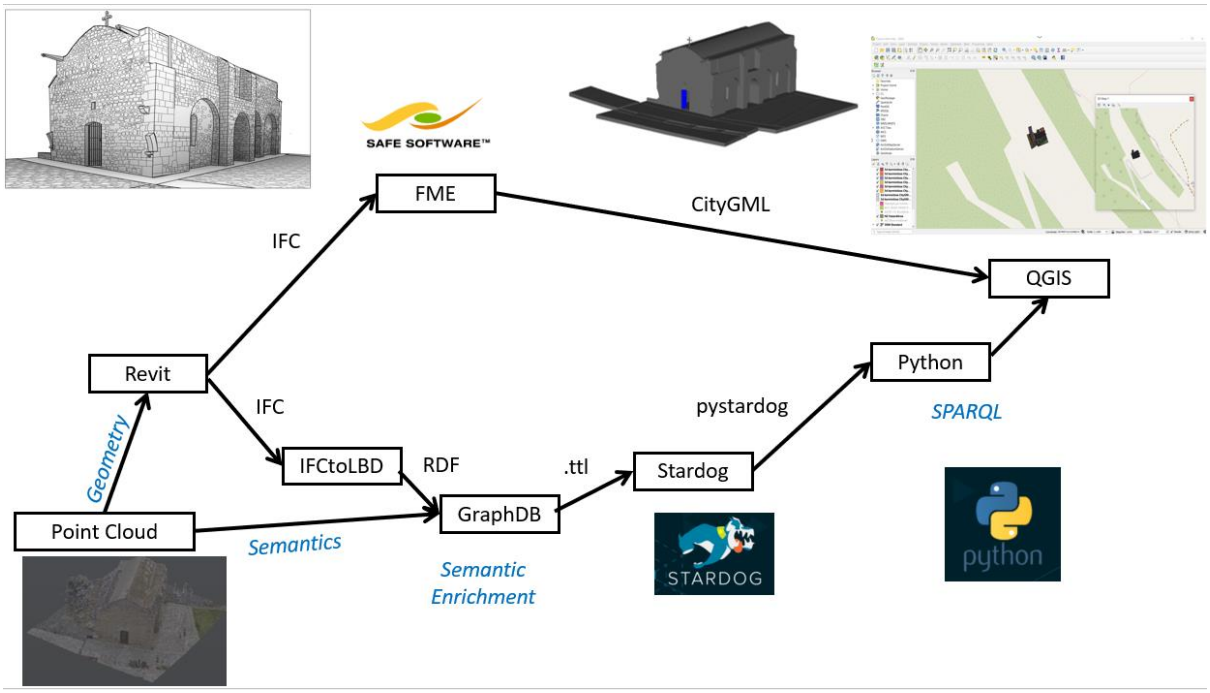

Figure 9: *Architecture of the proposed methodology.*

An integrated platform that has a goal to make the historic building resilient against the Natural Hazards. A connection between environmental data and building data will be developed to allow decision makings related to mitigation of damages of historic buildings from natural forces like wind, floods, earthquake and soil loss. Preserving heritage buildings is a multidiscipline task and experts from different fields are needed to share their knowledge during the restoration process. Stakeholders of a heritage building preservation can be the Structural Engineers, Geotechnical Engineers, Flood Engineers, and Archaeologists. The architecture of the proposed methodology can be seen in Figure 9.

The first step of the project application is the data collection. There are two types of data used in this thesis, the building-related data, and environmental related data. For the building data the case study of Karmiotissa church which has been digitally modelled in a BIM environment from DH-Lab of Cyprus University of Technology was selected as a case study. The building was scanned with a laser scanner and a 3D point cloud was generated. This point cloud provided two types of data that can be used in the project. The first type of data is the geometry of the building following the scan to BIM process. From the point cloud model a BIM model in Autodesk Revit was created by DH-Lab through a detailed digital reconstructing process. Furthermore, material properties were added to the different elements of the building so that a complete parametric BIM model was created with the fundamental material properties and characteristics.

Laser scanner also provided a detailed image of damages and building elements deformation both internally and externally. For this project, damages that can be detected from the point cloud will be assigned to the corresponding architectural element. The addition of building damages will be implemented with the aid of semantic web technologies and the semantic enrichment of RDF graph. Firstly, the IFCtoLBD conversion method is used to create an RDF graph of the building from the IFC file and then the damages can be assigned to the corresponding elements directly on the RDF database. The semantic enrichment method is visualised in GraphDB because it is a web-based tool with an easy user interface environment. The resulting database contains all the information added during the data enrichment phase and can be queried via the standard Semantic-web query language (SPARQL). Graph Database Management Systems are used to handle knowledge by bringing data model abstractions closer to how humans support for handling relationships and by enabling reasoning through machine-readable semantics representation. This approach empowers the effective management of the diverse data related to building damages and environmental impacts in a structured and meaningful way.

The core of this study will be the GIS environment where both geometric building data and semantic query will be supported so that environmental data can be associated with the building damages. The QGIS software was used to host the building model and layers of environmental hazards obtained from regional open geoportals. QGIS is an open software and supports all the fundamental geospatial data formats and cartographic data. QGIS allows users to analyse and edit spatial information and compose maps. QGIS provides a wide range of import and export options, and a same geospatial file can be used in other

applications. Finally, QGIS includes a Python application program interface (API) for extending its functionality and a Python console/editor. Although QGIS itself is primarily a desktop GIS software, there are opportunities for a QGIS map to be hosted in a web-based user-friendly dashboard. Currently there are many open-source platforms that allow you to publish QGIS projects as web services, QGIS Server, QGIS Cloud and GeoNode are few examples.

The objective is to visualize the building model in QGIS, enabling users to assess the impact of surrounding environmental hazards. To achieve this, the BIM model is transformed into a GIS-compatible format by converting the building's IFC file to CityGML using the FME workflow. Additionally, the visualization of building damages in QGIS is necessary to support risk assessment and conservation processes. Since building damages cannot be directly visualized, they need to be incorporated during the semantic enrichment phase. This involves connecting the enriched RDF turtle file format into QGIS, which allows for querying both the geometric and semantic information of the model. By integrating building damages with natural elements, users can interact with the model and assign risk indicators and vulnerability parameters. QGIS provides support for Python programming, allowing Python scripts to be executed through the Python Console or Python plugins. With Python, the RDF file of the semantically enriched model can be added to QGIS and queried to extract information related to damages. While GraphDB is not directly supported by Python, an alternative RDF database called Stardog is selected. To facilitate communication between Python and Stardog databases, the pystardog framework is employed. It serves as a connector between Python and Stardog, enabling the extraction of semantic information within the QGIS software.

3.2.1. Conversion of the IFC model to CityGML with FME

The transformation system of the IFC model to CityGML was succeeded using Feature Manipulation Engine (FME), by Safe Software. IFC model was generated from Autodesk Revit. In this section the basic process of transforming a BIM IFC LOD 300 model to a LOD 4 CityGML model with the FME workspace is presented. The transformers that FME provides along with the customised transformers that were created for this task are explained. The FME allowed the restructuring of the IFC data model and transformomg it to the CityGML destination data format. FME enables the creation of various workspaces in which the format of the input and output data can be specified, as well as the use of a special combination of transformers that allows the data structure to be edited to meet specific needs. The input file (“Reader”) in the FME project created for this study is the.IFC- LoD 3 model exported from Revit. The.GML data format, compliant with the CityGML standard, is selected as the output file.

The IFC file was created in accordance with the IFC hierarchical. In this regard, two “Readers” were required: the first as a “Single Merged Feature Type” and the second as a “Individual Feature Type.” The Single Merged Feature Type is needed to read all of the IFC features and populate the table with the “id”, “parent id”, and “feature type” fields.

Based on the similarity of representing building elements in IFC and in CityGML through the FME workspace,the conversion begins by obtaining new valid gml IDs based on the IFC element IDs. CityGML model can mapped following the IFC parent-child relationship. Each feature was assigned an attribute that could be associated with the gml ID of its parent element. An example of the differen parent-child relationship between IFC and CityGML can be the case of opening layers in IFC of windows and doors to the wall. While in a CityGML model, doors and windows are defined as abstract objects and not as actual figures and are represented with the same parent-child relationship. “Create parent and child lookup" shown in Figure 10, is the first workspace created for this task. IFC features have links to their parent features, but links to the grandparent features are required to remove unnecessary intermediate features. We use two separate Industry Foundation Class STEP (IFC) readers to accomplish this. This first reader, "All," reads all IFC features and populates a lookup table with feature and parent IDs as variables, as well as a lookup table with parent types.

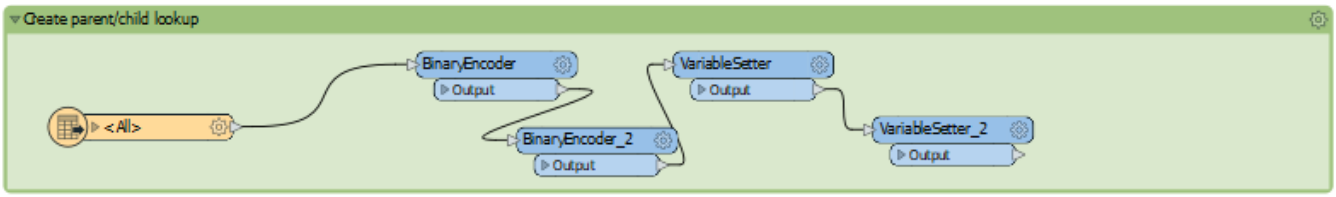

***Figure 10**: Create parent/child lookup*

The transformers "BinaryEncoder" and "VariableSetter" are used to code the values and associate them with the corresponding variables as it can be shown in Figure 11.
The BinaryEncoder transformer is utilized to convert binary data into text using either Base64 or Hexadecimal encoding methods. Base64 encoding transforms characters into a system that includes Latin letters, digits, slash, and plus, while Hexadecimal (HEX) encoding uses the base numerical system of 16 to represent binary numbers in a concise form. This transformer enables the conversion of attributes of various data types into text format. For the second "Reader," which contains both geometric and non-geometric data, the "GeometryRemover" transformer is employed to convert geometries into non-geometric data, specifically as "IfcBuilding." The GeometryRemover transformer eliminates the geometry component entirely, effectively converting spatial data into non-spatial data. The AttributeRenamer transformer is then utilized to manually associate the "Id" attributes of the IFC model with those of the GML model.

Table

VariableSetter_2_Output

Columns...

	ype_name	ifc_type_object_id	ifc_unique_id	fme_feature_type	_unique_id	_parent_id
1	allType	<missing>	2LnEzxjjL5JQ$ZX...	IfcTypeObject	324C6E457A78...	<missing>
2	allType	<missing>	1BZGF$D3b2Qh...	IfcTypeObject	31425A4746244...	<missing>
3	allType	<missing>	23y94KFWbAdx...	IfcTypeObject	32337939344B4...	<missing>

***Figure 11:** The VariableSetter Output*

Following that, the same transformer combination is used for each geometric data (“IfcWindow”, “IfcBuildingElementProxy”, “IfcDoor”, “IfcRoof”, “IfcSlab”,

“IfcWallStandardCase”, and “IfcWall”). Because standard geometries in IFC are composed of “solids,” but they are represented as “multisurfaces” in CityGML, an ad hoc transformer called “ConvertGeometry” is created Figure 12. The correct conversion of the geometries was made possible by this transformer. The same combination of transformers is applied to each geometric data type, such as "IfcWindow," "IfcBuildingElementProxy," "IfcDoor," "IfcRoof," "IfcSlab," "IfcWallStandardCase," and "IfcWall." Since standard geometries in IFC are represented as "solids" but need to be transformed into "multisurfaces" in CityGML, a custom transformer called "ConvertGeometry" is developed specifically for this purpose. The "ConvertGeometry" transformer ensures the accurate conversion of geometries during the transformation process.

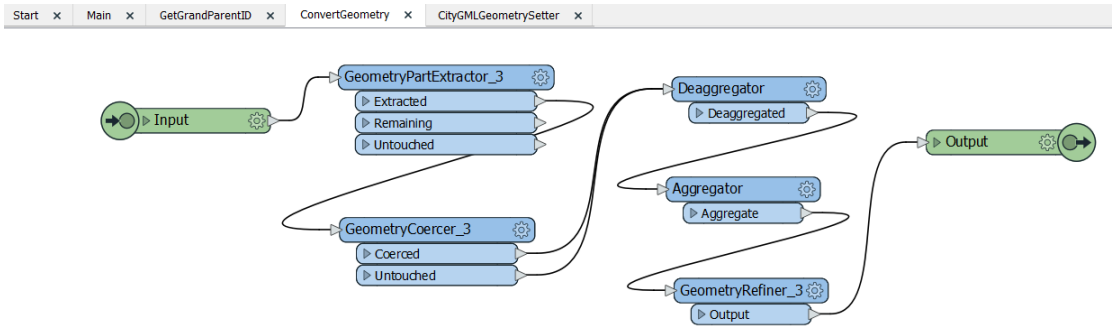

Figure 12: *ConvertGeometry custom transformer.*

A custom transformer was used to convert the complex IFC solid geometry to a MultiSurface geometry that can be supported and used in CityGML format. The transformer is named as ConvertGeometry and it is used for individual IFC types. This transformer separates the IFC solid geometry from the property sets and then it converts it into a surface. However, since the original geometry might have various levels of complexity, a "Deaggregator" transformer is used to break down multi-level geometries into simpler components. This is done by setting the Deaggregator's Mode to Flatten All. Once the multi-level geometry is flattened, it is re-assembled into MultiSurfaces, which are more suitable for use in CityGML. Each custom transformer necessitates the creation of a new workspace containing a mix of transformers. In this case, “GeometryPartExtractor” is used to extract the geometries from the features, “GeometryCoercer” was used to make them “composite surface,” and “Deaggregator” was used to disaggregate them on multiple levels. Deaggregator is used to decompose an aggregate feature into its components as it can be seen from the geometric representation and the data structure representation of the feature of Figure 13.

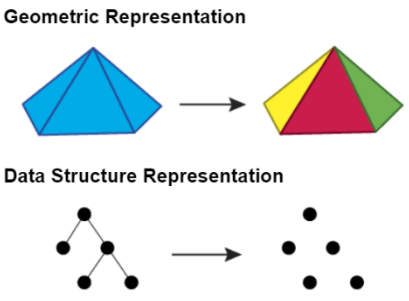

Figure 13: *Geometric and Data Structure Representation*

Following that, the “Aggregator” is used to combine geometries into “multisurfaces,” and the “GeometryRefiner” is used to perform “refinements” on the geometry of features. Aggregator combines feature geometries into heterogeneous or homogeneous aggregates. It is used to combine feature attributes without any geometry. This is done in order the features can be received by this transformer. This transformer is shown on a Geometric level and a data level. Following the geometries conversion, the “BinaryEncoder” and “VariableRetriever” are added to read the pre-set “_parent id” variable and attribute the corresponding “_parent type”. The “ifc unique id” field was renamed to “gml id” using “AttributeRenamer.” This step is useful for establishing a relationship between the IFC and CityGML standards. AttributeRenamer, renames one or more attributes while attributes current values are remained. The names are added, and values of the attributes do not change.

This custom transformer employs a BinaryEncoder transformer with an Attribute to Encode User Parameter. The VariableRetriever tranformer is then added to set the _gparent id. A variable that was previously set by the VariableSetter transformer is read using the Variable Retriever transformer. The “Tester” transformer is used to test the hierarchy of each feature in turn. Tester transformer evaluates one or more tests on a feature, so that the feature can be routed according to the outcome of the test(s). The Tester evaluates each feature against one or more tests that are defined by user and outputs the feature via the Passed/Failed port if fulfils the defined conditions. Test Clauses are used to construct a test which are connected with Logical combinations of AND, OR, and NOT, and parentheses to define evaluation order.

Then, a new ad hoc transformer named “GetGrandParentID” (Figure 16) is created, the “_parent id” field is codified, and the corresponding value is assigned in the “_gparent id” one, which was then decoded using the “BinaryDecoder.” IFC features are linked to their parent features. The first step is to remove intermediate features (like Openings) that are not needed and are linked to their grandparent. To implement this two separate IFC readers are used. This first reader labelled as <All> reads all the IFC features and generates a lookup table of feature and parent IDs as variables, and a lookup table of parent types. IFC geometry is not used in this reader, so the execution of the task runs quickly. FME runs its readers sequentially and lookup tables will be completely created before the second reader begins. Using the lookup tables stored in the variables, the custom transformer GetGrandParentID creates the CityGML parent link to the building.

Figure 14 shows the get grandparent ID custom transformer was created so that all figures that have a parent link set to the IFC Building need to move up one link to create the CityGML parent link to the building, using the lookup tables stored in the variables. In order to be able to write out a CityGML file, a strict naming convention is needed for some attributes. CityGMLGeometrySetter custom transformer is used to prevent data entry errors that can occur. Finally, the _gparent id is decoded, and another User Parameter for Destination Attribute is generated using the BinaryDecoder transformer.

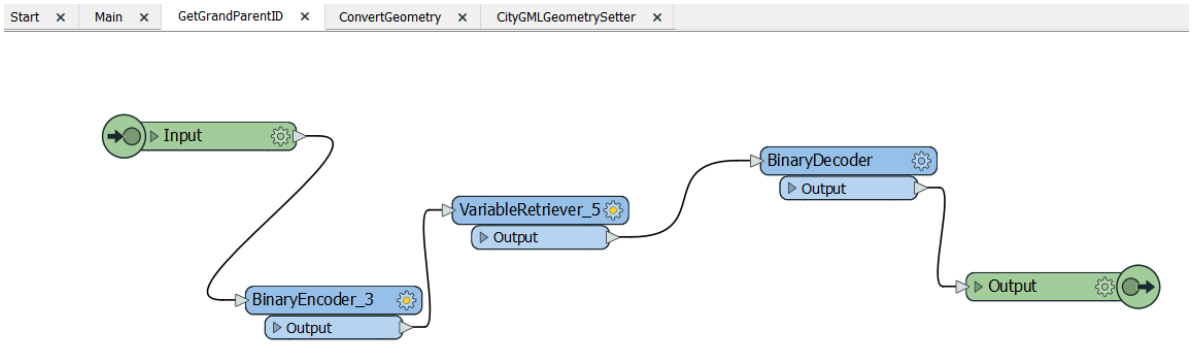

Figure 14: *Get grandparent ID custom transformer.*

In the workspace setup, the final component is called the "CityGMLGeometrySetter," illustrated in Figure 15. This component is composed of two parts: the "AttributeCreator" and the "GeometryPropertySetter." The "AttributeCreator" is responsible for generating attributes such as "citygml lod name" and "citygml feature role." These attributes can be derived from fixed values, existing attribute values, calculations, or even used to reference nearby features. On the other hand, the "GeometryPropertySetter" is designed to appropriately assemble these attributes within the geometry properties. (Software Tutorial “Writing CityGML from FME).

The "AttributeCreator" function involves creating attributes that can be obtained from fixed values, existing attribute values, and calculated expressions. These values can also be used to point to nearby features. The "GeometryCoercer" is a tool that modifies the geometry type of a feature. It can change the way a shape looks. This transformer is utilized to modify the geometry representation of an area feature, treating it as if it were a linear feature. This might be done either due to specific processing requirements that involve lines, or because the intended output format portrays lines differently than polygons.

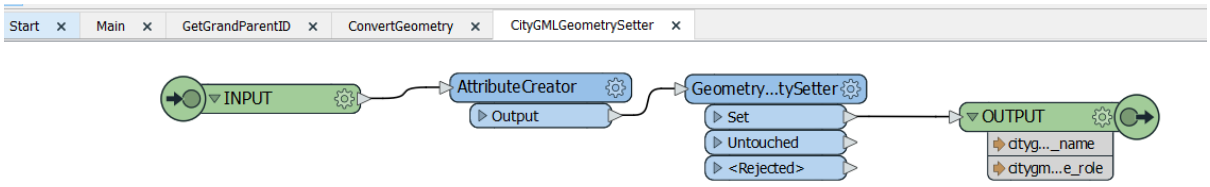

Figure 15: *CityGMLGeometrySetter custom transformer.*

The next part was to remove the current complex geometry of the IFC and to set a gml_id by renaming the ifc_unique id using the AttributeRenamer transformer. The conversion begins by generating new GML IDs, rooted in the original IFC element IDs. An essential element of this process involves translating the parent-child relationships internal to the IFC model to the corresponding structure in the CityGML framework. To facilitate this alignment, each distinct feature within the CityGML model is equipped with an attribute that establishes a meaningful connection with the GML ID of its parent element. This ID links the parent-child associations within the CityGML model. An example of the different parent-child relationship between IFC and CityGML can be the case of opening layers in IFC of

windows and doors to the wall. While IFC may depict windows and doors as individual layers connected to walls, CityGML treats them as abstract components with a shared parent-child dynamic. The complete process of an IFC window transformation into a CityGML can be seen in Figure 16.

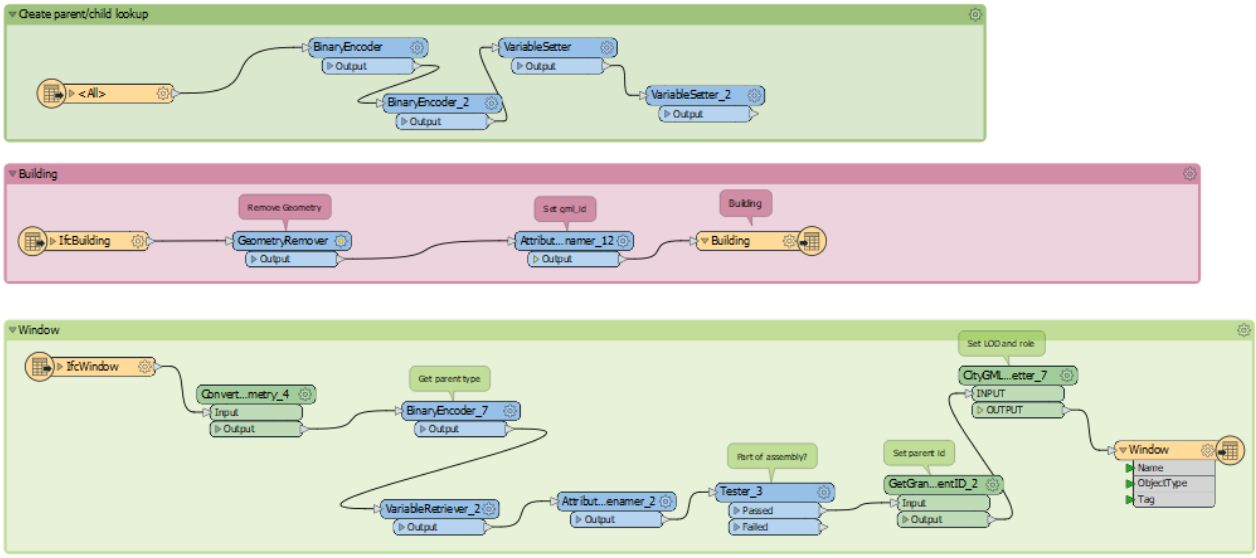

Figure 16: *Shows the example of the FME conversion of the IFC file to CityGML giving the example of the IFCWindow.* (BIM to GIS (Intermediate) | IFC LOD 300 to LOD 4 CityGML[6])

3.2.2. Summary

Using laser scan data, a comprehensive 3D model of the building is generated using BIM technology. This model accurately represents the building's geometry, including its structural elements and architectural details. Semantic web technologies are employed to enrich the BIM model with environmental data and information about damages. This process involves establishing connections between the building data and relevant environmental data sources, as well as associating the damages with their respective locations and causes. To seamlessly integrate with GIS, the BIM model, originally in IFC format, is converted to CityGML format. This conversion is facilitated by utilizing FME (Feature Manipulation Engine) software, which enables data transformation and manipulation. FME is utilized to specify the input and output data formats, and to employ transformers that manipulate the data structure as needed. Custom transformers may be developed to handle specific tasks, such as converting complex solid geometries from the IFC format to MultiSurface geometries in the CityGML format. Once the data has undergone transformation, it is written into a CityGML file using the "Writer" transformer within FME. This resulting CityGML file incorporates the converted BIM model, along with the integrated environmental data and damage information. The CityGML file, which encompasses the merged building and environmental data, is visualized within a GIS environment utilizing QGIS software. This visualization enables stakeholders to assess the building's conservation status and analyze the impact of surrounding hazards. By integrating BIM technology, semantic web technologies, FME data transformation capabilities, and GIS visualization, the

project provides a platform for informed decision-making regarding the preservation and resilience of the historic building. The integration of building and environmental data facilitates a holistic understanding of the building's vulnerability to natural hazards, supporting the development of strategies to mitigate risks and enhance its resilience.

4. Project Implementation

4.1. Case study – Karmiotissa Church

The church of Panagia Karmiotissa shown in Figure 17 is located north of Pano Polemidia area in Limassol, Cyprus. The church was constructed in late 13th-early 14th century. The architecture of the building follows the Gothic style and, specifically, it has a single-nave, without apse basilica, roofed with a pointed arch and two attached rooms on the northern side, which today can be meet in a ruinous state. (Digital Heritage Lab n.d). The church was digitized by a team of researchers from the Cartography, Photogrammetry and Remote Sensing Laboratory of the School of Civil Engineering and Geodesy of the University of Ljubljana, Slovenia with collaboration of Digital Heritage Research Lab of the Cyprus University of Technology (DH-Lab) as part of the European Erasmus + mobility program for teaching and practice. The digitization of the building was implemented using state-of-the-art equipment for 3D digital scanning and recording, as well as unmanned aerial vehicles (drones). The terrestrial laser scanning techniques were applied internally and externally to obtain the whole 3D model of the church.

Figure 17: *The medieval church of Panagia Karmiotissa, Pano Polemidia, Limassol, Cyprus*

Photogrammetry is a technique that uses images taken from various points of view to create a 3D reconstruction of buildings (Grussenmeyer et al., 2001). The resulting point cloud is enriched with colour information, which is an advantage of this technique. This could aid in informing people about the state of conservation of historical buildings. Laser-grammetry is the simplest and fastest technique (Fuchs et al., 2004). It is a real-time and direct acquisition solution that uses a laser beam to project onto the surface to be measured. (Boehler et al., 2002). Laser scanners calculate angles (horizontal and vertical) and distances by calculating the time of flight or comparing the phase shift of a modulated signal's transmitted and received waves.

The data were then processed resulting in the export of the exact 3D model of the church. Data from the laser scanner and drones were used to generate the point cloud of the building. The point cloud was then imported by the DH-Lab team in Autodesk Revit to represent the building in a parametric 3D BIM environment as it can be seen in Figure 18

and Figure 19 of a 3D parametric model of a church, developed by a point cloud from Autodesk Recap.

Figure 18: *Point Cloud Model of Panagia Karmiotissa (Autodesk Recap)*

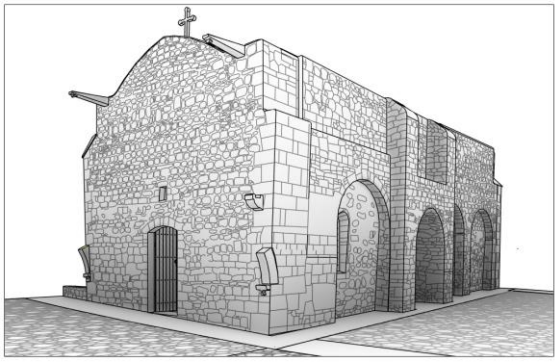

Figure 19*: Building Information Model of Panagia Karmiotissa (Autodesk Revit)*

4.2. Transformation of Karmiotissa church BIM model to CityGML with FME

The process of transforming the IFC file to CityGML with FME (Safe Software. n.d.). workspace was presented in detailed on the previous chapter. The IFC filed obtained from the Revit model was transformed into CityGML. The main workflow is described in summarry below and it can be seen in Figure 20:

1) Read in IFC data and create parent/child lookup

The IFC data was read using two readers. The first reader, named "All," extracted all the IFC features of the entire building. It created a lookup table of feature and parent IDs as variables, along with a table of parent types. This step facilitated the linking of child features to their parent and grandparent features.

2) Create building

To prepare the data for conversion, the GeometryRemover transformer was used to remove any existing geometry from the features. Then, the AttributeRenamer transformer assigned the IFC unique ID to the GML ID, ensuring consistent identification. The IFC solid geometry

was converted to MultiSurface geometry, which is compatible with CityGML. A custom transformer called ConvertGeometry was developed to separate the IFC solid geometry from the property sets and aggregate it into MultiSurfaces.

3) GetGrandparentID

In order to create the CityGML parent link to the Building, a custom transformer named GetGrandparentID was utilized. This step was necessary because most features had their parent link set to the IFC Building Story instead of the Building itself. The custom transformer used the lookup tables stored as variables to establish the correct parent link.

4) Write out to CityGML.

The final step involved writing the transformed data to a CityGML file. A custom transformer called CityGMLGeometrySetter was employed to set the CityGML Level of Detail (LoD) name and the Feature Role. This ensured compliance with the strict naming conventions required by CityGML. The process also accounted for data entry errors, preventing any inconsistencies in the resulting CityGML file.

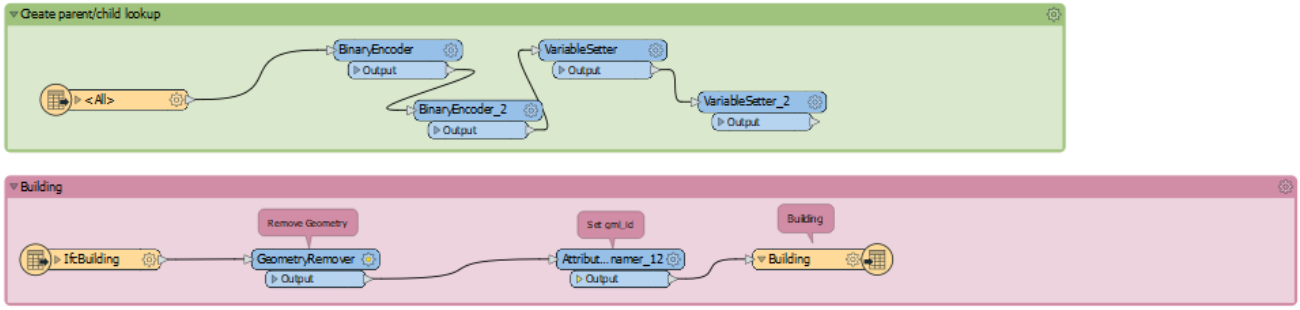

Figure 20: *FME workflow for the transformation of the IFC file to CityGML*

Figure 21 showcases the resulting CityGML model of the building in FZKViewer, comprising the roof, exterior wall, and other architectural elements. This CityGML representation corresponds to a detailed architectural model at Level of Detail (LoD) 4, encompassing roof structures, walls, interior architecture, and windows.

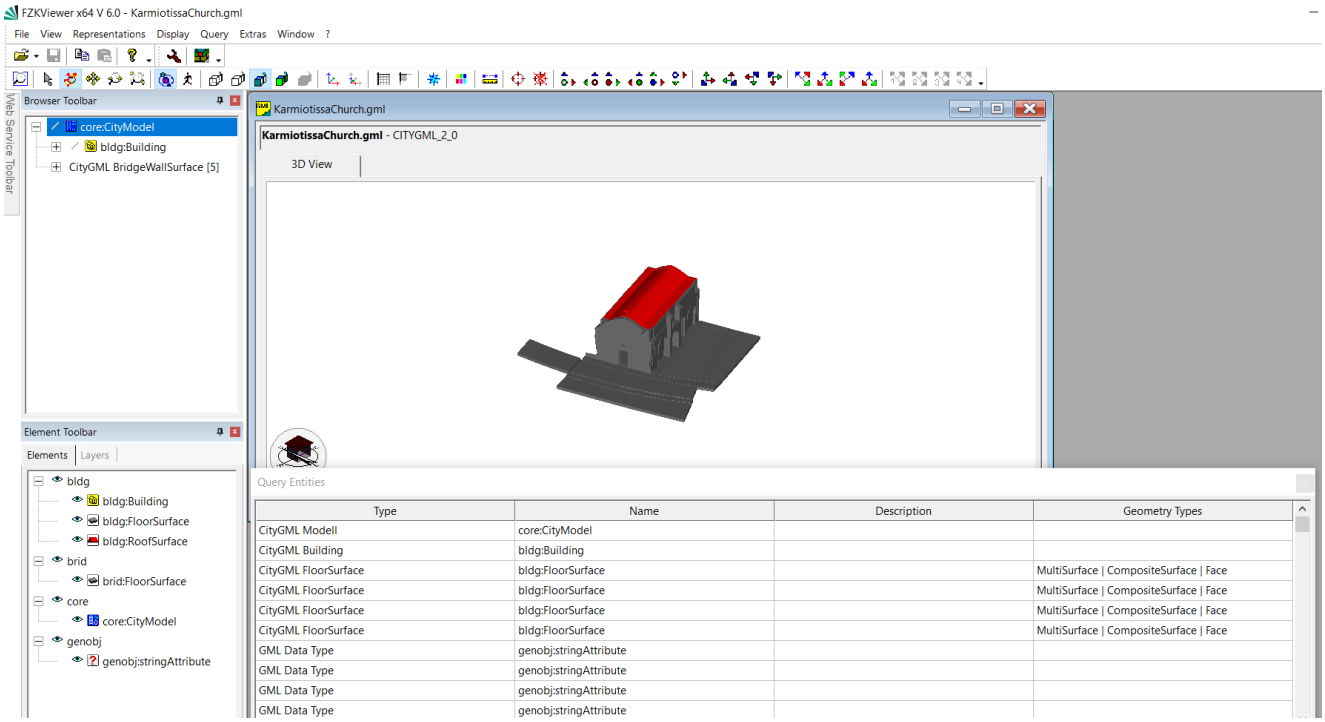

Figure 21: *Visualisation of the CityGML model of the structure in FZKviewer.*

4.2. Positioning of 3D Models for CityGML

It is important to note that IFC files lack geographic information and utilize a Cartesian coordinate system, where the origin of the file is set at (0, 0, 0). In order to properly position the CityGML model within QGIS, which is based on a Geographic Coordinate System (GCS), certain adjustments are necessary. GCS establishes Earth locations through a 3D spherical surface, utilizing angular measurements, a prime meridian, and a datum based on the spheroid. Unlike Cartesian coordinates, GCS's latitude and longitude do not offer consistent distance measurements, except along the equator where one degree of longitude is equivalent to one degree of latitude. Different regions across the globe have specific GCS systems developed to account for varying representations of distance in longitude and latitude.

The FZK Viewer offers a tool to set the desired coordinate system, facilitating the transformation process. By applying this transformation and selecting the appropriate coordinate system, the 3D GCS-based model can be accurately positioned and integrated into the CityGML format, enabling effective analysis and visualization of historic buildings and their surrounding environment in a geospatial context. (Jusuf et al., 2017). To position the CityGML model, which is originally based on Cartesian coordinates, onto the Geographic Coordinate System (GCS) used in QGIS, a transformation process is required. The IFC files do not inherently contain geographic information, and their Cartesian coordinates have the origin at (0, 0, 0). GCS is defined by a spherical surface and uses latitude and longitude to locate points on Earth. However, it's essential to highlight that the measurement of distances using latitude and longitude is not uniform, except along the equator where one degree of longitude corresponds to one degree of latitude. Diverse GCS systems have been created for various regions to address the diverse ways in which distance is represented in terms of longitude and latitude.

To convert the 3D Cartesian model into a 3D GCS-based model suitable for CityGML, a projected coordinate system is selected. Projected coordinate systems convert the curved surface locations to flat plane locations, which is necessary for 3D projection. In this case, the selected coordinate system is "EPSG:3857," which is relevant for Cyprus. When reading the IFC files, a bounding box is determined based on the model's size. The FZK Viewer, a software tool, provides a feature for setting the desired coordinate system. By applying this transformation and selecting the appropriate coordinate system, the CityGML model can be positioned correctly within the QGIS environment, aligning it with the Geographic Coordinate System used for spatial representation in QGIS. This process ensures the proper integration of the 3D GCS-based model into the GIS platform, enabling effective analysis and visualization of the historic buildings and their environmental context within the selected geographical area.

To visualize the building in its context and query the geometries, the GML file was imported into QGIS. The cartographic data, as well as the 3D model of the building, can be visualized using the 3D Map window in the QGIS software as it is illustrated in Figure 22.

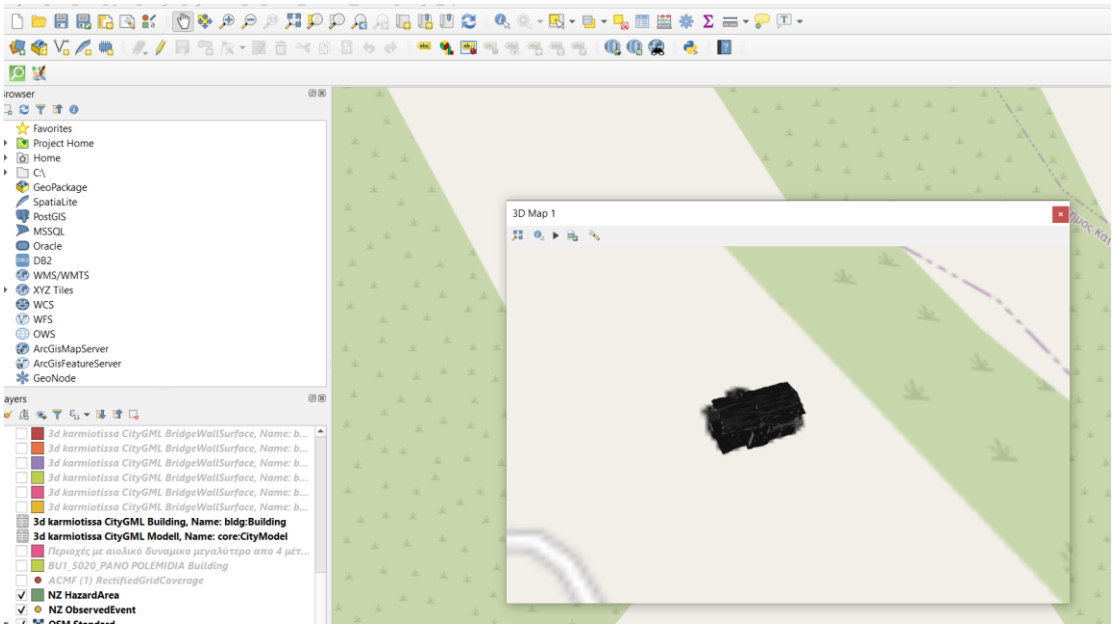

Figure 22: *The 3D model of the building can be visualised in the QGIS map from 3D map window with coordinates based on ESPG:3857*

4.3. GIS Data

4.3.1. Flood Risk GML data

Flood Risk Maps were acquired from the Department of Water Development of Cyprus and referred to areas that have been identified as Potentially Serious Flood Risk Areas based on historical data are shown in *Figure 23*.

The Flood Risk Maps present 3 flood scenarios.

1) Flood with a probability of 1 in 500 years (low probability i.e., rare/extreme phenomenon)
2) Flood with a probability of 1 in 100 years (average probability)
3) Flood with a probability of 1 in 20 years (high probability)

For each of the three scenarios the extent of the flood and the depth of the water are presented.

Using the 3 flood scenarios based on the map the impact of flood on the structure can be assessed. The data download process is implemented through "GML" file packages. The GML files contain the necessary information to represent the flood extent and water depth for each scenario, enabling further analysis and assessment of the potential impact on the structure.

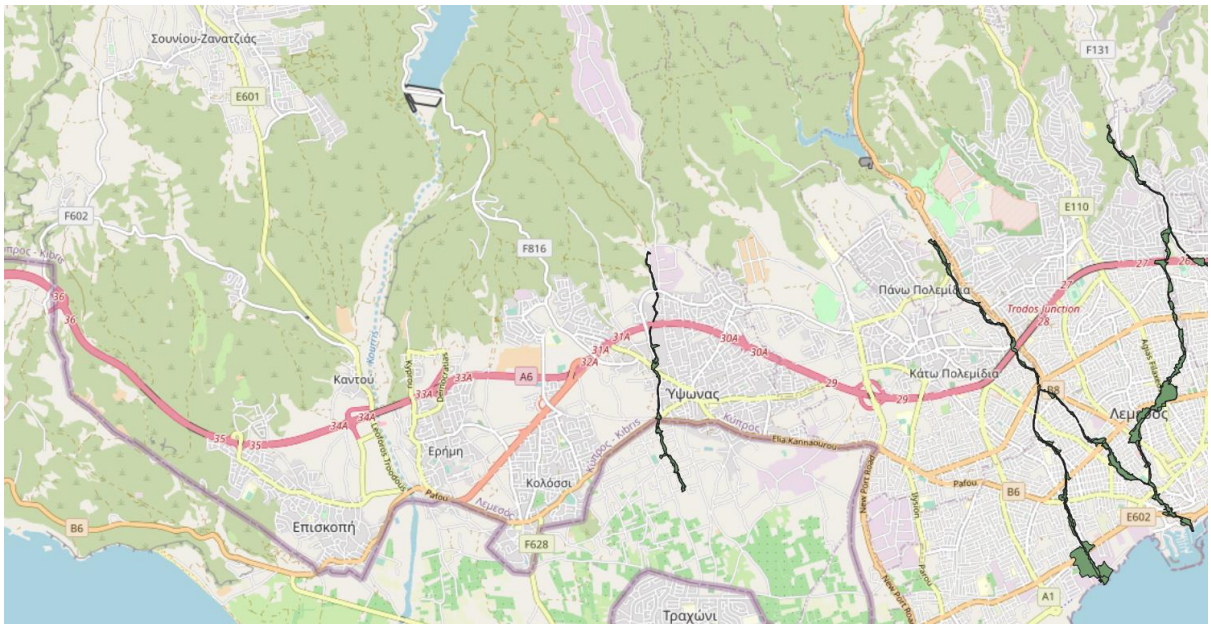

Figure 23: *Flood Risk Maps acquired from the Department of Water Development of Cyprus*.

4.3.2 Earthquake Hazard Zones GML data

Map of Earthquake Hazard Zones and Other Geological Hazards (INSPIRE) are shown in Figure 24. The maps were provided from the Geological Survey Department of Cyprus portal and historical earthquakes can be shown. Yellow points on the map indicate the epicentre of past earthquakes. The earthquake hazard zones identify areas that are susceptible to seismic activity and potential ground shaking. These zones are determined based on various factors such as historical seismicity, fault lines, and geological characteristics. By visualizing the earthquake hazard zones on the map, it becomes possible to assess the level of seismic risk in different areas. By analyzing the Map of Earthquake Hazard Zones and considering the locations of historical earthquakes, engineers can gain insights into the potential earthquake risks in the area and make informed decisions regarding the design,

construction, and retrofitting of structures to enhance their resilience against seismic events.

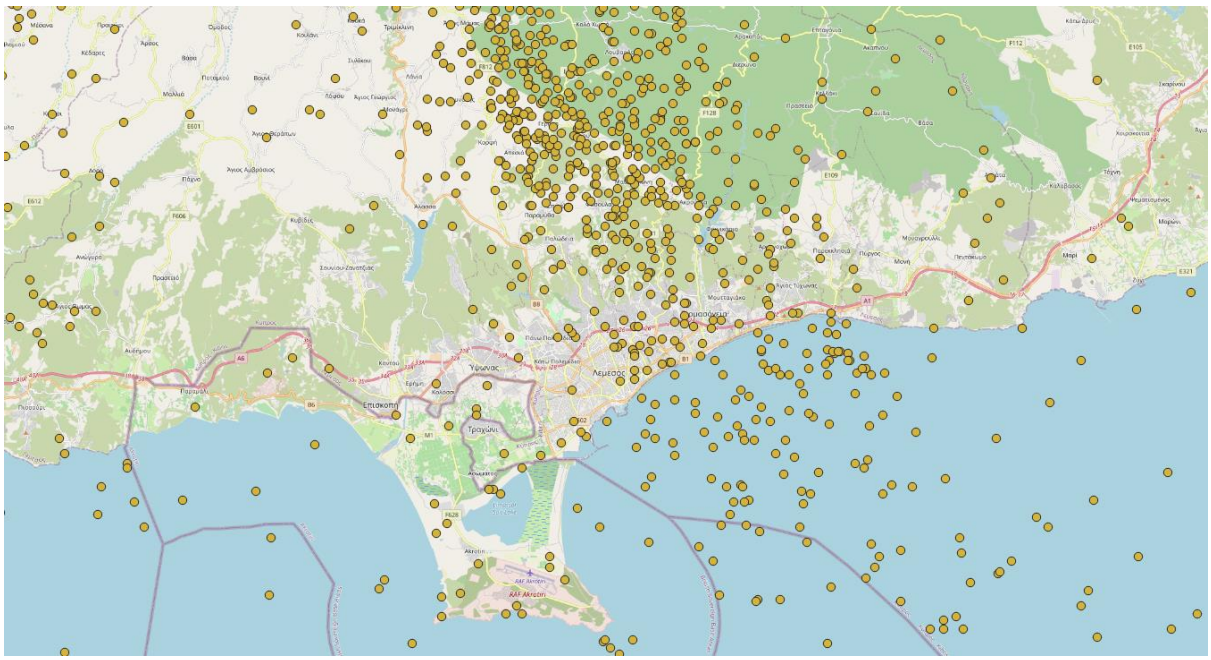

Figure 24: *Map of Earthquake Hazard Zones and Other Geological Hazards (INSPIRE).*

4.3.3. Wind GML data

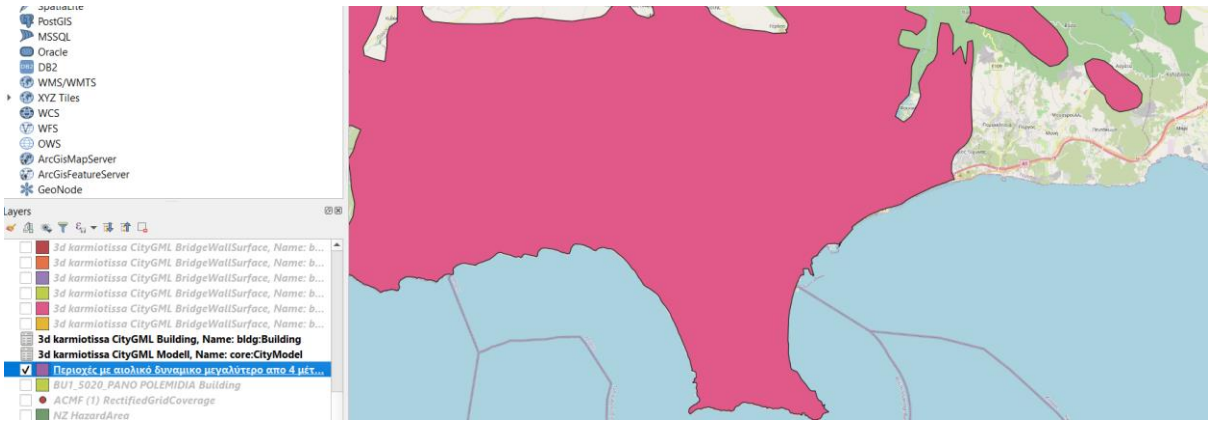

Figure 25: *GML layer shows the areas with a wind speed larger than 4m/s in QGIS*.

Figure 25 shows the areas experiencing higher wind speeds, which is essential for assessing wind hazards, understanding wind patterns, and making well-informed decisions regarding infrastructure, construction, and land use planning. The inclusion of a GML layer aids in identifying areas that may require precautionary measures to mitigate the potential impact of these high wind speeds. Figure 26 shows the building model in QGIS alongside the GML data representing environmental hazards. The yellow spots indicate past earthquakes in the region, while the dark-green layer represents instances of flooding. It is evident from the map in figure 26 that the building is not directly threatened by flooding. However, it is susceptible to wind forces and earthquakes, as indicated by the presence of these hazards.

Furthermore, regarding the church's placement with respect to recorded earthquake epicenters, this geographic proximity to historical earthquake events offers conservation engineers significant advantages. By understanding the church's proximity to past earthquake occurrences, engineers can conduct a risk assessment to gauge the potential impact of seismic events on the building's structural integrity. This assessment involves a careful analysis of the building's design, materials, and construction methods, coupled with the historical seismic activity data.

In the context of linking past earthquakes to cracks, this knowledge is invaluable. If the church has experienced earthquakes in the past, it's likely that these seismic events might have contributed to cracks or structural vulnerabilities. Conservation engineers can examine the building's historical records and conduct on-site inspections to identify any existing cracks or structural damages that might have resulted from previous earthquakes. By understanding the correlation between seismic activity and structural issues, engineers can develop targeted strategies for reinforcement, retrofitting, or restoration to enhance the building's resilience against future earthquakes. Thus, the knowledge of past earthquake occurrences and their potential impact on the church's structural integrity empowers conservation engineers to undertake proactive measures and ensure the preservation of this historic structure.

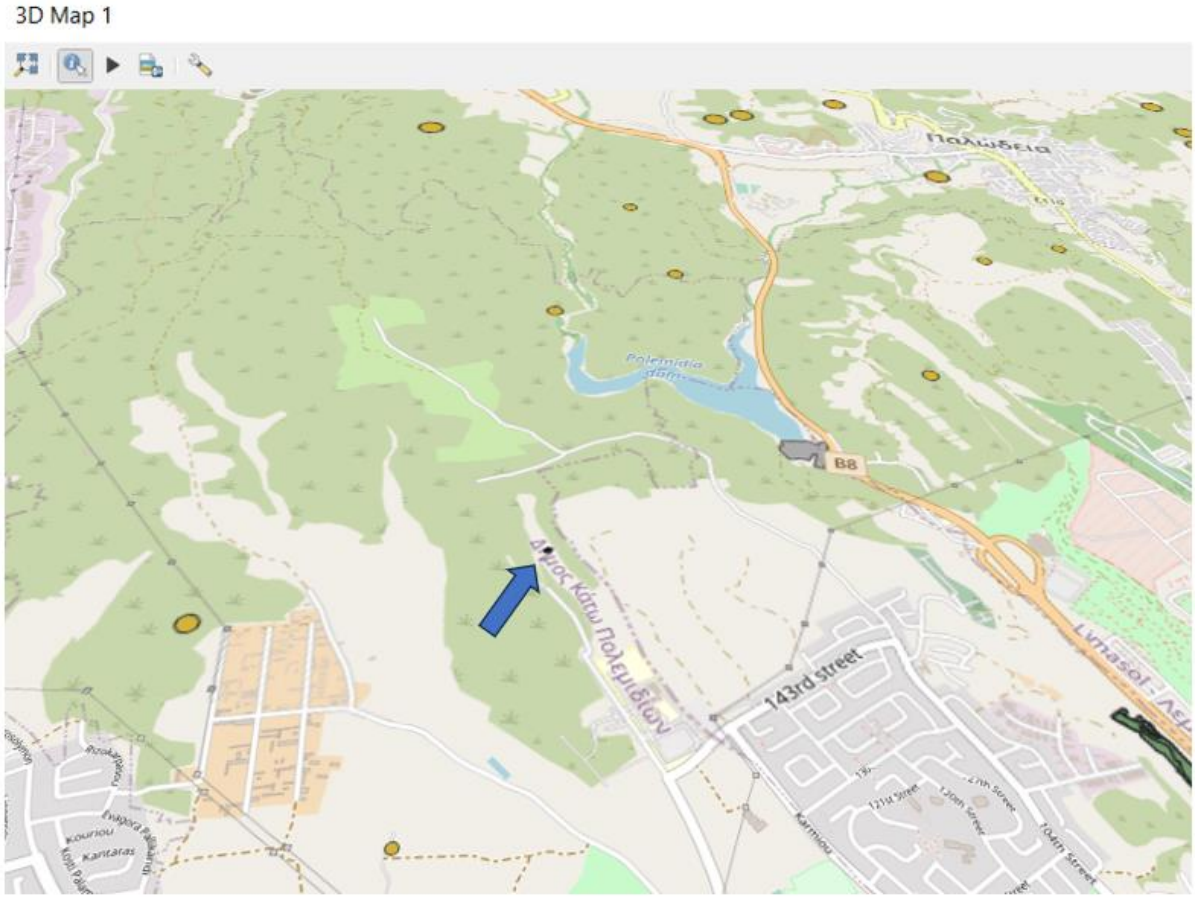

Figure 26: 2D visualisation of the building in QGIS where the local natural risks are located.

4.3.4 Conclusion

The process that was implemented to digitize the church of Panagia Karmiotissa and create a comprehensive 3D model was presented. Cutting-edge equipment and techniques, such as terrestrial laser scanning and photogrammetry, were utilized by DH-Lab to generate a highly detailed and precise representation of the church. These 3D models serve multiple purposes, including documentation, preservation, and visualization of cultural heritage. Photogrammetry is valuable for capturing the visual appearance and condition of buildings, producing high-resolution images and point clouds that enable detailed analysis of architectural features. The conversion of an IFC file to a CityGML model was presented, along with the step-by-step process and techniques employed to ensure accurate data conversion and proper positioning within a geographic coordinate system. By transforming an IFC file into CityGML, the building information can be seamlessly integrated into a 3D city model and utilized in GIS software like QGIS. The adoption of a projected coordinate system, such as EPSG:3857, is crucial for converting the 3D Cartesian coordinates from the IFC file to a 3D geographic coordinate system suitable for visualization and use within GIS software. The resulting CityGML model offers diverse applications, including contextual visualization of the building, analysis of its characteristics and vulnerabilities, and assessment of potential risks such as flooding and seismic hazards.

5. Semantic Data Management

By constructing an ontology and defining relationships between different natural elements and their subclasses, has significant implications for the field of heritage conservation. This process enables the description of damages that occur on heritage buildings due to various natural phenomena. The ontology essentially serves as a structured framework that captures and organizes knowledge about these natural hazards and their effects on historic structures. By establishing relationships between concepts like earthquakes, flooding, wind, rain, and their subclasses within the ontology, a comprehensive representation of the natural events is created that can potentially impact cultural heritage buildings. This means that the ontology can capture various levels of detail, from general natural events to specific types of damages caused by them.

This structured representation of knowledge is incredibly valuable because it provides a solid foundation for various processes related to heritage conservation. Conservation engineers can analyse the ontology to understand the potential risks and vulnerabilities of heritage buildings to different natural events. They can identify patterns and trends in damages caused by specific events over time. The ontology allows for the creation of predictive models that simulate the potential impacts of different natural events on heritage buildings. Engineers can simulate scenarios and assess the potential damages under various conditions. When making decisions about conservation efforts, restoration, or retrofitting, engineers can refer to the ontology to understand the historical and potential damages caused by specific natural events. This informed decision-making improves the effectiveness of preservation strategies. The ontology provides a standardized language for communication among conservation professionals, researchers, policymakers, and other stakeholders. It ensures that everyone is on the same page when discussing risks and mitigation strategies. The ontology can be integrated with other tools, systems, and data sources, making it possible to automate data collection, update analysis results in real time, and integrate with GIS and BIM for comprehensive visualization and assessment.

A comprehensive understanding of the relationship between natural elements and their impact on heritage buildings was achieved through the development of an ontology. The ontology serves as a common language and framework for representing and organizing information about natural elements and their effects on heritage buildings. The ontology plays an important role in enhancing the analysis, assessment, and preservation of heritage buildings by providing a structured and systematic approach to understanding the relationship between natural elements and their impact on these structures.

Protégé 5.1 was selected as the tool for developing the ontology due to its flexibility and capabilities in application development. Its graphical knowledge acquisition system simplifies the input of content knowledge specific to this application, enhancing knowledge browsing and entry for users. Ontologies can be stored in Protégé using various formats such as relational databases, UML, XML, and RDF ((N. F. Noy, et al., 2003). Protégé 5.1 provides a user-friendly interface, making it accessible for engineers and stakeholders in the

cultural heritage field who may not be comfortable to working with complex ontology development tools. Protégé 5.1 also supports OWL for representing ontologies.

The natural element ontology, presented in Turtle syntax, includes the "Nature" class and its subclasses: "Earthquake," "Flooding," "Rain," and "Wind," as illustrated in Figure 27 and 29.

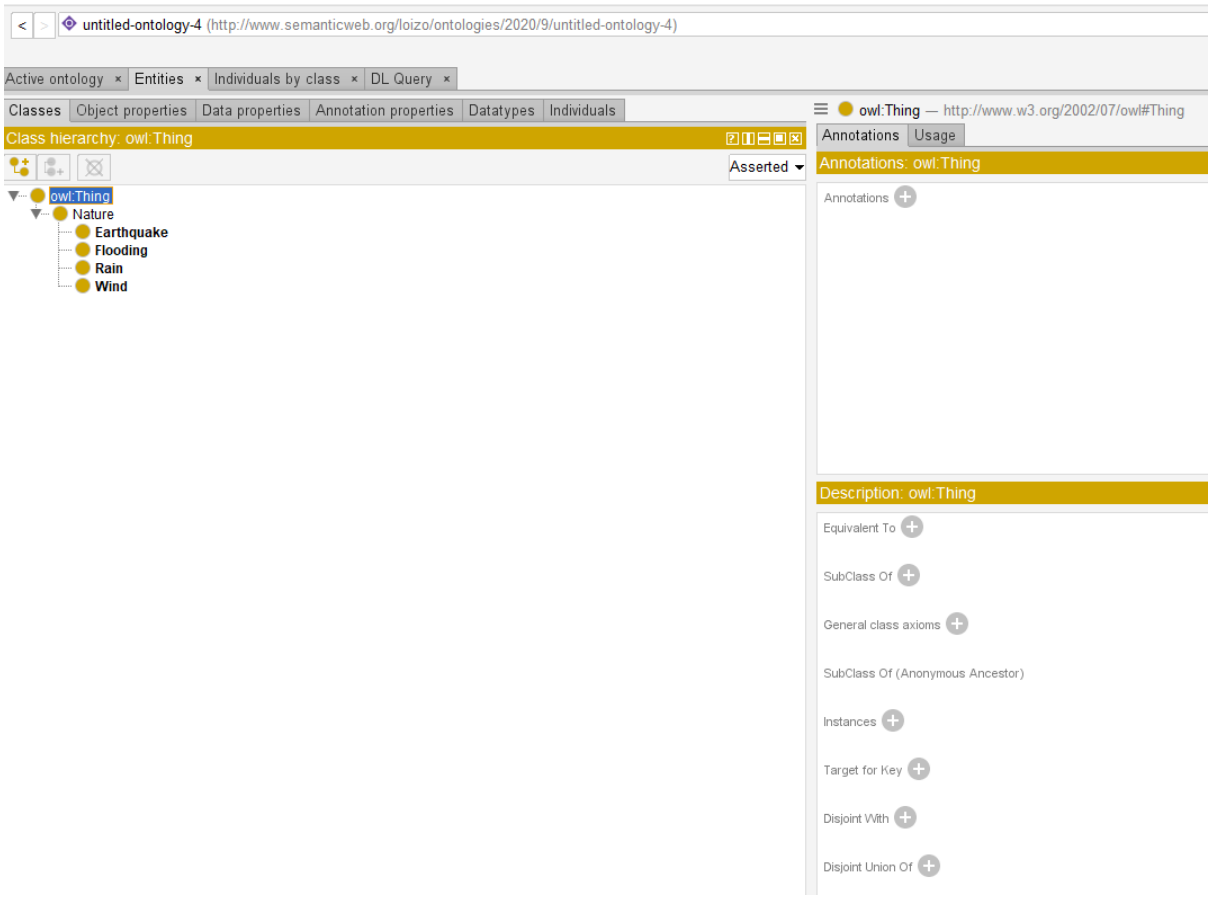

Figure 27: *The construction of the OWL ontology in Protégé for the environmental elements:*

Protégé also provides a valuable feature allowing the addition of comments as annotations to classes. Furthermore, properties were established for the classes, specifying their domains, data types, and ranges. Each property was associated with the relevant class as the domain. Figure 28 demonstrates how the domain of "Historic Earthquakes" is linked to the earthquake class. Historic earthquakes refer to recorded seismic events that occurred near the church.

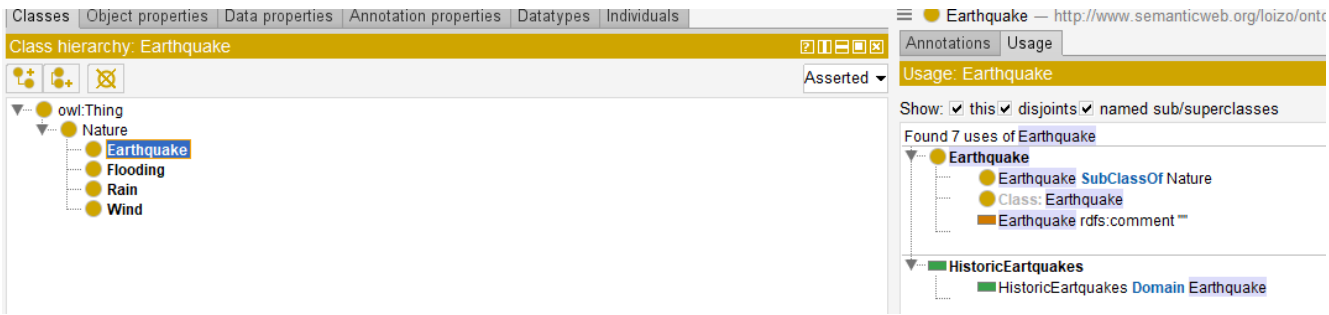

Figure 28: *Earthquake class annotated with historic earthquakes.*

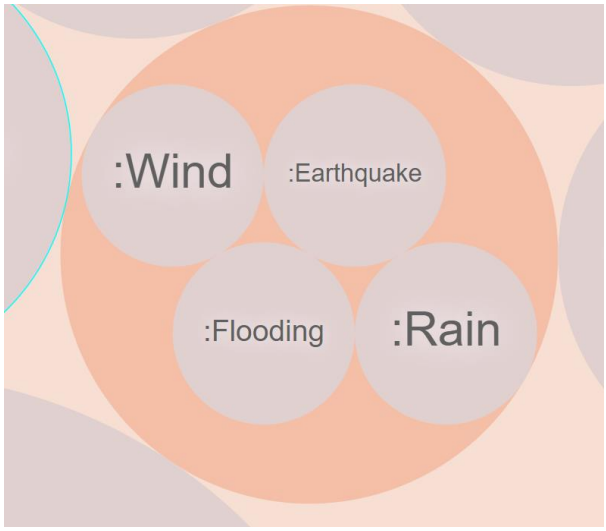

Figure 29: *The nature class with four subclasses of Rain, Flooding, Wind and earthquake visualised in GraphDB.*

5.1. IFC to Linked Building Data Converter

IFCtoLBD tool facilitates the conversion of IFC files that are used in BIM into Linked Building Data (LBD) ontologies. BIM systems generate IFC files to store building data and information about different building elements, such as walls, floors, doors, and windows, in a standardized format.

The IFCtoLBD converter is a software tool designed to convert IFC files, which are typically in STEP format, into Linked Building Data (LBD) ontologies. It supports the conversion of IFC files exported from different BIM systems into RDF graphs. By taking the IFC graphs as input, the converter transforms them into RDF Abox graphs based on the ifcOWL ontology. This converter is a modified version of Jyrki Oraskar's IFCtoLBD repository, specifically version 0.1, with significant modifications and self-moderation. It operates as a command-line tool without a graphical user interface and does not include a mapping step to the OWL version of IFC.

The IFCtoLBD repository is implemented in Java and is freely available as an open-source project. It enables the conversion of various IFC schemas to RDF using LBD ontologies. This repository is hosted on GitHub platform. The conversion process takes IFC files as input and generates output in the turtle file format. The tool leverages multiple ontologies, including the Building Topology Ontology (BOT[1]), Building Element Ontology (BEO[2]), and Distribution Element Ontology (MEP), among others. In summary, the IFCtoLBD converter offers a solution to convert IFC files into RDF graphs using LBD ontologies. This facilitates the integration of BIM data into semantic web environments and enables the utilization of linked data principles for the exchange and analysis of building information.

[1]https://w3c-lbd-cg.github.io/bot/

[2]https://pi.pauwel.be/voc/buildingelement/index-en.html

5.2. Building data Semantic-Enrichment

Using the IFCtoLBD conversion method the IFC model was converted into an RDF format. The next part was to enrich different building elements with cracks and erosion damages based on the building survey and point cloud. The semantically enrichment process was implemented by adding manually the cracks on the Turtle file using Notepad ++ as it can be seen in Figure 30. Turtle is a text-based format, you can open the .rdf file using a plain text editor. Turtle is a specific serialization format for RDF data, which provides a human-readable and compact representation of RDF triples.

Instead of manually adding damages using a text editor, automated methods to extract relevant information from the building survey and point cloud data can be explored in the future. By developing algorithms or scripts that can process this data and generate RDF triples representing cracks and damages. This reduces the need for manual intervention and minimizes errors. Another approach is to develop scripts or tools that can convert the survey data into RDF triples and seamlessly integrate it with the existing ontology. This approach ensures that the data enrichment process is not a separate manual step but an integrated part of the entire workflow. Another possible approach is to build a user-friendly GUI application that allows conservation engineers to interactively mark and define cracks and damages directly on the RDF model. This GUI can provide visualization tools that help engineers identify and mark damaged areas, which are then automatically converted into RDF triples. For the scope of this thesis the semantic enrichment process is implemented manually.

```
inst:wall_45
    a bot:Element ;
    a beo:Wall ;
    rdfs:label "Wall xyz"^^xsd:string ;
    rdfs:comment "Description of Wall"^^xsd:string ;
    bot:hasGuid "f92c2898-fd68-44ef-9178-3348e340017b"^^xsd:string ;
    bot:hostsElement inst:door_124 ;
    props:tag ""^^xsd:string ;
    props:combustible false ;
    props:thermalTransmittance "2.400E-1"^^xsd:double ;
    props:isExternal true ;
    props:extendToStructure false ;
    props:loadBearing false ;
    props:compartmentation false ;
    loizos:hasCrack inst:crack_1 ;
    loizos:hasErosion inst:erosion_1 .
inst:door_124
    a bot:Element ;
    a beo:Door ;
    rdfs:label "A common door"^^xsd:string ;
    rdfs:comment "Description of a standard door"^^xsd:string ;
    bot:hasGuid "157c866c-9c08-4348-a0ed-4d57cd66c9e2"^^xsd:string ;
    props:tag ""^^xsd:string .

inst:crack_1
    a loizos:Crack .

inst:erosion_1
    a loizos:Erosion .
```

Figure 30: *The semantically enrichment process on the Turtle file format using Notepad.*

Using the point cloud model, it was possible to identify types of damages and deterioration mechanism and associate those damages to their natural cause. Different types of damages were identified based on their nature of origin. Structural cracks related to earthquake, building weak points and erosion of external elements due to rain, wind and atmospheric environment were observed. Rain, for example, has been identified as a significant contributory factor to the extent of stone erosion. Importantly, rain is thought to be the cause of building façade surface erosion. Detachment occurs because of the wind and rain's long-term, continuous, repetitive, and synergetic action. Figure 31 shows how the inspected cracks were mapped on the building point cloud model side view.

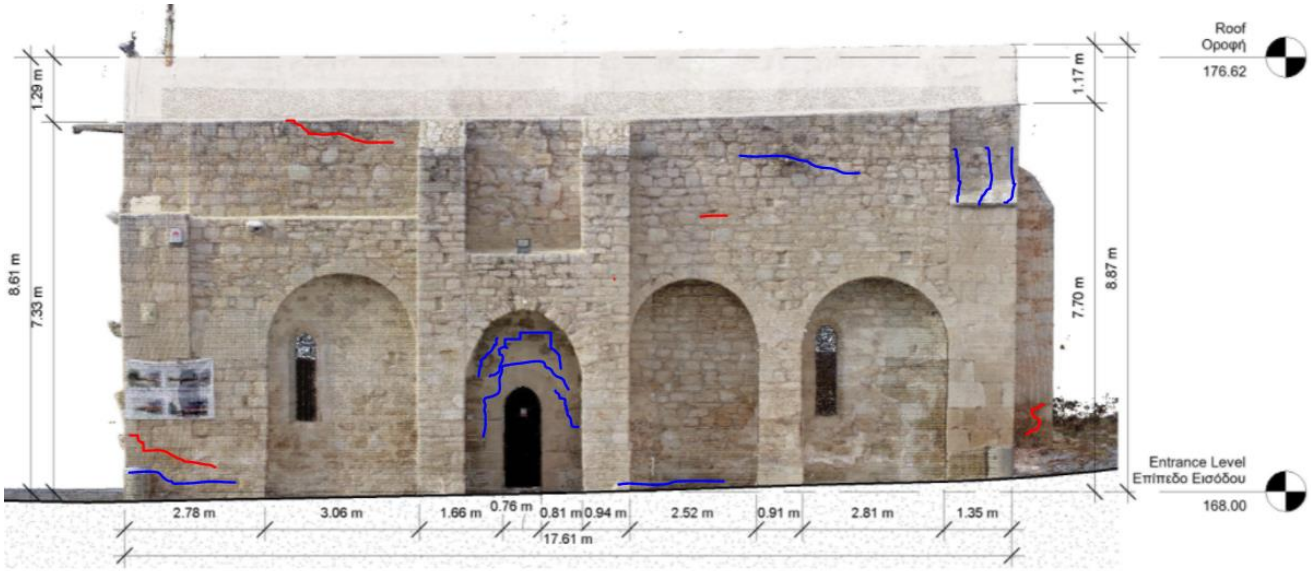

Figure 31: *Cracks and Erosion patterns on the building were manually added on the model during semantic enrichment process.*

Wind-driven rain (WDR) is rain with a horizontal velocity component provided by the wind, and it is one of the primary causes of surface erosion. The detachment of material from a stone masonry building façade caused by the physical impingement of erosion. Detachment occurs because of WDR's long-term, continuous, repetitive, and synergetic action. This erosive effect caused surface pitting, and the pits eventually acted as a drainage system, directing water down into the run-off water collection trays. That is, gradual erosion of the horizontally laid stones ridges created vertical grooves, allowing water to run off. Wind and rain erosion, as well as daily and seasonal thermal cycles, all contributed to the natural aging of materials on exposed surfaces of any structure.

Historic buildings are susceptible to significant damage from windy weather, which often carries sand and dust particles. To accurately assess the impact of wind on these structures, it is essential to have precise information about the local wind conditions, including the speed and direction, to conduct simulations. On average, the annual wind speed recorded at the location is 4 m/s. Computational Fluid Dynamics (CFD) can be employed to study wind erosion at heritage buildings, allowing for a detailed analysis of how the movement of particles in the wind contributes to the erosion of exposed surfaces. Erosion can be performed by rainwater, wind, ice or the sulphate and chloride environment of the air and water due to the close proximity of the sea.

Historical structures are frequently distinguished by an irregular form, both in plan and elevation, a lack of vertical joints and transversal braces, in-plane flexibility or the absence of floor slabs, and shallow foundations. Because of these characteristics, they are extremely vulnerable to even minor seismic events. The shearing of the bearing elements is the primary cause of seismic damage to masonry structures during an earthquake.

Cracks observed from the building surveying were divided in the three following categories, according to their nature.

Crack 1 – Wind erosion

Crack 2 – Seismic/structural Crack

Crack 3 – Flood erosion

This categorization enables the model to be effectively used in different areas with varying natural hazards. As it is shown in Figure 26 of section 4, it's evident that the church is not susceptible to flooding, which implies that the focus of damages is primarily on rain erosion and earthquake-induced structural damages. This observation aligns with the categorized cracks and their respective natures, as identified through the building survey. By categorizing cracks in this manner, a clear framework for understanding the nature of damages is provided but also streamlined the analysis and decision-making processes for conservation engineers. This categorization allows engineers to quickly assess the relevant types of damages that might affect a particular structure based on its vulnerability to specific natural phenomena. As a result, the model's adaptability and versatility make it a valuable tool for heritage conservation in different geographic regions and contexts.

The IFCtoLBD tool generated RDF files, which were then stored in Ontotext GraphDB 24. Graph databases are particularly well-suited for analyzing interconnected data by representing it as nodes and relationships with unique identifiers (Fatima & Wasnik, 2016). GraphDB, a web-based triplestore, serves as the storage environment for RDF triples, providing a user-friendly interface for data retrieval and display. It allows querying of data using SPARQL. In order to facilitate communication with the application, LBD were utilized to define the RDF graph of the BIM model, which was stored in a GraphDB web database. A new repository was created, assigned a unique ID, and provided with a base URL for the LBD ontology. The RDF structured data was loaded in the Turtle file format.

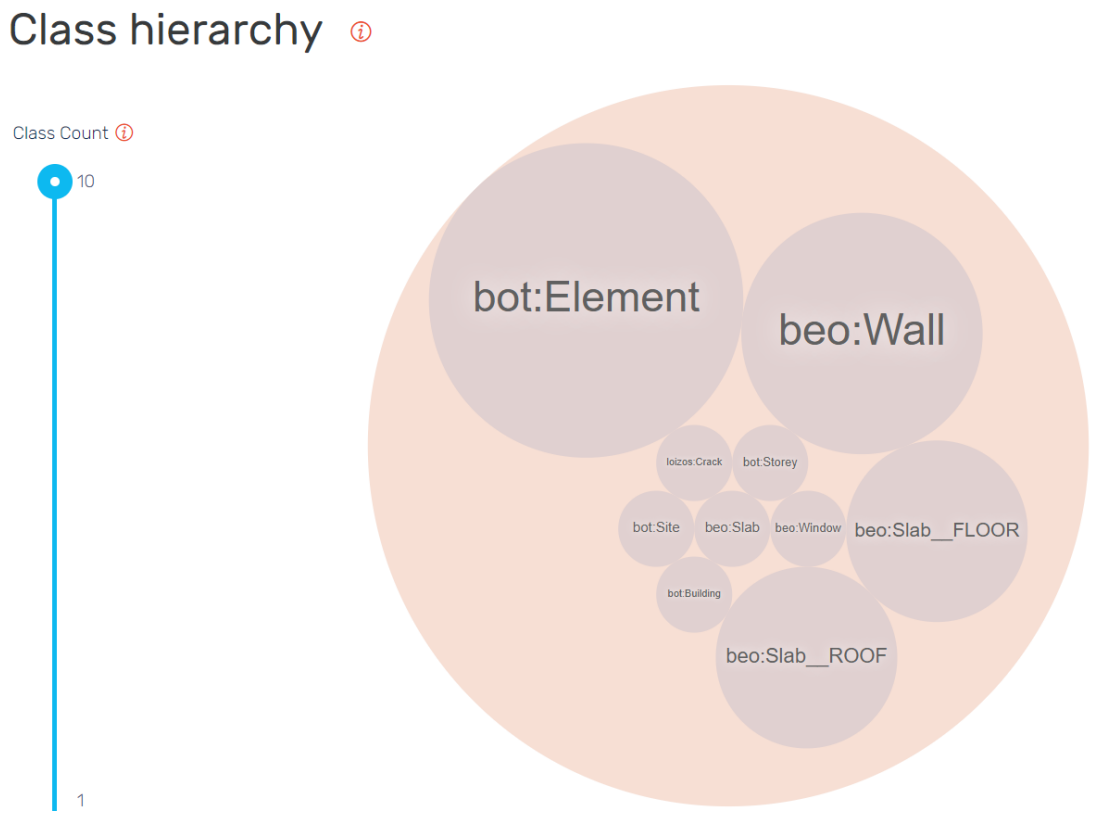

Figure 32: *Structuring IFC and cracks as liked data. The biggest circles are the parent classes and the nested ones are their children. GeaohDB*

Class relationships in the RDF graph are organized through property hierarchies, which can be defined using various ontologies. The BOT ontology, for example, defines relationships among sub-components of a building, such as structural elements, walls, and storeys. It focuses on topology specific to the building domain but does not offer a comprehensive overview of all topological relationships. On the other hand, the BEO is based on the IfcBuildingElement subtree in the IFC specification and provides a taxonomy of classes that define common building elements. Some classes in BEO serve as subject classes, while others function as object classes, and the relationships between these classes, represented as RDF statements or "predicates," are established through links or edges.

By defining classes, a clear and standardized vocabulary is established to represent different elements and relationships within the built environment. This vocabulary ensures that all stakeholders involved in the project, including conservation engineers, researchers, and policymakers, share a common understanding of the terms used to describe building components, hazards, damages, and other relevant concepts. The utilization of classes also enables the establishment of relationships between different elements in the RDF graph. These relationships are crucial for capturing the complex interconnections and dependencies between various components. For instance, by using ontologies like BOT and BEO, the thesis can define how structural elements, walls, storeys, and other building components are related to each other. This not only allows for a more accurate representation of the building's composition but also facilitates the modelling of potential impacts and damages caused by natural hazards.

Furthermore, classes help in creating a structured framework for querying and analysing the data. Conservation engineers can use these defined classes to formulate queries that extract specific information from the RDF graph. This facilitates tasks such as identifying vulnerabilities, assessing risks, and predicting potential damages.

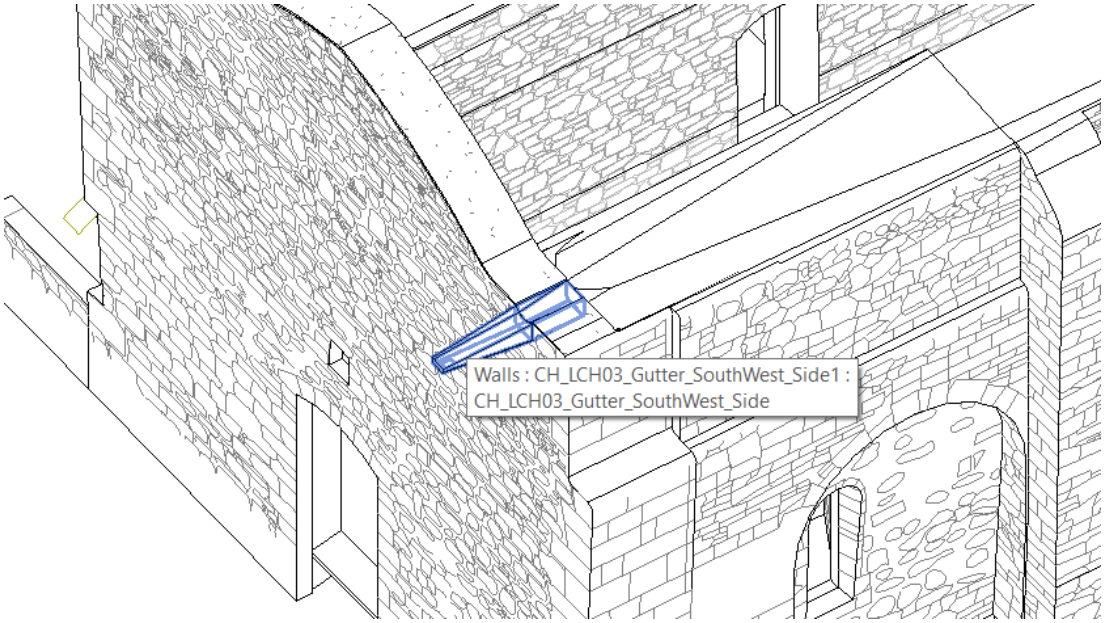

Figure 33: *The gutter of the southwest of the building with crack visualised in Autodesk Revit.*

The semantically enriched model is viewable in GraphDB, allowing for visual exploration. A crack has been identified and linked to the gutter located on the southwestern side of the interior wall. Figure 33 provides a visual representation of this specific crack. Cracks commonly appear in gutters due to the influence of strong winds. The exposed nature of gutters makes them vulnerable to wind-related damage. In this case, the selected gutter is situated on the southwestern side of the building, facing the sea where prevailing winds originate. As the gutter is not a load-bearing element, the observed cracks are not a result of seismic activity. Additionally, being located at the roof level, the gutter is not subject to erosion caused by flooding. Therefore, the assigned crack type for this element is "crack 1."

RDF Triplets

Figure 34 presents an illustrative example of the RDF graph data model that represents a specific section of the wall associated with a crack. This example showcases the outcome of the semantic enrichment process, where the crack was integrated into the building's Turtle file format. The depicted RDF graph snapshot specifically describes a crack classified as "crack 1," indicating its origin from wind erosion.

Figure 34*: RDF graph data model of the part of the wall that was associated with a crack.*

This graph shows several nodes that represent entities such as the Gutter part of the wall which is part of the Entrance Level. Each edge has an identifier that tells us what relationship holds between those nodes. For example, the Entrance Level which is defined by bot:Element prefix contains element of the gutter part of wall described defined by beo:Wall Prefix. IRIs are written as prefixed names. PREFIXES are used so that you don't have to type it in full each time it is referenced. Wind pressures are greater in the southwest-facing corners where the Gutter part is located. Furthermore, the southwest direction of wind is assigned on the crack.

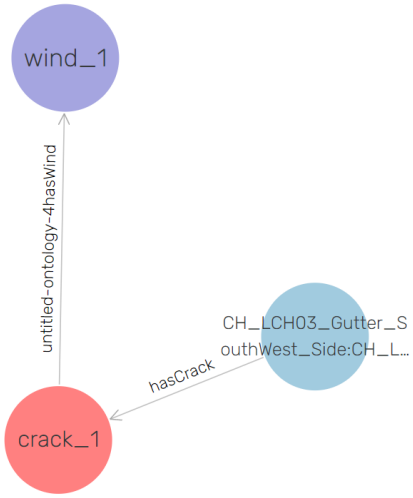

Figure 35: *Nature element is added as an extra node that is linked with the type of crack.*

In the triple of Figure 35, crack 1 refers to erosion and the wind element from the Nature ontology was added to label the cause of this crack. In this graph we also have nodes representing datatype values (i.e., "literals") such as strings, numbers, dates. These edges are the "attributes" of the nodes and are used to represent the characteristics of the nodes.

Table 1: Query of the database with SPARQL.

Natural Elements	Ontology	Types of Cracks	Ontology	Building Elements	Ontology
Wind	nature:Wind	Crack 1 - Wind Erosion	loizos:Crack	Wall	bot:Element& beo:Wall
Earthquake	nature:Earthquake	Crack 2 - Crack from Earthquake	loizos:Crack	Slab	bot:Element& beo:Slab__FLOOR
Flooding	nature:Flooding	Crack 3 - Flooding Erosion	loizos:Crack		

Data stored in RDF format were able to be retrieved with SPARQL as it can be seen in Table 1. Triple patterns are the fundamental building blocks of RDF and SPARQL queries. GraphDB was an important tool to visualise the generated graph of the semantically enriched model and tools to visually explore relationship and class hierarchy was provided. Furthermore, GraphDB provided the opportunity to successfully query the graph with SPARQL. The next step was to query the graph database in QGIS so that the cracks can be assessed with correspondence of the natural hazards and environmental parameters that are added in the QGIS map as GML layers. Also, QGIS was selected as the hosting platform for the project. QGIS does not support directly triple stores like GraphDB. So that it was concluded to use Python language as a way of communication between the graph database and QGIS. Python, is a versatile programming language, can act as a bridge between QGIS and triple stores. Stardog, being a knowledge graph database that supports RDF data and SPARQL queries, can be accessed using Python through a Python wrapper library called pystardog.

5.3. Query Data in Stardog Studio

Stardog allows you to query RDF databases using SPARQ. The decision to choose Stardog as the triplestore for querying the database within the QGIS environment stems from its compatibility with Python scripting and the ability to create SPARQL queries that map data to ontological instances in the QGIS environment. Stardog is implemented in Java and provides extensive support for RDF and all OWL 2 profiles, enabling advanced reasoning capabilities. It utilizes SPARQL as the query language and offers APIs for Jena, Sesame, and SNARL, which is the Stardog Native API for the RDF Language. (Mouzakitis, S et al., 2017).

The shortest path that connects all query keywords in a BIM instance is searched using the path query function provided by the Stardog RDF database management system and extract the structure of the shortest path to generate the SPARQL query. Path queries in Stardog can traverse an RDF graph, return all intermediate nodes on each path and use arbitrary SPARQL graph patterns in the query. Without any complex programming, one can easily obtain a query path in the Stardog database.

Stardog's path query function enables the investigation of unidirectional relationships for a query keyword and presents the results in a data path format. The SELECT clause is used to project variables for the results, allowing users to specify which information they want to retrieve from the database. The query searches for common nodes in different path files to find the shortest path(s) that contain all the query keywords. This enables users to discover and analyse the relationships between different entities and find the most relevant paths connecting them based on the specified query criteria.

For querying data with SPARQL language, Stardog Studio is utilized as an IDE (Integrated Development Environment) for Knowledge Graph Engineers shown in Figure 36. It offers features such as data exploration, search and browsing of classes and properties, visualization of inbound and outbound relationships, writing and execution of SPARQL queries, visualization of RDF Turtle file format, and creation and editing of OWL defined schemas in a form-based manner. Stardog Studio provides a user-friendly interface for

managing the semantically enriched database, which was previously created and explored in GraphDB using IFC building data and manually added damages.

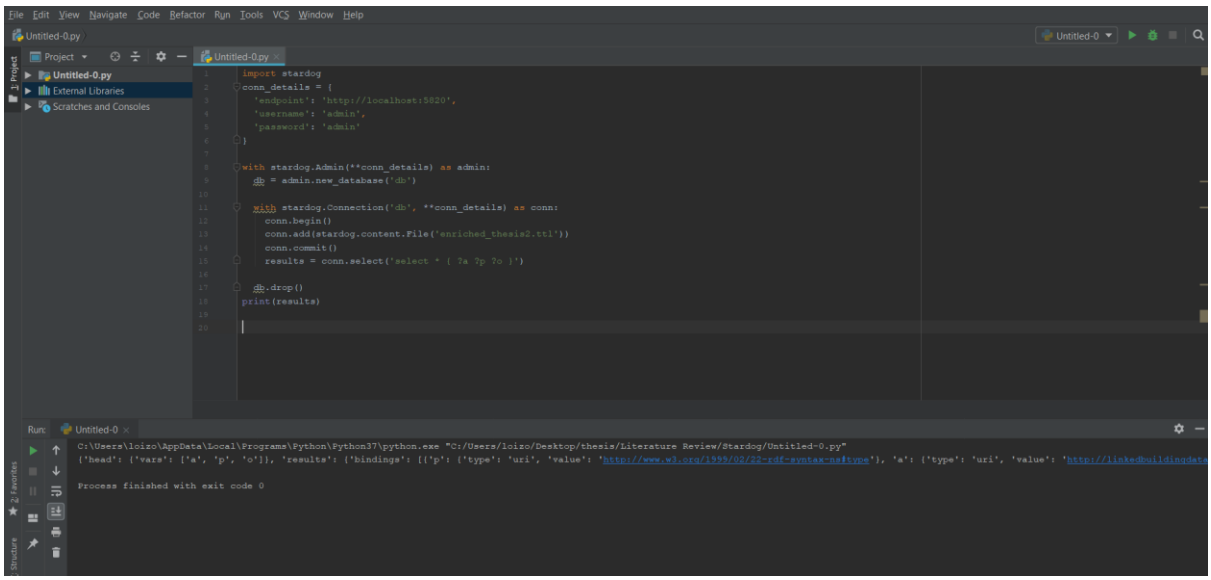

Figure 36: Stardog's features are used with the Stardog Studio platform in the browser.

To extract information from these datasets, SPARQL Queries were used. The query execute subcommand was used with a query string, a query file, or the name of a stored query to execute a SPARQL query against a Stardog database. This command can be used to execute any SPARQL query type (SELECT, CONSTRUCT, DESCRIBE, ASK, or any update query type).

Ask queries return a boolean value indicating whether or not the specified pattern in the WHERE clause matches any results. The DESCRIBE query returns the RDF graph, and the specific triples returned for a node depend on the system implementation. A CONSTRUCT query searches for patterns in the WHERE clause and returns an RDF graph as a result. Queries can also update the database by inserting or deleting triples based on query results using Insert or Delete queries. The basic components of SPARQL queries are triple patterns, which are similar to RDF graph triples but allow variables in any position. Triple patterns are used to find matching triples in a graph, with variables acting as wildcards that can match any node. In the implemented query, the SELECT clause specifies the variable "Wind" to be returned. The query aims to determine if there were any wind effects from natural forces that affected the building. The triple pattern in the query matches triples in the graph where "wind" is the predicate and "rdf:type" is the object. From the query results, the type "wind_1" was identified, indicating that "wind_1" caused the formation of "crack 1" on the SW Gutter part of the wall as it can be shown in Figure 37.

```
PREFIX nature: <http://www.semanticweb.org/loizo/ontologies/2020/9/untitled-ontology-4>
prefix wind: <http://www.semanticweb.org/loizo/ontologies/2020/9/untitled-ontology-4#Wind>

SELECT ?wind
{
  ?wind rdf:type nature:Wind .
}
```

Run to File | Text | Visualize | 1 Results, 264 ms

wind

http://linkedbuildingdata.net/ifc/resources20210630_212301/wind_1

Figure 37: *This triple pattern matched all the triples in the graph that have "hasWind" as the predicate and Crack as the object.*

Ask

The next query asks if there is any Wind responsible for a Crack on the gutter part of the structure. The result on Figure 38 was simply true without any detail about which crack or wind matched this pattern. Ask query can be used to return a boolean result of true or false. In this example it was found out that there are cracks on the building originated from wind forces. This crack can be described as wind-erosion damage.

```
PREFIX loizos:<https://loizos.org/thesis#Crack>
PREFIX wind: <http://www.semanticweb.org/loizo/ontologies/2020/9/untitled-ontology-4#Wind>
PREFIX nature: <http://www.semanticweb.org/loizo/ontologies/2020/9/untitled-ontology-4>
ASK {
    ?wind a nature:Wind .
    ?crack nature:hasWind ?wind .
}
```

Run to File | 192 ms

```
ASK query returned: true
```

Figure 38: *Ask query returns a true/false result.*

5.4. Python in QGIS

Pystardog

Stardog Knowledge Graph can be accessible using Python with the wrapper library called pystardog. This can be implemented using the Stardog Knowledge Graph through the Python wrapper library called pystardog. This library facilitates communication with the Stardog HTTP server, offering access to a wide range of functions, including executing SPARQL queries. The interaction with Stardog's functionality is enabled via an HTTP API, which pystardog wraps for ease of use with Python. The implementation involves creating a Python virtual environment to host pystardog commands, allowing isolated environments with specific dependencies. The implementation is chosen to be hosted in Jupyter Notebook within the Anaconda environment, providing an open-source platform for creating and sharing documents with live code, visualizations, and narrative text (Randles et al., 2017). Pystardog utilizes the stardog.admin.Admin and stardog.connection classes to interact with the Stardog Database Management System (DBMS), facilitating actions like managing the server and interacting with databases. The process emphasizes efficient communication between Python and Stardog's capabilities, enabling seamless integration and analysis within a controlled environment.

Pystardog database connection was created by giving the endpoint of the server http://localhost:5820 with the username and the password that are required to authenticate the database as shown in Figure 39.

```
import stardog

conn_details = {
  'endpoint': 'http://localhost:5820',
  'username': 'admin',
  'password': 'admin'
}
with stardog.Admin(**conn_details) as admin:
  db = admin.new_database('db')
```

Figure 39: Pystardog database connection.

A new database was created and connected to a database on a Stardog server. Turtle (.ttl) file format is added to the database by calling the add method of the connection object. Finally, the database was queried with the select method by selecting and the RDF data were printed successfully. The full process can be seen in figure 40**.**

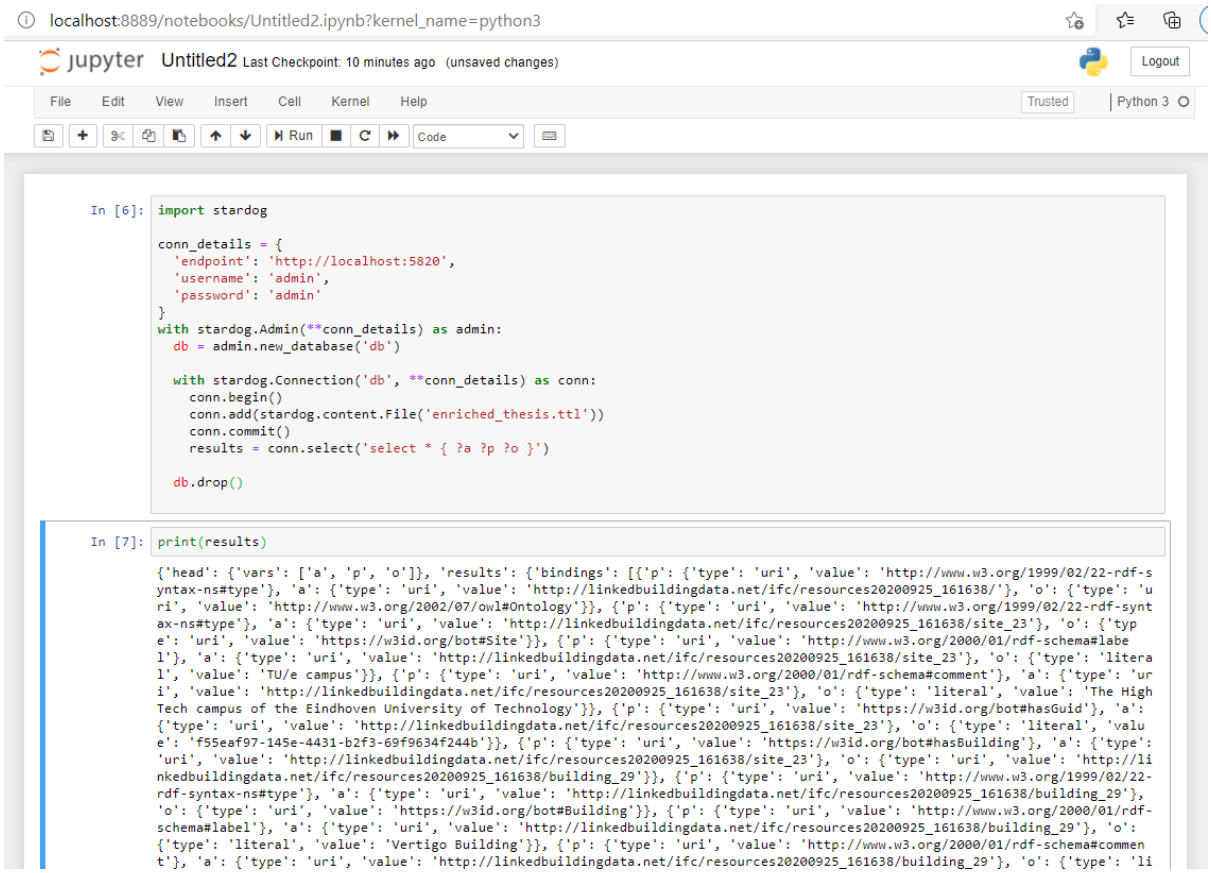

Figure 40: *Execution of the query process with the Pystardog command.*

By utilizing the Pystardog command, it became possible to perform queries on the Turtle RDF file containing enriched building data, including information about cracks and environmental factors. This Turtle RDF file can be seamlessly loaded into a connected Stardog database through the execution of Python code. Given the widespread adoption of Python within the geospatial field, QGIS incorporates a Python console for scripting purposes, alongside a Code Editor tool that relies on the PyQScintilla2 package. This package serves as the underlying foundation for both the console and the editor. The specific implementation involved the use of the Python Code Editor to execute the pystardog script. Pystardog, encapsulated within a Python virtual environment, functions as a wrapper library. This framework effectively encompasses the entirety of the external RDF graph within the Stardog Knowledge Graph, granting access to an extensive array of functionalities, including the execution of SPARQL queries, administrative tasks related to Stardog, and the utilization of the Reasoning API. Notably, Pystardog facilitated the connection between a Python Jupyter notebook and Stardog databases, enabling seamless interaction and querying of the RDF data.

5.5. Query Data with SPARQL language in QGIS

The QGIS Python Console is a shell that allows the user to run Python commands interactively. Code Editor helps to edit and save Python files while also provides advanced features for managing Python scripts in QGIS. QGIS comes with a Python API for interacting

with its objects (features, layers, or interface). Python console is the most direct way to interact with QGIS API. The Python editor, which is part of the Python Console panel and provides a better way to work on longer scripts with multiple class and function definitions, was used for this thesis.

The Pystardog wrapper library has been integrated into the Python console of QGIS, enabling its usage within the QGIS environment. This integration establishes a virtual Stardog environment within QGIS, providing users with the ability to interact with the RDF graph of the semantically enriched model. Additionally, this integration allows for the visualization of the building model alongside the environmental layers directly within the QGIS interface. Essentially, users can execute queries on the RDF graph and simultaneously view the spatial representation of the model and its associated data layers in QGIS. The integration ensures that all the query capabilities available in Stardog can now be seamlessly performed within the QGIS platform, utilizing a turtle-based syntax for implementing queries. This integration enhances the workflow by combining querying and visualization within a single environment, streamlining the analysis of the semantically enriched model and its linked data. Figure 41 shows the results of the search query that reads all the data of the semantically enriched turtle file with name “enriched-thesis.ttl file”.

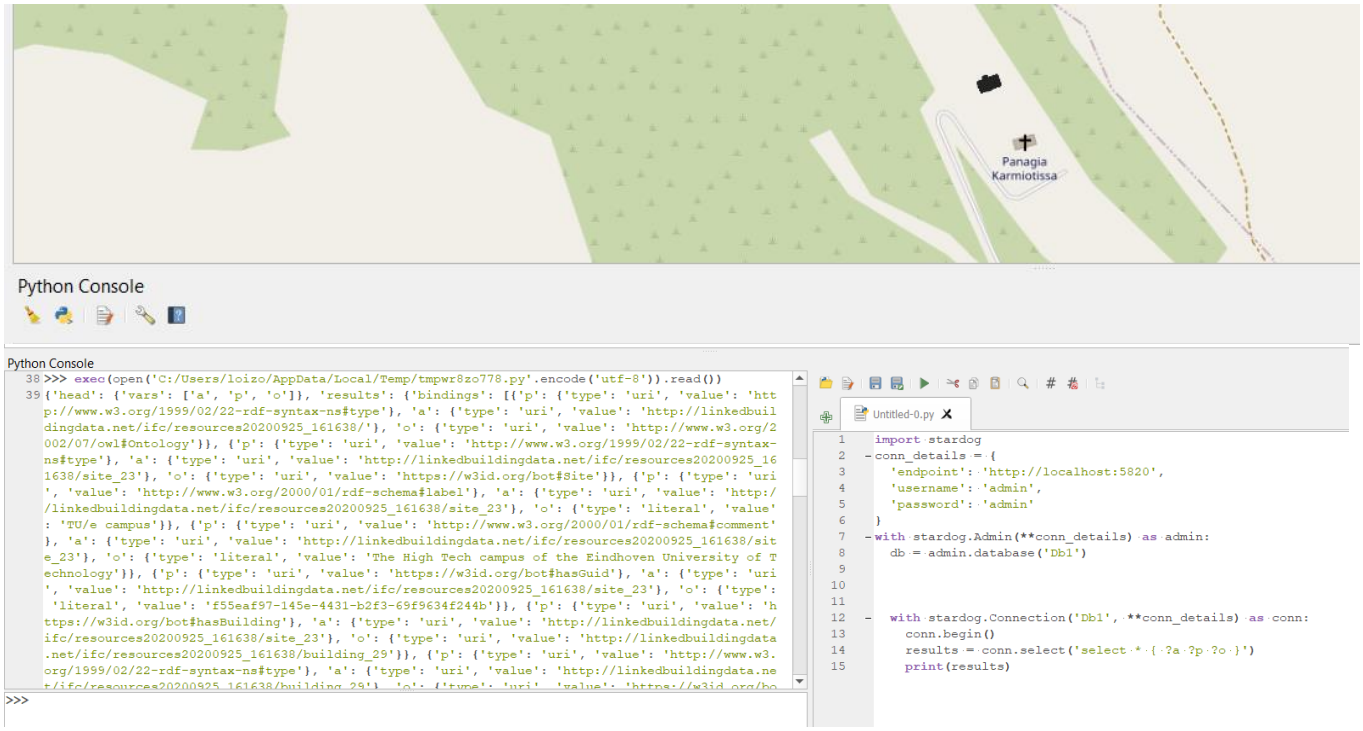

Figure 41: *Query the enriched heritage building database in QGIS software.*

5.6. Conclusion

The process for creating a knowledge graph by enriching building data with information about damages and environmental factors and storing this data in a Stardog triplestore was presented. Protégé was used to create an OWL ontology for the natural elements that could affect a heritage building and used the IFCtoLBD tool to convert IFC files to RDF using LBD ontologies. Then manually added information about damages to the RDF data using a text editor was done, and the resulting data were stored in a GraphDB database. Stardog was used to query the GraphDB database using SPARQL queries and used pystardog to connect to the Stardog database and add the enriched RDF data to it. Finally, QGIS Code Editor tool run pystardog scripts and connect to the Stardog database.

The development of an ontology to describe the relationship between natural elements and their potential impact on heritage buildings was presented. Ontologies are formal systems for representing knowledge in a domain, and they can be used to structure and organize data in a way that is meaningful and easy to understand. Protégé is a popular tool for creating and editing ontologies, as it allows users to create and define classes, properties, and relationships between different concepts. By developing an ontology for natural hazards and their potential impact on heritage buildings, it is possible to represent and classify the various types of natural elements that may affect these buildings and the potential damages that they may cause. Using a tool like Protégé can help to ensure that the ontology is well-structured and follows best practices for knowledge representation. The use of annotations and properties can also be helpful for adding additional context and information to the ontology, making it easier to understand and use for various purposes. By creating an ontology for natural hazards and their potential impact on heritage buildings offers a structured and organized framework to categorize and classify the diverse range of natural elements that could potentially pose a threat to these historical structures. By defining relationships between these natural elements and the resulting damages they might cause, the ontology enables a comprehensive understanding of the potential risks.

The IFCtoLBD tool for converting IFC files to Linked Building Data (LBD) ontologies. LBD is an open data model and ontology for representing building information in a way that is linked and interoperable with other data sources. The IFCtoLBD tool is a java-based conversion tool that uses a number of ontologies, such as the BOT and BEO, to convert IFC files to RDF and represent building information in a way that is linked and interoperable. The process of enriching building elements with cracks and erosion damages based from the building survey and the point cloud data was presented. Tools like IFCtoLBD that can convert BIM represented in IFC format to the RDF format used in LBD ontologies, as this allows for the integration and analysis of building data with other data sources. By manually adding cracks to the turtle file and using a tool like GraphDB, it is possible to represent and classify the various types of damages that a building may have and the potential causes of these damages. Understanding the nature and causes of damages can be important for assessing the vulnerabilities of a building and developing strategies for mitigating potential risks and preserving the building's integrity. Factors such as wind, rain, and earthquakes can all

contribute to the erosion and deterioration of building materials, and understanding these factors can help to identify potential vulnerabilities and develop appropriate protection measures. The manual addition of cracks to the turtle file, coupled with tools like GraphDB, allows for the systematic representation and classification of various damage types that a building might exhibit, along with their potential causes. This enables a holistic view of the building's health, aiding conservation engineers in assessing vulnerabilities and devising strategies to mitigate risks and uphold structural integrity. Conservation engineers gain a deeper comprehension of damage types and their origins, aiding in identifying root causes and implementing effective mitigation measures. By recognizing the potential contributions of factors like wind, rain, and earthquakes to material erosion and deterioration, engineers can gauge the building's susceptibility to these hazards and make informed decisions. By having a clear picture of potential vulnerabilities, engineers can formulate targeted strategies to safeguard the building, enhancing its longevity and historical value. A precise understanding of damage causes guides efficient allocation of resources towards preventive and restorative efforts, optimizing budget utilization. A standardized representation through ontologies provides clear communication among engineers, researchers, policymakers, and stakeholders, leading to informed discussions on risks and protective measures. This approach facilitates collaboration among different disciplines, such as architecture, engineering, and heritage preservation, resulting in more holistic solutions. Finally, the integration of data sources empowers engineers to make evidence-based decisions by correlating damage patterns with environmental factors.

Stardog was used in the process of querying building data with information about cracks and erosion damages. Stardog is a powerful tool for managing and querying knowledge graphs, and it can be particularly useful for analyzing large datasets and performing reasoning tasks. By using Stardog to execute SPARQL queries, it is possible to extract relevant information from a database and visualize it in a meaningful way. The ability to use Stardog with Python scripts and QGIS also expands the possibilities for analyzing and visualizing data, allowing for the integration of building data with other datasets and the creation of maps and other visualizations to better understand the characteristics and vulnerabilities of a building.

The Pystardog wrapper library allows the user to interact with the Stardog Knowledge Graph through the QGIS platform using Python. This allows the user to query the RDF graph of the semantically enriched model and at the same time visualize the building model along with the environmental layers in QGIS. Queries written in Stardog's can be executed in the QGIS Python console, providing the user with the ability to access and analyze the data stored in the Stardog database. This integration of Stardog and QGIS allows for more powerful and efficient analysis and visualization of building data, particularly in the context of natural hazards and their impact on building structures.

The integration of a virtual Stardog environment within QGIS offers several benefits for the analysis and visualization of the semantically enriched model of a building:

1. **Seamless Workflow:** Having a virtual Stardog environment directly within QGIS streamlines the workflow for users. Conservation engineers can perform both RDF

graph querying and building/environmental visualization tasks within the same software interface, eliminating the need to switch between different tools.

2. **Data Integration:** Users can effortlessly combine and analyze both the semantically enriched model and environmental data layers. This integration allows for a more comprehensive analysis by considering the interplay between building components and their surroundings.
3. **Comprehensive understanding:** The simultaneous visualization of the building model and environmental layers provides a contextual understanding of how natural elements and external factors impact the building. This aids in identifying patterns, correlations, and potential causes of damages or vulnerabilities.
4. **Interactive Exploration:** QGIS's visualization capabilities allow users to interactively explore and navigate the enriched model and environmental layers. This interactive exploration enhances the user's ability to gain insights and make informed decisions.
5. **Holistic Decision-Making:** The combined analysis of the building model and environmental data supports more holistic decision-making processes. Users can assess the impact of natural elements on the building's condition and plan remediation strategies accordingly.
6. **Improved Communication:** Visual representations of the building and its surroundings support better communication among stakeholders, presenting information in a more intelligible and understandable manner.
7. **User-Friendly Interface:** QGIS offers a user-friendly interface for working with geospatial data and visualizations. Integrating the virtual Stardog environment maintains this user-friendly experience while adding powerful RDF graph querying capabilities.

6. Discussion and Conclusion

6.1. Introduction

The main goal of the project was to use digital technologies to allow a holistic damage documentation of heritage buildings by combining BIM, GIS, and Semantic Web technologies. BIM was used to create a parametric representation of the building, GIS was used to visualize the building in a geographic context and add environmental data, and Semantic Web technologies were used to store and query data about the building and its damages. The project involved converting the BIM model from IFC to CityGML and using manual work to add data about the building damages to the model. The final product was queried in GIS using the Stardog database. It's important to note that natural disasters can have a devastating impact on cultural heritage and it's important to use technologies like BIM, GIS, and Semantic Web to help preserve and study these structures. By digitally modelling and analysing these buildings, we can better understand their characteristics and vulnerabilities, and potentially develop strategies for protecting them against future disasters.

This project introduced an approach for a complete integration of BIM data and environmental data in a GIS platform towards the protection of the cultural heritage. The project built a bridge between the environmental characteristics and building elements that can allow a constant monitoring of buildings against natural disasters, so that building damages and deterioration mechanisms can be assessed and evaluated. To achieve this goal two different types of integration were introduced that can coexist and support each other. One was the geometric integration of building with the environmental data for a visual representation in QGIS and the other was the semantic integration of the building damages with the environmental data that generated them. In order to have a tangible application a real BIM model of a historic church in Cyprus was selected as a case study. The building was assessed based on the environmental characteristics of the region where it is located and based on the building damages that were recorded with a laser scanner and during a visual inspection. The following research question was set to establish the problem that was needed to be solved and to provide a clear pathway of reaching this target.

6.2. Research questions

How can digital technologies, including BIM, GIS, and open data, be effectively utilized to document, analyze, and assess historic buildings, their environmental context, and damages caused by natural phenomena, while providing user-friendly systems for cultural heritage management?

Digital technologies, such as BIM, GIS, and open data, offer powerful tools for documenting, analysing, and assessing historic buildings in the context of their environment and potential damages caused by natural phenomena. By effectively integrating these technologies, user-

friendly systems for cultural heritage management can be developed to support preservation efforts. BIM technology enables the creation of detailed and parametric 3D models of historic buildings, capturing their structural and material properties, as well as architectural characteristics. These models serve as a comprehensive digital representation of the building, facilitating documentation and visualization of its complex features. GIS technology supports BIM by analysing the surrounding environmental context through geospatial data. Incorporating data from governmental portals and third organizations, GIS provides critical information on factors like flood zones, seismic hazards, and climate patterns that may impact the building's preservation. By combining BIM and GIS, engineers and stakeholders can gain a holistic understanding of the building's vulnerabilities to natural hazards and environmental influences. Open data sources further enrich the analysis by providing access to a wide range of information, including historical records, photographs, technical reports, and research findings related to the cultural heritage building. This open data can be integrated with BIM and GIS datasets, contributing to the development of a comprehensive knowledge base for the building's conservation and management. User-friendly platforms like QGIS allow operators in the field, who may not be familiar with complex databases and 3D models, to easily access and interact with the information. To achieve this goal the main research question was divided into three sub-questions that were used as a guideline for the project implementation.

What are the challenges and solutions for integrating BIM and GIS data, considering data incompatibility, differences in coordinate systems, and data structures?

The BIM model was converted into a GIS-readable model so that it could be visualized alongside with the environmental layers in a GIS software. The BIM model was transferred into a GIS by converting the building's IFC file to CityGML using the FME workflow. The conversion from BIM to CityGML was primarily implemented by identifying the building's exterior shell. That was the main reason that the geometric transformations were problematic. Geometries in BIM and GIS are modelled differently (planar vs. volumetric). A problematic transformation in this case study was the failure of converting the floor slabs into CityGML. To solve this issue the floor slabs were embedded to the exterior wall.

Overall, this approach had some advantages: both BIM and GIS models remained independent without additional standardization efforts. The FME transformation was executed quickly and with a high detail level of the final CityGML product at LOD 4. Both external and internal architecture of the church was able to be visualise successfully as a CityGML model. Achieving interoperability between BIM and GIS models was difficult. Data transfer was difficult due to different modelling paradigms. The IFC encoding in BIM and the CityGML encoding in GIS have different types of modelling geometries. Geometries in IFC are specified in parametric form, while points, edges, and surfaces are found in CityGML.

BIM models use a Cartesian coordinate system, whereas CityGML models use a geodetic reference system. (Herle, S et al., 2020). A solution for achieving consistent and continuous interoperability between IFC and CityGML has yet to be discovered. Converting BIM data to GIS data was challenging due to differences in the reference system, spatial scale, level of granularity, geometric representation methods, storage, and access methods, as well as

semantic mismatches between BIM and GIS data models. Deng et al., 2016). CityGML objects are only partially matched with IFC model schema, which necessitated additional information or complex processing that was not easily automated.

How can GIS technology be employed to analyse and visualize the environmental context of historic buildings, incorporating geospatial data from governmental portals and independent organizations?

GIS technology plays a crucial role in cultural heritage building preservation by enabling the analysis and visualization of the environmental context surrounding historic buildings. By incorporating geospatial data from governmental portals and independent organizations, GIS provides valuable insights into potential threats and vulnerabilities posed by the surrounding environment. Through geospatial analysis, engineers can identify factors such as flood risks, wind exposure, and climate changes that may impact these heritage structures. The visualization capabilities of GIS allow stakeholders to better understand the spatial relationship between the buildings and their surroundings, raising awareness about the need for preservation. Additionally, GIS supports scenario analysis, enabling stakeholders to assess the long-term effects of urban development and climate change on cultural heritage buildings. Continuous monitoring of environmental conditions using GIS ensures timely responses to evolving threats and aids in the development of adaptive preservation strategies. Overall, GIS technology empowers stakeholders in cultural heritage building preservation to make informed decisions and take proactive measures to safeguard these valuable structures.

How can heterogeneous datasets, such as technical reports, photographs, and documents, be incorporated and semantically enriched in 3D digital models to support management and conservation efforts?

Semantic web technologies were applied to support the non-geometric data. Initially, an ontology was constructed in Protégé to describe the concept of the environmental threats and their relationship with each other. Those threats were later linked to the building RDF graph to describe the crack formation. For the building RDF graph construction, the IFC structure of the building model was converted into a semantic RDF graph with the IFCtoLBD conversion. The IFC file of the BIM model was exported from Revit. Then the damages were assigned to the corresponding elements along with the environmental root of cause directly on the RDF turtle file of the building by following a semantic enrichment process. Semantic Web technology helped to achieve semantic interoperability between building information, physical damages and environmental information. RDF graph database was used to express data, information, and knowledge in the form of statements. Engineers can be able to query information and retrieve details about the origin of the crack formation and the impact of the damage on the buildings. This ability is provided with the semantic integration of the building elements, types of building damages, and natural forces. The model can be used as an information system for conservation applications. To allow queries in the QGIS platform, a link between the QGIS and RDF graph database was required. The query process had to be executed in Python and then to be hosted in QGIS via the Python console/editor. Python was used to connect to Stardog databases via Pystardog. This was the only possible solution

since QGIS does not support direct queries of RDF graphs and python was successfully used as an intermediate route. Stardog allowed a fast and precise execution query time. The incorporation of building damages and natural elements allowed the user to interact with the model and assign risk indicators and vulnerability parameters to it based on the natural root of caused of the damages. This method had the advantages of keeping the data in its original structure.

How can digital technologies aid in assessing and predicting damages to historic buildings caused by natural phenomena, enabling engineers to forecast and prevent further failures?

The information obtained from the point cloud model and the identification of different types of building damages and deterioration mechanisms associated with their natural causes can greatly inform retrofit or renovation efforts to strengthen and protect the building against future natural hazards. By understanding the specific types of damages caused by different natural elements (e.g., earthquakes, rain, wind), retrofit or renovation efforts can be targeted towards addressing those vulnerabilities. For example, if structural cracks related to earthquakes are identified, the focus can be on strengthening the building's structural elements through reinforcement or retrofitting techniques. By understanding the impact of natural elements on specific materials can guide material selection and protection strategies. For instance, if rain is identified as a significant contributor to stone erosion, measures can be taken to protect the building's façade from the damaging effects of rainwater, such as applying protective coatings or implementing drainage systems to divert water away from vulnerable areas. The observed damages and their associated natural causes can inform design modifications to mitigate future risks. For example, if wind and rain synergistically contribute to the detachment of external elements, design changes can be implemented to improve the building's resistance to such forces, such as altering the shape or orientation of architectural features to reduce their vulnerability to wind-driven rain. By using the information derived from the point cloud model and the identification of damage types and deterioration mechanisms associated with natural causes, retrofit or renovation efforts can be tailored to address specific vulnerabilities and strengthen the building's resilience against future natural hazards. This approach allows for targeted interventions, appropriate material selection, design modifications, proactive maintenance, and adaptive strategies to protect and preserve the building for the long term.

A database management can provide the possibility to efficiently store a large number of heritage models that can be queried. The database can be used to store additional information like metadata and original survey data like laser scan point clouds, orthographic imagery, and surface models, (C. Dore and M. Murphy 2012). Spatial information is an essential component of architectural heritage documentation. The heritage building relationship with the landscape can be supported and virtual exploration of historical sites can be provided as well. For example, the visualization of the building geometry in GIS. Future research will concentrate on how existing ontologies for defining damage causes such as MONDIS and DOT can be combined with the proposed ontology. The RDF graph core

ontology can be used for adding more specific information, such as taxonomies for different types of damage or national assessment standards. The use of ontologies for damage mapping successfully conveys improved user accessibility, content reliability, and the possibility of integrating other information systems (Cacciotti et al.,2013).

Digital technologies can play a crucial role in assessing and predicting damages to historic buildings caused by natural phenomena, enabling engineers to forecast and prevent further failures. The use of point cloud models obtained from laser scanning and the identification of different types of building damages and deterioration mechanisms associated with their natural causes provide valuable insights for retrofit or renovation efforts. By understanding the specific damages caused by different natural elements, engineers can target their interventions towards addressing those vulnerabilities. This includes strengthening structural elements in response to earthquake-induced cracks, implementing protective measures against rainwater erosion, or making design modifications to improve resistance to wind forces. Digital databases can efficiently store and manage many heritage models, allowing for easy retrieval and query of information. Additionally, the use of ontologies can facilitate the integration of different damage mapping systems and support the evolution of damage over time, including version control and linking with repair and maintenance actions.

What are the key considerations in developing user-friendly systems for cultural heritage management that provide to the needs of operators in the field who may not be accustomed to working with databases, 3D models, and information systems?

In the domain of cultural heritage management, creating user-friendly systems that provide the specific requirements of field operators lacking expertise in databases, 3D models, and information systems holds great significance. To ensure the effective adoption and utilization of such systems, several essential factors need careful consideration. Initially, it is vital to design an intuitive user interface marked by clarity, organization, and visual attractiveness, enabling the presentation of complex data in a user-friendly manner. Providing sufficient training and continuous assistance, including comprehensive tutorials, help documentation, and responsive customer support, is essential. The integration of visual aids like images, diagrams, and maps can greatly enhance understanding, while standardized naming conventions and adaptable design accommodate different skill levels. The inclusion of familiar tools and compatibility with existing software further simplify operations. Customization choices, clearly defined workflows, and minimized manual data entry contribute to user empowerment. Through consistent user testing, feedback gathering, and iterative enhancement approaches, these user-centric systems are consistently refined to meet the ever-evolving demands of cultural heritage management.

BIM can be a powerful tool for the renovation and documentation of historic structures. It can provide a detailed 3D model of the building that can be used to understand the complex structure and make informed decisions about conservation work, retrofits, and renovations. BIM also allows for the sharing of data across various applications, which can make these processes more efficient and effective. Additionally, the integration of semantics and parametric BIM elements can be used to create a 3D reconstruction of a historic building,

which can be particularly useful for understanding the architectural trends and characteristics of different periods. An HBIM library can be used to store and access data about these trends and characteristics, which can aid in the renovation process. Overall, BIM can be a valuable tool for preserving and studying cultural heritage structures.

6.3. Drawbacks

The proposed work offers valuable insights into heritage conservation, yet it is not without its drawbacks. One notable limitation is the lack of automation in the process. The semantic enrichment involved manual editing of the RDF turtle file, which can be time-consuming and prone to errors. A more user-friendly approach could involve annotation and interaction directly within the QGIS platform using graphical interfaces, streamlining the process and making it more accessible. Scalability is another concern. The current implementation may face challenges in handling larger datasets or accommodating diverse scenarios. As the workload grows, the system's performance might degrade, potentially affecting its practicality for larger-scale applications. The manual effort required for semantic enrichment is labour-intensive and can be a problem in the workflow. This process demands high expertise and attention to detail, which could limit its efficiency and hinder the adoption of the approach. Additionally, the use of RDF triples for relationships can be limiting, capturing only one relationship at a time between a subject and an object. This might not fully capture complex interconnections between various elements, potentially reducing the model's ability to represent intricate relationships comprehensively. Integrating heterogeneous datasets within a 3D digital model introduces challenges due to differing formats, structures, and qualities. Ensuring harmonization across these datasets requires substantial effort, and semantic mismatches and interoperability issues can emerge, necessitating additional mapping and alignment tasks. Regular maintenance and updates are essential to preserve the accuracy and relevance of the model. Ensuring technical expertise and training for effective utilization is crucial, while addressing data privacy and security concerns remains essential.

To overcome the drawbacks identified in the proposed work and enhance its effectiveness in heritage conservation, several strategies can be considered:

1. **Automation and User-Friendly Interfaces:** To address the lack of automation and enhance user-friendliness, developing graphical interfaces directly in a web platform rather than QGIS can significantly improve the process. These interfaces could allow users to annotate, interact, and enrich the model seamlessly, reducing the need for manual RDF editing.

2. **Semi-Automation:** By incorporating semi-automated methods that use machine learning or AI algorithms to assist in the semantic enrichment process. These methods can analyze patterns in the data and suggest possible annotations, reducing the manual effort required.

3. **Improved Representation:** To address the limitations of RDF triples, consider adopting more expressive semantic models, such as graphs or more advanced RDF

modeling techniques, which can better represent complex relationships and interactions between various elements.

4. **Standardization and Data Quality:** To establish data standards and quality control processes to ensure that heterogeneous datasets are in formats that can be easily integrated.
5. **Interoperability:** To prioritize adopting standardized formats and ontologies, such as those recommended by the semantic web, to facilitate seamless interoperability between different systems and datasets.
6. **Regular Maintenance and Updates:** To implement a robust maintenance plan to keep the model accurate and up to date. This includes continuous monitoring of data sources, regular data updates, and addressing evolving data privacy and security concerns.
7. **Training and Expertise:** Offer training programs to users, conservation engineers, and stakeholders to ensure effective utilization of the integrated model. This will enhance their understanding of the system's capabilities and increase its adoption.

6.4. Conclusions and future works

Finally, future applications of the proposed model to a wide range of case studies, diverse in typology, historical period, and scale, will provide additional development directions while considering the specificity and uniqueness of each built heritage process. The proposed model holds the potential for further exploration and application in various case studies covering different characteristics such as building types, historical eras, and sizes. By extending the use of the model to a diverse array of case studies, it becomes possible to evaluate its effectiveness across a wide spectrum of contexts. Different types of buildings and environmental characteristics offer opportunities to test the model's adaptability and robustness. As each built heritage process carries its own unique challenges and attributes, applying the model to multiple cases allows for a more comprehensive understanding of its strengths and limitations. The future applications of the proposed model to a diverse range of case studies serve as a dynamic testing ground, shaping its evolution and ensuring that it remains adaptable and effective.

To summarize, this project demonstrated a method for integrating BIM, GIS, and Semantic Web technologies for the preservation and study of a historic church. The BIM model was converted to a GIS-readable model using FME and then visualized in a GIS platform with environmental data. The model was then semantically enriched with data about building damages using Semantic Web technologies, and the enriched model was stored in a Stardog database. The model was then queried in GIS using the Stardog database and Python, allowing for the analysis of the building's characteristics and vulnerabilities and the potential development of strategies for protecting it from future disasters. The project highlighted the potential for combining these technologies to better understand and preserve cultural heritage.

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