Coordinator UNISA
Fernando Fraternali

Tutor UNISA
Barbara Messina
Co-tutor UNISA
Salvatore Barba

Coordinator UCLM
Rena C. Yu

Tutor ULCM
José Antonio Lozano Galant

Anna Sanseverino

Application of BIM methodology for structural inspection and maintenance

ECO-Systems: semi-automated monitoring procedures to implement different kinds of data into *Enriched COoperative Systems*

UNIVERSITÀ DEGLI STUDI DI SALERNO
Dipartimento di *Ingegneria Civile*
Rischio e Sostenibilità *nei Sistemi dell'Ingegneria Civile, Edile ed Ambientale*
Universidad de Castilla-La Mancha
CAMPUS DE EXCELENCIA INTERNACIONAL
Escuela Técnica Superior de Ingeniería de Caminos, Canales y Puertos
Escuela Internacional de Doctorado

UNIVERSITY OF SALERNO
Department of Civil Engineering

UNIVERSITY OF CASTILLA-LA MANCHA
Escuela Técnica Superior de Ingeniería de Caminos, Canales y Puertos

Bi-nationally supervised PhD in:
Risk and Sustainability in Civil Engineering, Architecture, Environmental Engineering Systems
Coordinator Professor Fernando Fraternali

XXXIV Cycle (A.A. 2018 – 2022).

Territorio, Infraestructuras y Medio Ambiente (Verificado según R.D. 99/2011)
Coordinator Professor Rena C. Yu

Application of BIM methodology for structural inspection and maintenance

ECO-Systems: semi-automated monitoring procedures to implement different kinds of data into *Enriched COoperative Systems*

Scientific Disciplinary Sector ICAR 17

PhD Candidate
Anna Sanseverino

Tutor UNISA
Professor Barbara Messina

Co-Tutor UNISA
Professor Salvatore Barba

Tutor UCLM
Professor José Antonio Lozano Galant

UNIVERSITÀ DEGLI STUDI DI SALERNO
Dipartimento di Ingegneria Civile
Rischio e Sostenibilità nei Sistemi dell'Ingegneria Civile, Edile ed Ambientale
Universidad de Castilla-La Mancha
CAMPUS DE EXCELENCIA INTERNACIONAL
Escuela Técnica Superior de Ingeniería de Caminos, Canales y Puertos
Escuela Internacional de Doctorado

“He who influences the thinking of his time influences all the moments that follow him. Leave your opinion for eternity”

Hypatia of Alexandria – philosopher, astronomer, mathematician

To my beloved ones, the pillars of my existence

Index

Premise 9

Abstract 13
Sommario 21
Resumen 29

PART I – From the physical realm to digital ECO-Systems 39

1. Structural Health Monitoring and BIM procedures 39
1.1 The Italian regulation concerning BIM implementation 43
1.2 The seven dimensions of BIM and the Levels of Development 48
1.3 Information systems reflections concerning Digital Twins 52
1.4 Scan-to-BIM vs Mesh-to-BIM 54

2. Monitoring Enriched COoperative Systems 59
2.1 BIM-based approaches for structural health monitoring ECO-Systems 61
2.2 Generation of Open BIM models for information exchange 63
2.3 A methodology for the standardisation of Scan-to-BIM Modelling 65

PART II – Bridge digitisation: the case study of the Olivieri Viaduct 75

3. Shortcomings in infrastructure digitisation 75
3.1 Overview of the Italian infrastructure assets 77
3.2 The high number of infrastructure artworks and the absence of a unified management system 80
3.3 Outdated infrastructure heritage with possible design and execution errors and inadequate maintenance schedules 86
3.4 Current traffic loads and flows that differ from the original design 88

4. Bridges inspection and digitisation: regulation and recent applications 91
4.1 Bridges defects identification: inspection protocols in other countries 92
4.2 Evolution of the Italian regulation for Bridge inspection 105
4.3 Inspection levels 117

4.4 Inspection typologies 131
4.5 Literature review covering BIM for bridge inspections 139
4.6 An approach to combining LG20, ASPI, and AINOP requirements 163
4.7 Bridge parts classification according to the current Italian regulation 169

5. Updating the current state of knowledge on the Olivieri Viaduct 183
5.1 Case study: the Olivieri Viaduct 184
5.2 TLS survey of the viaduct and its surrounding 188
5.3 Georefencing, federated models setting up, and structural modelling to update the current state of knowledge 191

6. Pilot case study setting up 199
6.1 C.U.G.R.I. platform for the digitisation of Inspection data 200
6.2 Component structural modelling and shared parameters setting up 202
6.3 Olivieri Viaduct classification according to the Italian regulation 207
6.4 Proposal for a procedural workflow aimed at digitising the infrastructures included in the C.U.G.R.I.-SAM agreement 210

7. VPL Scripts for Level of Information enhancement 215
7.1 Automation tools for data export procedures 216
7.2 From the C.U.G.R.I. platform to BIM: procedures to import inspection results 241

Part III – Sensor databases: the case study of the Temple of Neptune 253

8. Integrated 3D survey for the generation of a BIM database 253
8.1 UAS photogrammetric survey 255
8.2 Mesh-to-BIM application and PBR material for enhanced visualisation 256
8.3 How to bridge the gap in the Scan-to-BIM applications 258

9. The case study monitoring system 259
9.1 Case study: the Temple of Neptune 261
9.2 A TLS-photogrammetric integrated database 264
9.3 The inertial seismometers monitoring system 271

10. Structural BIM modelling 277
10.1 Integrated point cloud management 280
10.2 Temple structural element analysis and BIM object database setting up 283
10.3 Manual Scan-to-BIM modelling within the Revit environment 296

11. Procedural workflows for Mesh-to-BIM applications **305**
11.1 Workflow A: Urban context meshes importing as a *unicum* into BIM 306
11.2 Workflow A.1: Data enrichment via PBR photogrammetric material 312
11.3 Workflow B: Mesh model parametrisation into the BIM environment 323

12. Seismometers network integration within the shared environment **341**
12.1 Discretisation of the monitoring network and LOI enhancement 342
12.2 Open BIM models exportation for data exchange and assessment 359

Conclusions **369**
Conclusioni 374
Conclusiones 379

Acknowledgements **385**

References **387**
Figure index 421
Table index 441

Premise

The research activities carried out as part of this dissertation for the pursuit of the doctoral degree in *“Risk and Sustainability in Civil Engineering, Architecture, Environmental Engineering Systems”* have seen the PhD candidate Anna Sanseverino engaged in an in-depth study on the subject of BIM-type information modelling applied to complex systems both at national research institutes – alma mater University of Salerno – and international ones – the Spanish Universidad de Castilla-La Mancha [UCLM] and the South African Tshwane University of Technology [TUT].

From the 6th of August to the 5th of September 2019, she visited the South African TUT in the framework of the mobility envisaged by the project *“A Social and spatial investigation at the Moxomatsi village, Mpumalanga”* [SSIMM] afferent to the *“Italy-South Africa joint Research Project”* [ISARP 2018-2020], carrying out survey activities of the site under study and integrative teaching activities.

From the 16th of September 2019 to the 31st of July 2020, she attended the University of Castilla-La Mancha [UCLM] in the framework of the European Erasmus+ project. There she had the opportunity to further investigate the use of BIM technology applied to infrastructures in the framework of the activity concerning *“BIM for Design and Construction Management”* [*BIM en Diseño y Dirección de Proyecto*]. The research activities carried out during the first period spent at UCLM resulted in the stipulation of an agreement for the PhD Candidate to obtain the European double doctorate; as a result, she will be awarded the additional PhD title “Doctora por la Universidad de Castilla La-Mancha” in *“Territory, Infrastructure and Environment”*. The Spanish doctoral activities formally started in March 2021, with enrolment at the UCLM international doctoral school in October 2021. Two further mobility periods spent at UCLM aimed at thesis research followed the Erasmus+ activities going from the 6th of December 2021 to the 31st of January 2022 (2 months) and from the 6th of March to the 2nd of April 2022.

In *primis*, the cultural exchange with the South-African university allowed her to delve into the complex relationship between structural systems and the surrounding urbanised and non-urbanised environment, recognising its ecosystemic organisation. An emblematic case is precisely that of the so-called *Coromandel House*. This South-African private residence seems to rise out of the landscape in which it was built in the Mpumalanga region, which also bears the all-Italian heritage of the Italian architect who designed it, Marco Zanuso. The collaborative experiences with TUT, therefore, culminated in the production of two conference proceedings, the first more closely related to mobility activities [1] and the second concerning a BIM-type approach for the digitisation of the Coromandel House [2].

On the other hand, the research activities carried out within the framework of the Erasmus+ mobility at the Spanish University of Castilla-La Mancha [UCLM], first of all concerned the *"Design, Size and Operation of a Transport Infrastracture and Integration Environment"* [*Diseño, Dimensionamiento y Explotación de una Infraestructura de Transporte y su Integración en el Entorno*], an application case developed within the historical landscape of the city of Aranjuez (Autonomous Community of Madrid, Spain), as well as an introduction to the principles of coding. Subsequently, concepts more closely related to the BIM methodology were addressed, i.e., standardisation, the creation of digital terrain models (aimed at the integration of BIM and GIS systems), tools for coordination, visualisation, and interoperability, and the integration of BIM modelling within complex urban systems pertaining to *City Information Modelling* [CIM].

Although being the primary driver of the research activities, the general methodology for the digitisation and monitoring of structures and infrastructures with the support of the BIM technology was only fully defined after the in-depth studies carried out and the practical applications conducted. A moment of further experimentation in comparison to the two case studies proposed here was also the application *"An HBIM Methodology for the Accurate and Georeferenced Reconstruction of Urban Contexts Surveyed by UAV: The Case of the Castle of Charles V"* [3], which allowed for the definitive optimisation of the macro-methodology developed and of some of the automation procedures proposed in the third part of this thesis work.

Whenever possible, the proposed methodology provides for the further integration of the existing documentation inherent to a structure undergoing digitisation with data from a three-dimensional survey. Consequently, within the general framework, of optimising scan-to-BIM procedures lies the actual objective of this thesis: developing digital models that are first of all informative and updatable with data from various sources. These BIM models will constitute digital repositories of the available datasets concerning the asset under study and monitoring. For this purpose, a series of procedural workflows have been developed, supported by automated routines for importing data into what will be defined as *Enriched COoperative Systems for monitoring* [*Monitoring ECO-Systems*].

The two chosen case studies, thus, represent two assets with a characterising aspect, in which the supporting structure coincides almost totally with the final form. The first case study, the *Olivieri Viaduct* in Salerno (Italy), in particular presented the possibility of using BIM modelling not just as a final product but rather as a support for the analysis and discretisation into elementary components of a viaduct for the purpose of classifying the individual components in accordance with the indications provided by the regulations for Risk Classification and Management, Safety Assessment and Monitoring of Existing Bridges recently introduced in Italy [4]. The model firstly developed then is connected through direct links and reimportation of the inspection results to the Bridge Management System [BMS] being developed by C.U.G.R.I. [*Consorzio inter-Universitario per la previsione e prevenzione dei Grandi Rischi*].

The second case study, the Greek *Temple of Neptune* in Paestum (Italy), on the other hand, allowed her to conduct an experiment mainly oriented toward the connection of Sensor-Based Data to a BIM-type model. In this case, the operation strictly concerning the structural modelling phase has instead involved an adequate reflection and discretisation of the structural components, going back to their primary generators, for the preliminary realisation of a dataset of fully parametric BIM objects – also aiming at possible reuse for later applications. As mentioned, the monitoring data available for the second case study were fully digital in nature, coming from both active sensors – *Seismometers* and *Terrestrial Laser Scanners* [TLS] – and passive sensors – *Unmanned Aerial Systems* [UAS].

Although the automation of the protocols used to generate the procedures presented hereto still has a long way to go, they are fundamental in defining the basis for developing multimedia systems capable of reproducing the complex spatial relationships between the built environment and its individual artefacts. Hence, the information digitisation of complex realities is crucial to promote maintenance programmes in order to update the existing databases and develop, through 3D digital ecosystems, techniques for the preservation of the built heritage.

12

Abstract

The main objective of the present thesis work is to develop an efficient methodology for setting up and managing up-to-date and updatable *Monitoring ECO-Systems*, intended as *Enriched COoperative Systems*. It is thus organised into twelve chapters clustered in three main parts. The first part covers an introduction to *Building Information Modelling* [BIM], *Structural Health Monitoring* [SHM], and the overall standardised Scan-To-BIM methodology proposed hereto. Subsequently, the second part presents a procedural and semi-automated methodology within the framework of the macro Scan-to-BIM approach for the digitisation of the Italian Infrastructure Heritage, particularly focusing on bridges, viaducts, and overpasses. The pilot case study for the developed procedure is the Olivieri Viaduct (Salerno, Italy). On the other hand, the third part deals with automated procedures for the integration of data from sensors in a BIM environment, developed on the Temple of Neptune (Paestum, Italy). It was chosen for the extensive existing database and for the possibility of integrating data from the innovative system of seismometers recently arranged for monitoring micro-displacements. Therefore, this application allows to implement pieces of information from both active sensors – i.e., *Terrestrial Laser Scanners* [TLS] and *Seismometers* – and passive sensors – i.e., cameras mounted on *Unmanned Aerial Vehicles* [UAV].

As explained in the first part, in a more distinctively figurative way, we could exhaustively describe the *Building Information Modelling* [BIM] methodology as the ideal combination of symbolic representation – starting from the cavemen's drawing and fast-forwarding to the 3D digital twins of the physical world – and numerical modelling – that indeed dates back to the Greeks, i.e., Pythagoras. However, much like the prisoners of the cave of the well-known Plato's allegory, we are every day more convinced that the digital reproduction of the phenomenal world can become itself the reality. If not, at the very least, it can flawlessly mirror it. On the contrary, it is not to forget that the whole experience of the world is just not equal to the objective reality, may this even exist, but a version of it mediated by our observation, thus a discretisation of it, no matter how faithful it may come to be, should never propose as the absolute truth.

The concept of *Structural Health Monitoring* [SHM] is relatively recent too. Starting from the early years of the 21st century, the problem of monitoring the physical-chemical-mechanical conditions of structures and infrastructures for civil use began to be thought of in a significantly different way than in the last century. Indeed, over the previous twenty years, it has been realised that novel construction materials, such as reinforced concrete and pre-stressed steel may have a long life but not an indefinitely long one. More has also been understood regarding materials of the past, i.e., wood. Thus, it has become clear that carrying out correct and methodical maintenance is essential and can significantly extend the useful life of a structure or infrastructure. All these arguments have then led to the definition of the modern concept of structural health and the need for its monitoring, similarly to what happens to human health.

Furthermore, specifically for the highly historicised Italian territory, SHM constitutes a good tool for the historical and architectural heritage to enhance the management of the assets. Particularly, the ***Guidelines for risk classification and management, safety assessment and monitoring of existing bridges*** underline the importance of predictive models. It then appears clear how current experimentation focuses always more on conjugating the SHM numerical modelling with the BIM modelling technology, often employing advanced programming tools – such as *Visual Programming Language* [VPL] script – so as to add visualisation to asset management systems, to provide a highly beneficial cognitive aid for processing overwhelming amounts of information.

As a result of the presented considerations, it arises the main objective of the present thesis project, i.e., the development of a methodology for long-term management in a BIM environment of structural *monitoring Enriched COoperative Systems* [*ECO-Systems*], which falls within the topics of the *ninth sustainable goal – Industry, innovation, and infrastructure*.

The *monitoring ECO-system* is designed as an open environment that needs continuous input to maintain its order; the inputs will be represented by up-to-date and updatable information, in order for the ECO-system to function properly. It is therefore imperative when organising a facility management BIM system to clearly establish implementation and data management procedures, i.e., to define the so-called *Common Data Environment* [CDE, in italian *Ambiente di Condivisione Dati – ACDat*]. The proposed methodology moves towards a standardisation of the modelling procedures of the existing built environment, while also being easily adaptable *ex-novo* modelling, by simply leaving out the initial integrated survey.

Monitoring ECO-systems are thus configured as systems whose input data come from monitoring operations, whether these are carried out in a predominantly *analogue* fashion rather than in an almost entirely *digital* way.

The secondary objective of the present work is then the generation, by the end of each modelling stage, of properly mapped thus easily accessible *Open BIM* models for efficient information exchange, which falls within the topics of the *seventeenth sustainable goal – Partnership for the Goal*.
A consolidated Scan-to-BIM approach usually involves first surveying the structure and the surrounding landscape on which to develop a BIM model. For said reason, it is hereby proposed a framework for the standardisation of some well and lesser-known practices implemented in this process to be able to trace data sources and the quality of their reproduction along the whole modelling process.
The reported tested Scan-to-BIM methodology, which employs the Autodesk software package, is meant as a *good operational practice* and can be organised into six sequential steps as follows: (1) *Three-dimensional survey* [3DS]; (2) *Georeferencing* [GEO]; (3) *Federate modelling and Shared Coordinates setting* [FSC]; (4) *Structural modelling* [STR]; (5) *Level of Information enhancement* [LOI]; (6) *Open BIM Models Exportation* [IFC].
Each step of the proposed workflow is necessary to the subsequent, but it stays updatable thanks to the BIM environment. The modelling of the existing heritage is rarely a straightforward process and may, in some cases, be iterative, thus the necessity of repeating some steps or, at least, exchanging some of them. Remarkably, the LOI phase is present at different levels, a constant throughout the process, whether performed manually or via VPL scripts, by populating *ad-hoc* parameters with varying types of information.

As previously mentioned, the second part of the thesis work deals with the digitisation of the Italian Infrastructure Heritage, that, to date seems to have been forgotten, generally lacking maintenance planning or even completely neglected. Infrastructural artworks are sporadically recalled, sadly on the occasion of catastrophic events, which unfortunately seem to provide the only catalyst for the initiation of legislative changes, leading to the current imperative to introduce a digital system for the management of Italian bridges, viaducts and overpasses. Therefore, the case study of the Olivieri Viaduct presented in the following chapters, will concern the setting up of an optimised *Bridge Management System* [BMS], intended as a framework for the *Structural Health Monitoring* [SHM] of the Italian Bridge Infrastructure.
Information is key to effective bridge management; therefore, an essential module of a management system is the information model. Databases are at the heart of the module and ultimately form the basis and quality of all decisions and actions considered by the BMS. The addition of visualisation to asset management provides a beneficial cognitive aid for processing overwhelming amounts of

information. This can be achieved via *Bridge Information Modelling* [BrIM], which is not just a geometrical representation of bridges but is an intelligent virtual 3D model of the bridge as it contains all data about every component for its whole life cycle. It improves the quality and accuracy of drawings, as well as constructability, and enhances collaborations.
An in-depth analysis of the national and international regulatory aspects concerning the protocols for inspection and identification of structural criticalities for bridges and elevated infrastructures was therefore due. In particular, the analysis focuses on what was reported internationally in a selection of countries chosen either because they constituted a regulatory benchmark or because they were part of the course of study pursued by the PhD Candidate. Indeed, the United States proposes a regulatory structure articulated between documents that offer an overview of the different professional figures that take part in the analysis and development of a maintenance plan, thus constituting a cultural reference for many countries.
Spain and Argentina, on the other hand, while incorporating certain concepts typical of *Latin* normative frameworks, present substantial differences, whose analysis highlights how the tools of representation and information modelling must adapt to operational peculiarities that can vary widely even among culturally close environments.
Subsequently, an extensive literature review was conducted on the state of the art concerning the application of the BIM methodology to the digitisation of infrastructure assets – in particular bridges, viaducts and flyovers – and data regarding inspection practices aimed at the definition of monitoring and maintenance procedures, followed by an analysis of the evolution of the relevant Italian regulatory system, starting from the 1960s up to the more recent application of the *Guidelines for the Risk Classification and Management, Safety Assessment and Monitoring of Existing Bridges* issued in 2020.

The first experimental phase involving the updating of the Olivieri Viaduct information database began with a survey campaign of the bridge and the underlying valley in order to produce initial modelling of the infrastructure within its urbanised context, to extrapolate updated technical drawings of the complex system.
The survey campaign was undertaken in the framework of the Project: *CUR_CIS2020 Methodologies for the punctual assessment of hydrogeological risk in heavily populated areas and tools for regional development strategies – Application to the case study Strategic Infrastructure Corridor* [*CIS*] *at regional level; Salerno-Cava de' Tirreni – A3 Naples-Salerno motorway section and other downstream road infrastructures*. The project objective concerns procedures to process and integrate various types of 2D and 3D data in a GIS environment. The survey was carried out by the *geomatics* and *surveying & representation* groups of the *Laboratorio Modelli*

– *Surveying and Geo-Mapping for Environment and Cultural Heritage*, Department of Civil Engineering [DICIV], University of Salerno.
Given its relevance, the Olivieri Viaduct and the surrounding urban context appeared to be the perfect case study to develop an operational methodology for the massive digitisation of both the structural geometry and the relative state of conservation of the infrastructural structures belonging to the category of 'bridges viaducts and overpasses' located along the A3 motorway, within the framework of the C.U.G.R.I [*Consorzio inter-Universitario per la previsione e prevenzione dei Grandi Rischi – Inter-University Consortium for the Forecasting and Prevention of Major Risks*] agreement with the *Autostrade Meridionali* [SAM] company concerning the commissioning of the *Service for the surveillance of the major infrastructures of the A3 Naples-Pompei-Salerno motorway – in accordance with the circulars of the Ministry of Public Works No. 6736/61 of 19.7.67 and No. 34233 of 25.02.1991 – and related support activities, such as non-destructive technical tests, laboratory tests, etc.*
Afterwards the validated and optimised procedures for the information exchange concerning both the register and the cataloguing data on the infrastructure, as well as the models in an open format as a basis for further enhancing the level of knowledge concerning the very structure are presented. The bulk of the data thus produced is then organised to be fed into the BMS developed by C.U.G.R.I.'s IT technicians, where it is archived according to regulatory requirements.
For the purpose, the shared parameters *Form Link* [*Link Scheda*] and *GlobalStructureCode* [*CodiceOperaGlobale*] were introduced. They would respectively contain a working link to the directory of the BMS hosting the inspection form filled in for each component, and a unique identifier for each component, necessary to organise the error-free data feed concerning each component named according to the nomenclature, numbering and cataloguing carried out within the BIM environment.
A subsequent phase is then envisaged for the re-importation of the data resulting from the detailed inspections – summarised by the *Relative Defectiveness Indicator* [Dr] plotted by the BMS – to the editable BIM environment, Autodesk Revit [LOI enhancement phase]. The BrIM model thus becomes a fully updated repository containing the health status of the infrastructure models through which it is also possible to provide an advanced graphic visualisation of the synthetic data grouped, e.g., into the *Attention Classes* [CdA] imposed by the regulations.

As further explained in the third part, many researchers have already pointed out the necessity to integrate the current *Structural Health Monitoring* [SHM] procedures, including but not limited to *Bridges Management Systems* [BMS], with data coming from sensors, both in terms of measuring instruments connected to a *Digital Twin* of the physical asset via the so-called *Internet of Things* [IoT] and three-dimensional survey data. Indeed, for preventive and systematic maintenance of structures, periodic visual inspections are essential to detect structural defects at an early stage and to initiate necessary interventions. Modern technologies such as *unmanned aircraft systems* [UAS] equipped with high-resolution cameras increasingly support the inspection process and the associated documentation. In addition, processing methods and linked data models allow for effective data management.

Besides the historical relevance of the case study proposed below, the Temple of Neptune at Paestum – one of the best-preserved artefacts of Greek origin in Italy – has been chosen for the possibility of carrying out experimental applications starting from the rich already existing database built up over more than a decade. Furthermore, additional information coming from the innovative seismometric monitoring system – whose measuring points are placed on the cornice of the external colonnade of the Temple of Neptune and data collection manholes near the stylobate – has been subsequently implemented. The first laser scanner survey crucial herein for scan-to-BIM modelling dates back to 2011. The knowledge of the site was updated several times mainly with photogrammetric surveys oriented to the acquisition of material data. The most up-to-date of which, designed to acquire both the temple and the surrounding context with a good level of detail, was carried out in 2017. The subsequent photogrammetric survey carried out in 2020 was, in turn, focused on the survey of the area surrounding the temple of Neptune, having been requested due to the new excavations made upon the placement of the seismometric monitoring system.

The monitoring system network consists, among other specific equipment, of experimental measurement instruments – *UNISA Folded Pendulum*, seismometers developed and patented by the *Research Group in Applied Physics* of the University of Salerno engaged in the study of gravitational waves – set in place under the supervision of the scientific coordinators: professor Luigi Petti (Department of Civil Engineering – University of Salerno) and the director of the *Archaeological Park of Paestum and Velia*, i.e., the archaeologist Gabriel Zuchtriegel.

Due to BIM working with a cartesian reference system, upon linking a georeferenced RCP point cloud to a Revit project, the point cloud will be automatically moved closer to the new internal origin, obliterating the previous coordinate values. On the other hand, when the generation of the BIM instances is forced in place using VPL scripts, in order to keep the geographical coordinates, approximation failures occur in the reprojected objects, above all in the case of meshes and visualisation and modelling issues will arise afterwards.

Therefore, given the issues connected with employing a topographic coordinates system within a BIM environment, in order to set up the shared environment [FSC] for the Monitoring ECO-System of the Temple of Neptune, it was necessary to perform a translation from the global to local reference system on both the photogrammetric point clouds – directly within the Agisoft Metashape environment by subtracting a fixed quantity to the x, y, and z values of the GCPs – and on the integrated point cloud used as a reference for the subsequent Scan-to-BIM application. Fully parametric structural families were then modelled from scratch and placed in the BIM project using the integrated point cloud as a baseline.

Although the long-term purpose of a BIM modelling is to standardise as many elements as possible, when the object to model is unique, as in the case of the urban context, which is typically different and distinctive from any asset, the aim should focus on standardising the process to reproduce it most authentically, for further in-depth study. Hence, the methodological applications proposed in the third part involves two workflows developed to reproduce texturised photogrammetric meshes of the urban context, and some detailed areas of interest within a BIM environment, by parametrising the very components of the mesh model, its triangular faces. Particularly the first procedure can be further enhanced by means of *Physically Based Rendering* [PBR] materials, generating the advanced maps as a result of the photogrammetric process; while the second one may come in handy when the objective of the application is an accurate reproduction of selected areas for future qualitative and quantitative assessments. The aim is indeed to bridge the gap between the type of detail a survey can reach, precisely a photogrammetric one, when speaking about the colorimetric data, and what is possible to reproduce in a BIM environment when talking about distinctive if not unique elements such as the urban context or detailed relevant elements, such as frieze/decorations or damaged areas.

The two procedural workflows presented – defined *Workflow A and B* for the sake of simplicity – are to all intents and purposes Mesh-to-BIM approaches. Therefore, for their effective implementation, some preliminary actions on the mesh surveyed model must be undertaken. Mesh simplification is a common practice for minimising model size by reducing the number of faces while preserving the shape, volume, and boundaries. Criteria for mesh decimation are generally user-defined, selecting the reduction method (working on the number of vertices, edges, or faces) and the reduction target, indeed, several commercial and open-source editing and modelling software include a mesh simplification module for handling this post-processing task efficiently. Therefore, for an average notebook (Core i7 16GB of RAM, 2GB GPU) to be able to process the developed scripts and manage the results, it is advisable to keep the mesh faces count under 600’000 units, for the first method proposed, and under 20’000 units, for the second one, simplifying and splitting in more

than one project the original photogrammetric mesh model (via Agisoft Metashape and ISTI-CNR MeshLab).
Eventually, the monitoring network consisting of seismometric sensors placed between the end of 2020 and the beginning of 2021 was also modelled using *ad-hoc* developed MEP families with a lower level of geometric detail – LOG 200 (purely volumetric). Subsequently, the information database related to the measurement instruments and real-time monitoring data available to date were linked to the MEP model via a VPL script [Script 10] customised onto this specific seismometer network. The full comprehension and utilisation of the seismometer signals are still under evaluation, as the network is still in the run-in phase, so the BIM interface had to be designed to be sufficiently flexible and upgradeable. To this end, the script was explicitly designed for possible future upgrades of the monitoring system by choosing Microsoft Excel as the source database and further automating the implementation of possible additionally required system descriptors defined as *shared parameters* [Script 9]. Furthermore, the linked pictures useful to better understand the system have been made available online via an openly shared Google Drive folder.

With regard to the first proposed case study, the greatest challenge was to simplify and optimise the procedure for the effective implementation of BIM-type models in the processes of cataloguing and inspecting existing bridges, viaducts and overpasses, so that it would become a valid support tool rather than a barrier for the C.U.G.R.I. technicians, who are not experts in the field of three-dimensional information modelling. On the other hand, the direct confrontation with experts specialised in structural design and monitoring allowed the undersigned to fill in some technical gaps, while also receiving valuable feedback in real-time.
On the other hand, the second application showed how the management of the existing heritage cannot be separated from an accurate investigation of the state of conservation of the materials and a detailed 3D reconstruction. The morphological and colourimetric reconstruction of complex structures, elements and specific damaged areas in the BIM environment is essential for the development of databases to store data and facilitate the planning of refurbishments and, in general, any intervention activity on the asset under study.
Alternatively, should the integration of sensor-based data become a common practice for monitoring procedures, this praxis will certainly optimise conservation assessments, accurately highlighting changes in the geometry and texture of the asset, by merely comparing updated survey data with the modelled asset at regular intervals.

Sommario

L'obiettivo principale del presente lavoro di tesi è quello di sviluppare una metodologia efficiente per la creazione e la gestione di *ECO-sistemi di monitoraggio* aggiornati e aggiornabili, intesi come *Sistemi COoperativi Integrati* [*Enriched COoperative Systems*]. Il corpus è dunque organizzato in dodici capitoli raggruppati in tre parti principali. La prima parte tratta un'introduzione al *Building Information Modelling* [BIM], allo *Structural Health Monitoring* [SHM] e alla metodologia per un approccio standardizzato di tipo Scan-To-BIM proposto in questa sede. La successiva seconda parte presenta una metodologia procedurale e semi-automatizzata, sviluppata all'interno del macro-approccio Scan-to-BIM, per la digitalizzazione del patrimonio infrastrutturale italiano, con particolare attenzione a ponti, viadotti e cavalcavia. Il caso di studio pilota per la procedura sviluppata è il Viadotto Olivieri (Salerno, Italia). La terza parte si occupa, invece, di procedure automatizzate per l'integrazione di dati provenienti da sensori in ambiente BIM, sviluppate sul Tempio di Nettuno (Paestum, Italia) scelto sia per la ricca banca dati storicizzata già disponibile, sia per la possibilità di integrare ulteriormente dati provenienti dall'innovativo sistema di sismometri di recente disposti per il monitoraggio dei micro-spostamenti. Questa applicazione permette dunque di implementare tanto informazioni provenienti da sensori attivi – cioè *Laser Scanner Terrestri* [TLS] e *Sismometri* – quanto da quelli passivi – cioè fotocamere montate su *Aereomobili a Pilotaggio Remoto* [APR].

Come spiegato nella prima parte, in modo più distintamente figurativo, potremmo descrivere esaustivamente la metodologia del *Building Information Modelling [*BIM] come la combinazione ideale di rappresentazione simbolica – a partire dal disegno degli uomini delle caverne per arrivare ai gemelli digitali tridimensionali che raffigurano il mondo fisico – e di modellazione numerica – che risale ai Greci stessi e in particolare a Pitagora. Tuttavia, proprio come i prigionieri della caverna della nota allegoria di Platone, siamo ogni giorno più convinti che la riproduzione digitale del mondo fenomenico possa diventare essa stessa la realtà. Oppure possa quantomeno rispecchiarla in modo impeccabile. Al contrario, non bisogna dimenticare che l'intera esperienza del mondo non è uguale alla realtà oggettiva, se mai questa esistesse, ma piuttosto ne è una sua versione mediata dalla nostra osservazione, quindi una sua discretizzazione che, per quanto fedele possa risultare, non dovrebbe mai proporsi come verità assoluta. Anche il concetto di *Structural Health Monitoring* [SHM] è relativamente recente. A partire dai primi anni del XXI secolo, il problema del monitoraggio delle condizioni fisico-chimiche-meccaniche di strutture e infrastrutture ad uso civile ha iniziato a essere pensato in modo significativamente diverso rispetto

al secolo scorso. Negli ultimi vent'anni, infatti, ci si è resi conto che i nuovi materiali da costruzione, come il cemento armato e l'acciaio precompresso, possono avere una vita lunga ma non indefinita. Sono state inoltre acquisite maggiori conoscenze sui materiali del passato, come il legno. È così emerso chiaramente che una corretta e metodica manutenzione è essenziale al fine di prolungare in modo significativo la vita utile di una struttura o di un'infrastruttura. Tali argomentazioni hanno quindi determinato la definizione del moderno concetto di salute strutturale e la necessità di un suo monitoraggio, analogamente a quanto avviene per la salute umana.
Inoltre, proprio per il territorio italiano altamente storicizzato, la SHM costituisce un valido strumento nell'ottica di una migliore gestione del patrimonio storico e architettonico. In particolare, le *Linee Guida per la classificazione e la gestione del rischio, la valutazione della sicurezza e il monitoraggio dei ponti esistenti* sottolineano l'importanza dei modelli predittivi. Appare quindi chiaro come la sperimentazione attuale si concentri sempre più sulla coniugazione della modellazione numerica SHM con la tecnologia di modellazione BIM, spesso impiegando strumenti di programmazione avanzati – come gli script del *Visual Programming Language* [VPL] – in modo da aggiungere la visualizzazione ai sistemi di gestione dei beni, per fornire così un aiuto cognitivo altamente vantaggioso nell'elaborazione di quantità ingenti di informazioni. Da queste considerazioni scaturisce l'obiettivo principale del presente progetto di tesi, ovvero lo sviluppo di una metodologia per la gestione a lungo termine in ambiente BIM di *Sistemi COoperativi Integrati* per il monitoraggio strutturale [*ECO-Systems*], che rientra a pieno titolo nelle tematiche del *nono obiettivo sostenibile – Industria, innovazione e infrastrutture*.
L'*ECO-sistema di monitoraggio* è concepito come un ambiente aperto che necessita di input continui per mantenere il suo ordine; gli input saranno perciò rappresentati da informazioni aggiornate e aggiornabili, affinché l'ECO-sistema funzioni correttamente. Nell'organizzare un sistema BIM di facility management è quindi indispensabile stabilire chiaramente le procedure di implementazione e di gestione dei dati, ovvero definire il cosiddetto *Common Data Environment* [CDE, in italiano *Ambiente di Condivisione Dati* – ACDat]. La metodologia proposta mira per tanto a una standardizzazione delle procedure di modellazione dell'ambiente costruito esistente, pur essendo facilmente adattabile alla modellazione *ex-novo*, semplicemente tralasciando la fase iniziale di rilievo integrato.
Gli ECO-sistemi di monitoraggio si configurano quindi come sistemi i cui dati di input provengono da operazioni di monitoraggio, siano esse svolte in modo prevalentemente analogico piuttosto che in maniera quasi interamente digitale. L'obiettivo secondario del presente lavoro è poi la generazione, al termine di ogni fase di modellazione, di modelli Open BIM correttamente mappati e quindi facilmente fruibili per un efficiente

scambio di informazioni; obiettivo questo che rientra anch'esso pienamente nelle tematiche del *diciassettesimo obiettivo sostenibile – Partnership for the Goal*.
Un approccio consolidato di tipo Scan-to-BIM prevede solitamente il rilievo della struttura e del paesaggio circostante a partire dal quale sviluppare un modello BIM. Per questo motivo, in questa sede si propone un sistema di standardizzazione di alcune procedure, note e meno note, messe comunemente in atto in questo tipo di processi finalizzate al tracciamento delle fonti dei dati e della qualità di riproduzione degli stessi durante l'intero iter di modellazione. La metodologia Scan-to-BIM sperimentata, che si avvale del pacchetto di software Autodesk, è intesa come una buona pratica operativa e può essere organizzata in sei fasi sequenziali, elencate di seguito: (1) *Rilievo tridimensionale* [3DS]; (2) *Georeferenziazione* [GEO]; (3) *Modellazione federata e impostazione delle coordinate condivise* [FSC]; (4) *Modellazione strutturale* [STR]; (5) *Miglioramento del livello di informazione* [LOI]; (6) *Esportazione di modelli BIM aperti* [IFC].
Ogni fase del flusso di lavoro proposto è necessaria alla successiva, ma rimane aggiornabile in ambiente BIM. La modellazione del patrimonio esistente è raramente un procedimento semplice e, in alcuni casi, può essere iterativa, con la conseguente necessità di ripetere alcune fasi o, almeno, di alternarne alcune. È interessante notare che la fase LOI è in realtà presente a diversi livelli e rappresenta una costante di tutto il processo, sia che venga eseguita manualmente o tramite script VPL, popolando parametri predisposti *ad hoc* con vari tipi di informazioni.

Come già accennato, la seconda parte del lavoro di tesi si concentra sulla digitalizzazione del patrimonio infrastrutturale italiano, che ad oggi sembra essere stato dimenticato, il più delle volte privo di una pianificazione della manutenzione o addirittura del tutto abbandonato. Le opere d'arte infrastrutturali vengono sporadicamente ricordate, generalmente in occasione di eventi catastrofici, che purtroppo sembrano essere l'unico catalizzatore per l'avvio di modifiche legislative, sfociate nell'attuale imperativo di introdurre un sistema digitale per la gestione di ponti, viadotti e cavalcavia italiani. Pertanto, il caso di studio del Viadotto Olivieri, presentato nei capitoli successivi, riguarda la messa a punto di un *sistema di gestione dei ponti* [BMS] ottimizzato, inteso come quadro di riferimento per il *monitoraggio dello stato di salute strutturale* [SHM] delle infrastrutture soprelevate italiane.
L'informazione è un elemento chiave per una gestione efficace dei ponti; pertanto, un modulo essenziale di un sistema di gestione consiste nella messa a punto di modello informativo. I database sono il cuore di questo modulo e, in ultima analisi, rappresentano la base e il livello qualitativo di tutte le decisioni e le azioni previste dal BMS. L'aggiunta della visualizzazione alla gestione degli asset fornisce un utile aiuto cognitivo per l'elaborazione di quantità eccessive di informazioni. Questo risultato si può ottenere attraverso il cosiddetto *Bridge Information*

Modelling [BrIM], che non si limita a una rappresentazione geometrica dei ponti, ma è piuttosto un modello virtuale intelligente tridimensionale del ponte, che contiene le informazioni riguardanti ogni suo componente per l'intero ciclo di vita. Il BrIM è in grado quindi di migliorare la qualità e l'accuratezza dei disegni, nonché la realizzabilità, e di potenziare le attività di collaborazione.
Era quindi doverosa un'analisi approfondita degli aspetti normativi nazionali e internazionali relativi ai protocolli di ispezione e identificazione delle criticità strutturali per ponti e infrastrutture sopraelevate. In particolare, l'analisi si concentra su quanto riportato a livello internazionale in una selezione di paesi scelti o perché costituivano un riferimento normativo o perché facenti parte del corso di studi perseguito dalla dottoranda. Gli Stati Uniti, infatti, propongono una struttura normativa articolata in documenti che offrono una panoramica delle diverse figure professionali che partecipano all'analisi e allo sviluppo di un piano di manutenzione, costituendo così un riferimento culturale per molti Paesi. Spagna e Argentina, invece, pur incorporando alcuni concetti tipici dei quadri normativi *latini*, presentano differenze sostanziali, la cui analisi evidenzia come gli strumenti di rappresentazione e modellazione delle informazioni debbano adattarsi a peculiarità operative che possono variare molto anche tra ambienti culturalmente vicini.
Successivamente, è stata condotta un'ampia revisione della letteratura sullo stato dell'arte relativo all'applicazione della metodologia BIM alla digitalizzazione dei beni infrastrutturali – in particolare ponti, viadotti e cavalcavia – e dei dati relativi alle pratiche ispettive finalizzate alla definizione delle procedure di monitoraggio e manutenzione, seguita da un'analisi dell'evoluzione del sistema normativo italiano in materia, a partire dagli anni Sessanta fino alla più recente applicazione delle *Linee Guida per la classificazione e la gestione del rischio, la valutazione della sicurezza e il monitoraggio dei ponti esistenti* emanate nel 2020.

La prima fase sperimentale relativa all'aggiornamento del database informativo sul Viadotto Olivieri è iniziata con una campagna di rilievo del ponte e della valle sottostante, al fine di produrre una prima modellazione dell'infrastruttura nel suo contesto urbanizzato, dalla quale estrapolare elaborati tecnici aggiornati del sistema complesso.
La campagna di rilievi è stata intrapresa nell'ambito del Progetto: *CUR_CIS2020 Metodologie per la valutazione puntuale del rischio idrogeologico in aree fortemente popolate e strumenti per le strategie di sviluppo regionale – Applicazione a livello regionale del caso studio Corridoio Infrastrutturale Strategico [CIS]; Salerno-Cava de' Tirreni – tratta autostradale A3 Napoli-Salerno e altre infrastrutture stradali a valle*. L'obiettivo del progetto riguarda lo sviluppo di procedure volte all'elaborazione e all'integrazione di vari tipi di dati 2D e 3D in un ambiente GIS. In particolare, il rilievo è stato effettuato dai gruppi di

geomatica e di *rilievo e rappresentazione* del *Laboratorio Modelli – Surveying and Geo-Mapping for Environment and Cultural Heritage*, afferente al Dipartimento di Ingegneria Civile [DICIV] dell'Università degli Studi di Salerno.
Data la rilevanza del Viadotto Olivieri e del contesto urbano circostante, questo si è rivelato essere il caso di studio ideale per sviluppare una metodologia operativa per la digitalizzazione massiva tanto della geometria strutturale quanto del relativo stato di conservazione delle opere infrastrutturali appartenenti alla categoria "ponti, viadotti e cavalcavia" situate lungo l'autostrada A3, nell'ambito dell'accordo tra il C.U.G.R.I. [*Consorzio interuniversitario per la previsione e prevenzione dei Grandi Rischi*] e la Società *Autostrade Meridionali* [SAM] per l'affidamento del *Servizio di sorveglianza delle grandi infrastrutture dell'autostrada A3 Napoli-Pompei-Salerno – ai sensi della circolare del Ministero dei Lavori Pubblici n. 6736/61 del 19.7.2011. 6736/61 del 19.7.67 e n. 34233 del 25.02.1991 – e delle relative attività di supporto, quali prove tecniche non distruttive, prove di laboratorio, ecc*. Vengono quindi presentate a seguire le procedure validate e ottimizzate per lo scambio di informazioni relative sia all'anagrafica che ai dati di catalogazione dell'infrastruttura, nonché la produzione di modelli in formato aperto come base per migliorare ulteriormente il livello di conoscenza della struttura stessa. La mole di dati così prodotta viene quindi predisposta per essere immessa nel BMS sviluppato dai tecnici informatici del C.U.G.R.I., dove viene archiviata in conformità con le disposizioni normative.
In particolare, sono stati introdotti i parametri condivisi *Link Scheda* e *CodiceOperaGlobale* che conterranno, rispettivamente, un link funzionante alla directory del BMS che ospita la scheda di ispezione compilata per ogni componente, e un identificativo univoco per detti componenti, necessario al fine di organizzare l'alimentazione dei dati privi di errori relativi a ciascun componente in base alla nomenclatura, numerazione e catalogazione effettuata all'interno dell'ambiente BIM. In una fase successiva è prevista poi la reimportazione dei dati risultanti dalle ispezioni di dettaglio – sintetizzati dall'*Indicatore di Difettosità Relativa* [Dr] elaborato all'interno del BMS – verso l'ambiente BIM editabile, Autodesk Revit [fase di potenziamento del LOI]. Il modello BrIM diventa così un repository completamente aggiornato sulle condizioni di salute dei modelli infrastrutturali, attraverso il quale è possibile fornire anche una visualizzazione grafica avanzata dei dati sintetici raggruppati, ad esempio, nelle *Classi di Attenzione* [CdA] imposte dalla normativa.

Come illustrato nella terza parte, molti ricercatori hanno già evidenziato la necessità di integrare le attuali procedure di *Structural Health Monitoring* [SHM], includendo ma non limitandosi ai *Bridges Management Systems* [BMS], con i dati provenienti da sensori, sia in termini di strumenti di misura collegati a un *Digital Twin* dell'asset fisico attraverso il cosiddetto *Internet of Things* [IoT], sia per quanto riguarda i dati di rilievo tridimensionali. Infatti, nell'ottica di un'attività di manutenzione preventiva e sistematica delle strutture, le ispezioni visive periodiche sono essenziali nel rilevare precocemente i difetti strutturali e per intraprendere gli interventi necessari. Le moderne tecnologie, come i *sistemi aerei a pilotaggio remoto* [SAPR] dotati di telecamere ad alta risoluzione, sono sempre più spesso in grado di supportare il processo di ispezione e la relativa documentazione. Inoltre, i metodi di elaborazione e i modelli di dati collegati consentono una gestione efficace dei dati.

Oltre che per la rilevanza storica del caso di studio proposto di seguito, il Tempio di Nettuno – a Paestum, uno dei manufatti di origine greca meglio conservati in Italia – è stato per tanto scelto data la possibilità di realizzare applicazioni sperimentali a partire dalla già ricca banca dati esistente costruita nel corso di più di un decennio. Sono state inoltre implementate le informazioni aggiuntive provenienti dall'innovativo sistema di monitoraggio sismometrico – i cui punti di misura sono collocati sul cornicione del colonnato esterno del Tempio di Nettuno e i pozzetti di raccolta dati in prossimità dello stilobate. Il primo rilievo laser scanner, fondamentale per la fase di modellazione Scan-to-BIM, risale al 2011. La conoscenza del sito è stata poi variamente aggiornata soprattutto con rilievi fotogrammetrici orientati all'acquisizione di dati materici, il più aggiornato dei quali, finalizzato ad acquisire con un buon livello di dettaglio sia il tempio che il contesto circostante, è stato poi realizzato nel 2017. Il successivo rilievo fotogrammetrico effettuato nel 2020 è stato, invece, incentrato sul rilievo dell'area circostante il tempio di Nettuno, essendo stato richiesto in ragione dei nuovi scavi effettuati in occasione del posizionamento del sistema di monitoraggio sismometrico.

La rete del sistema di monitoraggio è costituita, oltre ad altre attrezzature specifiche, da strumenti di misura sperimentali – *UNISA Folded Pendulum*, sismometri sviluppati e brevettati dal *Gruppo di Ricerca in Fisica Applicata* dell'Università di Salerno impegnati nello studio delle onde gravitazionali – messi in opera sotto la supervisione dei coordinatori scientifici: il professor Luigi Petti (Dipartimento di Ingegneria Civile – Università di Salerno) e il direttore del *Parco Archeologico di Paestum e Velia* l'archeologo Gabriel Zuchtriegel.

Poiché il BIM lavora con un sistema di riferimento cartesiano, quando si collega una nuvola di punti RCP georeferenziata a un progetto Revit, questa viene automaticamente avvicinata alla nuova origine interna del progetto, cancellando i valori delle coordinate precedenti. D'altra parte, quando la generazione delle istanze BIM viene forzata in loco utilizzando ad esempio script VPL, al fine di mantenere le coordinate geografiche, si verificano errori di approssimazione negli oggetti riproiettati, soprattutto nel caso delle mesh, con conseguenti problemi di visualizzazione e modellazione.

Pertanto, date le problematiche legate all'impiego di un sistema di coordinate topografiche all'interno di un ambiente BIM, al fine di configurare l'ambiente

condiviso [FSC] per l'ECO-sistema di monitoraggio del Tempio di Nettuno, è stato necessario effettuare una traslazione dal sistema di riferimento globale a quello locale sia sulle nuvole di punti fotogrammetriche – agendo in questo caso direttamente all'interno dell'ambiente Agisoft Metashape sottraendo una quantità fissa ai valori x, y e z dei GCP – sia sulla nuvola di punti integrata utilizzata come riferimento per la successiva applicazione Scan-to-BIM. Famiglie strutturali interamente parametriche, sono state quindi modellate da zero e disposte nel progetto BIM utilizzando la nuvola di punti integrata come riferimento.
Sebbene lo scopo a lungo termine di una modellazione BIM sia quello di standardizzare il maggior numero possibile di elementi, quando l'oggetto da modellare è unico, come nel caso del contesto urbano, che è tipicamente diverso e distintivo in qualsiasi asset, l'obiettivo dovrebbe puntare piuttosto alla standardizzazione del processo per riprodurlo nel modo più autentico, in vista di futuri approfondimenti. Pertanto, le applicazioni metodologiche proposte nella terza parte riguardano due flussi di lavoro sviluppati per riprodurre mesh fotogrammetriche testurizzate del contesto urbano e alcune aree di interesse particolareggiate all'interno di un ambiente BIM, parametrizzando le componenti essenziali del modello di mesh, le sue facce triangolari. In particolare, il primo procedimento può essere ulteriormente migliorato attraverso l'impego di materiali di tipo *Physically Based Rendering* [PBR], generando mappe avanzate come risultato del processo fotogrammetrico; mentre il secondo può tornare utile quando l'obiettivo dell'applicazione è una riproduzione accurata di aree selezionate per future valutazioni qualitative e quantitative. L'obiettivo è infatti quello di colmare il divario tra il tipo di dettaglio che può raggiungere un rilievo, per l'appunto fotogrammetrico, quando si parla di dati colorimetrici, e quello che è possibile riprodurre in ambiente BIM, nel caso di elementi caratteristici se non unici, come il contesto urbano o elementi rilevanti di dettaglio, come fregi/decorazioni o aree danneggiate.
I due flussi di lavoro procedurali presentati di seguito – definiti *Workflow A* e *B* per semplicità – sono a tutti gli effetti approcci di tipo Mesh-to-BIM. Pertanto, per una loro efficace implementazione, è necessario intraprendere alcune azioni preliminari sul modello rilevato dalla mesh. La semplificazione della mesh è una pratica comune per minimizzare le dimensioni del modello riducendo il numero di facce preservandone la forma, il volume e i confini. I criteri per la decimazione della mesh sono generalmente definiti dall'utente, che seleziona il metodo di riduzione (lavorando sul numero di vertici, spigoli o facce) e l'obiettivo di riduzione; in effetti, molti software di editing e modellazione commerciali e open-source includono un modulo di semplificazione della mesh per gestire in modo efficiente questa attività di post-elaborazione. Pertanto, affinché un notebook medio (Core i7 16GB di RAM, 2GB di GPU) possa elaborare gli script sviluppati e gestire i risultati, è consigliabile mantenere

il numero di triangoli della mesh sotto le 600 000 unità, per il primo metodo proposto, e sotto le 20 000 unità, per il secondo, semplificando e dividendo in più progetti il modello di mesh fotogrammetrico originale (tramite Agisoft Metashape e ISTI-CNR MeshLab).
Anche la rete di monitoraggio costituita da sensori sismometrici posizionati tra la fine del 2020 e l'inizio del 2021 è stata modellata utilizzando famiglie MEP sviluppate *ad hoc*, ma con un livello di dettaglio geometrico inferiore – LOG 200 (puramente volumetrico). Successivamente, il database delle informazioni relative agli strumenti di misura e i dati di monitoraggio in tempo reale disponibili fino ad oggi sono stati collegati al modello MEP tramite uno script VPL [Script 10] customizzato su questa specifica rete sismometrica. La piena comprensione e l'utilizzo dei segnali dei sismometri sono ancora in fase di sperimentazione, poiché la rete è attualmente in collaudo; quindi, l'interfaccia BIM è stata pensata in modo da essere sufficientemente flessibile e aggiornabile in qualsiasi momento. A tal fine, è stato progettato espressamente per possibili aggiornamenti futuri del sistema di monitoraggio, scegliendo Microsoft Excel come database di origine e automatizzando ulteriormente l'implementazione di eventuali ulteriori descrittori del sistema definiti come *parametri condivisi* [Script 9]. Inoltre, le immagini collegate utili a comprendere meglio il sistema sono state rese disponibili online attraverso una cartella di Google Drive condivisa apertamente.

Per quanto riguarda il primo caso studio proposto, la sfida maggiore è stata quella di semplificare e ottimizzare la procedura per l'effettiva implementazione dei modelli di tipo BIM nei processi di catalogazione e ispezione di ponti, viadotti e cavalcavia esistenti, in modo che diventasse un valido strumento di supporto e non un ostacolo per i tecnici del C.U.G.R.I., non esperti nel campo della modellazione informativa tridimensionale. D'altra parte, il confronto diretto con esperti specializzati nella progettazione e nel monitoraggio strutturale ha permesso alla sottoscritta di colmare alcune lacune tecniche, ricevendo anche preziosi feedback in tempo reale.
La seconda applicazione ha invece evidenziato come la gestione del patrimonio esistente non possa prescindere da un'accurata indagine sullo stato di conservazione dei materiali e da una dettagliata ricostruzione in 3D. La ricostruzione morfologica e colorimetrica di strutture complesse, di elementi e di specifiche aree danneggiate in ambiente BIM è essenziale per lo sviluppo di banche dati che consentano di archiviare i dati e di facilitare la pianificazione di ristrutturazioni e, in generale, di qualsiasi attività di intervento sul bene oggetto di studio. D'altra parte, se l'integrazione di dati basati su sensori diventerà una pratica comune per le procedure di monitoraggio, questa prassi ottimizzerà certamente le valutazioni di conservazione, evidenziando con precisione i cambiamenti nella geometria e nella texture del bene, semplicemente confrontando i dati di indagine aggiornati con il bene modellato a intervalli regolari.

Resumen

El objetivo principal del presente trabajo de tesis es desarrollar una metodología eficiente para la creación y gestión de *ECO-Sistemas de Monitoreo* actualizados y actualizables, pensados como *Sistemas Cooperativos Enriquecidos*. Así, se organiza en doce capítulos repartidos en tres partes principales. La primera parte abarca una introducción a la *modelización de la información del edificio* [BIM], a la *monitorización de la salud estructural* [SHM] y a la metodología general estandarizada Scan-To-BIM que se plantea en este documento. Posteriormente, la segunda parte presenta una metodología procedimental y semiautomatizada en el marco del enfoque macro Scan-to-BIM para la digitalización del patrimonio de infraestructuras italiano, centrándose especialmente en los puentes, viaductos y pasos elevados. Siendo, en esta oportunidad, el caso de estudio piloto para el procedimiento desarrollado el Viaducto Olivieri (Salerno, Italia). Por otro lado, la tercera parte trata de los procedimientos automatizados para la integración de los datos de los sensores en un entorno BIM, desarrollados en el Templo de Neptuno (Paestum, Italia) elegido tanto por la rica base de datos histórica ya disponible como por la posibilidad de integrar aún más los datos del innovador sistema de sismómetros recientemente dispuesto para el seguimiento de los micro-desplazamientos. Esta aplicación permite, por tanto, la implementación de información procedente tanto de sensores activos – como escáneres *láser terrestres* [TLS] y *sismómetros* -; así como de sensores pasivos – cámaras montadas en *vehículos aéreos no tripulados* [VANT].

Como se ha explicado anteriormente, de una manera más figurativa, podríamos describir exhaustivamente la metodología del *Building Information Modelling* [BIM] como la combinación ideal de la representación simbólica -que parte del dibujo de los hombres de las cavernas y llega a los gemelos digitales en tres dimensiones del mundo físico y de la modelización numérica que, de hecho, se remite a los legados griegos de Pitágoras. Sin embargo, al igual que los prisioneros de la caverna de la conocida alegoría de Platón, cada día estamos más convencidos de que la reproducción digital del mundo fenoménico puede convertirse en la propia realidad. Si no, al menos, puede reflejarla impecablemente. En realidad, no hay que olvidar que el conjunto de la experiencia del mundo no es igual a la realidad objetiva, aunque ésta exista, sino una versión de la misma mediada por nuestra observación, por lo que una discretización de la misma, por muy fiel que sea, nunca debe proponerse como la verdad absoluta. El concepto de *monitorización de la salud estructural* [SHM] es también relativamente reciente. A partir de los primeros años del siglo XXI, el problema de la monitorización de las condiciones físico-químicas-mecánicas de las estructuras e infraestructuras de uso civil comenzó a plantearse de una manera significativamente diferente a la del

siglo pasado. En efecto, en los últimos veinte años se ha comprendido que los nuevos materiales de construcción, como el hormigón armado y el acero pretensado, pueden tener una vida larga, pero no indefinida. También se ha aprendido más sobre el comportamiento de los materiales del pasado, como la madera. Así, ha quedado claro que llevar a cabo un mantenimiento correcto y metódico es esencial y puede alargar considerablemente la vida útil de una estructura o infraestructura. Todos estos argumentos han llevado a la definición del concepto moderno de salud estructural y a la necesidad de su seguimiento, de forma similar a lo que ocurre con la salud humana.

Al mismo tiempo, específicamente para el territorio italiano, altamente cargado de historia, la SHM constituye una buena herramienta para mejorar la gestión del patrimonio histórico y arquitectónico. En ese sentido, las *líneas guía para la clasificación y gestión de riesgos, la evaluación de la seguridad y la vigilancia de los puentes existentes* destacan la importancia de los modelos predictivos. Así pues, parece claro que la experimentación actual se tiene que enfocar cada vez más en la conjugación de la modelización numérica SHM con la tecnología de modelización BIM, empleando a menudo herramientas de programación avanzadas – como el script *Visual Programming Language* [VPL] – para añadir la visualización a los sistemas de gestión de activos, con el fin de proporcionar una ayuda cognitiva muy útil para el procesamiento de cantidades ingentes de información. Como resultado de las consideraciones expuestas, surge el objetivo principal del presente proyecto de tesis, que es el desarrollo de una metodología para la gestión a largo plazo en un entorno BIM de los *Sistemas COoperativos Enriquecidos* [*ECO-Systems*] de monitorización estructural, que se enmarca dentro de los temas del *noveno objetivo sostenible – Industria, innovación e infraestructuras*.

El *ECO-sistema de monitorización* está concebido como un entorno abierto que necesita aportaciones continuas para mantener su orden. Éstas aportaciones estarán representadas por información actualizada y actualizable, para que el ECO-sistema funcione correctamente. Por lo tanto, a la hora de organizar un sistema BIM de gestión de instalaciones es imprescindible establecer claramente los procedimientos de implementación y gestión de datos, es decir, definir el llamado *Entorno Común de Datos* [*Common Data Environment* – CDE]. Así, la metodología propuesta avanza hacia una estandarización de los procedimientos de modelización del entorno construido existente, siendo al mismo tiempo fácilmente adaptable a la modelización *ex-novo*, simplemente dejando de lado la etapa de levantamiento integrado inicial.

Los ECO-sistemas de vigilancia se configuran así como sistemas cuyos datos de entrada proceden de las operaciones de vigilancia, tanto si éstas se realizan de forma predominantemente analógica como si son casi totalmente digitales.

El objetivo secundario del presente trabajo es, pues, la generación, al final de cada etapa de modelización, de modelos BIM abiertos debidamente mapeados y, por tanto,

fácilmente asequibles para un intercambio de información eficaz que se enmarca en los temas del *decimoséptimo objetivo sostenible – Asociación para el Objetivo*.
Un enfoque consolidado de Scan-to-BIM suele implicar primero el estudio de la estructura y el paisaje circundante sobre el que desarrollar un modelo BIM. Por ello, se propone un marco para la estandarización de algunas prácticas bien y mal conocidas implementadas en este proceso para poder trazar las fuentes de datos y la calidad de su reproducción a lo largo de todo el proceso de modelado. La metodología Scan-to-BIM testada, que emplea el paquete de software de Autodesk, se entiende como una buena práctica operativa y puede organizarse en seis pasos secuenciales: (1) *Levantamiento tridimensional* [3DS]; (2) *Georreferenciación* [GEO]; (3) *Modelado federado y establecimiento de coordenadas compartidas* [FSC]; (4) *Modelado estructural* [STR]; (5) *Mejora del nivel de información* [LOI]; (6) *Exportación de modelos BIM abiertos* [IFC].
Cada paso del flujo de trabajo propuesto es necesario para el posterior, pero se mantiene actualizable gracias al entorno BIM. El modelado del patrimonio existente no suele ser un proceso sencillo y, en algunos casos, puede ser iterativo, de ahí la necesidad de repetir algunos pasos o, al menos, de intercambiar algunos de ellos. Cabe destacar que la fase de LOI está presente en diferentes niveles, siendo una constante a lo largo de todo el proceso, tanto si se realiza manualmente como a través de scripts VPL, rellenando parámetros *ad-hoc* con distintos tipos de información.
Como se ha mencionado anteriormente, la segunda parte de la tesis aborda la digitalización del patrimonio infraestructural italiano, que, hasta la fecha, parece haber sido abandonado, faltando por lo general la planificación del mantenimiento o incluso estando completamente abandonado. Las obras de infraestructura se rememoran esporádicamente, lamentablemente en ocasión de eventos catastróficos, que desgraciadamente parecen ser el único catalizador para impulsar cambios legislativos, lo que ha llevado al imperativo actual de introducir un sistema digital para la gestión de los puentes, viaductos y pasos elevados italianos. Por lo tanto, el caso de estudio del viaducto Olivieri que se presenta en los siguientes capítulos, se refiere a la creación de un *Sistema de Gestión de Puentes* [BMS] optimizado, destinado a convertirse en un marco para la *Monitorización de la Salud Estructural* [SHM] de la infraestructura de puentes italiana.
La información es la clave para una gestión eficaz de los puentes; por lo tanto, un módulo esencial de un sistema de gestión es el modelo de información. Las bases de datos están en el centro del módulo y, en última instancia, configuran la esencia y la calidad de todas las decisiones y acciones consideradas por el BMS. La incorporación de la visualización a la gestión de bienes proporciona una benéfica ayuda cognitiva para procesar cantidades masivas de información. Esto puede lograrse mediante el *Modelado de Información de Puentes* [BrIM], que no es sólo una representación geométrica de los puentes, sino que es sobre todo un modelo virtual inteligente en tres

dimensiones del puente, ya que recoge toda la información sobre cada componente durante todo su ciclo de vida. Este modelo permite mejorar la calidad y la precisión de los planos, así como la constructibilidad, y favorece la colaboración.
Por lo tanto, cabe realizar un análisis exhaustivo de los aspectos normativos nacionales e internacionales relativos a los protocolos de inspección e identificación de criticidades estructurales para puentes e infraestructuras elevadas. El análisis se ha centrado particularmente en los aspectos internacionales de una selección de países elegidos, ya sea porque constituyen un punto de referencia normativos para los demás países o porque forman parte de los estudios realizados por la doctoranda. En efecto, Estados Unidos propone una estructura normativa articulada entre distintos documentos que ofrecen una visión de conjunto de las distintas figuras profesionales que intervienen en el análisis y desarrollo de un plan de mantenimiento, constituyendo así una referencia cultural para muchos países. España y Argentina, por su parte, si bien incorporan ciertos conceptos propios de los marcos normativos *latinos*, presentan diferencias sustanciales cuyo análisis resalta cómo las herramientas de representación y modelización de la información deben adaptarse a peculiaridades operativas que pueden variar ampliamente incluso entre entornos culturalmente cercanos. Posteriormente, se ha realizado una amplia revisión bibliográfica sobre el estado de la técnica en lo que respecta a la aplicación de la metodología BIM a la digitalización de los activos de infraestructura – en particular, puentes, viaductos y pasos elevados – y los datos relativos a las prácticas de inspección destinadas a la definición de los procedimientos de supervisión y mantenimiento, seguida de un análisis de la evolución del sistema normativo italiano pertinente a partir de la década de 1960 hasta la aplicación más reciente de las *Líneas Guías para la Clasificación y Gestión de Riesgos, la Evaluación de la Seguridad y la Supervisión de los Puentes Existentes* emitidas en 2020.

La primera fase experimental consistente en la actualización de la base de datos de información del Viaducto Olivieri se inició con una campaña de reconocimiento del puente y del valle subyacente con el fin de elaborar una primera modelización de la infraestructura en su contexto urbanizado, para extrapolar los planos técnicos actualizados del sistema complejo. La campaña de reconocimiento se llevó a cabo en el marco del proyecto *CUR_CIS2020 Metodologías para la evaluación puntual del riesgo hidrogeológico en zonas fuertemente pobladas y herramientas para las estrategias de desarrollo regional – Aplicación al caso de estudio Corredor Estratégico de Infraestructuras [CIS] a nivel regional; analizando el tramo de la autopista Salerno-Cava de' Tirreni – A3 Nápoles-Salerno y otras infraestructuras viarias aguas abajo*. El objetivo del proyecto se centra en los procedimientos para procesar e integrar diversos tipos de datos 2D y 3D en un entorno SIG. En concreto, el estudio fue realizado por los grupos de *geomática* y de *levantamiento y representación*

del *Laboratorio Modelli – Surveying and Geo-Mapping for Environment and Cultural Heritage*, del Departamento de Ingeniería Civil [DICIV] de la Universidad de Salerno.
Dada su relevancia, el viaducto Olivieri y el contexto urbano que lo rodea aparecieron como el caso de estudio perfecto para desarrollar una metodología operativa para la digitalización masiva tanto de la geometría estructural como del estado de conservación relativo de las estructuras infraestructurales pertenecientes a la categoría de "puentes viaductos y pasos elevados" situados a lo largo de la autopista A3, en el marco del acuerdo entre el C.U.G.R.I.[*Consorzio inter-Universitario per la previsione e prevenzione dei Grandi Rischi – Consorcio interuniversitario para la previsión y prevención de grandes riesgos*] y la empresa *Autostrade Meridionali* [SAM] relativo a la puesta en marcha del *Servicio de vigilancia de las grandes infraestructuras de la autopista A3 Nápoles-Pompei-Salerno – de acuerdo con las circulares del Ministerio de Obras Públicas núm. 6736/61 de 19.7.67 y nº 34233 de 25.02.1991- y las actividades de apoyo relacionadas, como las pruebas técnicas no destructivas, los ensayos de laboratorio, etc.* A continuación, se presentan los procedimientos validados y optimizados para el intercambio de información relativa tanto al registro como a los datos de catalogación de la infraestructura, así como los modelos en formato abierto que sirvan de base para seguir mejorando el nivel de conocimiento de la propia estructura. La masa de datos así producida se organiza para introducirla en el BMS desarrollado por los técnicos informáticos de la C.U.G.R.I., en el cual se archiva de acuerdo con los preceptos normativos.
Se han introducido los parámetros compartidos *Enlace Ficha* [*Link Scheda*] y *CódigoGlobalEstructura* [*CodiceOperaGlobale*] que contendrían, respectivamente, un enlace funcional al directorio del BMS que alberga el formulario de inspección rellenado para cada componente, y un identificador único para cada componente necesario para organizar la alimentación de datos sin errores relativos a cada componente según la nomenclatura, la numeración y la catalogación realizadas en el entorno BIM. A continuación, se prevé una fase de reimportación de los datos resultantes de las inspecciones detalladas – resumidos por el *Indicador Relativo de Defectuosidad* [Dr] calculado por el BMS – al entorno BIM editable, Autodesk Revit [fase de enriquecimiento del LOI]. El modelo BrIM se convierte así en un repositorio totalmente actualizado que alberga el estado de salud de los modelos de infraestructura, a través del cual también es posible ofrecer una visualización gráfica avanzada de los datos sintéticos agrupados, por ejemplo, en las Clases de Atención [CdA] impuestas por la normativa.

Como se explica en la tercera parte, muchos investigadores ya han señalado la necesidad de integrar los actuales procedimientos de Monitorización de la Salud Estructural [SHM], incluyendo, pero no limitándose, a los *Sistemas de Gestión de Puentes* [BMS], con los datos procedentes de los sensores, tanto en términos de instrumentos de medición conectados a un Gemelo Digital del activo físico a través

del llamado *Internet de las Cosas* [IoT] como de los datos del levantamiento tridimensional. De hecho, para el mantenimiento preventivo y sistemático de las estructuras, las inspecciones visuales periódicas son esenciales para detectar los defectos estructurales en una fase temprana e iniciar las intervenciones necesarias. Las tecnologías modernas, como los sistemas de vehículos aéreos no tripulados [VANT] equipados con cámaras de alta resolución, contribuyen cada vez más al proceso de inspección y a la documentación asociada. Además, los métodos de procesamiento y los modelos de datos vinculados permiten una gestión eficaz de los datos.
Conjuntamente a la relevancia histórica del caso de estudio que se propone a continuación, se ha elegido el Templo de Neptuno en Paestum, – uno de los artefactos de origen griego mejor conservados de Italia – por la posibilidad de llevar a cabo aplicaciones experimentales a partir de la ya rica base de datos existente construida a lo largo de más de una década. Además, se ha implementado posteriormente información adicional procedente del innovador sistema de monitorización sismométrica – cuyos puntos de medición están situados en la cornisa de la columnata exterior del Templo de Neptuno y en las arquetas de recopilación de datos cerca de la estilóbata. El primer levantamiento con escáner láser, crucial en este caso para el modelado Scan-to-BIM, se remonta a 2011. Posteriormente, el conocimiento del sitio se actualizó en varias ocasiones, principalmente con levantamientos fotogramétricos orientados a la adquisición de datos materiales, el más actualizado de los cuales, diseñado para adquirir información tanto el templo como el contexto circundante con un buen nivel de detalle, se llevó a cabo en 2017. El levantamiento fotogramétrico realizado en 2020 se centró, a su vez, en el levantamiento de la zona que rodea al templo de Neptuno, habiéndose solicitado debido a las nuevas excavaciones realizadas con motivo de la colocación del sistema de monitorización sismométrica.
La red del sistema de monitorización se compone, entre otros aparatos específicos, de instrumentos de medición experimentales – *Péndulo Plegado UNISA*, sismómetros desarrollados y patentados por el *Grupo de Investigación en Física Aplicada* de la Universidad de Salerno dedicado al estudio de las ondas gravitacionales – colocados bajo la supervisión de los coordinadores científicos: el profesor Luigi Petti (Departamento de Ingeniería Civil – Universidad de Salerno) y el director del *Parque Arqueológico de Paestum y de Velia* el arqueólogo Gabriel Zuchtriegel. Debido a que BIM trabaja con un sistema de referencia cartesiano, al vincular una nube de puntos en formato RCP georreferenciada a un proyecto Revit, ésta se desplazará automáticamente hacia el nuevo origen interno, borrando los valores de coordenadas anteriores. Por otro lado, cuando se fuerza la generación de las instancias BIM en su lugar mediante scripts VPL, con el fin de mantener las coordenadas geográficas, se producen fallos de aproximación en los objetos reproyectados, sobre todo en el caso de mesh y surgirán posteriormente problemas de visualización y modelado. Por lo tanto, teniendo en cuenta los problemas relacionados con

el empleo de un sistema de coordenadas topográficas dentro de un entorno BIM, para configurar el entorno compartido [FSC] del ECO-Sistema de Vigilancia del Templo de Neptuno fue necesario realizar una traslación del sistema de referencia global al local tanto en las nubes de puntos fotogramétricas -directamente dentro del entorno Agisoft Metashape restando una cantidad fija a los valores x, y y z de los GCP- como en la nube de puntos integrada utilizada como referencia para la posterior aplicación Scan-to-BIM. A continuación, se modelaron familias estructurales totalmente paramétricas desde cero y se colocaron en el proyecto BIM utilizando la nube de puntos integrada como referencia.
Aunque el propósito a largo plazo de un modelado BIM es estandarizar el mayor número de elementos posible, cuando el objeto a modelar es único, como en el caso del contexto urbano, que suele ser diferente y distintivo de cualquier bien, el objetivo debe centrarse en estandarizar el proceso para reproducirlo de la forma más auténtica, para su posterior estudio en profundidad. Por ello, las aplicaciones metodológicas propuestas en la tercera parte implican dos flujos de trabajo desarrollados para reproducir mesh fotogramétricas texturizadas del contexto urbano, y algunas áreas de interés detalladas dentro de un entorno BIM, mediante la parametrización de los propios componentes del modelo de la mesh, sus caras triangulares. En particular, el primer procedimiento puede potenciarse aún más mediante materiales de *Physically Based Rendering* [PBR], generando los mapas avanzados como resultado del proceso fotogramétrico; mientras que el segundo puede resultar útil cuando el objetivo de la aplicación es una reproducción precisa de las áreas seleccionadas para futuras evaluaciones cualitativas y cuantitativas. El objetivo es, en efecto, salvar la distancia entre el tipo de detalle que puede alcanzar un levantamiento, precisamente fotogramétrico, cuando se habla de los datos colorimétricos, y lo que es posible reproducir en un entorno BIM cuando se habla de elementos distintivos, si no únicos, como el contexto urbano o elementos relevantes detallados, como frisos/decoraciones o zonas dañadas.
Los dos flujos de trabajo procedimentales que se presentan a continuación -definidos como *flujo de trabajo A* y *B* en aras de la simplicidad- son a todos los efectos enfoques Mesh-to-BIM. Por lo tanto, para su aplicación efectiva, es necesario llevar a cabo algunas acciones preliminares en el modelo mesh estudiado. La simplificación de la mesh es una práctica habitual para minimizar el tamaño del modelo reduciendo el número de triángulos y conservando la forma, el volumen y los contornos. Los criterios para la decimación de mesh son generalmente definidos por el usuario, seleccionando el método de reducción (trabajando sobre el número de vértices, aristas o caras) y el objetivo de reducción, de hecho, varios programas comerciales y de código abierto de edición y modelado incluyen un módulo de simplificación de mesh para manejar eficientemente esta tarea de post-procesamiento. Por lo tanto, en el caso de un ordenador portátil medio (Core i7 16GB de RAM, 2GB GPU) para poder procesar los scripts desarrollados y gestionar los resultados, es aconsejable mantener el recuento de triángulos de la mesh por debajo de las 600'000

unidades, para el primer método propuesto, y por debajo de las 20'000 unidades, para el segundo, simplificando y fraccionando en más de un proyecto el modelo original de la mesh fotogramétrica (a través de Agisoft Metashape y ISTI-CNR MeshLab).
Finalmente, la red de monitorización formada por los sensores sismométricos colocados entre finales de 2020 y principios de 2021 se modeló también mediante familias MEP desarrolladas *ad-hoc* con un nivel de detalle geométrico menor – LOG 200 (puramente volumétrico). Posteriormente, la base de datos de información relacionada con los instrumentos de medición y los datos de monitorización en tiempo real disponibles hasta la fecha se vincularon al modelo MEP a través de un script VPL [Script 10] customizado en esta red sismológica específica. La plena comprensión y utilización de las señales de los sismómetros aún está en evaluación, ya que la red está todavía en fase de rodaje, por lo que la interfaz BIM tenía que ser diseñada para ser suficientemente flexible y actualizable. Para ello, se ha diseñado explícitamente el script para posibles actualizaciones futuras del sistema de monitorización, eligiendo Microsoft Excel como base de datos de origen y automatizando aún más la implementación de posibles nuevos descriptores del sistema definidos como parámetros compartidos [Script 9]. Además, las imágenes vinculadas útiles para comprender mejor el sistema se han puesto a disposición en línea a través de una carpeta de Google Drive compartida abiertamente.

En cuanto al primer caso de estudio propuesto, el mayor reto era simplificar y optimizar el procedimiento para la implantación efectiva de modelos tipo BIM en los procesos de catalogación e inspección de puentes, viaductos y pasos superiores existentes, de forma que se convirtiera en una herramienta válida de apoyo y no en una barrera para los técnicos del C.U.G.R.I., que no son expertos en el campo del modelado de información tridimensional. Por otra parte, la confrontación directa con expertos especializados en diseño y monitoreo de estructuras permitió a quien escribe llenar algunas lagunas técnicas y a la vez recibir una valiosa retroalimentación en tiempo real.
Por otro lado, la segunda aplicación mostró cómo la gestión del patrimonio existente no puede separarse de una investigación precisa del estado de conservación de los materiales y de una reconstrucción 3D detallada. La reconstrucción morfológica y colorimétrica de estructuras complejas, elementos y zonas específicas dañadas en el entorno BIM es esencial para el desarrollo de bases de datos que permitan almacenar datos y facilitar la planificación de las reformas y, en general, de cualquier actividad de intervención sobre el bien en estudio. Por otra parte, si la integración de datos basados en sensores se convierte en una práctica habitual para los procedimientos de supervisión, esta práctica optimizará sin duda las evaluaciones de conservación, señalando con precisión los cambios en la geometría y la textura del bien, simplemente comparando los datos de levantamiento actualizados con el bien modelado a intervalos regulares.

38

PART I – From the physical realm to digital ECO-Systems

1. Structural Health Monitoring and BIM procedures

The concept of BIM – intended in its modern sense as *Building Information Modelling* or *Building Information Model* – was first introduced by Charles Eastman in the mid-1970s when he patented the *Building Description System* [BDS] prototype. In the USA, this was followed in the 1970s and 1980s by the introduction of the term *Building Product Models* while, in Europe, *Product Information Models* were being investigated. The first documented use of the term *Building Modelling* in the modern sense was by Robert Aish in 1986. Finally, Van Nederveen and Tolman first used the term *Building Information Model* in 1992, while Jerry Laiserin is the one who made the term BIM popular. The intended purpose was therefore to realise a two-way collaboration throughout the entire life cycle of a building, based on the generation, location, and exchange of intelligent three-dimensional models, i.e., including structured datasets.
In a more distinctively figurative way, we could exhaustively describe the Building Information Modelling [BIM] methodology as the ideal combination of symbolic representation – starting from the cavemen's drawing and fast-forwarding to the 3D digital twins of the physical world – and numerical modelling – that indeed dates back to the Greeks, i.e., Pythagoras. However, much like the prisoners of the cave of the well-known Plato's allegory[1], we are every day more convinced that the digital reproduction of the phenomenal world can become itself the reality. If not, at the very least, it can flawlessly mirror it. On the contrary, it is not to forget that the whole experience of the world is just not equal to the objective

[1] An Athenian philosopher living in ancient Greece, Plato is famous in part for penning the Socratic dialogue *The Allegory of the Cave*, one of the most significant pieces of work in literary history.

reality, may this even exist, but a version of it mediated by our observation, thus a discretisation of it, no matter how faithful it may come to be, should never propose as the absolute truth. Borrowing Werner Heisenberg:

“We have to remember that what we observe is not nature in itself but nature exposed to our method of questioning”.

Therefore, the discretisation of the perceived reality becomes a model via the accurate selection of the variables chosen to describe some of its facets, worthy of a thorough investigation or, better said, being monitored.
The concept of *Structural Health Monitoring* [SHM] is relatively recent too. Starting from the early years of the 21st century, the problem of monitoring the physical-chemical-mechanical conditions of structures and infrastructures for civil use began to be thought of in a significantly different way than in the last century. Indeed, over the previous twenty years, it has been realised that novel construction materials, such as reinforced concrete and pre-stressed steel may have a long life but not an indefinitely long one. More has also been understood regarding materials of the past, i.e., wood. Thus, it has become clear that carrying out correct and methodical maintenance is essential and can significantly extend the useful life of a structure or infrastructure. All these arguments have then led to the definition of the modern concept of structural health and the need for its monitoring, similarly to what happens to human health. Indeed, considering the rapid and incisive diffusion of the concept, the acronym SHM has been introduced to briefly indicate Structural Health Monitoring, which is an interdisciplinary subject that incorporates synergistic knowledge and experience technologies in civil, mechanical, control and computer engineering and includes: detection, localisation, quantification, and prevision of remaining life [5].
Furthermore, in order for SHM systems to become efficient support tools for the localisation and quantification of damage, they almost always need to implement artificial intelligence techniques. To answer the challenge of ageing structure, we look towards developing advanced sensor and actuator technologies that hold the promise of heralding the next stage of evolution. Popular terms such as *Internet of Things* [IoT] and smart structures were coined as a result of the intersection between advances in other engineering disciplines with civil engineering to produce the new field of structural health monitoring. The field of SHM is now at a vital crossroads, where researchers are challenged to develop technologies for the monitoring and retrofitting of older buildings and at the same time to push the boundaries of SHM through the creative use of cutting-edge technologies and data processing algorithms [6].

As already mentioned, developing a structural health monitoring strategy requires a multidisciplinary approach involving many fields, such as sensors and sensor networks, signal processing, modal testing, numerical modelling, probabilistic analysis, damage diagnosis and damage prognosis. Each of these topics is a discipline-specific subject by itself and is equally important in developing effective SHM strategies. A typical SHM strategy comprises several key components, including sensors, data acquisition, data transmission, data processing, data management, health evaluation and decision making. Sensing technology and signal interpretation algorithms are two critical factors in developing successful SHM strategies for large civil engineering structures. SHM is a process of in-service damage identification and health evaluation for an engineering structure through an automated monitoring system. SHM uses sensing systems and necessary hardware and software facilities to monitor structural responses and operational conditions of the structure [7]. Here, damage is defined as changes to the material and/or geometric properties of these systems, including changes to the boundary conditions and system connectivity, which adversely affect the system's performance. A wide variety of highly effective local non-destructive evaluation tools are available for such monitoring [8].

Reasons for setting up SHM systems are the possibility of knowing the integrity of in-service structures on a continuous real-time basis, which are fundamental data for manufacturers, end-users, and maintenance teams. Indeed, SHM allows optimal use of the structure, a minimised downtime, and the avoidance of catastrophic failures; gives the constructor an improvement in his products; drastically changes the work organisation of maintenance services: by aiming to replace scheduled and periodic maintenance inspection with performance-based (or condition-based) and by drastically minimising the human involvement, and consequently reducing labour, downtime and human errors, and thus improving safety and reliability. The economic motivation is even more robust, principally for end-users. In effect, the envisaged benefits for structures with SHM systems are constant maintenance costs and reliability instead of increasing maintenance costs and decreasing reliability for classical structures without SHM [9].

Furthermore, specifically for the highly historicised Italian territory, SHM constitutes a good tool for the historical and architectural heritage to enhance the management of the assets. The purpose of SHM may differ case by case, however main possible objectives can be synthesized as follows: measure the vibrations induced by environmental actions, traffic, wind or by rare events such as earthquakes; evaluate the effects coming from foundation settlements or from soil-structure interaction with dynamic local amplifications; measure the evolution of existing cracks (opening or closure); determine the actual structural

behaviour to assess seismic vulnerability and effectiveness of restoration interventions used to repair the damage caused by catastrophic events; evaluate the enhancement of the structural response to dynamic (wind, earthquake) actions as result of relevant structural modifications after the adoption of invasive protection strategies (e.g., base isolation or passive control systems); make a long-term analysis of the structural dynamic response and its modification after final retrofitting and reconstruction; observe the damage produced by the degradation of the material along its physical (dissolution, hydration, frost), chemical (acids and salts dissolved that produce corrosive solutions) or biological nature (engraftment of lichen and weeds) [10].
Particularly the ***Guidelines for risk classification and management, safety assessment and monitoring of existing bridges*** underline the importance of predictive models. These are degradation curves defined as structure life cycle functions, which express the decay over time of one or more performance indices. The underlying assumption is that these benchmarks are equal to a certain initial value (design value) at the end of construction, but, over time, they undergo a progressive decay. Therefore, from the perspective of monitoring systems, these parameters acquire the meaning of condition index. They express the variation of the current state due to degradation and damage compared to a reference state, i.e., intact, in which the as-built structure is supposed to be [4].
It then appears clear how current experimentation focuses always more on conjugating the SHM numerical modelling with the BIM modelling technology, often employing advanced programming tools – such as *Visual Programming Language* [VPL] script – so as to add visualisation to asset management systems, to provide a highly beneficial cognitive aid for processing overwhelming amounts of information [11]. This field of investigation is defined as facility management and falls under the so-called 6th dimension of BIM[2].

[2] It is worth mentioning that while many references in the literature point to the 6th dimension of BIM as Facility Management and the 7th as Sustainability [21], a 2018 systematic literature review by Charef et al. revealed that 86% of professionals, who actually use 6D, allocate Sustainability to it, while 85% of professionals who use 7D allocate it to Sustainability [256]. In reality, the concept of BIM definitions is far from being resolved, and the debate is still open as to whether there can only be seven dimensions, or perhaps an 8th can be introduced, covering safety and/or design optimisation, followed by a 9th concerning lean construction, a 10th dealing with construction industrialisation, and so on [257]. For the purposes of this paper, it was decided to regard the management phase as 6D and sustainability as 7D, as further explained in section 1.2.

1.1 The Italian regulation concerning BIM implementation

It is well-known that Building Information Modelling [BIM] is one of the most promising technologies to increase productivity in the architectural, engineering and construction [AEC] industries [12]. Increasingly, it is becoming the standard for the design, construction, and management of new buildings, notwithstanding some resistance from certain specialists and objective difficulties in the practical application to civil infrastructure. However, practical case studies have proved that using a common BIM platform leads to an incremental rise in field productivity of up to 40%. It is worth noting that among the many definitions provided in the literature of what BIM is, which only partially address its multiple uses [13], the most recurrent is that of methodology [14], extended to the technological framework when its theoretical principles are translated into action, by employing operational strategies.

On the other hand, BIM - in its duality of model and modelling - is also, more generally, a repository of information capable of reaching a variegated multiplicity of stakeholders [15]. In this sense, BIM represents a means of communication over time, which goes beyond the barriers of physical space. Therefore, BIM has become a broader concept than a simplistic definition; perhaps it would be better to define it as a comprehensive approach to the much-needed informatisation of the built heritage and the heritage to come, which can be shaped into practical implementation strategies, addressing technological specificities on a case-by-case basis. In particular, BIM in its technological declination, is mainly aimed at the development of one or more accurate virtual models of a digitally reconstructed asset, thus allowing for better analysis and control than manual processes, and leading to an important cost reduction, as errors could be detected and corrected in advance.

Furthermore, current trade practice increasingly requires more and more specific skills and extremely tight deadlines; this reveals the taste to orient software technologies to a more conscious use, aiming at procedural strategies for the use of shared platforms [16]. The aforementioned reasons are leading many countries to implement BIM strategies imposing or encouraging its use in public projects thanks to BIM's economic and technical advantages [17]. Indeed, it is appropriate to focus on the timeline and modalities of the Italian regulation framework for BIM implementation.

Following the issuing of the ***European Directive 2014/24/UE***, which presented the Member States with the requirements of specific electronic tools for public

work contracts and design contests[3], BIM was introduced into the Italian legal system by the means of the ***Ministerial Decree 560/2017 of 1/12/2017*** [18] – effective date 12/01/2018 – which actively implemented the statement of the ***Article 23, Comma 13, of Legislative Decree No. 50 of 18 April 2016*** – also known as ***Codice degli Appalti***[4].
The ***Ministerial Decree 560/01.12.2017*** – also called ***Baratono Decree*** or ***BIM Decree*** [18]– defines the methods and timeframes for the gradual introduction, for contracting stations, granting administrations and economic operators, of electronic methods and tools. In particular, its different articles deal with: Art. 3 – preliminary obligations of contracting stations; Art. 4 – interoperability; Art. 5 – optional use of electronic methods and tools; Art. 6 – timing of gradual introduction: the obligation to use electronic methods and tools in public procurement will take place gradually, according to the timetable set out in the Decree itself (Figure 1.1).

[3] The statement of the ***Article 22 – paragraph 4 of the European Directive 2014/24/UE*** reads as follows: *"For public works contracts and design contests, Member States may require the use of specific electronic tools, such as of building information electronic modelling tools or similar. In such cases the contracting authorities shall offer alternative means of access, as provided for in paragraph 5, until such time as those tools become generally available within the meaning of the second sentence of the first subparagraph of paragraph 1."* [258]

[4] The essential content of ***Article 23, Livelli della progettazione per gli appalti, per le concessioni di lavori nonché per i servizi" of the D.Lgs. 50/2016*** is reported as follows*: "1. La progettazione in materia di lavori pubblici si articola, secondo tre livelli di successivi approfondimenti tecnici, in progetto di fattibilità tecnica ed economica, progetto definitivo e progetto esecutivo ed è intesa ad assicurare: [...] h) la razionalizzazione delle attività di progettazione e delle connesse verifiche attraverso il progressivo uso di metodi e strumenti elettronici specifici quali quelli di modellazione per l'edilizia e le infrastrutture; [...] comma 13. Le stazioni appaltanti possono richiedere per le nuove opere nonchè per interventi di recupero, riqualificazione o varianti, prioritariamente per i lavori complessi, l'uso dei metodi e strumenti elettronici specifici di cui al comma 1, lettera h). Tali strumenti utilizzano piattaforme interoperabili a mezzo di formati aperti non proprietari [IFC], al fine di non limitare la concorrenza tra i fornitori di tecnologie e il coinvolgimento di specifiche progettualità tra i progettisti. L'uso dei metodi e strumenti elettronici può essere richiesto soltanto dalle stazioni appaltanti dotate di personale adeguatamente formato. Con decreto del Ministero delle infrastrutture e dei trasporti, da adottare entro il 31 luglio 2016, anche avvalendosi di una Commissione [Baratono] appositamente istituita presso il medesimo Ministero, senza oneri aggiuntivi a carico della finanza pubblica sono definiti le modalità e i tempi di progressiva introduzione dell'obbligatorietà dei suddetti metodi presso le stazioni appaltanti, le amministrazioni concedenti e gli operatori economici, valutata in relazione alla tipologia delle opere da affidare e della strategia di digitalizzazione delle amministrazioni pubbliche e del settore delle costruzioni. L'utilizzo di tali metodologie costituisce parametro di valutazione dei requisiti premianti di cui all'articolo 38."* [259]

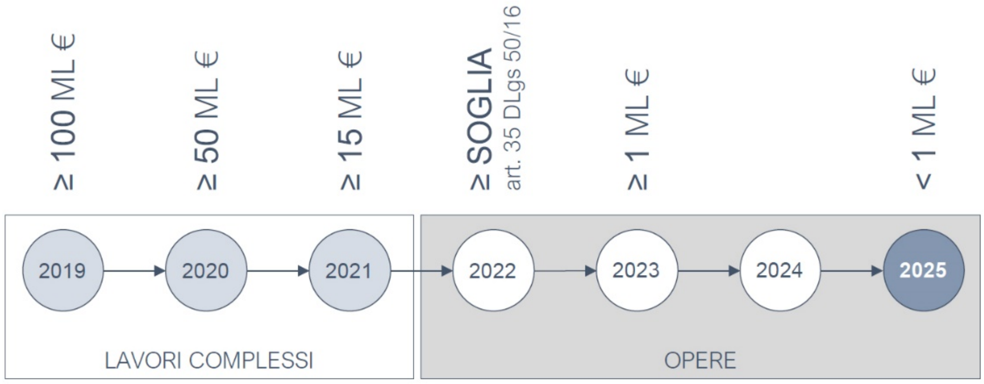


Figure 1.1 – Timeframe for the progressive introduction of BIM according to DM 560/2017 [19]

Moreover, the *Italian National Unification body* [UNI] has published parts ***1, 4, 5, 6, and 7 of the national standard UNI 11337***[5] to regulate the digital management of construction information processes and, specifically: models, drawings and information objects for products and processes; evolution and information development of models, drawings, and objects; information flows in digitised processes. In Figure 1.3, it is presented an overview of the 11337 parts already published (in green) and still awaited and/or to be updated (in yellow).

- ***UNI 11337-1: 2017*** covers the general aspects of digital information process management in the construction sector, such as the information vehicle structure, the process information structure, and the information structure of the product. The standard is applicable to any type of product in the sector, be it a building or an infrastructure, and to any type of process (conception, production, operation).
- ***UNI 11337-4:2017*** covers the qualitative and quantitative aspects of digitised management of the information process in the construction sector, to support decision-making, with the aim of: specifying the objectives of each of the phases of a process introduced in UNI 11337-1. The model, the objects, and the information content are instrumental in achieving these objectives; define a common scale of information development level of the model objects; define a common scale of processing and approval states of the information content.

[5] The UNI 11337 [260] actively implement into the Italian legal system the ***European Standard EN ISO 19650-1 (December 2018)*** [261]***: Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM) – Information management using building information modelling – Part 1: Concepts and principles.***

- ***UNI 11337-5:2017*** defines the roles, rules, and flows necessary for the production, management and transmission of information and their connection and interaction in digitised construction processes.
- ***UNI/TR 11337-6:2017*** contains the guidelines for drafting the Information Content.
- ***UNI 11337-7:2018*** Knowledge, skills, and competence requirements for the professional figures involved in the digital management of information processes.

In addition, the following additional parts of the standard will be provided:

- ***UNI 11337-2***: Naming and classification criteria for models, products, and processes.
- ***UNI 11337-3*** (2015 version that precedes the BIM Decree): Models for collecting, organising, and filing technical information for construction products (digital information sheets for products and processes).
- ***UNI 11337-8****:* Integrated information and decision management processes.
- ***UNI 11337-9***: Information management during operation, via the setting up of shared platforms, i.e., the *Common Data Environment* [CDE], defined as *Ambiente di Condivisione Dati* [ACDat] by the Italian regulation.
- ***UNI 11337-10***: Automated model check.
- ***UNI 11337-11*** (introduced following the 2019 update of the ISO 19650 guidelines): Data protection and blockchain security.

Eventually, the ***reference practice UNI/PDR 74:2019*** [20], concerning the requirements for a BIM management system, will be incorporated into a planned twelfth part of the UNI 11337.

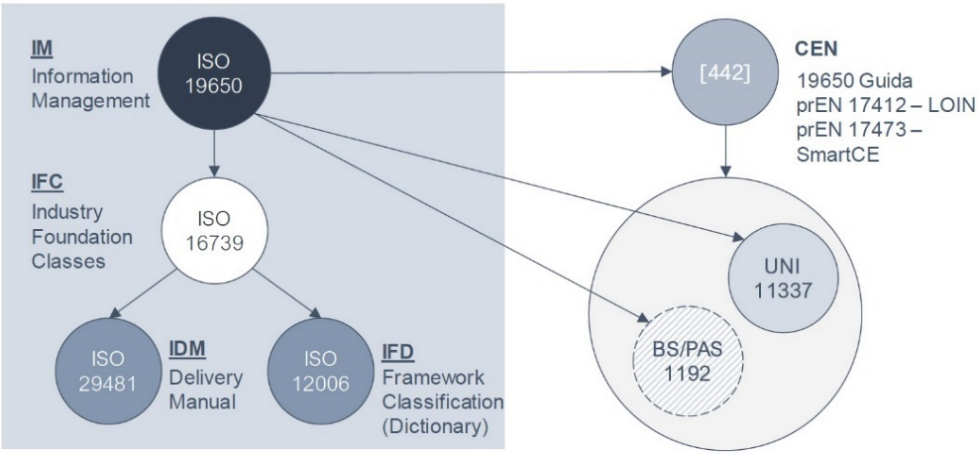


Figure 1.2 – Schema of the voluntary international regulation concerning information management and Industry Foundation Classes adoption [19]

Parte	Titolo	Numero Norma Pubblicata
1	**Modelli, elaborati e oggetti informativi per prodotti e processi**	**UNI 11337-1:2017**
2	Criteri di denominazione e classificazione di modelli, prodotti e processi	-
3	Modelli di raccolta, organizzazione e archiviazione dell'informazione tecnica per i prodotti da costruzione (schede informative digitali per prodotti e processi)	**UNI/TS 11337-3:2015**
4	**Evoluzione e sviluppo informativo di modelli, elaborati e processi**	**UNI 11337-4:2017**
5	**Flussi informativi nei processi digitalizzati**	**UNI 11337-5:2017**
6	**Linee Guida per la redazione del capitolato informativo**	**UNI/TR 11337-6:2017**
7	**Requisiti di conoscenza, abilità e competenza delle figure coinvolte nella gestione e nella modellazione informativa**	**UNI 11337-7:2018**
8	Processi integrati di Gestione delle Informazioni e delle Decisioni	-
9	Gestione informativa in fase di esercizio (Piattaforma collaborativa e Fascicolo del fabbricato)	-
10	Organizzazione delle figure coinvolte nella gestione e nella modellazione informativa	-
11	Sicurezza dati e block-chain	-

Figure 1.3 – Issued Parts of the UNI 11337 (as of 2018) [21]

1.2 The seven dimensions of BIM and the Levels of Development

Although the initial effort to create a BIM is greater than the classical 2D/3D workflows based only on geometry, the advantage of BIM technology becomes effective in the successive phases. Ideally, BIM modelling allows to fully take advantage of the parametric design of smart objects creating multidimensional relationships between themselves and external databases while keeping the digital asset easily updatable. Indeed, the sole three physical dimensions are no longer sufficient to describe the BIM, thus needing to introduce its universally acknowledged seven dimensions fundamental to integrating external data into the informative modelling processes [21].

Three-dimensional geometric model [3D]

The digital model of the work is carefully detailed so as to be as faithful as possible to the real asset. The basic activity carried out is called *model checking* in which it is verified that the model respects the design and regulatory requirements (*code checking*), identifying any design errors, and any geometric and other conflicts present (*clash detection*).

Time analysis [4D]

Time management, relative to the entire project life cycle, is an essential variable within the design. Time planning will take place using new tools and methodologies. Within the models, it is possible to associate time and planning data with each component to minimise any errors arising from inefficient planning of the various activities contributing to the project.

Cost analysis [5D]

To further optimise the design phase, it is possible to schedule the costs over time. The cost estimator chooses the items from a list of prices to be associated with the different tasks, thus determining the correct final amount in an automated manner.

Management phase [6D]

In addition to what is planned, the model also brings the organisation of the construction site and post-construction management phase. This technology leads to improved management, especially in terms of maintenance.

Sustainability [7D]

The concept of sustainability encompasses environmental sustainability (ability to reproduce and maintain natural resources), economic sustainability (create income and employment) and social sustainability (produce well-being). Adopting this technology makes it possible to improve analytical processes to increase the sustainable design.

Anyhow, it seems reductive to constrain the facility management aspects to just one dimension; the application of the whole BIM methodology constitutes a lifecycle platform, supporting the implementation of *Information Technologies* [IT] for the creation and the management of a facility's lifecycle. Namely, BIM shares many similarities with *Product Lifecycle Management* [PLM], which originated in the automobile industry in the mid-1980s and became widespread in the late 1990s. PLM is the process of managing a product throughout its lifecycle, which aims to improve product quality and reduce waste as well as risks through the integration of design and engineering processes and the reuse of information. BIM and PLM are so similar in the concept that many people refer to BIM as *Project Lifecycle Management* [PLM] or *Building Lifecycle Management* [BLM], stressing the importance of BIM as a platform for the creation and management of information about buildings throughout their design, construction, and serviceable life. Conceptually, once a BIM has reached full maturity (*Level 3*)[6], it is capable of playing the role of a lifecycle platform by providing a single information source, which enables project participants to query, view, and reuse current information. With current commercial technology and practice, however, information is still generated and managed by multiple systems and multiple parties through different phases of a project. Consequently, it is critical to have data interoperability and integration technologies that can minimize data loss during the data exchange, sharing, and integration processes [22].

On the other hand, in order to understand the concept of as-built, or as-is, modelling, it is necessary to define the concept of *Level of Development* [LOD] – according to the USA regulation –, also known as *Level of Definition* – according to UK legislation. It is worth mentioning that the LOD is meant as a grading

[6] In order to allow for greater organisation between the actors in the process and a better awareness of the use of data, the *UNI 11337-4* standard defines the working status of models by providing four levels of BIM maturity: *level 0* – all project-related information is in paper form; *level 1* – also called the sharing phase, in which the information content is not complete and, therefore, subject to change; *level 2* – the publication phase, in which the information content is considered complete and shared between the various parties; *level 3* – the final design phase, defined as the archiving phase [21].

system that defines the complexity of the model although the rating scale varies depending on the regulations. Furthermore, for the purpose of the present discussion, the LOD is intended as a composition of the *Level of Geometric Detail* [LoD, also defined by the Italian regulation as LOG][7] and the enclosed *Level of Information* [LOI][8]. The *American Institute of Architects* [AIA] adopted, in 2008, a five-level LOD definition system – varying from LOD 100 to LOD 500[9].

The Italian regulation has then transposed the AIA definition of LOD into a seven-level schema, ranging from LOD A – *symbolic object* corresponding to AIA's LOD 100 – to LOD F and G – *as-built object* and *updated object*, both corresponding to AIA's LOD 500[10].

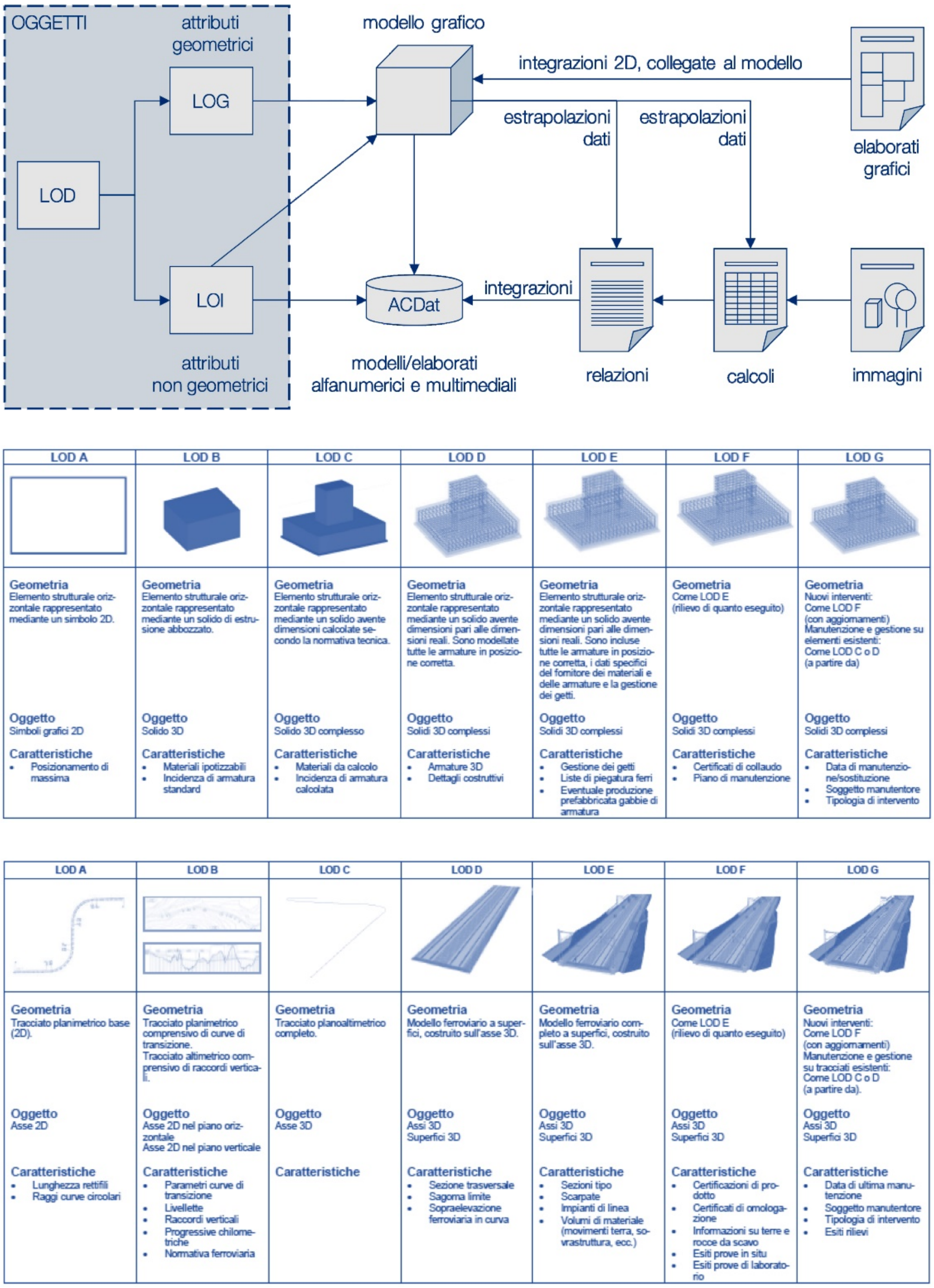
The *as-built object* refers to the validated virtualisation of the specific production system as it has been constructed in situ. The qualitative and quantitative characteristics are specific and refer to the individual production system laid or installed, also including information regarding the operation, maintenance, repair and possible replacement. On the other hand, it is only possible to reach the level of the *updated object* when implementing a *Digital Twin* [DT].

[7] The *Level of Geometric Detail* [LoD o LOG] mainly refers to the graphical information of a BIM model and the degree of geometric accuracy, which can be related to the required scale of the final drawings and, therefore, directly to the design phases.

[8] The *Level of Information* [LOI] refers to the non-geometrical data – infographic data, texts, documents, tables, etc. – i.e., the information derived from a multidisciplinary approach. In short, it includes any type of documentation that can provide information on any phase of the object's life cycle, even though it is not directly related to the object itself, but also to the context in which it is inserted.

[9] The LOD definitions were first published in the *G 202-2013 BIM Protocol*, and subsequently detailed and enhanced by the *BIM Forum* in 2019 [37].

[10] The UNI 11337-4 [38] defines the Italian LODs as follows: LOD A – symbolic object; LOD B – generic object; LOD C – defined generic object; LOD D – detailed object, corresponding to the later-introduced AIA's LOD 350; LOD E – specific object; LOD F – as-built object; LOD G – updated object [21].



	LOD A	LOD B	LOD C	LOD D	LOD E	LOD F	LOD G
Geometria	Elemento strutturale orizzontale rappresentato mediante un simbolo 2D.	Elemento strutturale orizzontale rappresentato mediante un solido di estrusione abbozzato.	Elemento strutturale orizzontale rappresentato mediante un solido avente dimensioni calcolate secondo la normativa tecnica.	Elemento strutturale orizzontale rappresentato mediante un solido avente dimensioni pari alle dimensioni reali. Sono modellate tutte le armature in posizione corretta.	Elemento strutturale orizzontale rappresentato mediante un solido avente dimensioni pari alle dimensioni reali. Sono incluse tutte le armature in posizione corretta, i dati specifici del fornitore dei materiali e delle armature e la gestione dei getti.	Come LOD E (rilievo di quanto eseguito)	Nuovi interventi: Come LOD F (con aggiornamenti) Manutenzione e gestione su elementi esistenti: Come LOD C o D (a partire da)
Oggetto	Simboli grafici 2D	Solido 3D	Solido 3D complesso	Solidi 3D complessi	Solidi 3D complessi	Solidi 3D complessi	Solidi 3D complessi
Caratteristiche	• Posizionamento di massima	• Materiali ipotizzabili • Incidenza di armatura standard	• Materiali da calcolo • Incidenza di armatura calcolata	• Armature 3D • Dettagli costruttivi	• Gestione dei getti • Liste di piegatura ferri • Eventuale produzione prefabbricata gabbie di armatura	• Certificati di collaudo • Piano di manutenzione	• Data di manutenzione/sostituzione • Soggetto manutentore • Tipologia di intervento

	LOD A	LOD B	LOD C	LOD D	LOD E	LOD F	LOD G
Geometria	Tracciato planimetrico base (2D).	Tracciato planimetrico comprensivo di curve di transizione. Tracciato altimetrico comprensivo di raccordi verticali.	Tracciato planoaltimetrico completo.	Modello ferroviario a superfici, costruito sull'asse 3D.	Modello ferroviario completo a superfici, costruito sull'asse 3D.	Come LOD E (rilievo di quanto eseguito)	Nuovi interventi: Come LOD F (con aggiornamenti) Manutenzione e gestione su tracciati esistenti: Come LOD C o D (a partire da).
Oggetto	Asse 2D	Asse 2D nel piano orizzontale Asse 2D nel piano verticale	Asse 3D	Assi 3D Superfici 3D	Assi 3D Superfici 3D	Assi 3D Superfici 3D	Assi 3D Superfici 3D
Caratteristiche	• Lunghezza rettifili • Raggi curve circolari	• Parametri curve di transizione • Livellette • Raccordi verticali • Progressive chilometriche • Normativa ferroviaria		• Sezione trasversale • Sagoma limite • Sopraelevazione ferroviaria in curva	• Sezioni tipo • Scarpate • Impianti di linea • Volumi di materiale (movimenti terra, sovrastruttura, ecc.)	• Certificazioni di prodotto • Certificati di omologazione • Informazioni su terre e rocce da scavo • Esiti prove in situ • Esiti prove di laboratorio	• Data di ultima manutenzione • Soggetto manutentore • Tipologia di intervento • Esiti rilievi

Figure 1.4 – Level of development schema (upper) and example of LOD applied to Structures (middle) and Infrastructure (lower) [19]

1.3 Information systems reflections concerning Digital Twins

It is common knowledge that the history of digital twin is quite recent, and its origin are set in the early two-thousands Product Lifecycle Management model proposed by Michael W. Grieves [23]. Hence, the concept of digital twin of a physical asset has been borrowed from mechanical engineering. It is defined as *"a numerical representation of the observed assembly that incorporates all necessary data to validate the assembly operating behaviour by comparing model responses to real-world information"*. It is, therefore, intended as a simulation tool capable, if needed, of performing live corrections of the asset behaviour by outputting commands directly to the asset. In the maintenance field, digital twins are often employed to control and record the crucial data of an asset (temperature, humidity, rotational speed, etc.) so that the operator can instantly detect discrepancies with his own previsions. Regardless of the mechanical definition, when the concept of DT is related to BIM, its well-established limits blur, and it is often confused with the BIM model itself [24]. Namely, its definition varies from the one corresponding to an as-built BIM model to a *Cyber-Physical System* [CPS]. A sufficiently accurate description of DT applied to the AEC sector is probably to be found in the middle; a DT could then be defined as a three-dimensional representation of the physical asset, to which it is linked via a continuous flow of data that keeps the digital copy up to date. Thus, a change in the physical object's state directly leads to a change in the digital object's state and vice-versa [25].

It appears clear that a DT can contribute substantially to asset management in the operation-and-maintenance phase. These types of DT can be divided into three categories, characterised by an increasing degree of interactivity with the real environment: the monitoring one, which focuses on obtaining data from the physical parts to update the virtual correspondent; the analysis one, which uses the data collected from the physical parts to perform analysis, becoming a support tool in decision-making processes; the action one, which employs the real-world data for analysing and subsequently taking action on the physical counterpart via retrofitting and/or automatic control [25].

The hereby proposed methodology, through the setting up of *Scan-to-BIM* and *Mesh-to-BIM* standardised applications for the development of monitoring ECO-Systems, clearly belongs to the first category of Digital Twins, whose full potential may not be developed yet, but at the same time lays the foundations for the implementation of a continuous bidirectional link between the physical realm and the digital one.

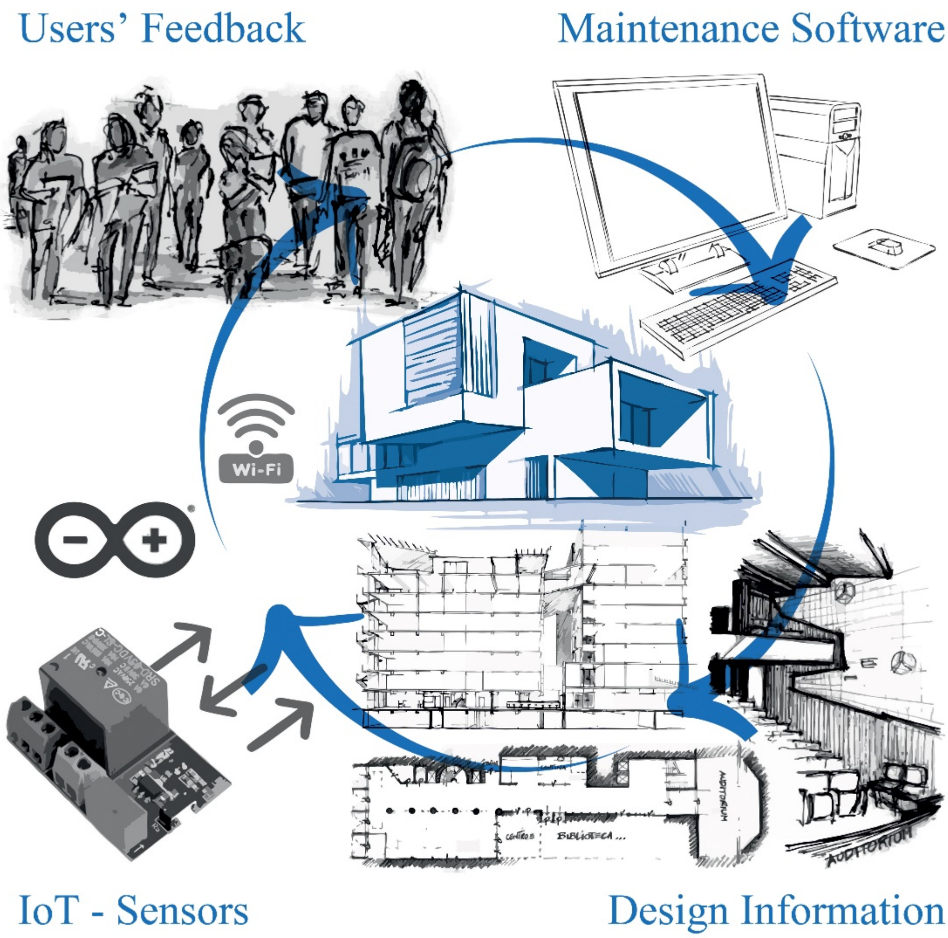


Figure 1.5 – Graphic representation of a Digital Twin [AoE]

1.4 Scan-to-BIM vs Mesh-to-BIM

In recent years, digitisation of the built heritage and the related registration processes of the surrounding environment have made significant progress and can now quickly reach a large number of users via multiple devices [26]. Over the past decades, despite the growing interest, the application of BIM methodology to the built heritage still poses some unaddressed challenges, such as interoperability, big data and the lack of automated processes: to provide an efficient interface between software and physical data, it is then imperative to create flexible and adaptive data collection systems [27]. Capturing a physical site or space using scan data to develop an intelligent 3D model using BIM software is known as Scan-to-BIM [28,29]. New advanced sensing technologies allow us to address these challenges by gathering semantic information needed to produce an accurate and detailed 3D model. Although, when compared to new buildings, existing assets require the acquisition of additional information for a correct assessment of their current state: models need to be enriched with more than just geometric data and information, such as historical information, degradation or deformation analysis and information on performed or to-be-performed maintenance. All these data are crucial for the maintenance and preservation of the building itself. Ideally, the whole data set coming from a three-dimensional survey is indispensable for the Scan-to-BIM modelling of built heritage. Still, in reality, it is rarely possible to use the complete raw information. In this sense, researchers are working on the implementation of Artificial Intelligence (AI) for the semantic subdivision of 3D point clouds. Working with a classified point cloud makes it possible to speed up architecture’s analysis, maintenance operations and conservation plans, leading to a semantically enriched hierarchy that can be preparatory to successive applications such as the reconstruction phase of 3D models (CAD or BIM) [30].
The association of heterogeneous information to 3D data by means of automated segmentation and classification methods can help to characterize, describe, and better interpret the object under study, whereas the term semantic segmentation (or simply classification) for point clouds means to group similar data into subsets (called segments) that have characteristics/features useful to distinguish and identify in classes its different parts [31].

Integrated 3D Survey database

With regard to the survey and representation of historical assets, laser scanning is the most promising tool and is widely used for Scan-to-BIM applications due to its high accuracy and speed, proving to be extremely suitable in the acquisition of complex geometries. Photogrammetry, on the other hand, produces better detail at the graphic/photographic level, i.e., texture, but requires more processing time also producing less *dense* results. LiDAR and photogrammetry can complement each other [32] and are getting tremendous attention in the development of remote sensing technology. Numerous studies have attempted to use multi-sensor data in various applications, such as for the generation of 3D building models by integrating terrestrial and aerial data [33,34]. Despite the advantages, there are some challenges with heterogeneous point cloud data.

Several studies formulate validation criteria for point cloud and semantic segmentation in relation to BIM [35,36]. There is no shortage of more holistic validation works in which point cloud data quality criteria are established for Scan-to-BIM and *Scan-vs-BIM*, with *Level of Accuracy* [LOA][11] and *Level of Development* [LOD] being defined [37,38]. Apart from accuracy, they determine parameters for the completeness and density of the point cloud needed to model various building elements. For accuracy, researchers directly report deviations on reference datasets or refer to international specifications such as LOA and LOD [35,39,40].

A literature review of the experimental applications of Scan-to-BIM and Mesh-to-BIM

Given the richness in the data made available by the integrated 3D survey databases, numerous experimental applications have been proposed in an effort of preserving as much survey data as possible in the transition to BIM modelling. Although no unified method has yet been identified, the most common practice for a Scan-to-BIM process consists of manual modelling, involving the insertion of *ad-hoc* created intelligent objects, whose parameters are adapted to the specific characteristics of the study object. To facilitate this process, many researchers have opted for custom parametric modelling of objects, based on point clouds imported via plug-ins within the Autodesk Revit family editor [41]. However, the efficient transformation of remote sensing data into intelligent parametric as-built models is currently an unsolved challenge [28], still requiring manual

[11] It represents the required accuracy of the surveyed element (*measured accuracy*) and that of the reconstructed element (*represented accuracy*). According to the *United States Institute of Building Documentation* [*USIBD*], the LOA is organized in a five-level schema, ranging from LOA 10 to LOA 50, which correspond to increasingly narrow intervals – from 5 cm to ideally 0 mm – for the measurement comparison to be considered acceptable [262].

verification to increase their efficiency in a complex environment. Indeed, even though the modelling/conversion effort required for creating semantic BIMs from unstructured survey data is high and notable are the difficulties connected to accurately representing the variety of complex and irregular objects occurring in existing buildings and the lack of standards for their representation, the manual modelling and parametrising of existing architectural elements is still the most accurate way to interpret them. This is a common practice that aims to develop a library of reusable parametric objects for the optimisation of the following modelling stages. Therefore, a fully automated process for extracting semantics from raw data in BIM still poses a major issue worth to be investigated. Notably, there is still a lack of direct connection between the rich, geometrically accurate graphical data captured on-site and the discrete synthesis that even an as-built model type is capable of storing and reproducing. A BIM model often feels too much like an abstraction of the real world, so its practical use as a support tool for restoration and conservation purposes becomes rather ineffective.

The most recent research, primarily addressed to restoration interventions and aimed at identifying areas affected by degradation phenomena identified according to shared protocols, is based on the projection of photogrammetric orthophotos onto BIM objects that, although geometrically accurate, are not parameterised. While other techniques used to reproduce real textures, to preserve access to intelligent objects with the purpose of dissemination and preservation of cultural heritage, involve *decal types* [42] or the creation of textured surface materials through *diffuse maps* derived from photogrammetric orthoimages. An attempt in this respect, aimed at preserving access to smart objects, was realised by Ferreyra et al. in developing an application optimised for real-time visualisation [43]. The research investigates a methodological proposal for linking UAV survey data, via full-size orthoimages used as textures, to the sub-components of a built asset, such as a façade, and its sub-parts. UAVs can be the basis for the creation of an interactive image database for the metric reconstruction of 3D geometry. The goal is to establish an actual link between the collected data and BIM models, thus improving model productivity.

Nevertheless, there are several studies concerning the semi-automated generation of NURBS from transforming them into *masses* capable of accommodating photogrammetric textures applied as decals in Revit [39,44,45], as well as plug-ins developed via Autodesk Revit's Application Programming Interface (API), such as GreenSpider, which was created to recognise points from surveyed points and interpolate them to generate curves and surfaces [46]. The built heritage typically has complex (non-uniform, thus difficult to parametrise) geometries that turn their

digitisation through conventional methods into imprecise and time-consuming processes. As technology has advanced, researchers have then developed automated approaches for BIM reconstruction [47]. On the other hand, the NURBS, generated via software such as McNeel Rhinoceros, by transforming the surveyed three-dimensional model into a solid, can be also imported into the BIM environment via a VPL script developed through applications such as Dynamo for Revit o McNeel Grasshopper [48,49].
Other applications involved reverse modelling procedures, i.e., the conversion of numerical models produced from point clouds into mesh surfaces, generating polygonal connections that allowed for a more fluid and qualitative reliable 3D model of an entire territory, to be further optimised within environments such as 3D GIS [50]. New methodologies regarding the replication of unique complex details typical of the built heritage involve the manual, user-supervised cutting of the photogrammetric model; such portions of the resulting 3D model (OBJ) are then imported directly into a BIM environment (such as ACCA software Edificius) and positioned correctly in space, using the point cloud as a guideline, to be subsequently exported as IFC objects and exported to software environment, such as Autodesk Revit, for semantic enhancement. In this case, the limitation of the proposed methodology relates to the need for employing multiple pieces of software and the consequent time-consuming nature [51].

2. Monitoring Enriched COoperative Systems

"An isolated system or a system in a uniform environment (which for the present consideration we do best to include as a part of the system we contemplate) increases its entropy and more or less rapidly approaches the inert state of maximum entropy. We now recognize this fundamental law of physics to be just the natural tendency of things to approach the chaotic state unless we obviate it."

[Erwin Schrödinger – *About Ecosystems and entropy* in ***What is Life?***]

The term ecosystem was coined in 1935 by Tansley who defined it *as "the whole system – the physical sense – including not only the organism-complex [that is, the community], but also the whole complex of physical factors forming that define the environment of the biome, i.e., the habitat factors in the widest sense"*. Tansley went on to argue that ecosystems *"are the basic units of nature on the face of the earth"*, thus implying for that the term ecosystem stands for a physical description of a community in its habitat[12].

As a result of the presented considerations, it arises the main objective of the present thesis project, i.e., the development of a methodology for long-term management in a BIM environment of structural monitoring Enriched COoperative Systems [ECO-Systems], which falls within the topics of the *ninth sustainable goal – Industry, innovation and infrastructure*.

The *monitoring ECOsystem* is designed as an open environment that needs continuous input to maintain its order; the inputs will be represented by up-to-date and updatable information, in order for the ECOsystem to function properly. Like a physical system, which naturally tends towards entropy, an improperly managed digital system, i.e., one for which no management procedures have been established, tends equally to degenerate into chaos as to descend into functional obsolescence. It is therefore imperative when organising a facility management

[12] However, independent of the meaning attributed to *ecosystem*, the discipline of *ecosystem ecology*, in contrast to other ecological sub-disciplines, and in continuity with its history, does retain an emphasis on physical processes. Indeed, philosophical attention has been paid to whether ecosystem ecology should be regarded as an instance of the unification of the physical and biological sciences. For further information concerning the topic of ecosystem ecology see [263,264].

BIM system to clearly establish implementation and data management procedures, i.e., to define the so-called *Common Data Environment* [CDE, in italian *Ambiente di Condivisione Dati – ACDat*][13]. The proposed methodology moves towards a standardisation of the modelling procedures of the existing built environment, while also being easily adaptable ex-novo modelling, by simply leaving out the initial integrated survey.

Monitoring ECOsystems are thus configured as systems whose input data come from monitoring operations, whether these are carried out in a predominantly *analogue* fashion rather than in an almost entirely *digital* way. The term *analogue* here encloses all those operations that require a great deal of effort on the operator's part in the collection and storage of data, which are recorded only during a posterior synthesis phase into the digital platform.

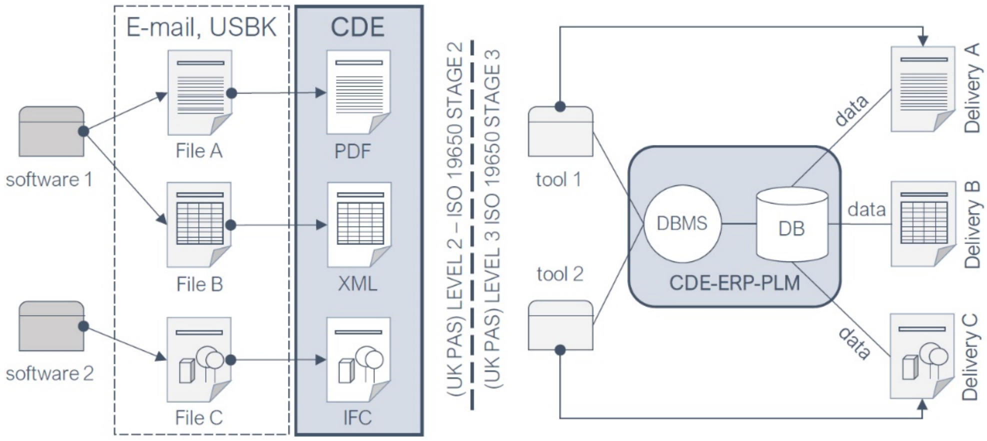


Figure 2.1 – Common Data Environment [CDE] schema according to the United Kingdom Regulation that implemented the ISO 19650 [19]

[13] According to the ISO 19650-1-2:2018 a Common Data Environment [CDE] is an *“agreed source of information for any given project or asset, for collecting, managing, and disseminating each information container (named persistent set of information retrievable from within a file, system or application storage hierarchy) through a managed process”*. While the UNI 11337-4 defines the Ambiente di Condivisione Dati [ACDat] as follows: *“an environment for the organised collection and sharing of data related to digital models and drawings, referring to a single work or a single set of works”*.

2.1 BIM-based approaches for structural health monitoring ECO-Systems

The first proposed case study, concerning the experimentation on the *Olivieri viaduct*, an infrastructural work of art belonging to the Salerno-Cava de' Tirreni Strategic Infrastructure Corridor, thus focuses on the development, through a pilot case study, of a procedural workflow for the digitisation of bridges, viaducts and overpasses of the A3 highway in the framework of the *C.U.G.R.I.* [*Consorzio inter-Universitario per la previsione e prevenzione dei Grandi Rischi*] agreement with the *Autostrade Meridionali* [SAM] company concerning the awarding of the *service for the surveillance of the major works of art of the A3 Naples-Pompei-Salerno*. The digitisation procedure starts from the cataloguing of the elementary components of a bridge, which is first analytically broken down by the human operator, and then recomposed in a synthesis process represented by the BIM modelling of the entire infrastructure. A certain degree of automation is then provided in order to minimise the risk of committing errors in the phase of extrapolating information from the BIM repository and transferring it to the monitoring platform developed by the C.U.G.R.I. technicians, as well as for the univocal assignment of the monitoring forms corresponding to each elemental component, in accordance with regulatory indications. At this stage, the human component is again decisively involved in the figure of the inspector, carrying the inspection paper sheets and camera and measuring instruments to the site, only to report later on the results of the surveys carried out within the monitoring platform. Subsequently, the results produced by the inspections in terms of *relative defectiveness* [Dr] will be plotted and re-entered into an editable BIM environment for graphical visualisation of the state of health of the infrastructure.
On the other hand, the second proposed case study, i.e., the implementation of a digital monitoring ECOsystem for the *Temple of Neptune at Paestum*, is characterised by a far more noticeable digital component due to the integration of monitoring data coming from different types of sensors. In this case, the word sensors both refers to active and passive acquisition systems used in the digital survey – lidar instrumentation and photographic cameras whether or not mounted on unmanned aerial vehicles [UAVs] – as well as actual seismometric sensors placed on the crowning of the temple's external colonnade to monitor micro-displacements. Therefore, the data coming from the integrated digital survey is implemented in the BIM environment firstly to serve for the Scan-to-BIM manual modelling phase and secondly as input for Mesh-to-BIM applications oriented to

an accurate digitisation of the context surrounding the object of study, as well as particular elements of detail for carrying out more in-depth investigations. While procedural workflows were developed for Mesh-to-BIM applications, in order to optimize the structural modelling phase of the temple it was instead decided to perform an initial in-depth analysis of the structural system through its accurate discretization into elementary components, in order to generate a dataset of fully parametric smart objects then fully adaptable to the surveyed geometry (point cloud) once inserted into the project. The monitoring system consisting of seismometric sensors located in 2020 was also modelled with a lower level of geometric detail – LOD 200 (purely volumetric). Then the information database related to the measurement instruments and real-time monitoring data, available to date, was linked to the MEP model of the seismometric monitoring systems. The script created for the automation of the latter process already provides for a possible future update of the system, still in the run-in phase, by automating the implementation of additional system descriptors defined as shared parameters.
Furthermore, comparing future survey data to the BIM model, having previously validated the Level of Accuracy of the model developed at the initial time (t_0), will also provide a fast and reliable tool to detect possible displacement of the structural components. *Monitoring Enriched Cooperative Systems* thus already own the potential for becoming fully working Digital Twins.

2.2 Generation of Open BIM models for information exchange

The secondary objective of the present work is then the generation, by the end of each modelling stage, of properly mapped thus easily accessible *Open BIM* models for efficient information exchange, which falls within the topics of the *seventeenth sustainable goal – Partnership for the Goal*.
As previously mentioned, one standard specification for the optimization of the construction industry process is interoperability, intended as the possibility to pass-over information between different software and platforms without losses [11]. Indeed, the *Business Dictionary* defines interoperability as the ability of a computer system to run application programs from different vendors and to interact with other computers across local or wide area networks regardless of their physical architecture and operation systems. Thus, in order to promote interoperability, it is indispensable to rely on a standard neutral exchange format and schema [52].
Various data formats and schemas used for interoperability have been developed, proposed, and utilized for the AEC sector. A data format is a specific protocol of how the data is stored and retrieved, and a schema is how a computer language or database is organized and structured. An open source and neutral data format could be the best approach for enhancing the data exchange process.
The majority of the formats and schemas are based on a markup language, such as the *eXtensible Markup Language* [XML]. Other formats and schemas are based on standard information exchanges, such as *EXPRESS language*, which is the formal language of *Standard for the Exchange of Product model* [STEP], and the *American Standard Code for Information Interchange* [ASCII] data. *Excel spreadsheet* [XLS] can be used, such as in the *Construction Operations Building Information Exchange* [COBie][52]. Being both an exchanging data format and a fully developed taxonomy[14] Industry Foundation Class [IFC] is used for exchanging building and construction industry data.

[14] According to the oxford dictionary, a taxonomy is the scientific process of classifying things by arranging them into groups. Indeed, in the context of BIM, a taxonomy is a hierarchical classification that allows categorising the smart objects according to specific criteria in relation to their properties. Other known taxonomies are: *OmniClass* – adopted in the USA; *UniClass* – developed in the United Kingdom; *MasterFormat and UniFormat* – European standards based on USA ones; *Sfb* – which was the first classification adopted in Northern Europe in the fifties and is still used In Belgium and Holland; *CoClass* – the Sweden classification and one of the most advanced European standard that may be adopted across Europe after the event of Brexit; *GuBIMClass* – a Spanish initiative led by the *Grupo de Trabajo BIM de Cataluña* which is based on the UniClass.

Namely, IFC – developed by the international non-profit organisation *buildingSMART* – is a comprehensive data model allowing the detailed geometric and semantic description of buildings and is considered *the de-facto* as software vendor-independent *BIM data exchange standard* [53], having been accepted as an ISO standard in 2013 with the issuing of the ***ISO 16739:2013*** [54].

2.3 A methodology for the standardisation of Scan-to-BIM Modelling

A consolidated Scan-to-BIM approach usually involves first surveying the structure and the surrounding landscape on which to develop a BIM model. For said reason, it is hereby proposed a framework for the standardisation of some well and lesser-known practices implemented in this process to be able to trace data sources and the quality of their reproduction along the whole modelling process.
The reported tested Scan-to-BIM methodology, which employs the Autodesk software package, is meant as a *good operational practice* and can be organised into six sequential steps as follows (Figure 2.2):

- Three-dimensional survey [3DS]
- Georeferencing [GEO]
- Federate modelling and Shared Coordinates setting [FSC]
- Structural modelling [STR]
- Level of Information enhancement [LOI]
- Open BIM Models Exportation [IFC].

Each step of the proposed workflow is necessary to the subsequent, but it stays updatable thanks to the BIM environment. The modelling of the existing heritage is rarely a straightforward process and may, in some cases, be iterative, thus the necessity of repeating some steps or, at least, exchanging some of them. Remarkably, the LOI phase is present at different levels, a constant throughout the process, whether performed manually or via VPL scripts, by populating *ad-hoc* parameters with varying types of information [3].

3DS: Three-Dimensional Survey

A three-dimensional survey is imperative when modelling the stratified cultural heritage where each detail may have contributed to defining the site's historic character. An integrated Laser Scanning – Photogrammetric survey is the most suitable choice. Namely, for medium-scale applications, TLS (Terrestrial Laser Scanning) and UAV (Unmanned Aerial Vehicle) surveys are carried out to be later georeferenced within a common coordinate system via control points measured with topographic instrumentation for their subsequent integration [3].
TLS and photogrammetric techniques have advantages and disadvantages; discriminating becomes the project budget rather than the required objectives or level of detail. Photogrammetric techniques require experience, above all in the

acquisition phase, in order to obtain an accurate final result; TLS, on the other hand, while easy to use, requires experience in setting up the parameters and is a highly time-consuming and costly activity. The choice of which method to use depends mainly on the complexity of the site to be investigated, the accuracy requirements, and the budget and time available. For this reason, the integration of multiple techniques is often the most suitable solution [3].

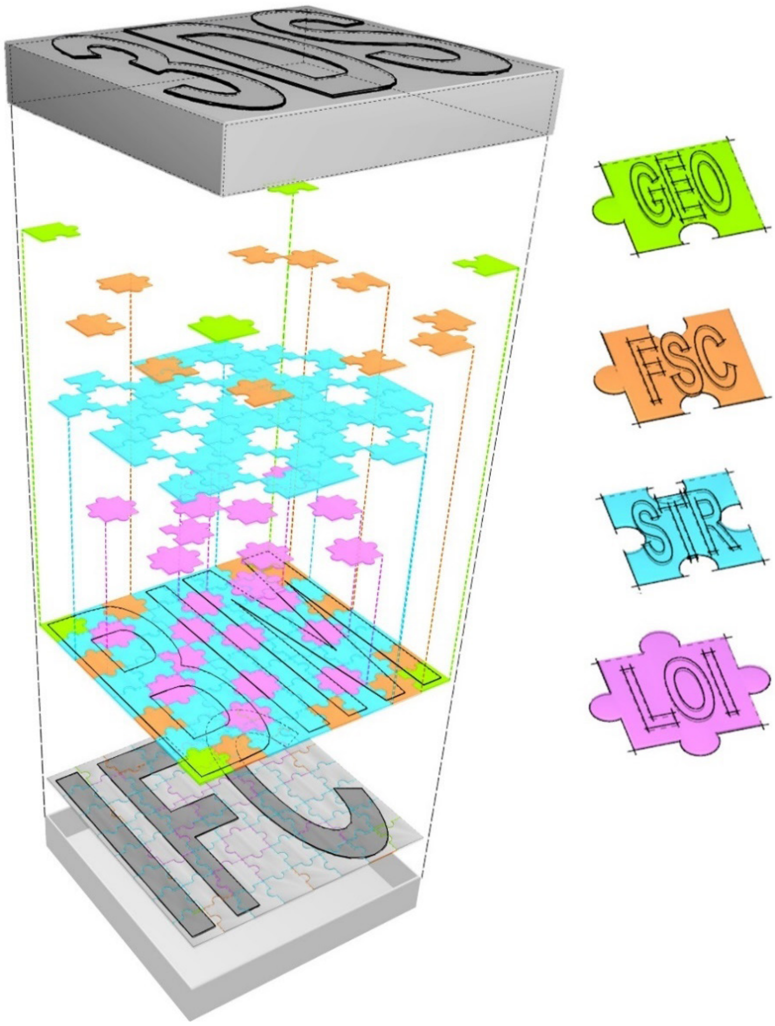


Figure 2.2 – In the Scan-to-BIM process, an accurate integrated survey (3DS - grey) represents the first fundamental phase, followed by the Georeferencing (GEO - green), the Federate modelling and Shared Coordinates setting up (FSC - orange), the Structural modelling (STR - cyan), and the Level of Information enhancement (LOI - magenta) stages that constitute the core of the BIM modelling methodology, culminating if necessary in the exportation to OpenBIM formats (IFC - grey) for information exchange [AoE].

GEO: Georeferencing

The georeferencing of the BIM models can be optimised by directly importing the mesh models of the surroundings, thanks to VPL (Visual Programming Language) scripts, in the same coordinate system of the surveyed model. For the visual script to work correctly, it is advisable to operate a rigid translation to a local coordinate system already at the end of the photogrammetric workflow and later revert to the global coordinate system by simply imposing the exact rigid translation – in the opposite sense – to the *Project Base Point* (PBP)[15] of the Revit projects [3].

In a nutshell, when working with topographic coordinates, within some software not designed to manage this type of coordinates (i.e., Meshlab, Dynamo, etc.), approximation issues in the correct interpretation of the exact coordinates arise, leading to an incorrect visualisation and consequent reproduction of the mesh. For this reason, it is advisable to operate a transformation from the global system to a local one – so that the x, y, and z coordinates of the points of the cloud and accordingly the vertices of the mesh may have the same order of magnitude – by operating a rigid translation. The rigid translation aiming to shift from a global to a local coordinate system has to be performed at the end of the photogrammetric process (in our formulation Agisoft Metashape), for example, by operating on the GCPs (Ground Control Points) used to scale and georeference the model: a fixed quantity is to be subtracted from both the longitude and latitude of the control points in the photogrammetric project. These quantities will then represent the inverse translation that will be imposed in the BIM environment by georeferencing the PBP, thus operating the rigid inverse translation [3].

FSC: Federated Models and Shared Coordinates

The federate modelling stage requires the particular BIM projects (when operating within the Autodesk Revit software[16]), such as the architectural, structural, and

[15] A Revit project store internal coordinates for all the elements that compose the model in a project. In detail, it is possible to distinguish between two different origin points: the *Project Base Point* [PBP] and the *Survey Point* [SP]: the PBP defines the origin (0,0,0) of the project coordinate system. Use the project base point as a reference point for measurements across the site; the survey point identifies a real-world location near the model, such as a corner of the project site or the intersection of 2 property lines. It defines the origin of the survey coordinate system, which provides a real-world context for the model. To learn more about Project Base and Survey Points, visit: https://autode.sk/3ygsFXO.

[16] The versions of the Autodesk Revit BIM Authoring tool employed for this thesis work are the 2021 (in its 2021.1.5 release) for the Olivieri Viaduct case study, and the 2022 for the Temple of Neptune case study. Indeed, the updated version of the Autodesk Revit

urban parts that may compose a complete superordinate model, to be linked into a shared environment, practically consisting of a higher-level project. The first importation of the sub-models has to employ the PBP as the original reference point, to later *publish* to them the shared coordinates [3].
The global system's partitioning into several sub-models linked together by georeferencing in a unified real-world coordinate system allows for the easier management of complex ECOsystems composed of assets of different natures that can be integrated, if necessary, at the required time. An indispensable moment in the preparation and management of federated model systems is, as already stated, the phase of *coordinate sharing* (publishing), having empirically experienced that this is the reference system retained, among the available ones, when exporting the model in IFC format. The correct georeferencing of all the constituent parts of a complex spatially-based monitoring ECOsystem, therefore, lays the foundations for effective integration of BIM and tridimensional GIS systems.

STR: Structural Modelling and Shared Parameters

Though the proposed applications will present structural BIM models, this stage may equally apply to an accurate architectural and/or mechanical modelling of the object of study. First, it is fundamental to import the integrated surveyed point clouds into the Autodesk ReCap Pro environment to be correctly read within a Revit project and used as guidelines for the proper scan-to-BIM modelling. Then the proper modelling process will start by placing already existing parametrised objects to fit the point cloud representing the surveyed asset or, in their absence, by realising *ad-hoc families.*
Usually, to achieve a metrically reliable BIM model, a manual Scan-to-BIM approach – within the Autodesk Revit environment – has to be applied, for the parametrisation of adjustable and updatable BIM objects. On the other hand, a Mesh-to-BIM implementation can be developed for those unique elements of the built environment, i.e., the assets surrounding.
Scan-to-BIM is a reverse-engineering methodology that employs a point cloud as the basis for parametric modelling of the architectural asset. To import the point cloud into Autodesk Revit it was mandatory to use Autodesk Recap Pro as intermediary software, where the point cloud was segmented into homogeneous

piece of software provided the introduction of a particular type of system family – the "tapered walls" – much needed in the modelling of ancient heritage in order to better adapt to state-of-the-art structural conditions. Furthermore, the applications of the second case study required the implementation of more complex Dynamo packages, whose updates succeeded in correcting many bugs in their coding.

regions to facilitate the subsequent modelling phase. Due to the irregular geometries of the built heritage, the proper modelling stage is never a straightforward procedure.

LOI: Level of Information enhancement

As already stated, the acronym LOI is not new to the parametric informative modelling technology; it stands for *Level of Information*, being seen as part of the equation that, together with the *Level of Geometric Detail* [LOG], defines the general concept of *Level of Development* [LOD], as defined in Figure 2.3. The LOI may include a vast amount of data in the form of parameters, which contribute to describing different aspects of a *smart* object. The current regulation provides a basic definition of it to be further implemented according to the specific cases. Furthermore, the awaited updated version of the UNI 11337-4 will introduce in the Italian regulations the concept of *Level of Information Need* [LOIN], as the specific information requested by the contractor (Figure 2.4)[17].

As already mentioned, the data enrichment of the BIM models occurs along the whole process, thus, it may seem reductive and probably wrong to place it in the last step. We will then intend the LOI as the additional information provided thanks to the *ad-hoc* developed implementation for the proposed methodology [3].

For the purpose of the present work, the LOI enhancement is mostly carried out via automatised procedure set through the ad-hoc developed, albeit repeatable, Visual Programming Language [VPL] scripts.

The introduction of VPL dates back to the early 80s, together with the diffusion of the personal computer, but its success came at the beginning of 2000 together with the success of the parametric design and the diffusion of dedicated tools for the purpose. As time goes by the application went far beyond and nowadays the implementation of VPL scripts allows the management of entire workflows [55].

Programming and Visual Programming utilize the same framework of formalisation. However, VPL allows defining the instructions and relationships of a program through a graphical (or Visual) user interface. Instead of typing text bound by syntax, the user connects pre-packaged nodes together.

Hence, these algorithms are represented as process charts rather than the code lines of conventional programming. The most common VP tools in the AECO project

[17] The *Level of Information Need* [LOIN], as introduced by the *ISO 19650-1-2:2018* [261,265] and the *EN 17412-1:2020* [266], is meant as a framework to define the extent and granularity of "information", i.e., reinterpretable representation of data in a formalised manner suitable for communication, interpretation, or processing [57].

industry are the following: Dynamo for Autodesk Revit – the VP tool chosen for the purpose of the present application –, Grasshopper and the Python language.
These tools generate algorithms based on visual expressions for creating process sequence scripts [56].
The Dynamo tool enables the user to work within a Visual Programming process wherein they connect elements together to define the relationships and the sequences of actions that compose custom algorithms. The addition of the visual characteristic to programming, makes it possible to lower the barrier to entry and frequently speaks to designers.
For the compute definition of a VPL algorithm, it is necessary to identify inputs, nodes, and outputs. *Inputs* correspond to the pieces of information required to generate, for instance, parameterised objects, such as geometric vectors defining the longitudinal geometry of a profile to be extruded along the direction of the said vector, together with structural and physical properties. *Nodes* are then identified as the elements connecting the information extracted from the input and are employed to process it for object generation and possibly optimisation. In order for the nodes to execute a series of processes, the entries and outlets of each one need to be adequately linked to one another through the so-called *Wires*, which effectively allow the information to *flow* across the script. Finally, *Outputs*, as the end results of the executed process, correspond to the generated and optimised smart objects which compose a BIM model[18].

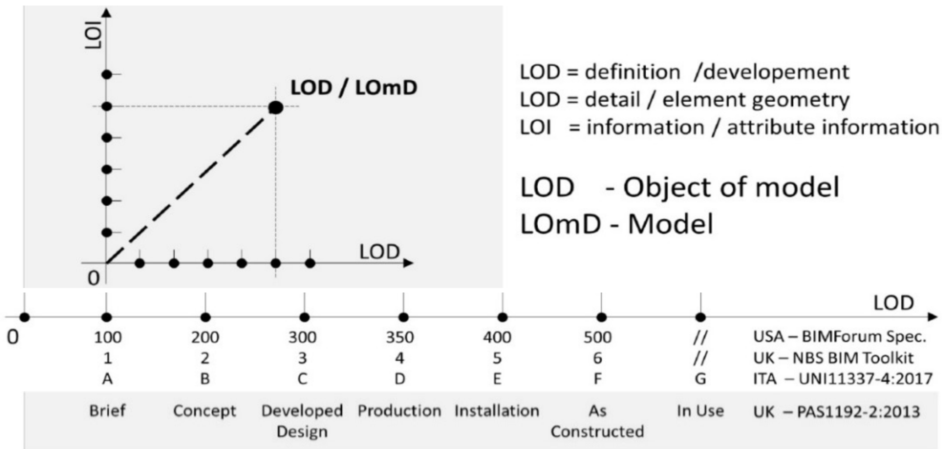


Figure 2.3 – Graphical representation of the LOD according to the UNI 11337-4:2017 [57]

[18] For more information about VPL and Dynamo for Revit, see https://primer.dynamobim.org/; https://forum.dynamobim.com/.

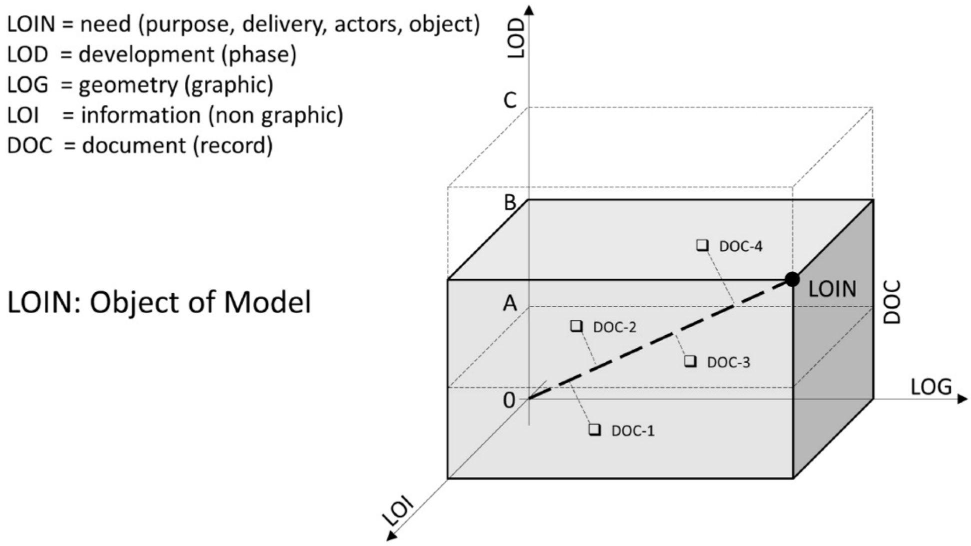


Figure 2.4 – Graphical representation of the LOIN definition to be introduced by the updated version of the UNI 11337-4:2017 [57]

IFC: Open BIM Models Exportation

As already mentioned, IFC [Industry Foundation Classes] provides a standardised, digital description of a built asset complying with ISO (international organisation for standardisation) certification. Physical elements, people and geometry are grouped into logical entities (known as IFC class names) and include their attached attributes (such as Global ID, description, relationships, and geometry). Entities are the main nodes of the schema and can be thought of as tables in a traditional database. Attributes are therefore the metadata contained in the columns of the table. A hierarchical tree of entities can be split into two: occurrences and types [11]. IFC provides three data formats: 1) an IFC data file using the STEP physical file structure; 2) an IFC data file using the XML document structure; and 3) a compressed data file [52].

The open standard developed by *buildingSMART* was first accepted as an ISO standard under the ***ISO 16739:2013*** [54], and has since issued several different versions and releases, with the most recent being IFC4. However, the most widely used and adaptable schema still remains the IFC2×3. Up to version IFC4, the IFC standard was mainly focused on buildings. However, due to increasing international demand, a substantial extension of the standard to support infrastructure facilities is being carried out [11,53].

In April 2017, in accordance with *buildingSMART*, the IFC also became the official ISO standard in its version IFC4 under the ***ISO 16739:2018 for data sharing in the construction and facility management industries – Part 1: Data scheme*** [58]**.** The infrastructure extensions of the IFC 4 release, include: IFC-Road, IFC-Bridge, IFC-Railway and IFC Tunnel [53]. The IFC-Bridge deals with the open exchange of Bridge Information Models [BrIM]. To facilitate BrIM, the building-related data schemas were borrowed to exchange bridge project data.
However, because IFC was intentionally designed for buildings and was unable to define bridge-related geometry in early versions, bridge-based data schemas were developed for steel bridge construction and fabrication and bridge life cycle. Indeed, neither BIM nor IFC were originally intended for non-buildings assets, so the adaptation of the BIM methodology to transportation Infrastructure will encounter many more challenges encountered when applying BIM to transportation infrastructure [52].
Interestingly, the definition of BIM for transportation infrastructure corresponded with the development of a microcomputing system for bridge management. Moving from a paper-based workflow to an electronic/computer workflow has then led to the rise of Bridge Information Modelling [BrIM] [52].

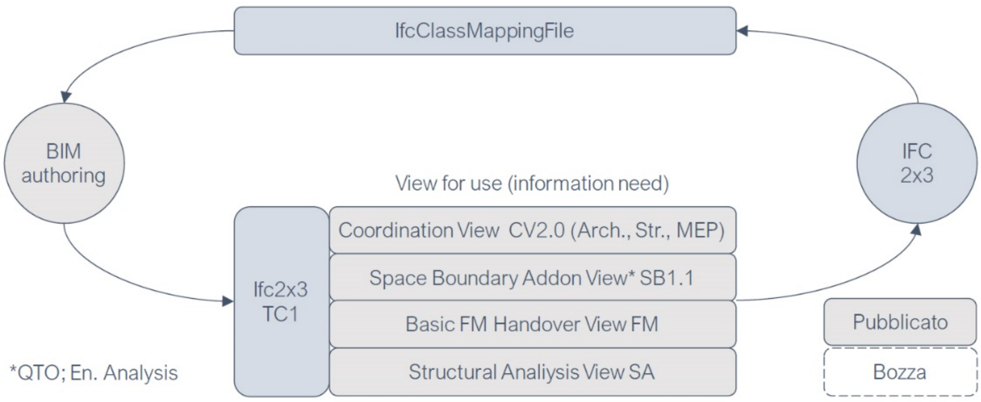


Figure 2.5 – IFC 2x3 Model View Definition [MVD][19] as required by the ISO 16739 [19]

[19] According to BuildingSMART: *"A Model View Definition (MVD) is a subset of the overall IFC schema to describe data exchange for a specific use or workflow, narrowing the scope depending on the need of the receiver. An IFC View Definition, or Model View Definition, MVD, defines a subset of the IFC schema, that is needed to satisfy one or many Exchange Requirements of the AEC industry. The method used and propagated by buildingSMART to define such Exchange Requirements is the Information Delivery Manual, IDM (also ISO 29481)."*

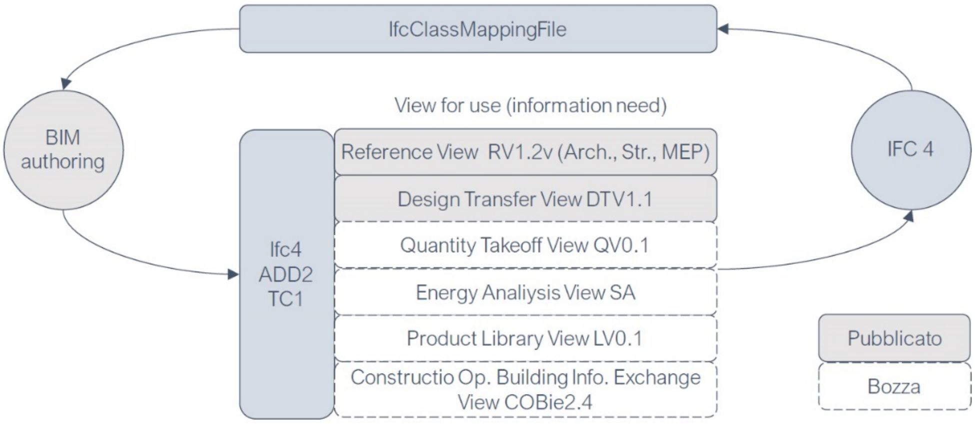


Figure 2.6 – IFC 4 Model View Definition [MVD] as required by the ISO 16739 [19]

PART II – Bridge digitisation: the case study of the Olivieri Viaduct

3. Shortcomings in infrastructure digitisation

To date, most of the Italian infrastructure heritage seems to have been forgotten, generally lacking maintenance planning or even completely neglected. Infrastructural artworks are sporadically recalled, sadly on the occasion of catastrophic events, which unfortunately seem to provide the only catalyst for the initiation of legislative changes, leading to the current imperative to introduce a digital system for the management of Italian bridges, viaducts and overpasses. Therefore, the case study concerning the Olivieri Viaduct, presented in the following chapters, will deal with the setting up of an optimised *Bridge Management System* [BMS], intended as a framework for the *Structural Health Monitoring* [SHM] of the Italian Bridge Infrastructure. Many BMSs lack 3D models of the structure and defects. Instead, the bridge and related defects are described with sketches, photos, explanations and parameters. BMSs are fundamental for developing future standards and software for the inspection-maintenance cycle. These systems offer information about bridges, bridge components, inspections, maintenance actions, and defects. A *Damage Information Model* [DIM] has to include at least the information stored nowadays within BMS. Further, it should support novel concepts for inspection, condition rating, and simulation with necessary data [59].

A typical modern BMS framework can be simplified into four modules: data acquisition, data analysis and interpretation, information model and decision support model. Information is key to effective bridge management; therefore, an essential module of a management system is the information model. Databases are at the heart of the module and ultimately form the basis and quality of all decisions and actions considered by the BMS. The addition of visualisation to asset management provides a beneficial cognitive aid for processing overwhelming amounts of information [11].

On how to actively implement a BMS the debate is still open; however current legislation requires the implementation of information systems such as BIM and GIS [Geographic Information System], thus promoting the need for an integration of these technologies. Indeed, infrastructures such as bridges, viaducts and overpasses, despite being linear, still present a relatively limited linear development, with a ratio between the longitudinal axis and the other two main dimensions of the cross-section, usually between 1:5 and 1:20. For this reason, when it comes to modelling structural components in detail, they are conceptually assimilated to vertical type structures, thus justifying a BIM-type approach with the tools classically associated with architecture. However, this does not mean leaving them out of a broader territorial context, defined through topographical references within a GIS [60]. Indeed, in recent years, interest in the application of BIM has broadened to encompass civil infrastructures such as dams, tunnels, bridges or roads [53]; these applications aim to exploit the potential of BIM models to optimise the design and assessment processes [61] and to compile dedicated databases consistent with regulatory requirements for infrastructure management [15,62]. The relevant literature is also looking for more appropriate definitions to refer to the application of BIM methodology to infrastructures; i.e., according to normative prescriptions, this practice generally involves the implementation of georeferenced data [63], thus spawning the terms GeoBIM [64] and InfraBIM [65]. As previously recalled, when specifically talking about bridges, an increasingly adopted acronym is BrIM – i.e., Bridges Information Modelling. Nevertheless, it is not yet widespread enough to determine a standard, as many researchers still prefer to use the all-encompassing BIM definition or incorporate it into the GeoBIM/InfraBIM framework. Therefore, from the perspective of BMS implementation, BrIM models – which are not a mere geometric representation of bridges but rather intelligent 3D virtual reconstruction of the bridges containing all data related to each component for their entire lifecycle – can effectively improve the quality and accuracy of drawings, as well as constructability, and improve collaborations [52].

Bridge management is a multi-step and multidisciplinary effort which requires the cooperation of different stakeholders and work coordination among different teams and organizations in large-scale projects is so important. A Bridge Management System offers a systematic approach towards management of bridges network while also allowing to organise of all the maintenance activities, in this way, BMS can effectively help to reduce the major repairs through effective preventive management [52].

3.1 Overview of the Italian infrastructure assets

The issue of the state of bridge maintenance in Italy was highlighted by the tragic events of 18 January 1967, involving the collapse of two central arches of the Ariccia Bridge (Figure 3.1, Left), located in the town of the same name. An editorial in *La Stampa* by Vittorio Gorresio on 20th of January 1967 was published with the headline: *"Nobody in Italy controls bridges"* (Figure 3.2, Right).
"It seems that there is no law, among the thousands that Parliament produces every year, Garrosio wrote, that provides for periodic inspections of artefacts such as bridges and roads" [66].
Since 1967, the situation in Italy does not seem to have changed, and in the last seven years, multiple disruptions have occurred in Italy involving road infrastructures and especially bridges and viaducts (Figure 3.2). These events, however, are only punctual manifestations of a much broader problem which can be traced back to the absence or inadequacy of maintenance management plans and systems. The investigations carried out on these events confirm, in fact, that the main causes of such failures are to be found in environmental factors (such as material degradation and flooding) and anthropogenic factors (such as increased vertical loads, errors during construction, poor maintenance). Another relevant aspect is that the earthquake does not prefigure a predominant cause for the collapse of bridges [67].
It is worth mentioning the collapse of the Morandi Bridge, a infrastructure work of art located in Genoa – length of 1182 metres and height above street level of 45 metres – which crossed the Polcevera torrent between the districts of Sampierdarena and Cornigliano. Designed by Riccardo Morandi and inaugurated, after 4 years of work, in September 1967, it collapsed, on August 14th, 2018. In detail, the 250 m long section overlooking the river and industrial area of Sampierdarena (Figure 3.3) failed following the collapse of the western support pylon (pile 9) [68], causing considerable direct damage (43 victims) and indirect damage (damage to traffic on the motorway section, potential economic damage to 1432 companies located in the area, approximately 300 displaced families) [69].
The report signed by engineers Giampaolo Rosati, Massimo Losa, Renzo Valentini and Stefano Tubaro states: *"It is identifiable in the moments of controls and maintenance interventions that, had they been carried out correctly, with high probability would have prevented the occurrence of the event. The lack and/or inadequacy of the controls and the consequent corrective actions constitute the weak links in the system; if they had been missing and, where they had been*

carried out, they had been carried out correctly, they would have broken the causal chain and the event would not have occurred" [70].

Figure 3.1 – Archive photo from *L'Unità* of the Ariccia Bridge after the collapse (Left). Front page of the newspaper *La Stampa* dated Friday 20th January 1967 (Right) [66]

Figure 3.2 – Bridge failures occurred in Italy in the last seven years (2013-2020) [71]

Figure 3.3 – Collapsed section of the Morandi Bridge [68]

The management and maintenance of bridges in Italy is a complex issue, not only for the technical reasons to be taken into account but, above all, for the social and economic aspects that complicate it significantly and that can produce, as seen for the Morandi Bridge, direct damage (human life and structural damage) and indirect damage (damage to business activities and the local population) [72].
Among these we have [71]: high number of infrastructural works; lack of a single management system on the whole national territory; dated infrastructural heritage with possible design and execution errors; absence/inadequacy of maintenance plans; current traffic loads and flows different from those considered by the project.

3.2 The high number of infrastructure artworks and the absence of a unified management system

Italy has a complex morphology, divided into hills, mountains (Alps and Apennines) and plains, with a dense network of waterways. This means that a large number of bridges, viaducts and tunnels are required.

As stated in the Infrastructure Development and Cohesion Fund Operational Plan 2014-2020, published by the Ministry of Infrastructure and Transport, the Italian road network extends over 180000 km, of which approximately 6,700 km are motorways and 19,800 km state roads. In addition: *"The toll motorway network (approximately 5,800 km) is characterised by the presence of three international tunnels (25.4 km), 566 tunnels (516 km) and 1,718 bridges and viaducts (681 km), and is mainly equipped with two lanes in each direction for approximately 68% of the network and with three lanes for the remaining part (approximately 31%) with a marginal share of four lanes (1.4%). On the network of over 25,000 km managed by ANAS (of which about 1,300 km consist of motorways under direct management and motorway slip roads and about 19,200 of state roads) there are more than 11,000 bridges and viaducts, 4,000 of which are over 100 metres long, and 1,200 tunnels, 842 of which are over 500 metres long."* [73].

The UPI Dossier Bridges: the results of the Provinces' monitoring indicates that: *"The Provinces of the Ordinary Statute Regions (excluding metropolitan cities) manage about 100,000 kilometres of roads on which at least 30,000 bridges, viaducts and tunnels insist"* [74]. These include: 5,931 structures already submitted to the attention of the Provinces (Figure 3.4); 1,918 structures indicated as priority 1, for which urgent interventions are required (Figure 3.5); 14,089 structures yet to be subjected to technical-diagnostic investigations (Figure 3.6).

These artefacts on the Italian territory are very diverse in terms of materials, dimensions, construction periods and static schemes, which causes difficulty in standardising the different evaluation and management criteria since each bridge presents peculiar challenges. To further complicate the situation, the management of the infrastructural heritage falls under the responsibility of various entities (both public and private), causing an undoubted split in management policies with consequent uncertainty regarding competencies, absence of original design documents and, in general, lack of awareness of the existing artworks on the part of the managing entities themselves.

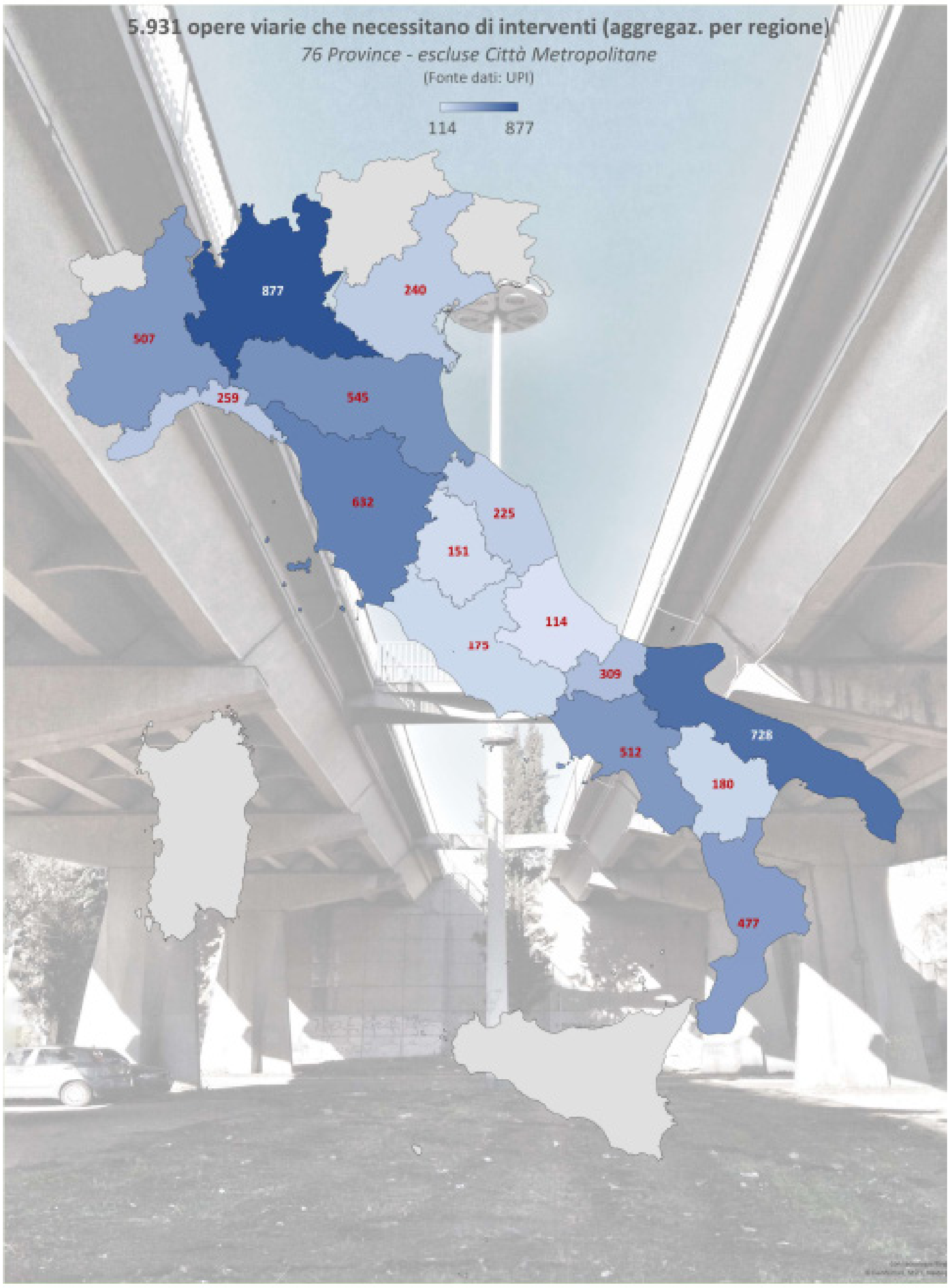


Figure 3.4 – 5,931 road structures requiring intervention (aggregated by region) [75]

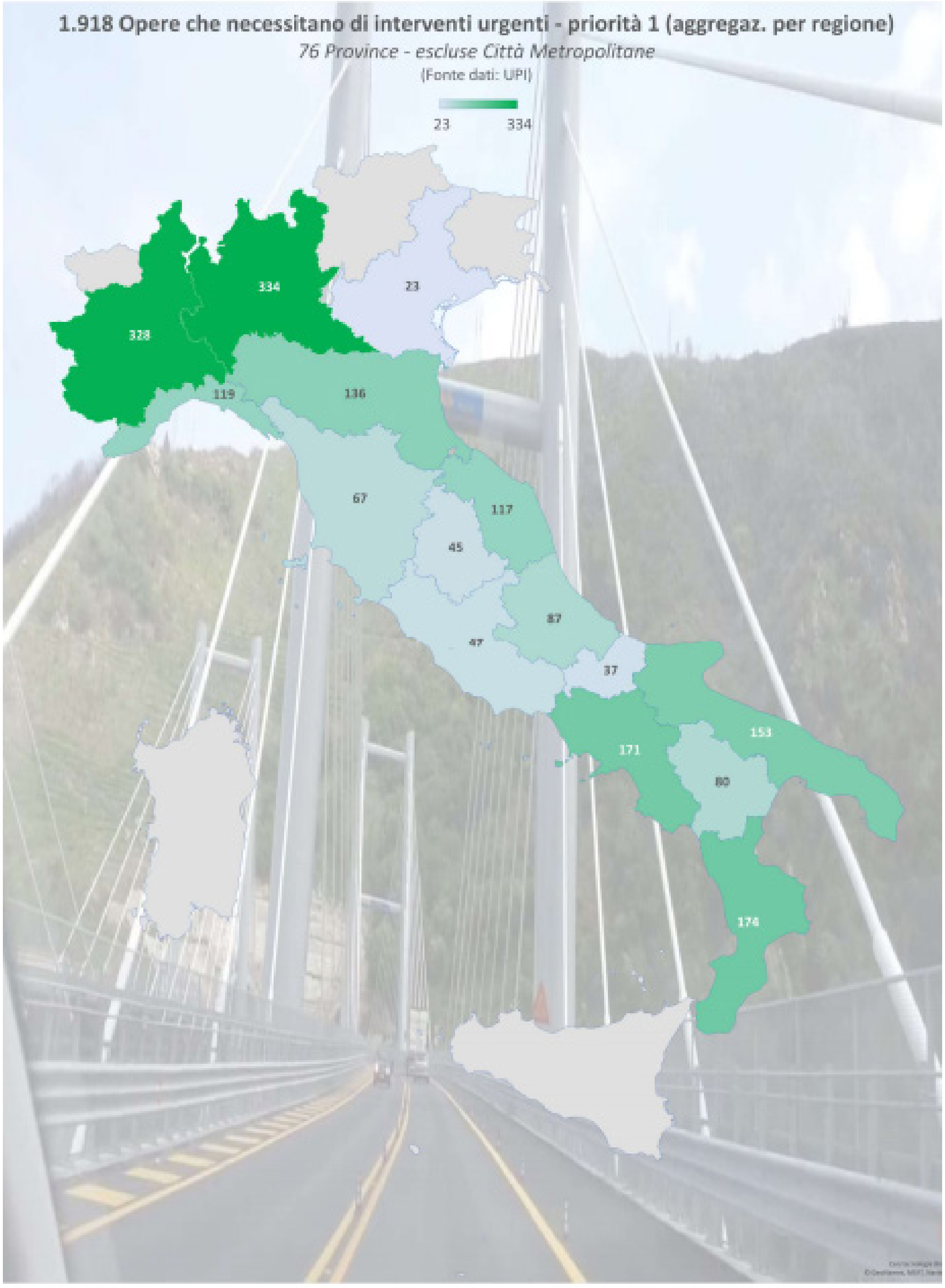


Figure 3.5 – 1,918 road structures requiring urgent action - priority 1 (aggregated by region) [75]

Figure 3.6 – 14,089 road structures requiring monitoring (aggregated by region) [75]

Regarding the latter aspect, a communication from ANAS, dated 19th December 2018, reported that of the 2,994 bridges whose ownership was unclear, resulting from the punctual census of all the artworks undertaken at the beginning of 2017, 983 were found to be owned and managed by ANAS, 586 by other managing entities (Municipalities, Provinces, Regions, motorway concessionaires, Consortia, etc.), while the remaining 1,425 turned out to be ownerless (Figure 3.7) [76].
In any case, of the approximately 14,500 bridges clearly owned by ANAS, 4991 had to be inspected by 2019. Unfortunately, according to reports on the inspections conducted up to December 2019, those on the main and critical bridges had stopped at not even a third of what they should have, 28 % corresponding to only 1,419 inspected bridges. In addition, pavement inspections had stopped, and the new trucks equipped with laser scanners had been sitting in storage for the entire year. These were the mandatory inspections required by legislation to be carried out by qualified engineers on the main viaducts (those with span lengths of more than 30 metres), and critical viaduct (Figure 3.8)[77].

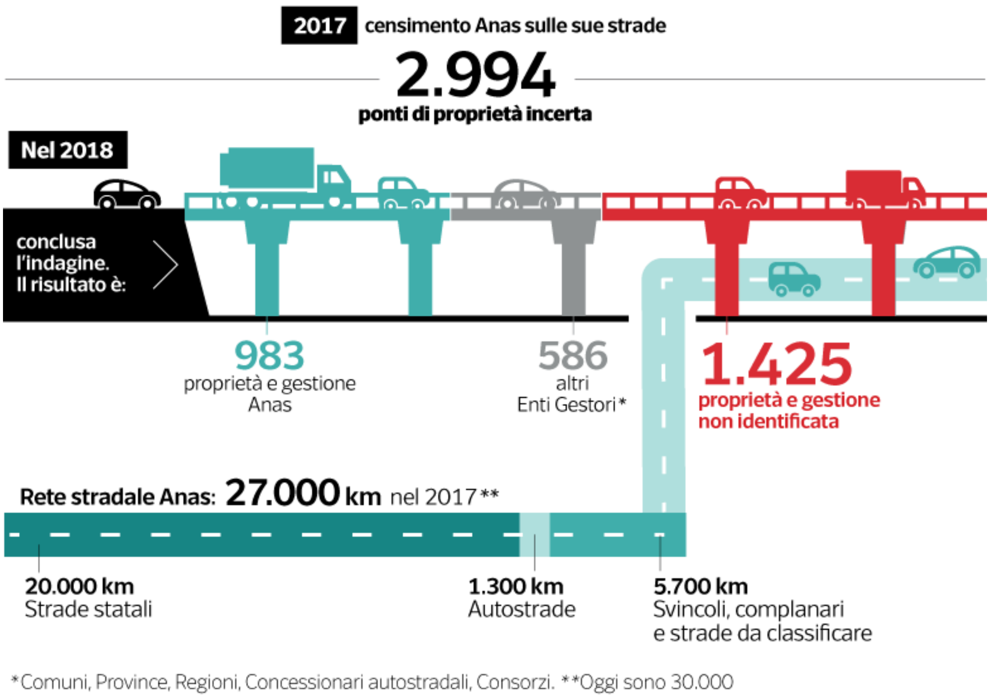


Figure 3.7 – 2,994 bridges of uncertain ownership according to the 2017 ANAS road census. In 2018, at the end of the survey: 983 bridges were found to be owned by Anas, 586 by other operators, and 1,425 by unidentified owners. As of 2017, Anas's road network was 27,000 km long, of which 20,000 km were state roads, 1,300 km of motorways, and 5,700 km of bypasses, coplanars and roads yet to be classified [76]

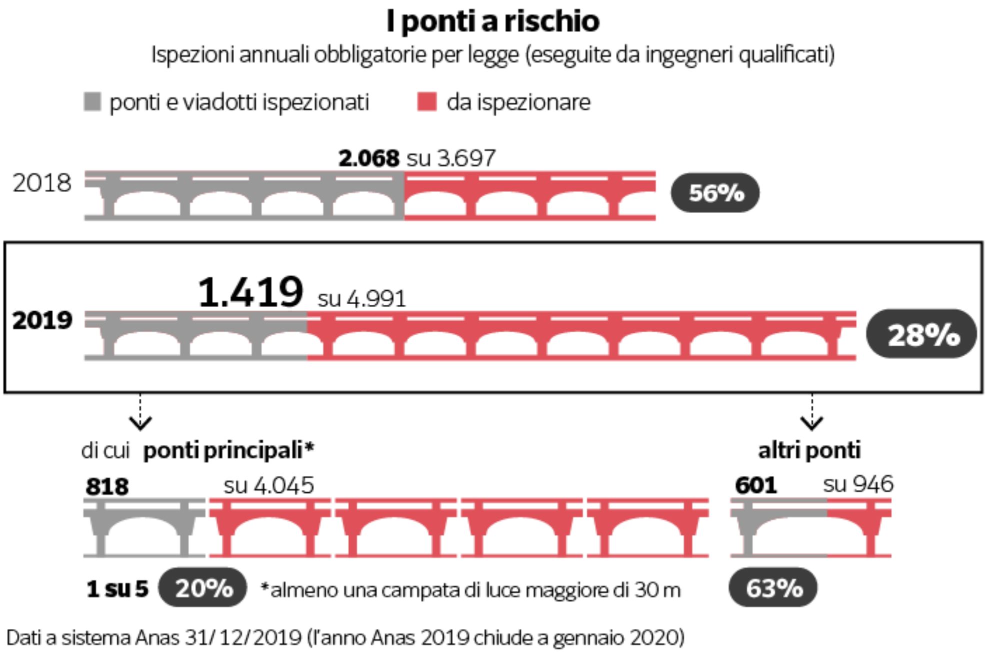


Figure 3.8 – Mandatory annual inspections to be carried out on at-risk bridges dated 2019: inspected (grey) and yet to be inspected (red). Of the bridges at risk, only 818 out of a total of 4,045 "main bridges" – i.e., those with a span greater than 30 m – and 601 out of a total of 946 "other bridges" were inspected. [77]

Therefore, when it comes to risk management of infrastructures, the situation in the national panorama is inhomogeneous, since the various managing bodies adopt their own methodologies and the infrastructural heritage, as already mentioned, is very diversified [67].

Moreover, different management methods, found in the literature[20], although applied to a sample of bridges - under the jurisdiction of the Province of Pisa – seem to report different orders of priority for intervention, not comparable with each other. Thus, the need arises to establish an advanced, simple and quick method of system classification that would also enable public administrations and small authorities to easily perform structural risk assessments of bridges and viaducts [72].

[20] Some of the most common risk management methods found in Literature: Method of A. Montepara et al.; Method of S. Valenzuela et al.; Method of P. Franchetti et al.; Method of 4Emme Service S.p.A; Method proposed by the Surveillance Handbook in 2015 [72].

3.3 Outdated infrastructure heritage with possible design and execution errors and inadequate maintenance schedules

Most of the bridges and viaducts in Italy were built after the Second World War, a period of intense activity in the field of road infrastructure construction; in fact, we can see (Figure 3.9) that no less than 52% of these were built before 1980 and only 15% are less than 18 years old. Another important aspect relates to the materials used, which were often of poor quality; almost all of the structures were then built in reinforced concrete and prestressed concrete, but at a time when there was still no awareness of the problems of durability, so that, to date, the useful life associated with a reinforced concrete construction using the technologies available at the time has been exceeded for these infrastructures [72,78]. As far as design and execution errors are concerned, these are often attributable to a lack of knowledge of the influencing factors and inexperience or the need to economise[21].

On the other hand, the causes of the absence or inadequate maintenance schedules are to be ascribed to the allocation to the different authorities in charge of managing the road infrastructures, the lack of knowledge of the existing structures, the lack of a widespread common approach based on emergency and not on prevention, and the limited economic budget (especially for small entities, such as Provinces and Municipalities) [72].

Regarding this last aspect, the UPI dossier reports that: *"In 2009 the Provinces had at their disposal for investments 1 billion 947 million (roads, schools). In 2013 it dropped to 1 billion 328 million to reach 981 million in 2015. In 2017, the drop is*

[21] According to the ***Design and construction of bridges with hints of pathology and diagnostics of existing works*** by Petrangeli [78], the most frequent errors are to be ascribed to the superficiality of the designers in considering the effects produced by: Thermal variations (Δt) and differential shrinkage; Viscosity; Concentrated forces: the diffusion of concentrated forces due to prestressing or constraining reactions in adjacent areas are known to give rise to tensile stresses in the concrete. These stresses, if not adequately absorbed by the reinforcement, can lead to the manifestation of various cracks; Local effects of accidental loads (specifically dynamic and fatigue effects); Low attention to structural and non-structural construction details: this can cause the formation of cracks, which can compromise the durability of the concrete, leading to its rapid degradation, thus affecting the safety of the work; The incorrect design of non-structural elements, such as downpipes; Hydraulic events (riverbed erosion, hydrodynamic thrusts, etc.); Insufficient characterisation of foundation soils; Errors in the packing, casting or curing of concrete; Positioning of reinforcements not in accordance with the design, that can occur, e.g., during casting and vibration of the concrete – indeed, reinforcement placed too close to the end of the section can oxidise and initiate corrosion.

to 712 million in 2018, a collapse of more than 51% (source: Siope). Expenditure on basic functions (roads, schools) went from 2 billion 168 million in 2010 to 1 billion 387 million in 2015: a change of - 36% (Source, Final Accounts)" [74].

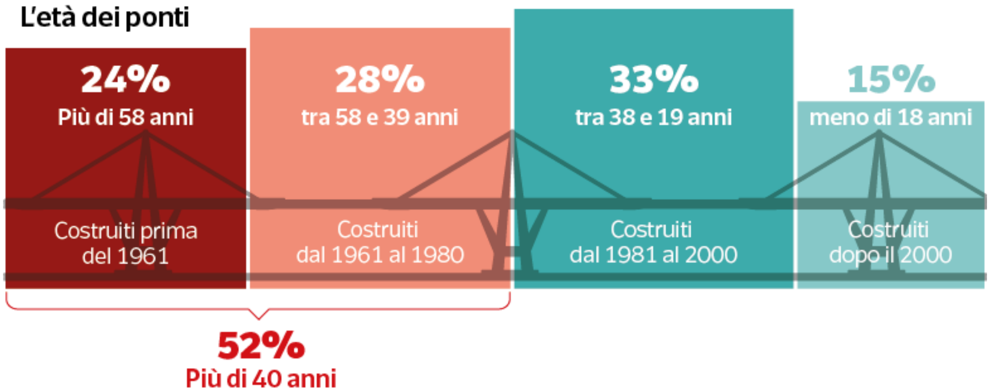


Figure 3.9 – The age of Italian bridges as of 2019: 24% of Italian bridges are more than 58 years old, having been built before 1961; 28% of those built between 1961 and 1980 are between 58 and 39 years old; 33% are between 38 and 19 years old, having been built between 1981 and 2000; while only 15% are less than 18 years old, having been built after 2000 [76]

3.4 Current traffic loads and flows that differ from the original design

Loads and traffic flows have changed over time and are nowadays much greater. This inevitably leads to structures being designed to bear lower loads than those actually occurring during normal operation, compromising the health and safety of the structure. In this regard, the results of a parametric study – conducted by the Department of Civil and Industrial Engineering of the University of Pisa and the Department of Architecture and Industrial Design of the University of Campania Luigi Vanvitelli [79] – are hereby reported. The study was carried out on 16 decks obtained by considering the nature of the Italian infrastructural heritage through the combination of the following variables:

- Four different calculation spans equal to: 5, 10, 20 and 40m
- Four different carriageway widths: from 6 m (characteristic of ordinary urban or extra-urban roads) to 22 m (typical of motorways with two lanes in each direction).

The purpose of this study was to evaluate the bending stresses resulting from the application of the loads indicated in the standards in force in the various eras, using a static beam scheme with simple support, which is common in both normal and prestressed reinforced concrete structures, and also enables easy comparison between the various geometric combinations adopted.

The results obtained from the parametric study are shown in Figure 3.10 and Figure 3.11. In conclusion, it comes out that although the standards implemented since the 1980s provide results in terms of bending stresses in line with the current ones, the previous standards, drafted in a historical period of intense activity in the field of the construction of road infrastructures, provide induced stresses on the structures which are often less than 50% of the current ones.

		Luce			
		5 m	10 m	20 m	40 m
		M_{Ed}	M_{Ed}	M_{Ed}	M_{Ed}
1933	l=6m	325	1075	4428	15896
	l=8m	325	1075	4428	15896
1945	l=6m	244	832	2584	9648
	l=8m	244	832	2584	9648
	l=15m	407	1426	5168	19296
	l=22m	407	1426	5168	19296
1962	l=6m	593	1194	4335	14464
	l=8m	593	1194	4335	14464
	l=15m	798	1917	6942	23882
	l=22m	798	1917	6942	23882
1980	l=6m	823	1902	5069	15723
	l=8m	823	1902	5069	15723
	l=15m	1173	2640	7092	23188
	l=22m	1173	2640	7092	23188

		Luce			
		5 m	10 m	20 m	40 m
		M_{Ed}	M_{Ed}	M_{Ed}	M_{Ed}
1990	l=6m	945	2520	5723	14478
	l=8m	945	2520	5723	14478
	l=15m	1276	3402	7726	19545
	l=22m	1276	3402	7726	19545
2005	l=6m	1330	3080	6300	14874
	l=8m	1330	3080	6300	14874
	l=15m	1629	3827	8207	19002
	l=22m	1629	3827	8207	19002
2008-2018	l=6m	1058	2631	6425	16600
	l=8m	1073	2694	6675	17600
	l=15m	1310	3321	8365	19540
	l=22m	1357	3509	9115	22540

(Valori delle sollecitazioni espressi in kNm)

Figure 3.10 – Bending stresses for single-supported beams obtained from the parametric study conducted by Buratti et al. [79]

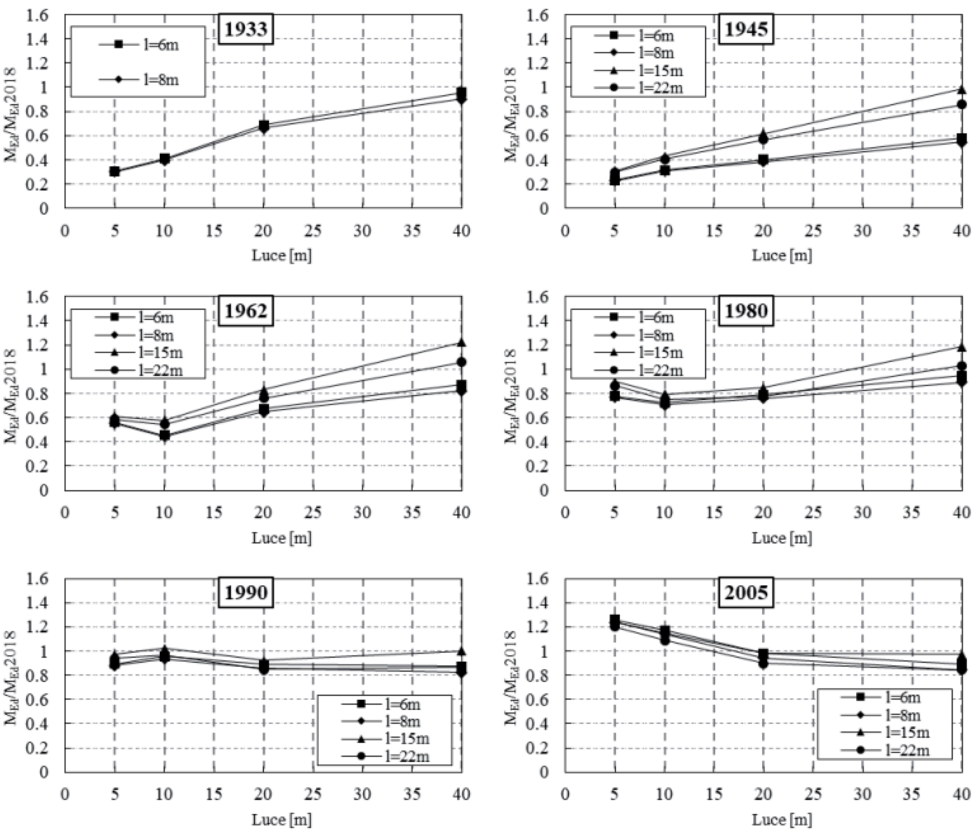


Figure 3.11 – Results of the parametric study conducted by Buratti et al. [79]

4. Bridges inspection and digitisation: regulation and recent applications

This section analyses the national and international regulatory aspects concerning the protocols for inspection and identification of structural criticalities for bridges and elevated infrastructures.
In particular, the analysis focuses on what was reported internationally in a selection of countries chosen either because they constituted a regulatory benchmark or because they were part of the course of study pursued by the PhD Candidate. Indeed, the United States proposes a regulatory structure articulated between documents that offer an overview of the different professional figures that take part in the analysis and development of a maintenance plan, thus constituting a cultural reference for many countries.
Spain and Argentina, on the other hand, while incorporating certain concepts typical of *Latin* normative frameworks, present substantial differences, whose analysis highlights how the tools of representation and information modelling must adapt to operational peculiarities that can vary widely even among culturally close environments.
Subsequently, an extensive literature review was conducted on the state of the art concerning the application of the BIM methodology to the digitisation of infrastructure assets – in particular bridges, viaducts and overpasses – and data regarding inspection practices aimed at the definition of monitoring and maintenance procedures, followed by an analysis of the evolution of the relevant Italian regulatory system, starting from the 1960s up to the more recent application of the ***Guidelines for the Risk Classification and Management, Safety Assessment and Monitoring of Existing Bridges*** issued in 2020 [4].

4.1 Bridges defects identification: inspection protocols in other countries

Bridge maintenance is the process of keeping bridge components in good condition to ensure a longer life, as planned at the time of design and construction. Bridge inspections allow engineers to identify small defects and potential problem areas in bridges before they develop into major problems.

Therefore, even if bridges are well designed and properly constructed, regular maintenance is essential to keep them in good serviceable condition. For this reason, such infrastructure must be regularly inspected and properly maintained. Any problem that was not detected in time could lead to a catastrophic accident, such as the failure of some parts or the complete collapse of the bridge, resulting in serious injury or even death.

United States of America inspection protocols

Currently, the bridge inspection process in the United States is complicated. According to the U.S. Department of Transportation, the approximately 700,000 bridges located across the U.S. are owned and maintained by both federal and state guidelines. Most of them are strapped for cash and have limited resources available to conduct adequate on-depth inspections.

Bridge inspections on a national level are regulated by a regulation called *National Bridge Inspection Standards* [NBIS][22], defined by the *Federal Highway Administration* [FHWA] of the *State Department of Transportation* [DOT]. Each *state's Department of Transportation* [State DOT] is required to inspect all highway bridges on public roads that are located completely or partially within state boundaries, with the exception of bridges owned by federal agencies. Furthermore, federal agencies perform additional inspections beyond those performed by State DOTs. Private-owned bridges, including commercial railroad bridges and some international crossings, are not legally required to adhere to NBIS requirements; however, many privately owned bridges over public roads are inspected in accordance with NBIS. States may use funds from the Highway Bridge Programme for bridge inspection activities. For bridges subject to NBIS requirements, information is collected on bridge composition and condition and reported to the FHWA, where the data is stored in the *National Bridge Inventory* [NBI] database. A *Sufficiency Rating* [SR] is calculated from the NBI data

[22] See § 650.311 Inspection interval of the NBIS [267].

elements on structural condition, functional obsolescence, and essentiality for public use. The SR is then used at the code level to determine the suitability for rehabilitation or replacement of the structure using funds from the Highway Bridge programme. As required by the Federal regulations, according to *National Bridge Inspection Standards* [NBIS] inspections must be carried out on a regular basis, according to the typology:

- *Routine* bridge inspections: every 24 months[23]

[23] See § 650.311 Inspection interval of the NBIS [267].
(a) Routine inspections. Each bridge must be inspected at regular intervals not to exceed the interval established using one of the risk-based methods at paragraphs (a1) or (a2) […]. Moreover, service inspections (a3) and additional routine inspection (a4) have to be taken into account.
(a1) Method 1. Inspection intervals are determined by a simplified assessment of risk to classify each bridge into one of three categories with an inspection interval as described below. (i) Regular intervals. Each bridge must be inspected at regular intervals not to exceed 24 months, except as required in paragraph (a)(1)(ii) of this section and allowed in paragraphs (a)(1)(iii) of this section. (ii) Reduced intervals. (A) State transportation departments, Federal agencies, or Tribal governments must develop and document criteria used to determine when intervals must be reduced below 24 months. Factors to consider include structure type, design, materials, age, condition ratings, scour, environment, annual average daily traffic and annual average daily truck traffic, history of vehicle impact damage, loads and safe load capacity, and other known deficiencies. (B) Certain bridges meeting any of the following criteria as recorded in the National Bridge Inventory (NBI) (see 650.315) must be inspected at intervals not to exceed 12 months […]. (C) Where condition ratings are coded three (3) or less due to localized deficiencies, a special inspection limited to those deficiencies, as described in § 650.313(h), can be used to meet this requirement in lieu of a routine inspection. In such cases, a complete routine inspection must be conducted in accordance with paragraph (a)(1)(i) of this section. (iii) Extended intervals. (A) Certain bridges meeting all of the following criteria as recorded in the NBI (see 650.315) may be inspected at intervals not to exceed 48 months […]. (B) State transportation departments, Federal agencies, or Tribal governments that implement paragraph (a)(1)(iii)(A) of this section must develop and document an extended interval policy and must notify FHWA in writing prior to implementation. Factors to consider include structure type, design, materials, age, condition ratings, scour, environment, annual average daily traffic and annual average daily truck traffic, history of vehicle impact damage, loads and safe load capacity, and other known deficiencies.
(a2) Method 2. Inspection intervals are determined by a more rigorous assessment of risk to classify each bridge, or a group of bridges, into one of four categories, with inspection intervals not to exceed 12, 24, 48, or 72 months. The risk assessment process must be developed by a Risk Assessment Panel (RAP) and documented as a formal policy. The RAP must be comprised of not less than four people, at least two of which are professional engineers, with collective knowledge in bridge design, evaluation, inspection, maintenance, materials, and construction, and include the NBIS program manager. The policy and criteria which establishes intervals, including subsequent changes, must be

- *Underwater* inspections: every 60 months[24];
- *Fracture-critical member* – renamed *nonredundant steel tension member* [NTSM] as of 2022 inspections: every 24 months[25];
- *Damage, in-depth, and special* inspections: interval to be determined on a case-by-case basis[26].

---

submitted by the State transportation department, Federal agency, or Tribal government for FHWA approval […].
(3) Service inspection. A service inspection must be performed during the month midway between routine inspections when a risk-based, routine inspection interval exceeds 48 months.
(4) Additional routine inspection interval eligibility. Any new, rehabilitated, or structurally modified bridge must receive an initial inspection, be in service for 24 months, and receive its next routine inspection before being eligible for inspection intervals greater than 24 months.

[24] See § 650.311 Inspection interval of the NBIS [267].
(b) Underwater inspections. Each bridge must be inspected at regular intervals not to exceed the interval established using one of the risk-based methods outlined in paragraph (b1) or (b2) of this section.
(b1) Method 1. Inspection intervals are determined by a simplified assessment of risk to classify each bridge into one of three categories for an underwater inspection interval as described in this section. (i) Regular intervals […]. (ii) Reduced intervals […]. (iii) Extended intervals […].
(b2) Method 2. Inspection intervals are determined by a more rigorous assessment of risk. The policy and criteria which establishes intervals, including subsequent changes, must be submitted by the State transportation department, Federal agency, or Tribal government for FHWA approval. The process and criteria must be similar to that outlined in paragraph (a2) of this section except that each bridge must be classified into one of three risk categories with an underwater inspection interval not to exceed 24, 60, and 72 months.

[25] See § 650.311 Inspection interval of the NBIS [267].
(c) NSTM inspections. NSTMs must be inspected at regular intervals not to exceed the interval established using one of the risk-based methods outlined in paragraph (c1) or (c2) of this section.
(c1) Method 1. Inspection intervals are determined by a simplified assessment of risk to classify each bridge into one of three risk categories with an interval not to exceed 12, 24, or 48 months. (i) Regular intervals […]. (ii) Reduced intervals […]. (iii) Extended intervals […].
(c2) Method 2. Inspection intervals are determined by a more rigorous assessment of risk. The policy and criteria which establishes intervals, including subsequent changes must be submitted by the State transportation department, Federal agency, or Tribal government for FHWA approval. The process and criteria must be similar to that outlined in paragraph (a2) of this section except that each bridge must be classified into one of three risk categories with a NSTM inspection interval not to exceed 12, 24, or 48 months.

[26] See § 650.311 Inspection interval of the NBIS [267]. *(d) Damage, in-depth, and special inspections. A State transportation department, Federal agency, or Tribal government must document the criteria to determine the level and interval for these inspections in its bridge inspection policies and procedures.*

According to the U.S. Department of Transportation, most states require that bridge inspection personnel should be certified professional engineers. All inspectors must complete bridge inspection training, and most states require regular refresher training[27].

Most bridge inspections are conducted by two-person teams, although a few states allow individuals to inspect bridges. Bridge inspection teams can include a:

- *Program manager:* Is the individual in charge of bridge inspection, reporting and inventory documentation.
- *Team leader:* Is the person who oversees and inspection team and is responsible for planning, performing, and reporting field inspections.
- *Load rater:* The individual who assigns load ratings to bridges. A load rating is the determined live load carrying capacity of a bridge sing as – built bridge plans and information gathered from the latest field inspection.
- *Underwater inspection diver:* A diver or crew who performs underwater bridge inspections.

The procedures for inspections, therefore, include: at least one qualified team according to the specifications, which is on the bridge in all types of inspections; the assessment of each bridge according to its limit load capacity – set out in the AASHTO[28] Manual – and the drafting of reports with the up-to-date results of previous inspections and maintenance.

During a bridge inspection, an inspector will be looking for defects like cracking in the concrete, movement in the bridge that should not be present, or issues with bearings. Other signs of decay inspectors look for are rust, corrosion, or even paint loss, since theses indications of wear and tear could point to deeper structural issues that might have arisen with the passage of time. Electrical infrastructure is also a critical aspect to bridge inspections, but it can sometimes be under-emphasized, as inspectors focus primarily on fundamental structural issues. To

[27] See § 650.309 Qualifications of personnel of the NBIS [267].

[28] *American Association of Highway and Transportation Officials* (AASHTO) is a nonprofit association that represents highway and transportation departments across the nation and serves as a liaison between State departments of transportation and the Federal government. AASHTO works to educate the public and key decision makers about the critical role that transportation plays in securing a good quality of life and sound economy for our nation, by setting design and installation standards, providing guidance and resources, and developing outreach materials. ***AASHTO/FHWA Joint Implementation Agreement for Manual for Assessing Safety Hardware*** describes the roles that AASHTO, FHWA, and agencies will play with regards to implementing safety hardware.

incorporate electrical considerations into bridge inspections, inspectors should be on the lookout for broken or out-of-date wiring, damage to the support structure that attaches wiring or other utility infrastructure to the bridge, and any other signs of old or poorly executed repairs in the electrical infrastructure on the bridge.
Finally, according to the NBIS[29], there are five basic types of bridge inspections, which are performed via different methodologies and techniques[30]:

- *Initial inspection:* Is the first inspection to be completed on a bridge inspection. The purpose of this inspection is to provide all the structure inventory and appraisal data, to establish baseline structural conditions, and to identify and list any existing problems or any locations in the structure that may have potential problems. Is a fully documented investigation performed by persons meeting the required qualifications for inspection personnel and it must be accompanied by an analytical determination of load capacity. The first step of this inspection should be used to determine all structure inventory and appraisal data required by the Bridge Inspection Standards. The second important aspect of this inspection is the determination of baseline structural conditions and the identification and listing of any existing problems or locations in the structure.

[29] See § 650.313 Inspection procedure of the NBIS [267].

[30] The techniques employed for bridge inspections according to the NBIS are hereby listed. *Visual inspection*: This is the primary method used to perform routine bridge inspections, and tools for cleaning, probing, sounding and measuring, and visual aids are typically used.
Acoustic inspections: This relatively simple technique is performed by dragging a chain or tapping a hammer on the surface of a bridge while listening to changes in sound pitch; an experienced professional can use this type of test to detect delamination, coating separation, and whether the structure could be splitting into layers.
Thermal inspections: Thermal or infrared data can detect changes in infrared radiation from the surface of a bridge which could indicate degradation or delamination in the concrete.
Coring and chipping: This tactic involves drilling holes into the surface of a bridge to learn about the condition of the steel reinforcement, access corrosion damage, and investigate the physical and chemical properties of the concrete elements.
Ground-penetrating radar (GPR) inspection: This type of testing uses electromagnetic radiation to look below the concrete surfaces of bridges to detect issues like delamination, voids, and cracks.
Half-cell potential inspection: This non-invasive testing method checks the voltage between the steel reinforcement within the concrete and an electrode that is placed on the concrete surface to monitor corrosion levels. Local vibration testing and damage evaluation for RC Bridge Decks: Studies have demonstrated that the local resonant frequency decreases due to the internal cracks of the deck, so by performing measurements with the portable vibrator periodically it is possible to evaluate the rate of deterioration of the bridge deck.

- *Routine inspection:* This is a regularly scheduled periodic inspection consisting of sufficient observations and measurements to determine the physical and functional condition of the bridge and to identify and developing problems. The routine inspection must fully satisfy the requirements of the National Bridge Inspection Standards. These inspections are generally conducted from deck, ground, or water levels, and from permanent work platforms and walkways. For this inspection is necessary a special equipment and in circumstances where its use provides the only practical means of access to areas of the structure that are being monitored. All the results of a routine inspection are to be fully documented with appropriate photographs and a written report that includes any recommendations for maintenance or repair if necessary.
- *In-depth inspection:* This is a close-up, hands-on inspection of one or more parts of the bridge above or below the water level to detect any deficiencies mot readily visible using routine inspection procedures. In this inspection is necessary traffic control and special equipment and personnel with special skills such as divers and riggers. Depth inspection is different if we talk about small bridges or large structures. On small bridges the inspection should include all critical elements of the structure but for large and complex structures, this inspection may be schedules separately for defined segments of the bridge that can be efficiently addressed by the same inspection techniques. Like the other inspections, In-Depth inspection must be completely and carefully documented.
- *Damage inspection:* The damage inspection is an unscheduled inspection to assess structural damage resulting from environmental or man-inflicted causes. The scope of inspection must be sufficient to determine the need for emergency load restrictions or closure of the bridge to traffic and to assess the level of effort necessary to affect a repair. If major damage has occurred, inspector must evaluate fractured members, section loss, make measurements for misalignment of member and check for any loss of foundation support.
- *Special inspection:* This is an inspection scheduled by the individual in responsible charge of bridge inspection activities. Special inspection is used to monitor a particular known or suspected deficiency and can be performed by any qualified person familiar with the bridge and available to accommodate the assigned frequency of investigation. Unless in satisfaction of the NBIS qualification requirements for inspection personnel, the individual performing an Interim Inspection must be carefully instructed regarding the

nature of the known deficiency and its functional relationship to satisfactory bridge performance. In this circumstance, guidelines, and procedures on what to observe and measure must be provided and a timely process to interpret the field results must be in place.

Spanish inspection protocols

In Spain, inspections are intended as the set of technical actions carried out following a previously established plan, in which all the necessary data are provided to know at a specific moment the state of conservation of a bridge.
Bridge inspections are carried out according to the *General Directorate of Roads*[31] of the *Ministry of Public Works*[32] recommendations, within the framework of the implemented Management System of road works, which allows:

- The estimation of the condition of the crossing works by means of the results obtained in the basic and main inspections.
- The establishment of repair priorities, functionality, traffic, the importance of the route depending on the place where the structure is located, its historical value, etc.
- The definition of the different repair alternatives with their cost, considering the magnitude of the damage and the accessibility circumstances in which the repair must be carried out.
- The control and follow-up of the action programs.

It is important to know that the inspection is not limited only to the bridge itself but is also based on the infrastructure or even on other structures or annexed elements whose state of conversation may have an impact on its functionality and durability.
The document establishes different levels of inspection that differ in intensity, frequency and human and material means used for their performance. Therefore, the different maintenance and conservation operations are determined according to

[31] The *General Directorate of Roads* [DGC – in Spanish *Dirección General de Carreteras*] of Spain is the governing body dependent on the General Secretariat of Infrastructures of the Ministry of Transport, Mobility and Urban Agenda whose scope of action is the State Roads Network.

[32] The *Ministry of Public Works* [MFOM – *Ministerio de Fomento*] in Spain was the ministerial department in charge of proposing and executing government policy in the fields of land, air and maritime transport infrastructures, as well as their control, organization, and administrative regulation. It was active between 1996 and 2020 when, with the same functions, it was renamed *Ministry of Transport, Mobility and Urban Agenda* [*Ministerio de Transportes, Movilidad y Agenda Urbana*].

the needs of the structure and always coordinating these actions at the level of the State Road Network.
According to the guide for carrying out main inspections of road works on the ***Red de Carreteras del Estado***[33], it is possible to quantify the state of conservation of the infrastructures, considering the following aspects:

- Intensity of the type of damage of the observed elements.
- Extent and evolution of the type of damage of the elements observed.
- The type of damage and its effect on the safety and durability of the element.

These aspects are evaluated, by means of a *Deterioration Index* that marks the range with which the deterioration of the infrastructures is evaluated according to this Guide [80]:

- *Index between 0 and 20:* Deterioration without significant a-priori consequences.
- *Index between 21 and 40:* Deterioration that can have a pathological evolution or reduce the service conditions or durability of the element if it is not repaired in due time.
- *Index between 41 and 60:* Deterioration that may have a pathology that implies a reduction of the service conditions or the durability of the element.
- *Index between 61 and 80:* Deterioration that may result in a modification of the resistant or functional behavior.
- *Index between 81 and 100:* Deterioration that compromises the safety of the element.

In addition, there is also an index for the evaluation of the State or Condition of the Structure, which allows prioritizing actions according to the urgency and severity of the deterioration observed:

- *Index between 0 and 20:* Structure without evident pathologies or with deteriorations without relevant consequences for the durability, service conditions or safety of the structure.
- *Index between 21 and 40:* Structure with deteriorations that may have a pathological evolution affecting the durability or service conditions of the structure. It is convenient to follow its temporal evolution for its objective determination.

[33] Guía de inspecciones básicas de obras de paso – Red de carreteras del estado issued by the Ministerio de Fomento [80].

- *Index between 41 and 60:* Structure with deteriorations that evidence a pathology that can suppose a reduction of the service conditions or the durability of the structure. It will be necessary to follow the evolution of the pathology in subsequent inspections. It may require action in the medium term to improve the durability of the structure.
- *Index between 61 and 80:* Structure with deterioration or pathologies that may result in a modification of the resistant behavior or a significant reduction of the service levels. It requires a short-medium term action. Depending on the nature of the damage, a special inspection may be required.
- *Index between 81 and 100:* Structure with deterioration or pathologies that compromise the safety of the element/structure. Requires special inspection and urgent action. In some cases, a limitation of use may be necessary.

Furthermore, according to the ***Guía de inspecciones básicas de obras de paso de la Red de Carreteras del Estado*** [80], there are three types of Inspections: basic or routine inspections, main inspection, and special inspection.

A *basic inspection* is a visual inspection conducted by non-specialized personnel whose purpose is to detect deterioration early and prevent it from degenerating into serious deterioration, as well as to locate damage in need of urgent repair.
The basic inspection is the basis of infrastructure maintenance and is usually carried out by road maintenance and surveillance personnel, who improve this task in those cases where they are provided with adequate training and a manual to identify bridge deficiencies.
Regarding the frequency with which this type of inspection should be carried out, frequency of 15 months is established.

A *Principal inspection* is a thorough visual inspection of all the elements of the bridge. This type of inspection must be executed by specialized personnel under the supervision of an engineer.
The Inspection Guide recommends that the first main inspection, called Zero Inspection, be carried out before the bridge is put into service. This will serve as a reference to determine the evolution of deterioration. The main inspections are performed by means of a series of simple auxiliary elements including ladders, hammers, plumb bobs, tape measures and all types of optical devices.
As for the frequency of the main inspections, the Guide establishes it at approximately 5 years, although it points out that the periodicity will be indicated

in the maintenance plan of the bridge and some authors claim that the frequency of this type of inspections should be reconsidered after each inspection.
The planning established for this type of inspections is as follows:

- Collection of the existing documentation of the bridge to be inspected and of the actions carried out on the bridge after its construction, such as previous inspections, maintenance operations or repairs carried out.
- Study of the documentation obtained and preparation of the Inspection Cards, which are specific for each of the elements of the bridge and have to be prepared before the field work.
- Analysis and preparation of the auxiliary means necessary to correctly carry out the inspections of all the elements of the bridge.

Within the main inspections, the Inspection Guide identifies a particular type, called *Detailed Inspection*. This type of inspection should be applied to a relatively small set of bridges with characteristics such as: large structures with a high percentage of uninspected elements after an inspection without special means of access, structures with singular elements without direct visual access, etc. Moreover, detailed inspections require extraordinary access means[34], such as bridge inspection walkways, which guarantee the possibility of inspecting all visible parts.
What differentiates this type of inspection from the Special Inspections that we will see below is that in Detailed Inspections, no tests or complementary measurements are taken, nor are repair projects carried out.
Eventually, *special inspections* are not carried out systematically or periodically, as opposed to the others, whereby the need to carry them out arises because of

[34] The auxiliary means required by the Guide for the main inspections of road works to facilitate the access of the inspecting personnel to the different parts of the structure – to perform a detailed Inspection – are listed as follows.
Operating under the bridge may require lifting platforms, cranes with buckets, whose limitations are due to the height of piers, accessibility, and availability of use of the area under the bridge (watercourses, roads, etc.) and the atmospheric conditions (wind).
Operating on the board requires walkways, articulated buckets, whose use may be restricted due to the deck dimensions (total width and width of sidewalks, edges), existence of conditioning elements on the platform (pendulums, suspenders, lampposts, anti-noise barriers), traffic restrictions on the bridge and the atmospheric conditions (wind).
Operating from any other location employs work at height equipment, which can be restricted by electrical installations and atmospheric conditions (wind).
Operating from the watercourse make it necessary to use boats, pontoons, diving equipment, limited by speed of the watercourse, visibility of the foundation, and water turbidity.
Lastly, *operation integrated in the structure* requires manholes (access to hollow piles and box girders), ladders, anchorages for fastening scaffolding or platforms, which most of the time need to be forecast in the project design and are applicable only to certain bridge typologies.

damage detected in a main inspection or, exceptionally, as a consequence of a particular situation, such as a vehicle impact, a flood or any other natural disaster.
According to the Spanish Inspection Guide, in this type of inspections, in addition to a visual examination, characterization tests, and complementary measurements are required. For this level of reconnaissance, a plan is required prior to the inspection, detailing, and evaluating the aspects to be studied, as well as the techniques and means to be used. Normally, this type of inspections result in rehabilitation, repair or reinforcement works that require the drafting of a damage characterization and evaluation report or a repair project. Therefore, these inspections necessarily involve the presence of special technicians and equipment.

Argentinian inspection protocols

Regarding the monitoring and surveillance of existing artworks, Argentina employs a *Bridge Management System* [SGP – *Sistema de Gestión de Puentes*], whose instruction manual was designed by the National University of Córdoba [UNC - *Universidad Nacional de Córdoba*] for the maintenance of the *National Road Network* [RVN – *Red Vial Nacional*] belonging to the *National Road Direction* [DNV – *Dirección Nacional de Vialidad*].
The *National Road Direction* did not have a systematic plan or *ad hoc* tools for the maintenance of major works (bridges). Indeed, the issue started to be treated seriously from the 1970s onwards, when the 1970s, when the so-called *Great Bridges* were opened to traffic. Subsequently, in 1987, a working group was formed to attend to bridge maintenance, an entity that later became the *Bridge Maintenance Division* [*Division de Mantenimiento de Puentes*], which functioned within the orbit of the *General Directorate of Conservation* [DGC]; to become, in 1990, the *Road Emergencies Division* [DEV – *División Emergencias Viales*]. The actions carried out in these units were always of a *reactive* type, i.e., the damage was repaired once it caused problems in the provision of the work. In 1999, the Bridge and *Viaduct Sub-Management* [SPV – *Subgerencia de Puentes y Viaductos*] was created and the Bridge Maintenance Division was implemented again. Then a management system was promoted but did not prosper because the *International Bank for Reconstruction and Development* [BRIF – *Banco Internacional de Reconstrucción y Fomento*], the financial agent of this initiative, considered the contracting to be inconvenient, after several changes to the original project. There were also some isolated initiatives, generated by the provincial or regional jurisdictions of the DNV, which did not materialise due to the lack of formalisation of the functions and tasks involved in the management of bridges at different levels. This past situation clearly showed a lack of a systemic policy for bridge

maintenance. In the meantime, the concerns expressed by the BRIF and the financing offered by this entity allowed the signing of a first agreement between the DNV and the National University of Cordoba [UNC], as a result of which several products were generated during the period 2005-2006, including the first version of a management software. In September 2006, the official presentation of these products took place, together with the ***Guidelines for a Pilot Stage for the Implementation of Bridge Maintenance Management.*** The so-called Pilot Phase was implemented in the northwest region of the country, made up of the provinces of Tucumán, Salta, Jujuy, Catamarca, La Rioja, Santiago del Estero and Formosa, since October 2006 [81].

This manual designed by the UNC also outlines the computer system that constitutes the SGP, called SIGMA [*Sistema Integral de Gerenciamiento y Mantenimiento Argentino*] Puentes, which is composed of a series of modules with interrelated targets and through which information is organised. The proposed SGP makes it possible to maintain an up-to-date computerised database by means of periodic and special inspection reports carried out on the bridges of the National Road Network [RVN]. The system also shows the state of preservation and functioning of the inventoried and surveyed bridges through a classification system that allows prioritising the bridges in the RVN so to keep track of possible future replacement, repair, or maintenance works.

The main result of SIGMA puentes is to establish a priority order for the execution of these works. For this purpose, it is divided into a series of modules encompassing different activities such as sorting and systematisation of the information of the bridges of the RVN in a database; the information is obtained from inspections (periodic or special), generating a form that will be studied by an engineer specialised in bridges, external to SIGMA, who will assess the component state of the bridge and then inform SIGMA of the results for subsequent processing of the information received and assign a global classification of the structural and operational state of the bridge. Afterwards, another agent external to SIGMA, a specialist in cost estimation, will have to translate the global classification of the bridge into repair and maintenance costs. Lastly, an order of priority will be established for the execution of this work according to the characteristics of the bridge and other aspects related to road safety, hydraulic and environmental vulnerability and other geopolitical factors.

The SGP developed contemplates three categories of inspections: Initial Inspection, Preliminary Inspection, and Detailed Inspection.

- *Initial Inspection* is the first visit, oriented to survey the bridge and complete the inventory with all the data that have not been provided by the information in the documentation and the bridge's history.
- *Preliminary Inspection* is aimed to survey the state of the bridge at a given time, paying attention to three fundamental aspects: structure, hydraulics and boulevard safety. It is carried out by means of a survey form designed to document the state of preservation of the most important structural components (structural aspect), the characteristics of the implementation site (hydraulic aspect) and the road characteristics of the bridge (road safety aspect).
- *Detailed Inspection* is carried out when, after the Preliminary Inspection, the bridge's classification indicates the need to carry out a more detailed inspection to obtain additional information, e.g., to better understand the bridge structure or its hydraulic characteristics.

Conservation teams are in charge of carrying out periodic maintenance work, detailed in the instruction manual, such as: cleaning the water channel; removing accumulated debris, perform local repairing of the deck, cleaning joints, painting railings, cleaning drains and support devices, etc. The performance or the absence of these works will then be shown in the preliminary inspections. Conservation work has to be carried out by the DNV, in the case of bridges belonging to national highways, and by provincial authorities, in the case of provincial roads. Anyhow, some works may also exceed the periodic maintenance works of the bridge, such as widening the deck to meet minimum traffic widths, reinforcing the piers, installing guardrails, among others, and so on to be determined on a case-by-case basis.

This international reference framework was, therefore, compared with the Italian regulatory framework reported below, for this comparison to highlight advantages and disadvantages as well as descriptive requirements of the development of shared information models. These peculiarities thus become useful in configuring the models as potential places for dialogue within the most open, interoperable, and culturally accessible information systems.

4.2 Evolution of the Italian regulation for Bridge inspection

The Italian corpus of legislation relating to the maintenance and inspection of road works consists of several ministerial decrees and circulars that have been issued over time. The milestones of this evolution are therefore listed below, culminating with the issuing of ***Guidelines for the Risk Classification and Management, Safety Assessment and Monitoring of Existing Bridges*** [4] and the development of the *Information Archive of Public Structures* [AINOP – *Archivio Informativo delle Opere Pubbliche*] [82].

Circular of the Ministry of Public Works No. 6736/61/A1 of the 19th of July 1967 - *Control of the stability conditions of road works* [83]

Following the tragic events that occurred in Ariccia in 1967, the need arose to functionally organise periodic inspections to assess the stability conditions of road works and check their state of the art in order to maintain their efficiency. To this end, the *Circular of the Ministry of Public Works of the 19th of July 1967 No. 6736/61/AI – Control of the stability conditions of road works* was issued. It was intended to focus attention on the need for a systematic surveillance plan. The rules for the inspection are thus established; it may be carried out either at intervals of about one year and conducted by engineers assigned to the zone or section, or at least every three months, in which case it must be conducted by engineers assigned to the zone or section. The inspection personnel must pay particular attention to any injuries or premonitory signs of subsidence, or incipient collapse, present on the visible structure (piers, pillars, ribs, slabs, etc.). If required, extraordinary checks on the static condition of the structures must be carried out by area or trunk engineers. The responsibility and organisation of the control service will fall to the municipal technical offices for municipal roads, to the technical offices of the Provincial Administrations for relevant roads, to the ANAS Departments for state roads, to the concessionary companies for concessionary roads and motorways. Finally, the *Civil Engineering Offices* [*Uffici del Genio Civile*] will have the task of occasionally verifying the planning and organisation of municipal and provincial control services, while it will be ANAS's task to verify that of the concessionary companies.

Circular of the Ministry of Public Works No. 34233 of the 25th of February 1991 – law no. 64 of 2 February 1974 – art. 1 ministerial decree 4 May 1990 – *Instructions relating to the technical regulation of road bridges* [84]

By a decree issued by the Ministry of Public Works, in agreement with the Minister of the Interior, new technical standards for the design, execution and testing of bridges are issued. In order to facilitate the application of these standards, instructions divided into 9 paragraphs are developed.

For existing bridges, paragraph 9 of the aforementioned instructions, *Management of road bridges*, states that *"it is the task of the entities proposed to manage the roads at the various existing levels and the competent Technical Offices to acquire knowledge of the characteristics of the works, paying particular attention to the state of the bridges, the reclassification of the roads, the increase in traffic loads"* [84].

The management system is based on the following points:

- *Supervision* [§ 9.2]: carried out at a predetermined frequency and with the task of detecting any external anomalies (cracks, anomalous deformations, exposed reinforcement, relative displacements, ground movements). The personnel in charge must report everything to the office they report to, which may order any inspections or checks depending on the importance of the anomaly detected.
- *Inspections* [§ 9.3]: aimed at ascertaining the stability conditions of the road works, as well as the state of conservation of the structures themselves and their accessory parts. The outcome of the inspections will be recorded on a specific report and, where necessary, the appointed technician will identify maintenance operations.
- *Maintenance* [§ 9.4]: is the complex of operations necessary to maintain the work in full efficiency, respecting its original characteristics. It is divided into ordinary and extraordinary. In the former, the superficial repair of structural parts, waterproofing and flooring, and the replacement and cleaning of accessory parts are carried out. In the second, the structural parts are repaired, expansion joints are replaced, work is carried out on supports and restraining devices, etc.
- *Static restoration, adaptation, restructuring* [§ 9.5]: Static restoration consist of the complex of interventions aimed at restoring the original load-bearing capacity of a deteriorated bridge. Adaptation means the complex of interventions that, in substantial respect of the original geometry and static scheme, enable the structure to withstand actions greater than or different

from those of the original project. Finally, restructuring is understood as the set of interventions aimed at restoring or even increasing the load-bearing capacity, interventions involving, however, a modification of the geometric characteristics (e.g., widening of the roadway) or of the original static scheme of the work. A complete project must be prepared that takes into account the existing structure and the future static layout. At the end of the interventions, the work will be subject to static testing according to the technical standards.

Ministerial Decree of 17th of January 2018 – *Update of the New Technical Standards for Construction* [85] and Ministerial Circular of 21st of January 2019 – *Instructions for the application of the Update of the "Technical Standards for Construction" referred to in the Ministerial Decree of 17 January 2018* [86]

Finally, we come to the Ministerial Decree of 14/01/2008 [87], ***Technical Standards for Construction*** [NTC2008], updated by the Ministerial Decree of 2018 [85] and the Ministerial Circular of 2019 [86].

Chapter 8 of the NTC2018 concerns Existing Constructions, referring to all works (only the Explanatory Circular dedicates a brief sub-chapter to bridges), and defines aspects concerning safety assessment, classification of interventions and definition of the reference model for analyses.

With regard to the safety assessment and the design of interventions [§ 8.2]: the standards in force at the time of the realisation of the work and the available construction techniques, any design and construction errors, and the actual state of the work itself must be taken into account.

In the definition of structural models, on the other hand, according to the level of knowledge, it will be necessary to understand the geometry and construction details, the mechanical properties of materials and soils, and the permanent loads.

Furthermore, the implementation of analysis and verification methods according to the available information and the use of coefficients associated with *confidence factors*, with which the capacity parameters are modified according to the level of knowledge, must be established.

Interventions are classified into the following categories [§ 8.4]:

- *Repair or local interventions*: all those interventions which do not significantly modify the global behaviour of the structure – but which increase the safety level of at least a part of it – fall into this category. They are carried out to achieve one or more of these objectives: favouring the development of ductile mechanisms, thus avoiding the formation of fragile mechanisms; improving the ductility of elements or parts, even if not damaged; reinforcing or replacing damaged elements and parts; modifying a limited part of the structure, provided that there is no significant change in stiffness, resistance to horizontal actions and deformation capacity of the structure.

- *Improvement interventions*: this category includes all interventions that can bring about changes in the local or global structural behaviour, also introducing new structural elements.
- *Adaptation interventions*: for this category of interventions the safety assessment is compulsory, with the aim of establishing whether the structure, following the intervention, is able to resist the expected combinations of design actions.

Only the last two types of intervention are subject to static testing.
The phases of the reference model for the analyses are summarised below [§ 8.5]:

- *Historical-Critical Analysis:* the objective is *"to understand the construction events, the instabilities, the deterioration phenomena, the stresses suffered by the building and, particularly frequent in masonry constructions, the transformations brought about by man that may have produced changes in the original static structure"*. Therefore, through available documentation, data is sought on the design and construction process, the period of construction with the relative techniques and regulations in use at the time, the subsequent modifications undergone, and the events that have affected it.
- *Survey:* this must certify the actual state of the work, identify the resistant organism, the quality and state of conservation of the materials, and also detect any instability in progress or stabilised, with particular attention to the cracking frameworks and damage mechanisms. Subsequent alterations suffered over the years, attested in the Historical-Critical Analysis stage, must be represented in this phase.
- *Material tests:* in order to achieve adequate knowledge of the characteristics of the materials and their degradation, available documentation, visual inspections in situ, and experimental investigations will be used.
- *Structural Modelling and Analysis:* for the structural model, the indications of Chapter 7 of the NTC apply. As far as structural analysis is concerned, it may be of the linear or non-linear type.
- *Verification Criteria.*

The first three steps are crucial for the achievement of a good *Knowledge Level* [LC - *Livello di Conoscenza*] of the construction, thus defining the associated confidence factors to be used in the strength checks. It should be remembered that there are three Levels of Knowledge provided for by the Standard, arranged in order of increasing depth.
While the phases set out by the NTC2018 make it possible to reach a sufficiently in-depth level of knowledge, on the other hand they take a long time and allow only the safety level of the individual work to be assessed. Finally, *Finite Element Modelling* [FEM] alone does not allow some of the damage affecting the structure to be taken into account [69].

Guidelines for the Risk Classification and Management, Safety Assessment and Monitoring of Existing Bridges – Annexed to the opinion of the Superior Council of Public Works no. 88/2019 [4]

As mentioned in the previous paragraph, the management and maintenance of existing road infrastructures is not easy. Among the various causes, there is the presence of a very high number of bridges and viaducts, which makes it impossible, in terms of human, time and economic resources, to accurately assess the risk status of the infrastructures themselves. In addition, the lack of a uniform risk management system throughout the country has led the *Higher Council for Public Works* [C.S.LL.PP. – *Consiglio Superiore Lavori Pubblici*] to establish, in 2019, a commission of experts to draw up a ministerial guideline aimed at defining and standardising the criteria for monitoring, assessing structural safety, and classifying the risk of existing bridges.
In order to proceed with the drafting of the Guidelines, three working subgroups and their respective coordinators were set up:

- *Subgroup 1 Census and Risk Classification:* whose coordinator was Professor Eng. Pietro Baratono.
- *Subgroup 2 Safety verification methods:* whose coordinator was Professor Eng. Edoardo Cosenza.
- *Subgroup 3 Indications on monitoring:* whose coordinator was Professor Eng. Andrea Del Grosso.

On 6 May 2020, the Ministry of Infrastructure and Transport released the Guidelines for the classification and management of risk, safety assessment and monitoring of existing bridges, viaducts, embankments, overpasses and similar works, with reference to road bridges and viaducts, where these are defined as *"constructions, with an overall span of more than 6.0 m, which allow the crossing*

of a depression in the ground or an obstacle, whether it be a course or sheet of water, another channel or communication route or a natural or artificial discontinuity" [4]. The guidelines represent a supplement to the current standards on the specific topic; in particular, they are consistent with the provisions of the Technical Standards for Construction [85] and its implementing Circular [86].
These Guidelines, introducing the use of a multilevel and multi-objective procedure for the risk management of existing bridges and defining the surveillance and monitoring activities, shall be subject to an experimental activity carried out for a period not exceeding twenty-four months, starting from the effectiveness of the decree, conducted by the Competence Centre of the Civil Protection Department, ReLUIS Inter-University Consortium [*Centro di competenza del Dipartimento della protezione civile, Consorzio interuniversitario ReLUIS*] [88].

***Information Archive of Public Structures* [AINOP – *Archivio Informativo delle Opere Pubbliche*]** [82]

Following the collapse of the Polcevera viaduct on the A10 Motorway in the Municipality of Genoa, the Law Decree no. 109 of 28/09/2018 was issued, containing ***Urgent measures for the city of Genoa, the safety of the national infrastructure and transport network, the seismic events of 2016 and 2017, work and other emergencies*** [89].
Among the dispositions taken there is the creation within the Ministry of Transport of the *National Information Archive of Public Structures* [AINOP – *Archivio Informativo delle Opere Pubbliche*), listed in Art. 13 of the aforementioned decree.
On 8 October 2019, Minister of Infrastructure and Transport Paola De Micheli signed Ministerial Decree No. 430 [82], which defines the modalities through which the subjects mentioned in Art. 13, comma 4 of DL 109/2018 [89], must make accessible their respective information services regarding public works for the sharing of data and information within the AINOP.
In particular, Art. 2 of DM 430/2109 defines the input procedures for the National Archive and the phases and timeframes within which the sharing of data and information must take place. In Art. 3, a permanent *Technical Table* is set up to coordinate the process and the *feeding* procedures for the AINOP, guaranteeing compliance with the timeframes set by Art. 2.
This archive was created in order to guarantee a constant monitoring of the state and the degree of efficiency of public assets through the constitution of a single database of the existing structures pertaining to the central and peripheral Administrations of the State, the Regions, the local authorities, and all the Italian

municipalities. This database is then divided into sections corresponding to the categories of structures being monitored, listed as follows:

- Bridges, viaducts and road overpasses;
- Railway bridges, viaducts and overpasses;
- Roads - national roads archive [ANS];
- National and regional railways - metros;
- Airports;
- Dams and aqueducts;
- Railway tunnels and road tunnels;
- Ports and port infrastructures;
- Public buildings.

Furthermore, these sections must be broken down into subsections, in which the following information must be included for each asset:

- the technical, design and location data with the historical analysis of the context and territorial evolutions;
- the administrative-economic data referring to the costs incurred and to be incurred;
- the data on the management of the structure also in terms of safety;
- the state and degree of efficiency of the work and the ordinary and extraordinary maintenance activities;
- the location of the work with respect to the European classification;
- the funding;
- the state of the works;
- updated documentation;
- the constant monitoring of the state of the structure;
- the geographical information system.

The information and documents inherent to the works contained in the AINOP will be organised in a *virtual file of the asset* that will allow an overall assessment of the safety level of the structures, also providing a greater control of the Public Structure during their entire life cycle; so as to enable simpler and more rapid planning of requalification or maintenance interventions and of their priority level.
An identification document will be drawn up for all the structures on the national territory, in which the technical, administrative and accounting data relating to the same works will be included. As stated in Art. 13, comma 4, this document will be developed starting from the data held by the Regions, Autonomous Provinces of

Trento and Bolzano, local authorities, ANAS, Rete Ferroviaria Italiana S.p.A, the motorway concessionaires, the derivation concessionaires, the Interregional Superintendencies for Public Works, the National Civil Aviation Authority, the Port and Logistics System Authorities, the State Property Agency and the subjects that in any capacity manage or hold data referring to a public structure or to the execution of public works.

On the basis of this data set, the AINOP will also generate an identification code of the individual structure [IOP – *Identificativo Opera Pubblica*] *"which uniquely distinguishes and identifies the asset, reporting its essential and distinctive characteristics such as the type, location, year of commissioning and the inclusion of the work in the structure"* [89].

The IOP code, which represents a sort of *tax code* of the public artwork and is expected to remain unique for the entire life of the structure itself (Figure 4.1), is automatically generated through an algorithm that elaborates the essential and distinctive characteristics of the asset itself.

The IOP code is composed of 18 alphanumeric characters:

- the first eight correspond to the location of the structure – the first two characters are alphabetical and indicate the type of structure to which the asset belongs; the following six characters are alphanumerical and indicate, instead, the name of the structure itself;
- the following two characters correspond to the type of coded structure;
- the last eight are, instead, a random alphanumeric code uniquely assigned to each public structure.

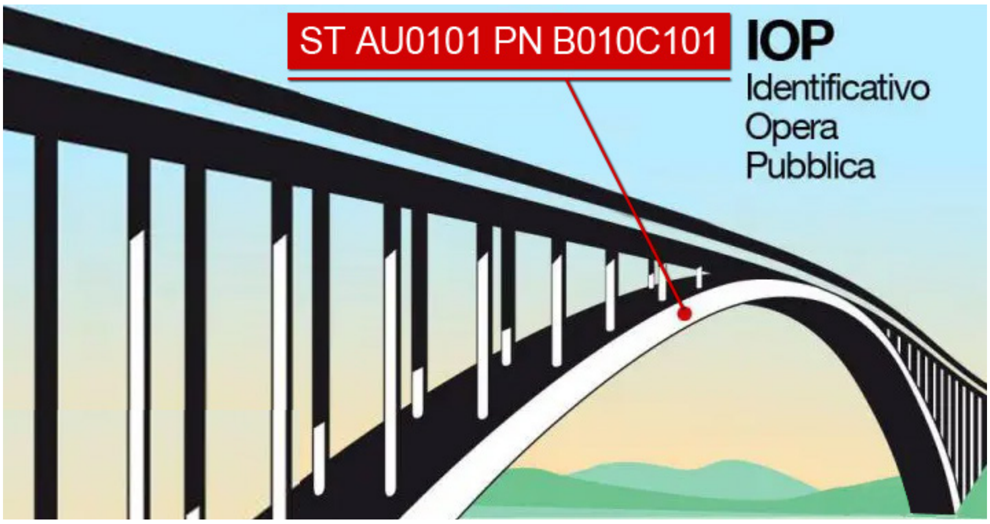


Figure 4.1 – Example of the IOP: public structures identification code [90] **– [MbA]**

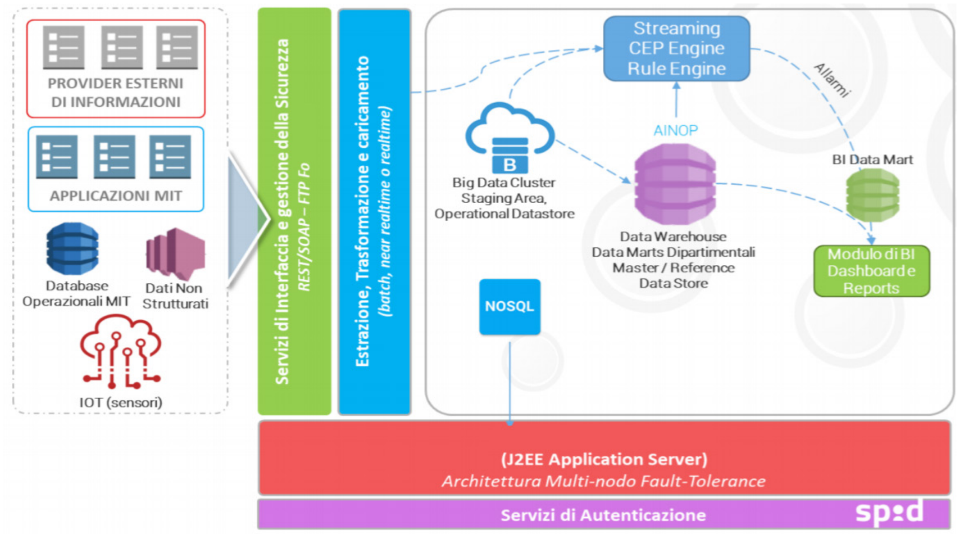


Figure 4.2 – Schematisation of the AINOP filing system [91]

According to ANCI [Associazione Nazionale Comuni Italiani] and the Italian Ministry of Infrastructure and Transport [MIT – Ministero delle Infrastrutture e dei Trasporti]: *"The data ingested by the system and coming from external information providers or from structures of the MIT itself, can be of a structural or non-structural type (e.g., documents); these data are entered through different channels, to then be checked, analysed and entered into what is defined as the Data Lake of public works, which allows large quantities of data from many different sources to be archived. Most importantly, the person accessing the AINOP archive will identify himself through the SPID authentication service"* [91].

The AINOP feeding modalities include three channels, as shown below (Figure 4.3), with increasing interaction complexity: manual entry, entry from CSV files, and web services [91].

The structure of the registry files (Figure 4.4) is, therefore, of the inverse pyramid type and is composed of the following data [91]:

- *IOP File*: contains the data common to all structures (e.g., type, location, etc.), after which the IOP is generated (Figure 4.5);
- *Basic register information*: contains the detailed structured data common to all structures, such as, for example, the territory to which they belong (Figure 4.6);
- *Specific register data*: contains the specific structured data for each structure (e.g. in the case of ports, the number of quays, in the case of airports, the number and detail of runways – Figure 4.7);

- *Extended register data*: contains structured and unstructured data (documents, images, videos) pertinent to the history and life of the structure itself (Figure 4.8).

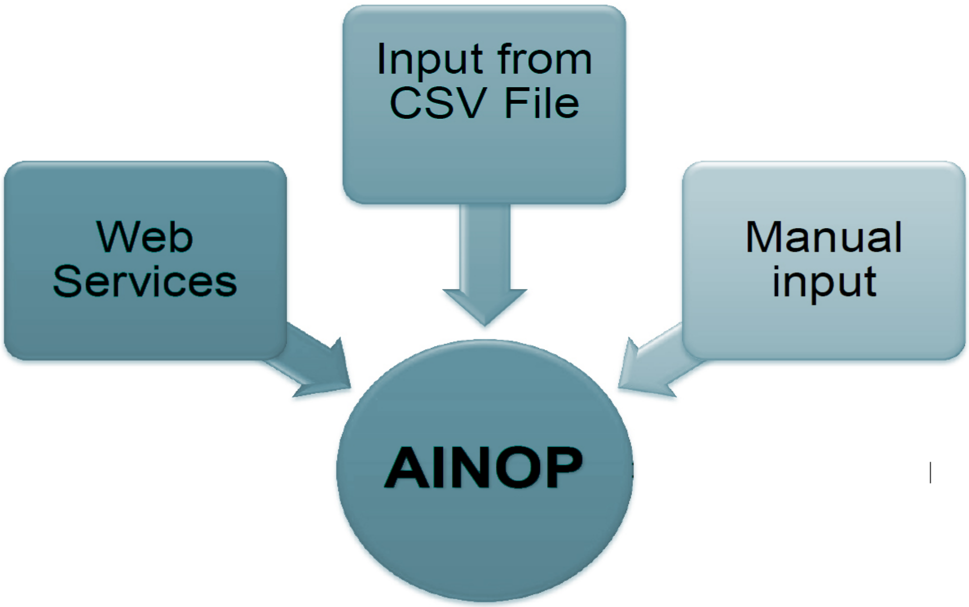


Figure 4.3 – AINOP *feeding* modality [91] **[MbA]**

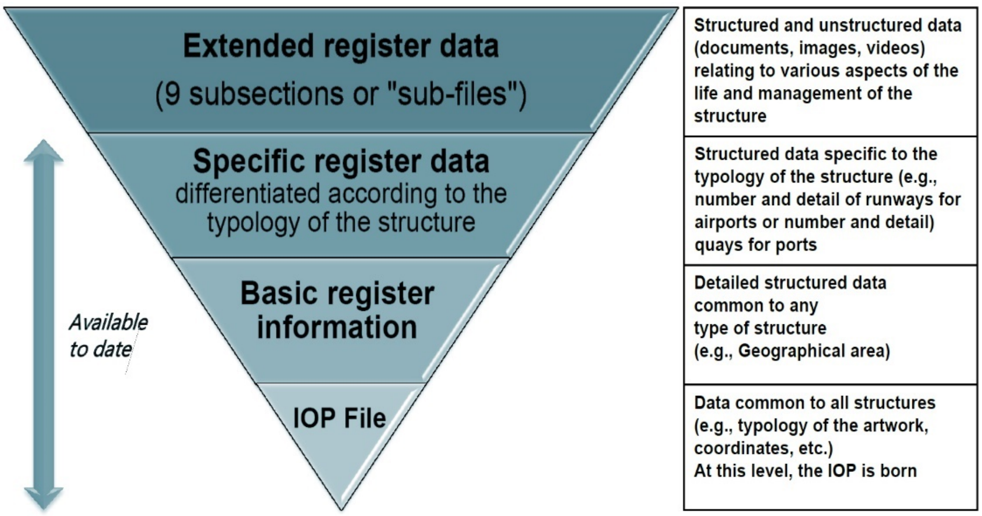


Figure 4.4 – Pyramidal data organisation of the AINOP database [91] **[MbA]**

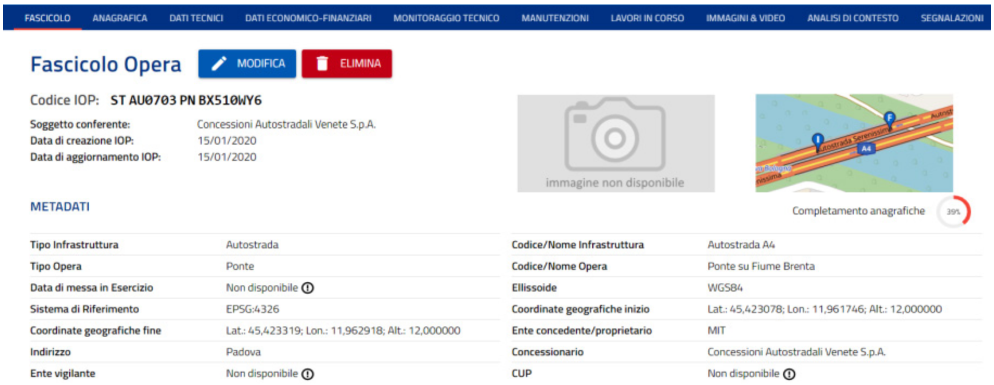


Figure 4.5 – Asset file form [91]

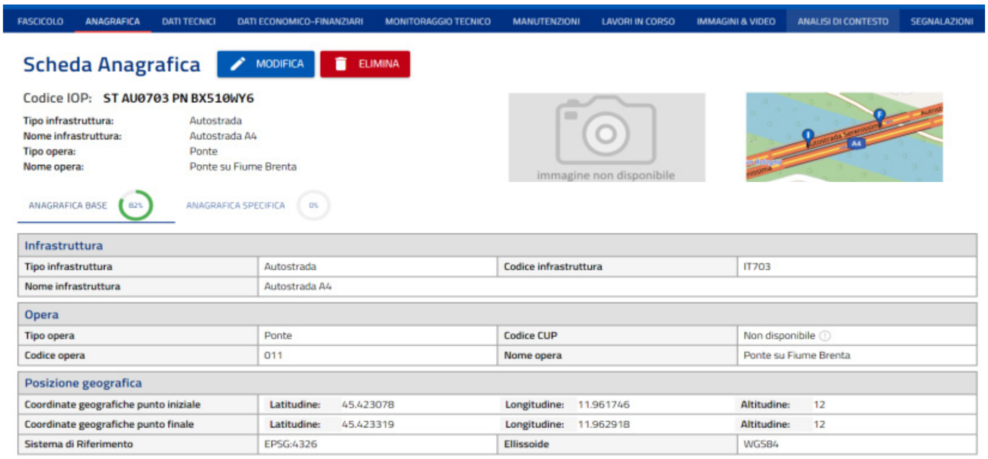


Figure 4.6 – Basic register data form [91]

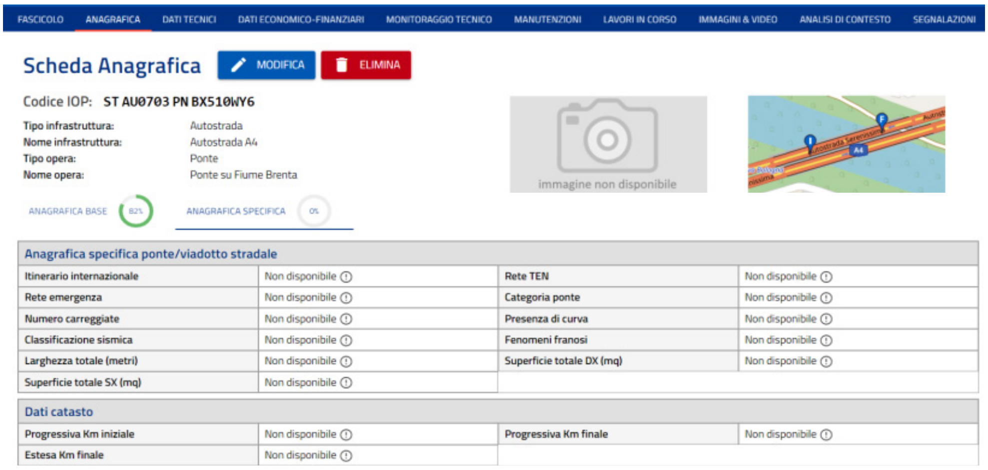


Figure 4.7 – Specific register data form [91]

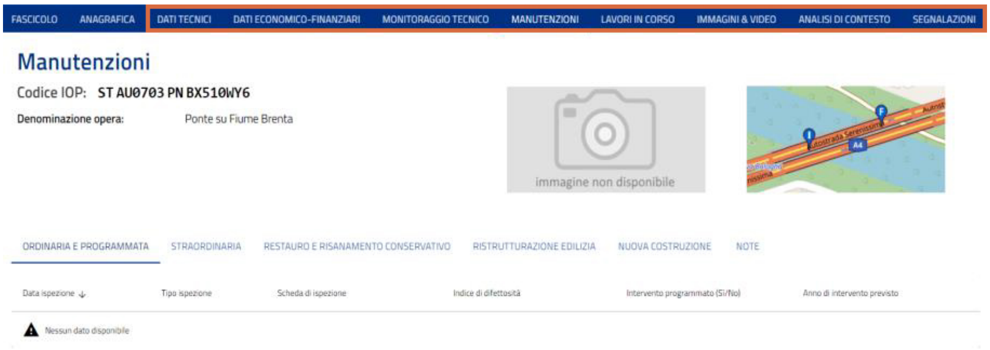


Figure 4.8 – Extended register data form [91]

Through the platform, it is, therefore, possible to identify a structure and its location in the territorial context; bring together all the data and information present in the various subsidiary and competing public archives; visualise data, information and documents of the asset, structured in a sort of virtual dossier; receive information that will allow the technical monitoring of the asset, with a view to preventing criticalities, also through intelligent alert systems on the state of the structure; identify possible workflows to make the design, implementation, maintenance and management of the structure efficient [91].

4.3 Inspection levels

The ***Guidelines for the Risk Classification and Management, Safety Assessment and Monitoring of Existing Bridges***, also called ***LG20***, propose a *so-called risk-based – Attention Class-dependent –* procedure for risk management of existing bridges. The topics covered are divided into three main macro-themes:

- *Part I*: census of the infrastructures, visual inspections and compilation of defect forms, analysis of the risks detected and classification on a territorial scale, and preliminary assessment of the asset;
- *Part II*: thorough inspection;
- *Part III*: surveillance and monitoring system.

The multilevel approach followed makes it possible to move from an assessment on a Territorial Scale, applicable to all bridges – which includes the census of the structures, visual inspections, and evaluation of the attention classes – to a more in-depth assessment on a limited number of bridges which includes the analysis of safety, risk, and resilience [92]. Indispensable to this end is the definition of *"progressive levels of in-depth knowledge of the artwork and the infrastructure network according to the criticality level of the artwork itself"* [69].

Thus, the system makes it possible to quickly identify road infrastructure to be prioritised for intervention to be undertaken, thus ensuring savings in terms of human, economic and time resources.

The approach is developed on 6 Levels (from 0 to 5), with increasing complexity, level of detail and onerousness in surveys and analyses (Figure 4.9).

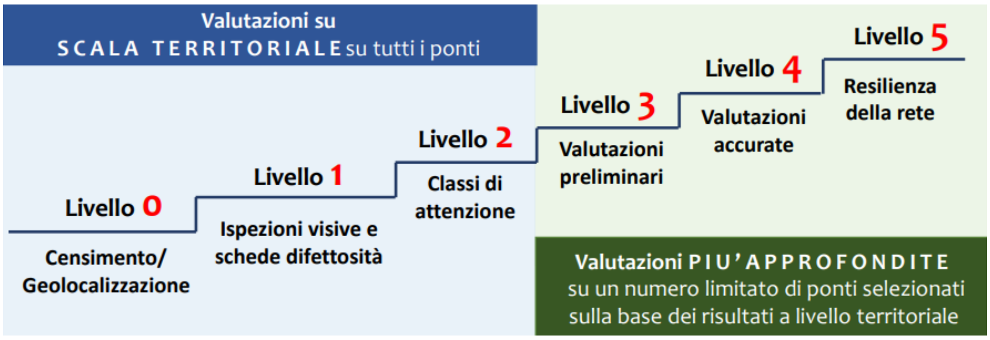


Figure 4.9 – Inspection levels proposed by the LG20 [92]

Level 0 – Census of the infrastructures

"The census of bridges envisaged by Level 0 of the multilevel approach consists in cataloguing all the structures on the territory, in order to know the number of structures to be managed and their main characteristics, both in relation to geometry and structural components, as well as with regard to the road network and the site where they are located" [4].

Data acquisition is carried out through the analysis of available documentation and information, both at the technical level (e.g., relating to design, execution, subsequent interventions, etc.) and at the administrative level, also allowing the development of a continuously updated database of Italian bridges[35].

In addition, the information collected makes it possible to subdivide existing road structures into macro-classes, identifying an order of priority to base the scheduling of in situ visual inspections on.

A ***Level 0 Bridge Census Form – Annex A of the LG20*** [93] contains useful information for the performance of the subsequent Levels[36], being consistent with the provisions of Ministerial Decree No. 430/2019, for the setting up of the *National Information Archive of Public Structures* [AINOP].

[35] The original technical documentation available that may be implemented is listed as follows. *Original documentation*: financing instruments, plans and programming instruments; *preliminary/outline project*: descriptive documents, graphs, documents inherent to the approval process; *definitive/executive project*: descriptive documents, graphs, documents inherent to the approval process; *executive/construction project*: descriptive documents, graphs, documents inherent to the approval process; *documents inherent to the direction of works*: accounting documents, graphs, documents inherent to the contract accounts; *documents inherent to the execution*: contractual documents, accounting documents; *variants during construction*: descriptive documents, graphs, contractual documents and accounting documents; *documents inherent to acceptance*: acceptance report and annexes; *maintenance interventions*: descriptive documents, graphs, contractual documents and accounting documents; *reports*: descriptive documents and graphs with dates; *project and interventions to increase the degree of safety*: descriptive documents and graphs; *available documents inherent to hydrological risk conditions* [92].

[36] The main data reported on the Level 0 Bridge Census Form are: Localisation, structural element material, structural typology, geometric dimensions, construction era, static scheme, road category, traffic data, analysis of alternative routes, geotechnical and hydrogeological characteristics of the site, owner and operating authority, original technical documentation available [92].

Level 1 – Visual inspections and defect forms

The integration and verification of the data collected in Level 0 is carried out by means of visual inspections of all the infrastructures on the territory, also allowing a fast and preliminary assessment of the state of conservation of such structures.

These inspections must be conducted by adequately trained technicians and require, to the possible extent, accessibility to the bridge so as to ensure a complete assessment – every element forming the extrados and intrados of the bridge is examined, at a distance no greater than 2 m, in order to have complete visibility even of closed compartments, such as caissons or hollow piers [92].

Advanced instrumentation is not required, but rather simple basic tools (Figure 4.10) are adequate to perform the geometric survey of the structure, i.e., photographic tools suitable for carrying out photographic surveys even at a distance and other tools that may be convenient for the purpose [92]. It is also possible to employ drones, remote-controlled or robotic means equipped with optics in the visible and infrared fields (RGB scanners).

The main types of surveys are listed as follows.

- *Complete and accurate photographic survey*: each photo is catalogued and numbered, additionally indicating both the area of the structure to which it refers and the type of defect (Figure 4.11).
- *Geometric survey*: rough geometric sketches are outlined to indicate the main dimensions (Figure 4.12).
- *Survey of the state of preservation of the structure*: specific forms are filled in, thus enabling to report the occurrence of degradation and defect phenomena, as well as their intensity and extent. In Annex B of the LG20 there are the *Defect Evaluation Forms* [*Schede di valutazione dei difetti*] [94]; each of them is related to a typology of the bridge constituent element and to its material. The bridge elements are numbered via an alpha-numeric code (Table 4.1 and Table 4.2) shown on the same ***Defect forms – Annex C of the LG20*** [95]. These forms thus include the specification describing the defects that may be detected during inspection, along with the respective evaluation criteria, causes and correlated degradation phenomena.

The ***Bridge defect evaluation form corresponding to Level 1*** – that can be found in ***Annex B of the LG20*** [94] – proposed and eventually used for the pilot case developed and further explained in chapter 6 of the present thesis were, therefore, formulated in accordance with the evaluation forms available in the literature by amending and integrating them.

Table 4.1 – List of defects reported on the Defect forms with their numbering; the code is assigned on the basis of the structural typology (concrete, steel and wooden bearing and non-bearing structures, foundations, and joints) of the bridge component affected by the degradation phenomenon [96]

Code	Difect description
c.a/c.a.p_1	Macchie di umidità passiva
c.a/c.a.p_2	Macchie di umidità attiva
c.a/c.a.p_3	Calcestruzzo dilavato/ammalorato
c.a/c.a.p_4	Vespai
c.a/c.a.p_5	Distacco del copriferro
c.a/c.a.p_6	Armatura ossidata e/o corrosa
c.a/c.a.p_7	Lesioni a ragnatela modeste
c.a/c.a.p_8	Fessure orizzontali
c.a/c.a.p_9	Fessure verticali
c.a/c.a.p_10	Fessure diagonali
c.a/c.a.p_11	Lesioni attacco pilastro
c.a/c.a.p_12	Riprese successiva deteriorate
c.a/c.a.p_13	Lesioni da schiacciamento
c.a/c.a.p_15	Lesioni in corrispondenza delle staffe
c.a/c.a.p_16	Staffe scoperte/ossidate
c.a/c.a.p_17	Armatura longitudinale deformata
c.a/c.a.p_18	Fessure longitudinali
c.a/c.a.p_19	Fessure trasversali
c.a/c.a.p_20	Distacco del timpano
c.a/c.a.p_21	Calcestruzzo dilavato/ammalorato
c.a/c.a.p_22	Lesioni distacco travi/traversi
c.a/c.a.p_23	Rottura staffe
c.a/c.a.p_24	Difetti delle selle Gerber
c.a/c.a.p_25	Lesioni attacco trave-soletta
c.a.p._1	Lesioni capillari ancoraggi
c.a.p._2	Testate di ancoraggio non sigillate
c.a.p._3	Distacco tamponi testate
c.a.p._4	Lesioni su anima lungo i cavi
c.a.p._5	Lesioni lungo suola del bulbo
c.a.p._6	Guaine in vista
c.a.p._7	Guaine degradate e fili ossidati
c.a.p._8	Fili aderenti in vista ossidati
c.a.p._9	Riduzione armatura di
c.a.p._10	Umidità dall'interno
c.a.p._11	Armatura scoperta/ossidata testate
c.a.p._12	Fuoriuscita barre ancoraggio

Code	Difect description
Legno_1	Macchie di umidità
Legno_2	Attacco di funghi
Legno_3	Attacco di insetti
Legno_4	Fessurazioni elicoidali
Legno_5	Fessurazioni longitudinali (legno
Legno_6	Fessurazioni trasversali
Legno_7	Ristagni d'acqua (Trappole d'acqua)
Legno_8	Danni da urto
Legno_9	Bulloni allentati
Legno_10	Delaminazione (legno lamellare)
Legno_11	Connessioni deteriorate
App_1	Piastra di base deformata
App_2	Ossidazione
App_3	Bloccaggio
App_4	Preregolazione Sbagliata
App_5	Presenza di detriti
App_6	Schiacciamento/fuoriuscita lastre di
App_7	Invecchiamento Neoprene
App_8	Deformazione orizzontale eccessiva
App_9	Schiacciamento/fuoriuscita neoprene
App_10	Ammaloramento pendoli in C.A.
App_11	Fuori piombo permanente pendoli
App_12	Ovalizzazione rulli metallici
App_13	Fuori sede rulli metallici
App_14	Deterioramento del Teflon
Ril/Fond_1	Scalzamento
Ril/Fond_2	Dilavamento del rilevato di approccio
Ril/Fond_3	Dissesto del rilevamento di approccio-
Ril/Fond_4	Dissesto del rilevato di approccio-Stabilità
Ril/Fond_5	Movimento di fondazione
Dif.Gen_1	Tracce di scolo
Dif.Gen_2	Ristagni d'acqua
Dif.Gen_3	Danni da urto
Dif.Gen_4	Lesioni caratteristiche in zona
Dif.Gen_5	Ristagni d'acqua nei cassoni
Dif.Gen_6	Fuori piombo

Code	Difect description
Acc_1	Difetto di saldatura
Acc_2	Rottura di saldatura
Acc_3	Sfogliamento vernice
Acc_4	Difetti di chiodatura
Acc_5	Bulloni allentati
Acc_6	Bulloni tranciati
Acc_7	Deformazione anime/piattabande
Acc_8	Deformazioni pareti travi scatolari
Acc_9	Lesioni ai nodi
Acc_10	Corrosione
Acc_11	Ossidazione

Code	Difect description
Giunt_1	Dislivello giunto pavimentazione
Giunt_2	Dislivello tra elementi contigui
Giunt_3	Riparazioni provvisorie Giunti
Giunt_4	Massetti lesionati
Giunt_5	Distacco tampone
Giunt_6	Deformazione tampone
Giunt_7	Ammaloramento profilati
Giunt_8	Deformazione/Rottura Elementi di
Giunt_9	Scossalina permeabile o assente

Table 4.2 – List of defects reported on the Defect forms with their numbering; the code is assigned on the basis of the structural typology (masonry and auxiliary elements) of the bridge component affected by the degradation phenomenon [96]

Code	Difect description	Code	Difect description
Mur_1	Fessure orizzontali	El.Acc_1	Stato della pavimentazione
Mur_2	Fessure verticali	El.Acc_2	Cordoli
Mur_3	Fessure diagonali	El.Acc_3	Convogliamento acque assente
Mur_4	Porzione di muratura mancante	El.Acc_4	Pozzetti intasati
Mur_5	Fessure trasversali	El.Acc_5	Scarichi corti
Mur_6	Fessure longitudinali	El.Acc_6	Scarichi ostruiti
Mur_7	Distacco del timpano	El.Acc_7	Scarichi danneggiati
Mur_8	Riprese successive deteriorate	El.Acc_8	Marciapiedi
Mur_9	Macchie di umidità/risalita	El.Acc_9	Pali di illuminazione mal
Mur_10	Dilavamento	El.Acc_10	Pali di illuminazione arrugginiti
Mur_11	Macchie di colore scuro	El.Acc_11	Sottoservizi mal ancorati
Mur_12	Efflorescenze	El.Acc_12	Guardiavia assenti
Mur_13	Patina biologica	El.Acc_13	Guardiavia danneggiati/ossidati/male
Mur_14	Polverizzazione		
Mur_15	Esfoliazione		

Figure 4.10 – Basic survey tools used for visual inspections [92]

Figure 4.11 – The Olivieri viaduct registered defects affecting girders and beams [96]

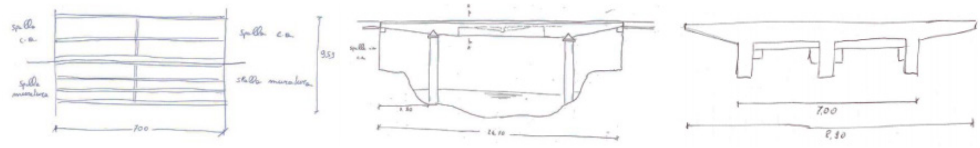


Figure 4.12 – Example of rough geometric sketches indicating the main dimensions [92]

In particular, the section of the form related to weight, extension, and intensity coefficients follows the indications proposed by the ***Handbook of Bridge Condition Assessment*** – developed by CIAS in collaboration with 4Emme – in which each defect is associated with a weight (G, highlighted in magenta in Figure 4.13), varying from 1 to 5 depending on its severity, an extension coefficient, k_1, and an intensity coefficient, k_2, whose possible values range from 0.2, 0.5, or 1.0 (respectively highlighted in yellow and green in Figure 4.13).
With regard to k_1, it will assume: the value of 0.2 when the defect affects a minimal part of the structure; 0.5 if the defect affects about 50 per cent of the surface; 1.0 in case the defect affects the entire part.
The values that the three coefficients can assume are listed in the Defect Survey and Evaluation Forms [95].
Additional degradation phenomena were then incorporated based on experience and literature in the field, i.e., the Inspection Handbook used by the ANAS and the Italian Railways Group, and the handbooks produced by the U.S. Departments of Transportation and the Federal Highway Administration [FHWA] [92].
Moreover, it is necessary to indicate whether the relevant defect has been closely investigated by checking the appropriate *seen* box (highlighted red in Figure 4.13).
In addition, to supplement the available information, the following parameters have been added: the NA [*Not Applicable – Non Applicabile*] box, to be checked if the defect is not applicable to the type of artefact and element under investigation, the NR [*Not Detectable – Non Rilevabile*] box if the defect is not detectable, and the NP [*Not Present – Non Presente*] box if the defect is not present (Highlighted in blue in Figure 4.13). The PS column indicates whether the type of defect in question is capable of *undermining the static equilibrium* [*Pregiudicare la statica*] of the work and is therefore used to mark those defects that may pose a structural risk to both the element and the entire work [92] (highlighted cyan in Figure 4.13).
For more effective planning, as reported in section 7.7 of LG20 and in case a Safety Management System is provided, a global numerical index can be defined by combining the data reported on the defect forms. For each type of defect found, in fact, it is possible to derive the product $(G \times K_1 \times K_2)$, which will represent a *measure* of the importance that that defect may acquire in the maintenance planning phase.

Scheda Ispezione Ponti di Livello 1

1	**Spalle** N ____ Strada di appartenenza: ____________ Progressiva km: ________
	Calcestruzzo Tecnico rilevatore: ____________ Data ispezione: __/__/____

Codice difetto	Descrizione difetto	visto	G	Estensione K1			Intensità K2			N° foto	PS	NA	NR	NP	Note
				0,2	0,5	1	0,2	0,5	1						
c.a/c.a.p._1	Macchie di umidità passiva	☐	1	☐	☐	☐			☐			☐	☐	☐	
c.a/c.a.p._2	Macchie di umidità attiva	☐	3	☐	☐	☐			☐			☐	☐	☐	
Dif. Gen_1	Tracce di scolo	☐	3	☐	☐	☐			☐			☐	☐	☐	
c.a./c.a.p._3	Cls dilavato / ammalorato	☐	3	☐	☐	☐			☐			☐	☐	☐	
Dif. Gen_2	Ristagni d'acqua	☐	2	☐	☐	☐			☐			☐	☐	☐	
c.a./c.a.p._4	Vespai	☐	2	☐	☐	☐	☐	☐	☐			☐	☐	☐	
c.a./c.a.p._5	Distacco del copriferro	☐	2	☐	☐	☐			☐			☐	☐	☐	

Figure 4.13 – Example of the Bridge defect evaluation template (for concrete abutments) corresponding to Level 1 that can be found in Annex B of the LG20 [94]

Proceeding to add up all the defects' indicators for each structural part $\left(\sum_i G_i \times K_{1,i} \times K_{2,i}\right)$, it is then possible to obtain a *measurement* of the condition of that very structural part, defined as *Relative Defectiveness*.
Indeed, the same LG20 states that *"it is possible to define indicators in a different way than described, providing it is adequately justified and described within the procedures of the Safety Management System"* [4].
A special form is devoted to auxiliary elements, whose maintenance interventions could potentially impact the maintenance work and whose malfunction can lead to the occurrence of superficial degradation phenomena.
Critical elements are, in addition, identified, i.e., those "elements that are particularly susceptible to degradation phenomena and whose possible malfunctions may significantly affect the overall structural behaviour of the bridge, i.e., the elements or conditions for which the presence of an advanced state of degradation is to be reported immediately" [4]. Here follows a list of the elements regarded as *critical*: the Gerber saddles, prestressing cables, very extensive and intense crack frames, incipient loss-of-support mechanisms or kinematics in place, joints of key elements for the bridge static stability, and undermining in the foundations.
In addition to the defect forms, a ***Descriptive Inspection form – Annex B of the LG20*** [97] is to be filled out to verify and supplement the data collected at Level 0.
Then, following the collapse of a section of the Madonna del Monte viaduct along the Turin-Savona highway on November 24, 2019 – whose cause is to be found in a landslide detachment that transported 30 thousand cubic meters of material downstream from a mountainside along the highway, hitting the bridge in the northbound direction, between the Savona and Altare toll booths – it became clear that it was crucial to provide a clear and thorough investigation of the area around the bridge, calling in experienced professionals to assess the primary and secondary factors in regard to potential landslide and/or flood events.

Thus, the ***Landslide and Hydraulic Form – Annex B of the LG20*** [98] was drafted, which constituent elements are associated with the three components of the Attention Class: hazard, vulnerability, and exposure.
Filling in the forms can be done via electronic/digital terminals (e.g., tablets, handheld devices, smartphones, etc.) and managed by the *Bridge Management System* [BMS]. Special attention should be paid to cases where more accurate and detailed assessments are required, thus going directly from Level 1 to Level 4. Such cases are [4]:

- Essential safety assessment according to ***NTC 2018 – § 8.3 Safety assessment*** [85];
- Structures with a high intrinsic *fragility*, for which fragile crisis situations may occur (i.e., prestressed concrete conjoint bridges, where shear transmission between segments occurs due to the development of friction between segments).

Special inspections must be carried out in the case of post-tensioned prestressed concrete cable-stayed bridges and bridges in areas exposed to alluvial, erosional, and landslide phenomena or areas identified as being at high hydrogeological risk, with possible interference with the structure. In the first case, therefore, neither conventional nor visual surveys allow a clear understanding of the state of conservation of the structure.
The data collected during the census (Level 0) and the subsequent visual inspections (Level 1) will, therefore, allow the identification of the most problematic cases that will require in-depth checks envisaged in Level 4.

Level 2 – Analysis of detected risks and classification on a territorial scale

Level 2 represents the core of the multilevel approach followed by the LG20. It contains useful indications for moving from a territorial scale assessment to an assessment that focuses on a limited number of road structures.
The classification method adopted entails the determination, for each bridge, of the *Attention Class* through a process of *classes and logical operators*, in which each primary and secondary parameter is grouped into classes that are combined according to logical workflows. Depending on the result, the analyses performed on the structure will have a different degree of difficulty and depth.
As stated in the LG20 Guidelines, the *Attention Class* [CdA] makes it possible to estimate the risk roughly; to obtain an effective estimate of the risk it would be necessary, however, to carry out more complex and in-depth analyses.
Here follows the *five Attention Classes* (Figure 4.14):

- *High Class*: for road bridges that fall into this class, more accurate assessments are required, both in terms of safety and geotechnical and/or structural characteristics, where necessary. Routine inspections and, when necessary, extraordinary inspections are required, as well as the setting up of periodic or continuous monitoring systems;
- *Medium-High Class*: for road bridges that fall into this class, a preliminary assessment is required, the carrying out of ordinary inspections and, where necessary, extraordinary inspections and the setting up of periodic or continuous monitoring systems;
- *Medium Class*: a preliminary assessment and routine periodic inspections are required for road bridges that fall into this class. The owner and/or operator will assess, on a case-by-case basis, whether it is necessary to install periodic or continuous monitoring systems and to carry out in-depth safety assessments;
- *Medium-Low Class*: for road bridges that fall into this class, in addition to the assessments and analyses already provided for, frequent periodic inspections are required;
- *Low Class*: for road bridges that fall into this class, periodic inspections are required in addition to the evaluations and analyses already planned.

The classification process can be summarised in three main steps [92]:

- *Step 1*. The risks relevant to bridge structures are identified by considering the characteristics of the structure itself and of its context, the different recurrence intervals and the nature of the prevailing impacts. Four types of risk are distinguished (Figure 4.15), each of them is analysed separately, thus defining a different Attention Class for each one.
- *Step 2*. The Attention Class is the result of the combination of three main factors: *Hazard*, *Vulnerability*, and *Exposure* (Figure 4.16). In turn, each of these factors is derived from the main parameters that influence them, called primary and secondary parameters (Figure 4.17). As previously mentioned, the approach used is based on *classes and logical operators*, wherein, depending on the value of the primary parameters, classes are subsequently corrected according to the secondary ones. These parameters come from reprocessing the data collected in Level 0 and Level 1.
- *Step 3*. The LG20 requires the evaluation of a unit parameter to obtain a synthetic index. The latter represents the overall CdA of the structure and is derived from the combination of the CdAs associated with the four types of risk (Figure 4.18).

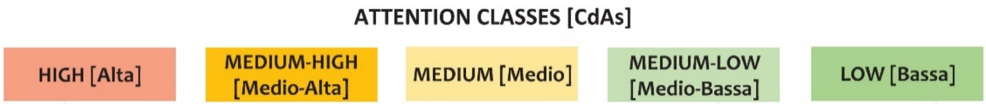


Figure 4.14 – The five colour-coded Attention Classes identified by the LG20 [92]

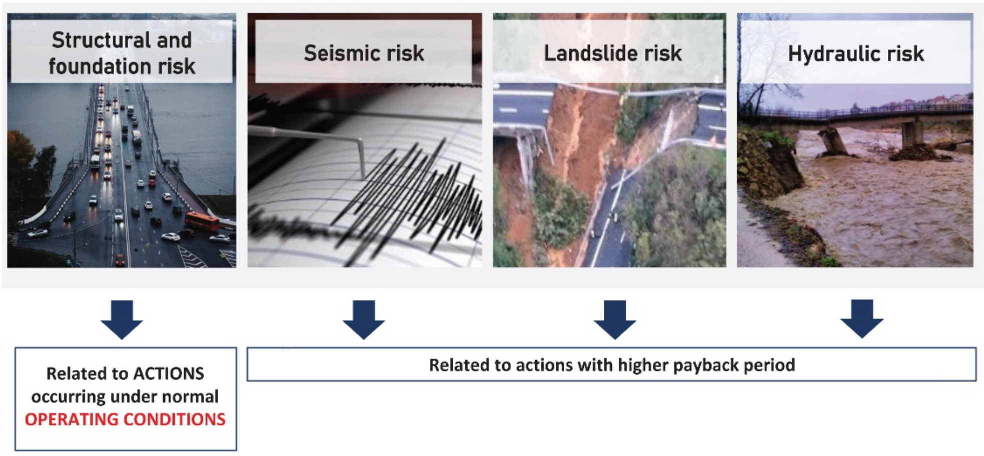


Figure 4.15 – The four types of risk: structural and foundation, seismic, landslide, and hydraulic [92]

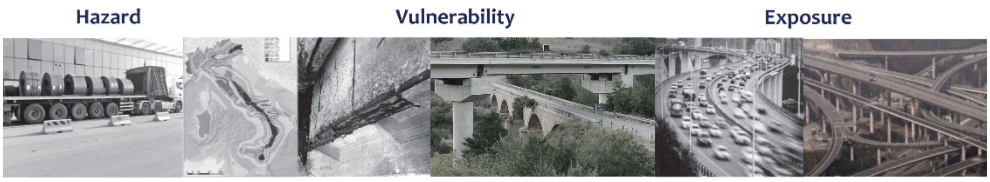


Figure 4.16 – The three main factors: Hazard, Vulnerability, and Exposure [92]

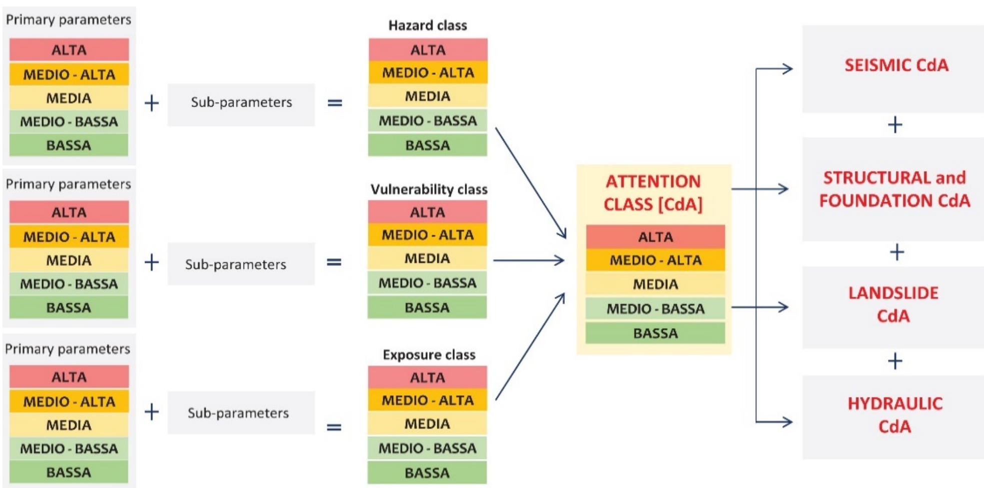


Figure 4.17 – Primary and secondary parameters combination to determine the Attention classes [CdAs] [92]

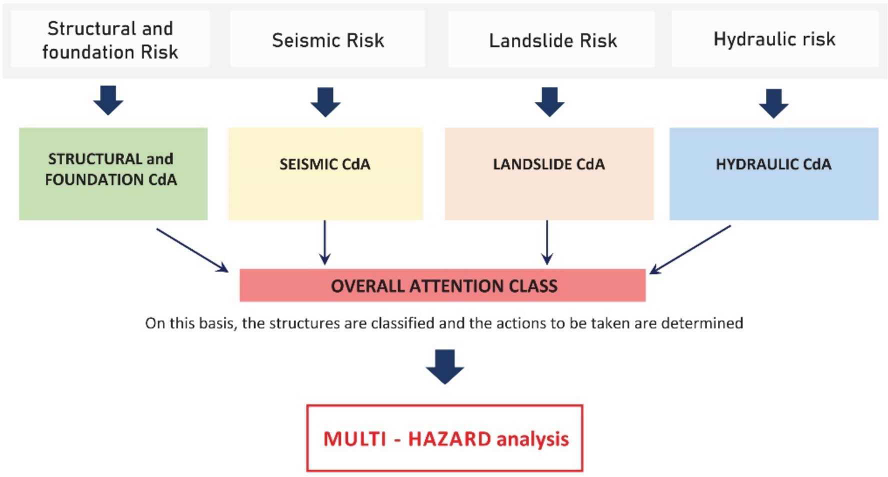


Figure 4.18 – Determination of the overall Attention Class [CdA] [92]

It should be noted that, in the definition of the possible combinations, *"Greater weight is given to the structural and foundational CdA as it is linked to the usual operating conditions of the structures. This implies that if the structural or the foundational CdA is high, the overall CdA is high regardless of seismic and hydraulic and landslide CdAs"* [4].
In the case of an extraordinary inspection or whenever an increase in degradation is detected during the periodic analysis of the structure's condition, the overall CdA is updated. The update can be accomplished by pursuing two paths:

- all the previous procedure is repeated, identifying the CdA for each type of risk, then arriving at the overall CdA through their combination;
- otherwise, it is necessary to proceed according to the index value representing the state of condition of the artefact. This index can be related to the relative defectiveness Dr:
  - the low class will correspond to DR values less than 5;
  - the high class will be assigned to DR values greater than 25;
  - the intermediate range may be divided into equal intervals of the index value or into equal periods of operating life when using the degradation curve referred to the type of work under examination.

Although all the activities envisaged by the levels beyond the second one (i.e., investigations, checks and verifications) are based on the overall CdA, it is recommended to always take into consideration the attention classes of the various relevant risks and, at the same time, to archive and make available within the databases (e.g., AINOP) both the overall CdA and the individual CdAs that make it up.

Level 3 – Preliminary assessment of the structure

After having acquired all the necessary tools for the assessment of the Attention Class, the next step is to assess the quality and type of defects found at Level 1. For instance, in the case of a Medium-High CdA, it is necessary to analyse in further detail the defects found during visual inspections and identify their causes.
Assuming that the design of the structure was carried out according to the regulations of the era, it is necessary to further estimate the demand induced upon the various elements that compose the bridge (i.e., slabs, beams, girders and main structures, piers, abutments, restraining devices and foundations), in order to compare the demand produced by the traffic loads predicted according to the past regulations with that resulting from the traffic models provided by the current standards [4] (Figure 4.19).
The most useful piece of information is the category of the road the bridge was designed for. In the case that the original design is not available, it is necessary to assume the category of road corresponding to the load patterns that induce less onerous effects than those envisaged by the current regulations.

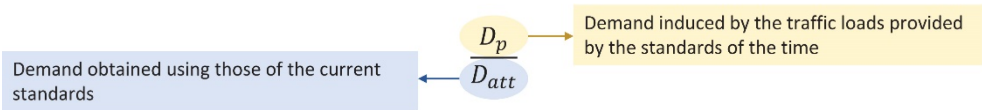


Figure 4.19 – Relationship between demand induced by the traffic loads provided by the standards of the time and the demand obtained using those of the current standards [71]

Level 4 – Accurate safety assessment

The objective of this level is to provide indications on how to carry out the safety assessments, starting from the first stages of investigation to the final stages of intervention.
In accordance with the latter, it is fundamental to fully understand the structure, thus reducing the uncertainties related to the load estimation, material and structure behaviour, etc. The stages of the investigation process are thus detailed, comprising different and interlinked activities.
Particularly relevant is Chapter 8 of the NTC2018 concerning Existing Constructions [85], for which the LG20 guidelines are intended as an initial attempt at integration. In the first part of said chapter, the fundamental concepts and strategies for the safety assessment of existing bridges are illustrated.
The fulfilment of this assessment must occur within a time horizon depending on the purpose for which the analysis was carried out. Therefore, the concept of *reference time* [t_{ref}] is introduced *"i.e., the timeframe to which the verification is*

conventionally referred" [4]. After this time has elapsed, the analyses are to be repeated and further checks must be carried out, additionally performing the necessary actions to achieve the required safety standard.

Some novelties introduced by the LG20 are represented by the assessment levels:

- *Adapted*: stands for a bridge where all the verifications required by the NTC are fulfilled using the loads and partial factors specified therein;
- *Operational*: is a bridge where all the verifications required by the NTC are satisfied using, in this case, a *reference time* [t_{ref}] of 30 years;
- *Transitable*: refers to a bridge whose verifications are satisfied, using again a shorter reference time (assumed not greater than t_{ref} = 5 years) and adopting the following measures: either *limitation of permitted loads* or *restriction of bridge use*.

For each of these assessment levels, useful indications regarding traffic loads and partial factors are given.

The process followed by the Multilevel Approach is summarised below (Figure 4.20).

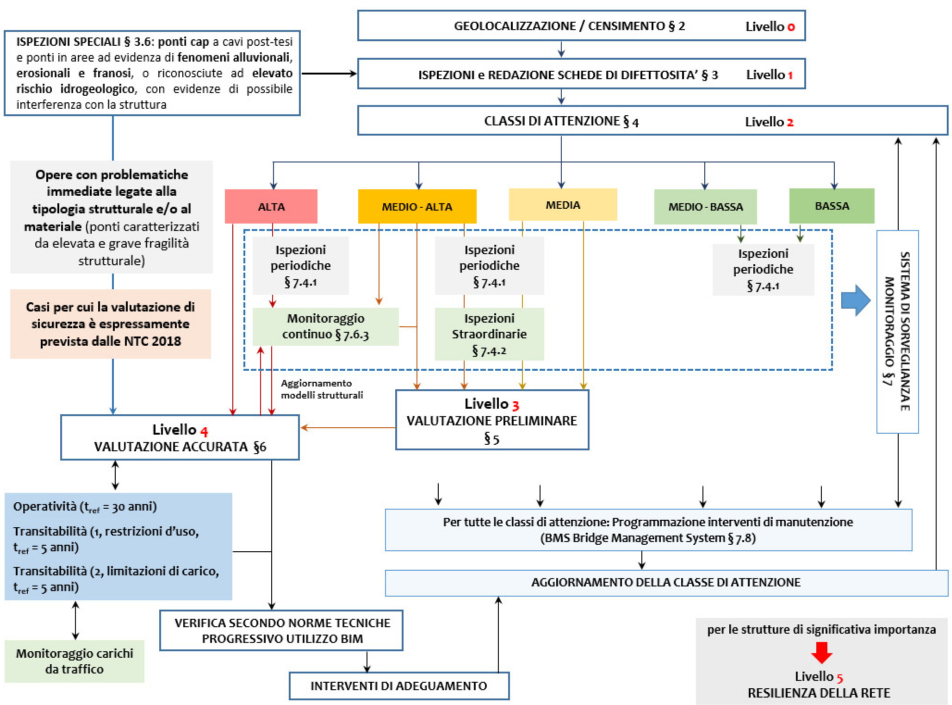


Figure 4.20 – Multilevel approach and analysis level dependencies [4]

Level 5 – Infrastructure network resilience

"Not explicitly dealt with in these Guidelines, it applies to bridges considered to be of significant importance within the network, duly identified. For such works, it is useful to carry out more sophisticated analyses such as the resilience of the road network branch and/or of their transport system; assessing the transport relevance, analysing the interaction between the structure and the road network it belongs to and the consequences of a possible interruption of the bridge service on the socio-economic context. Reference may be made to internationally attested authoritative documentation to undertake such studies" [4].

4.4 Inspection typologies

As previously mentioned, Level 1 according to the LG20 consists in carrying out visual inspections on all the structures on national territory, aimed at identifying the state of deterioration of the structure itself and at integrating and verifying the data collected in Level 0 – Census of structures. In particular, the surveillance and monitoring system for bridges and viaducts envisages routine periodic inspections and extraordinary inspections; the former are to be documented by means of the template forms contained in Annex B of the LG20 Guidelines, while the latter are to be found in specific Reports.
The inspections will provide a *snapshot* of the structure, thus making it possible to objectively describe the state of conservation of the structure and its surroundings.
Similarly, the surveillance system for road works of art developed by Autostrade per l'Italia S.p.A. [ASPI] is organised in different areas: visual inspections, special inspections, monitoring, assessment, instrumental controls.
Visual inspections according to LG20 and the ***2020 Surveillance Handbook*** developed by Autostrade per l'Italia [ASPI] [99] will be dealt with in further detail.

Routine Periodic Inspections

Routine periodic inspections, also referred to as Level 2 inspections, are carried out on the main structure, the foundations and auxiliary equipment, as well as analysing the condition of the surroundings in order to detect any possible factors that may increase the risk of flooding and landslides. The purpose of these inspections is to collect as much data as possible regarding the state of conservation of the structure, in order to define a representative numerical/quantitative value for each element investigated.
The minimum inspection interval is defined according to the current CdA and the typology; Type 1 refers to those structures included in a surveillance system in accordance with the 1967 Circular [83], while Type 2 concerns both new structures and those in operation for several years, for which the state of conservation and/or maintenance is unknown, as shown in Table 4.3.
It should be noted that the 1967 Circular No. 6736/61/AI stated that *"Regardless, however, of the (possible) reports and information provided by maintenance personnel, the department heads, area surveyors, branch or section engineers shall carry out at least once every three months an inspection of all the structures under their responsibility, to ascertain the state of consistency and conservation of the structures, as well as any instability that may appear in the visible parts of the structures"* [83].

Table 4.3 – Minimum interval of routine inspections according to the LG20 [4]

CDA -	*Bassa*	*Medio - Bassa*	*Media*	*Medio-Alta*	*Alta*
Frequenza Opere "Tipo 1"	Biennale	18 mesi	Annuale	In funzione del monitoraggio o semestrale	In funzione del monitoraggio o semestrale
Frequenza Opere "Tipo 2"	Annuale	9 mesi	Semestrale	In funzione del monitoraggio o trimestrale	In funzione del monitoraggio trimestrale

International standards and practices require a lower inspection interval, at least annually. Moreover, as reported by the LG20, degradation phenomena develop over a generally long time. Therefore, a three-monthly inspection interval was established only for those structures classified in Medium-High and High Attention Classes, both for continuity reasons and considering the old age of the bridges and viaducts present on the national road network.
It is essential to specify that the frequency and methods of inspection regarding the environmental conditions may also be based on the indications of the risk levels provided by the Basin Management Plans and other regional technical documents.
Furthermore, when it comes to pavements, in addition to the visual characterisation of defects, scanning with equipped vehicles or manually operated equipment may be carried out.
It is recommended that non-destructive tests be carried out (sclerometric tests, protective coat thickness measurements, humidity and pH measurements, electrical potential measurements).
It is worth emphasising that routine inspections do not replace Level 3 and Level 4 safety inspections. The data collected during the visual inspections are recorded in the template forms found in Annex B of the LG20. These include the defectiveness forms [94]. The following are some of the mentioned templates, in particular, the Bridge inspection forms referring to concrete abutments (Figure 4.21), piers (Figure 4.22) and arches (Figure 4.23).
As previously reported, each type of defect is associated with a weight, G, varying from 1 to 5 and a coefficient, K_1 and K_2, each of which may take the value of 0.2, 0.5 or 1.0.
In the case, for example, of abutments and piers, the types of defect include undermining, to which a weight, G, equal to 5 is associated since this phenomenon is one of the main causes of bridge collapses. The LG20 itself identifies it as a *critical element*, i.e., an element that is particularly subject to degradation phenomena and that can affect the overall behaviour of the bridge. It is, therefore, only possible to associate a K_1 value of 1.0 with it.

Scheda Ispezione Ponti di Livello 1

1	Spalle N ____	Strada di appartenenza: ________	Progressiva km: ________
	Calcestruzzo	Tecnico rilevatore: ________	Data ispezione: __/__/____

Codice difetto	Descrizione difetto	visto	G	Estensione K1 0,2	Estensione K1 0,5	Estensione K1 1	Intensità K2 0,2	Intensità K2 0,5	Intensità K2 1	N° foto	PS	NA	NR	NP	Note
c.a/c.a.p._1	Macchie di umidità passiva	☐	1	☐	☐	☐			☐			☐	☐	☐	
c.a/c.a.p._2	Macchie di umidità attiva	☐	3	☐	☐	☐			☐			☐	☐	☐	
Dif. Gen_1	Tracce di scolo	☐	3	☐	☐	☐			☐			☐	☐	☐	
c.a./c.a.p._3	Cls dilavato / ammalorato	☐	3	☐	☐	☐			☐			☐	☐	☐	
Dif. Gen_2	Ristagni d'acqua	☐	2	☐	☐	☐			☐			☐	☐	☐	
c.a./c.a.p._4	Vespai	☐	2	☐	☐	☐	☐	☐	☐			☐	☐	☐	
c.a./c.a.p._5	Distacco del copriferro	☐	2	☐	☐	☐			☐			☐	☐	☐	
c.a./c.a.p._6	Armatura ossidata/corrosa	☐	5	☐	☐	☐	☐	☐	☐		☐	☐	☐	☐	
c.a./c.a.p._7	Lesioni a ragnatela modeste	☐	1	☐	☐	☐			☐			☐	☐	☐	
c.a./c.a.p._8	Fessure orizzontali	☐	2	☐	☐	☐	☐	☐	☐			☐	☐	☐	
c.a./c.a.p._9	Fessure verticali	☐	2	☐	☐	☐	☐	☐	☐			☐	☐	☐	
c.a./c.a.p._10	Fessure diagonali	☐	5	☐	☐	☐	☐	☐	☐		☐	☐	☐	☐	
c.a./c.a.p._11	Lesioni attacco pilastri (spalle a telaio)	☐	3	☐	☐	☐	☐	☐	☐			☐	☐	☐	
c.a./c.a.p._12	Riprese successive deteriorate	☐	1	☐	☐	☐	☐	☐	☐			☐	☐	☐	
Dif. Gen_3	Danni da urto	☐	4			☐	☐	☐	☐		☐	☐	☐	☐	
Dif. Gen_6	Fuori piombo	☐	5	☐	☐	☐	☐	☐	☐		☐	☐	☐	☐	
Ril/Fond_1	Scalzamento	☐	5			☐	☐	☐	☐		☐	☐	☐	☐	
Ril/Fond_2	Dilavamento del rilevato	☐	1			☐			☐			☐	☐	☐	
Ril/Fond_3	Dissesto del rilevato - deformazioni	☐	2			☐	☐	☐	☐			☐	☐	☐	
Ril/Fond_4	Dissesto del rilevato - stabilità	☐	4			☐			☐		☐	☐	☐	☐	
Ril/Fond_5	Movimenti di fondazione	☐	5	☐	☐	☐	☐	☐	☐		☐	☐	☐	☐	
c.a./c.a.p._13	Lesioni da schiacciamento	☐	4			☐	☐	☐	☐		☐	☐	☐	☐	
Dif. Gen_4	Lesioni caratteristiche zone appoggio	☐	3	☐	☐	☐	☐	☐	☐			☐	☐	☐	
Eventuali note															

Figure 4.21 – Defect assessment form (Level 1) for concrete abutments [94]

Scheda Ispezione Ponti di Livello 1

3	Pile N ____	Strada di appartenenza: ________	Progressiva km: ________
	Calcestruzzo	Tecnico rilevatore: ________	Data ispezione: __/__/____

Codice difetto	Descrizione difetto	visto	G	Estensione K1 0,2	Estensione K1 0,5	Estensione K1 1	Intensità K2 0,2	Intensità K2 0,5	Intensità K2 1	N° foto	PS	NA	NR	NP	Note
c.a/c.a.p._1	Macchie di umidità passiva	☐	1	☐	☐	☐	☐	☐	☐			☐	☐	☐	
c.a/c.a.p._2	Macchie di umidità attiva	☐	3	☐	☐	☐			☐			☐	☐	☐	
Dif. Gen_1	Tracce di scolo	☐	3	☐	☐	☐			☐			☐	☐	☐	
c.a./c.a.p._3	Cls dilavato / ammalorato	☐	3	☐	☐	☐			☐			☐	☐	☐	
Dif. Gen_2	Ristagni d'acqua	☐	2	☐	☐	☐			☐			☐	☐	☐	
c.a./c.a.p._4	Vespai	☐	2	☐	☐	☐	☐	☐	☐			☐	☐	☐	
c.a./c.a.p._5	Distacco del copriferro	☐	2	☐	☐	☐			☐			☐	☐	☐	
c.a./c.a.p._6	Armatura ossidata/corrosa	☐	5	☐	☐	☐	☐	☐	☐		☐	☐	☐	☐	
c.a./c.a.p._7	Lesioni a ragnatela modeste	☐	1	☐	☐	☐	☐	☐	☐			☐	☐	☐	
c.a./c.a.p._15	Lesioni in corrispondenza staffe	☐	2	☐	☐	☐	☐	☐	☐			☐	☐	☐	
c.a./c.a.p._8	Fessure orizzontali	☐	2	☐	☐	☐	☐	☐	☐			☐	☐	☐	
c.a./c.a.p._9	Fessure verticali	☐	2	☐	☐	☐	☐	☐	☐			☐	☐	☐	
c.a./c.a.p._10	Fessure diagonali	☐	5	☐	☐	☐	☐	☐	☐		☐	☐	☐	☐	
c.a./c.a.p._16	Staffe scoperte / ossidate	☐	3			☐	☐	☐	☐			☐	☐	☐	
c.a./c.a.p._11	Lesioni attacco pilastri	☐	3	☐	☐	☐	☐	☐	☐			☐	☐	☐	
c.a./c.a.p._23	Rottura staffe	☐	4	☐	☐	☐			☐		☐	☐	☐	☐	
c.a./c.a.p._17	Armatura longitudinale deformata	☐	5			☐			☐		☐	☐	☐	☐	
c.a./c.a.p._12	Riprese successive deteriorate	☐	1			☐			☐			☐	☐	☐	
Dif. Gen_3	Danni da urto	☐	4			☐	☐	☐	☐		☐	☐	☐	☐	
Dif. Gen_6	Fuori piombo	☐	5	☐	☐	☐	☐	☐	☐		☐	☐	☐	☐	
Ril/Fond_1	Scalzamento	☐	5			☐	☐	☐	☐		☐	☐	☐	☐	
Ril/Fond_5	Movimenti di fondazione	☐	5	☐	☐	☐	☐	☐	☐		☐	☐	☐	☐	
c.a./c.a.p._13	Lesioni da schiacciamento	☐	4			☐	☐	☐	☐		☐	☐	☐	☐	
Dif. Gen_4	Lesioni caratteristiche zone appoggio	☐	3	☐	☐	☐	☐	☐	☐		☐	☐	☐	☐	
Eventuali note															

Figure 4.22 – Defect assessment form (Level 1) for concrete piers [94]

Scheda Ispezione Ponti di Livello 1

9	Piedritti N _____ Metallo o Acciaio	Strada di appartenenza: _____________ Tecnico rilevatore: _________________	Progressiva km: ___________ Data ispezione: __/__/___

N°	Descrizione difetto	visto	G	Estensione K1			Intensità K2			N° foto	PS	NA	NR	NP	Note
				0,2	0,5	1	0,2	0,5	1						
Acc_1	Difetti di saldature	☐	4	☐	☐	☐			☐		☐	☐	☐	☐	
Acc_2	Rottura di saldature	☐	5	☐	☐	☐			☐		☐	☐	☐	☐	
Acc_3	Sfogliamento vernice	☐	2	☐	☐	☐			☐			☐	☐	☐	
Acc_4	Difetti di chiodatura	☐	5	☐	☐	☐	☐	☐	☐		☐	☐	☐	☐	
Acc_5	Bulloni allentati	☐	4	☐	☐	☐			☐		☐	☐	☐	☐	
Acc_6	Bulloni tranciati	☐	5	☐	☐	☐			☐		☐	☐	☐	☐	
Acc_7	Deformazioni anime / piattabande	☐	3	☐	☐	☐	☐	☐	☐			☐	☐	☐	
Acc_8	Deformazioni pareti travi scatolari	☐	3	☐	☐	☐			☐			☐	☐	☐	
Dif. Gen_2	Ristagni d'acqua	☐	2	☐	☐	☐			☐			☐	☐	☐	
Acc_9	Lesioni ai nodi	☐	5	☐	☐	☐			☐		☐	☐	☐	☐	
Acc_10	Corrosione	☐	4	☐	☐	☐			☐		☐	☐	☐	☐	
Acc_11	Ossidazione	☐	2	☐	☐	☐			☐			☐	☐	☐	
Dif. Gen_3	Danni da urto	☐	4			☐	☐	☐	☐		☐	☐	☐	☐	
Dif. Gen_5	Fuori piombo	☐	5	☐	☐	☐	☐	☐	☐		☐	☐	☐	☐	
Eventuali note															

Figure 4.23 – Defect assessment form (Level 1) for concrete arches [94]

Extraordinary inspections

Extraordinary inspections are carried out in the event of criticalities, e.g., gravity 5 phenomena, or exceptional events, such as shocks, seismic events, floods, landslides and major accidents, that may affect the stability of the structure or whenever the predictive models show anomalous degradation behaviour. In the aforementioned cases, extraordinary inspections must be carried out within 60 days from when the need arises.

These inspections must be documented in a report, registered, and subsequently uploaded in the BMS, accurately indicating the operations carried out, the elements investigated – Identified by their code – and the results of the in situ and laboratory tests, together with adequate photographic documentation and geometric surveys. The report must conclude with an assessment of the state of conservation of the structure and the evolutionary trends of the degradation with indications for the actions that will be required afterwards.

Extraordinary inspections must be supported by non-destructive tests[37].

[37] Non-destructive tests that can support extraordinary inspections are listed as follows. Taking samples for mechanical and chemical-physical tests, sclerometric, SONREB (SONic-REBound tests that combine ultrasound and sclerometric ones) or equivalent tests, pull-out tests, ultrasonic or georadar tests for detecting voids and discontinuities, mapping of electrical potentials, soundings and inspections with an endoscope, magnetic and/or georadar tests on prestressing cables, diffuse humidity and pH measurements, determination of the state of tension. For metal structures, additional measures will be carried out, i.e., measurements on the residual thickness of protective paints, bolt tightening tests, and inspection of welds with ultrasound and/or penetrating liquids.

Special cases

In conducting inspections of any kind, special attention is required in the case of post-tensioned cable prestressed structures, pile and abutment dislocation, and groundwater drainage.
"Pre-stressed structures with post-tensioned and injected cables, including, in particular, those built between the 1960s and 1970s, can be affected by dangerous deteriorations resulting in the corrosion of the prestressing cables, thus adversely affecting the resistance of the structure and causing sudden collapses, even without overloading or traffic" [4]. It is precisely for this reason that, when emergency interventions are required, extraordinary inspections are to be carried out with non- and/or semi-destructive methods.
Foundation displacement, as stated earlier, is one of the most frequent causes of instability and collapse of bridges or riverbanks abutments; inspections, including underwater ones, must therefore be carried out in detail, and performed periodically, especially following even non-exceptional watercourse floodings.
In the case of groundwater drainage, a dedicated inspection form is required.

Visual inspections according to the 2020 Surveillance Handbook developed by ASPI [99]

The 2020 surveillance handbook represents a monitoring system for road structures developed by Autostrade per l'Italia [ASPI] and is organised in different areas: visual inspections, special inspections, monitoring, assessment, and instrumental controls. Namely, *"surveillance refers to integrated engineering services concerning the supervision and control of motorway artworks, the execution of tests and instrumental surveys, either functional or related to the surveillance itself"* [99].
In the following, visual inspections for structures with a shoulder-to-shoulder span greater than or equal to 10 m will be covered, thus excluding those with a smaller span. Moreover, as far as pavements and barriers are concerned, it is necessary to refer to more specific manuals.
The 2020 Surveillance Handbook has been drafted in accordance with national, technical, and scientific literature, providing requirements and operational guidance on the following topics:

- inspection typologies;
- related intervals;
- methods to carry out inspections;
- qualification to perform inspections;

- methods to document the results of inspection activities;
- feeding of the computer database supporting the management of the surveillance of works of art.

It also incorporates some aspects of the LG20, introducing additional surveillance activities. The primary purpose is to characterise the state of conservation of the artefact and to monitor it over time, thus planning repair and refurbishment interventions, assessing the risk associated with the artwork, and updating the CdA in accordance with the LG20. All the data collected can then be shared through the AINOP.
In order to provide useful tools for such activities, ASPI has introduced indicators that, starting from the defects of the structure, provide a global defect rating of the assets themselves.
The structures that must be monitored are:

- *working motorway structures*: open to traffic;
- *abandoned structures*: consisting of underpasses belonging to motorway sections closed to traffic, beneath which, however, there may still exist roads, rivers or others;
- *abandoned structures*: similar to the previous ones, but without roads, rivers or others underneath.

As in the case of LG20, inspections are divided into ordinary and extraordinary and are aimed at detecting defects caused by degradation, use and environmental phenomena in the structural and accessory elements of the asset. Attention must also be paid to situations that may occur in the area surrounding the structure, whether of a hydraulic or geological nature, that could potentially threaten the integrity and functionality of the infrastructure itself.
Unlike LG20, the Manual divides ordinary and extraordinary inspections respectively into two sub-categories: *basic and advanced ordinary inspections*, and *on-call and in-depth extraordinary inspections*.

- *Basic ordinary inspections*: are carried out on a visual basis and it is possible, during the course of the inspection, not to inspect one or more components or entire parts of the work, specifying the reasons for this.
- *Advanced ordinary inspections*: aim to describe the state of conservation of the work, detecting defects on all components.
- *On-call extraordinary inspections*: are an extremely detailed inspections with the aim of identifying defects and their causes and predicting their development.

- *In-depth extraordinary inspections*: are required in the event that criticalities are found during a quarterly inspection or when the engineer in charge deems it necessary to learn more about one or more deterioration phenomena, and no later than 60 days from when the need becomes known.

It is worth mentioning that before the ***2020 Surveillance Handbook by ASPI***, the reference standard was the ***2015 Surveillance Handbook*** [100] drawn up by *SPEA Engineering technicians* in collaboration with *Autostrade per l'Italia technicians*, according to the surveillance activities carried out on the ASPI road network, which presented the annexed *Defect Catalogue*, containing the identification sheets for the 103 defects detected[38].

With regard to the rating for each defect, it is assessed according to the seriousness of the situation, taking into account the percentage of the defect that may affect the safety coefficient, its evolution over time, the importance of the structural part where it was found, the safety for users or third parties involved (e.g., underlying roads, etc.). The value range starts from a minimum value of 10 up to a maximum value of 70 [100]:

- Defects that do not require intervention
    - 10: the defect does not evolve into other defects
    - 20: the defect can evolve into other defects not requiring intervention;
    - 30: the defect may evolve into other defects requiring intervention.
- Defects requiring scheduled intervention
    - 40: the defect requires intervention over the medium to long term
    - 50: the defect requires intervention over the medium-short term;
    - 60: the defect has an influence on the statics, but does not significantly reduce the safety coefficients (less than 5%); it needs short-term intervention.
- Defects requiring immediate intervention (e.g., traffic restriction, road closure, and so on):
    - 70: The defect causes a reduction in safety coefficients.

[38] For each defect the information had to be provided: defect order number; defect denomination; classification of the defect; structural parts, identified by means of a code, in which the defect is present; defect description; causes of the defect; correlations with other defects; possible notes; defect type, i.e., extensive, intensive and qualitative; rating of the defect; illustration of the defect by means of a photograph or drawing.

The period referred to in the definition of the rates is less than two years for the *short term*, 2 to 5 years for the *medium term* and more than five years for the *long term*.
Class 40 ratings are further subdivided in order to better organise the scheduling phase:

- 40: the defect does not need to be reported;
- 41: the defect is evolving but does not yet necessitate reporting;
- 42: the defect must be reported, although it is assigned to the sole joint-continuity structural part:
- 43: the defect shall be reported for all other parts and components involved.

Outlined below (Figure 4.24) is the logic diagram used for the awarding of ratings.

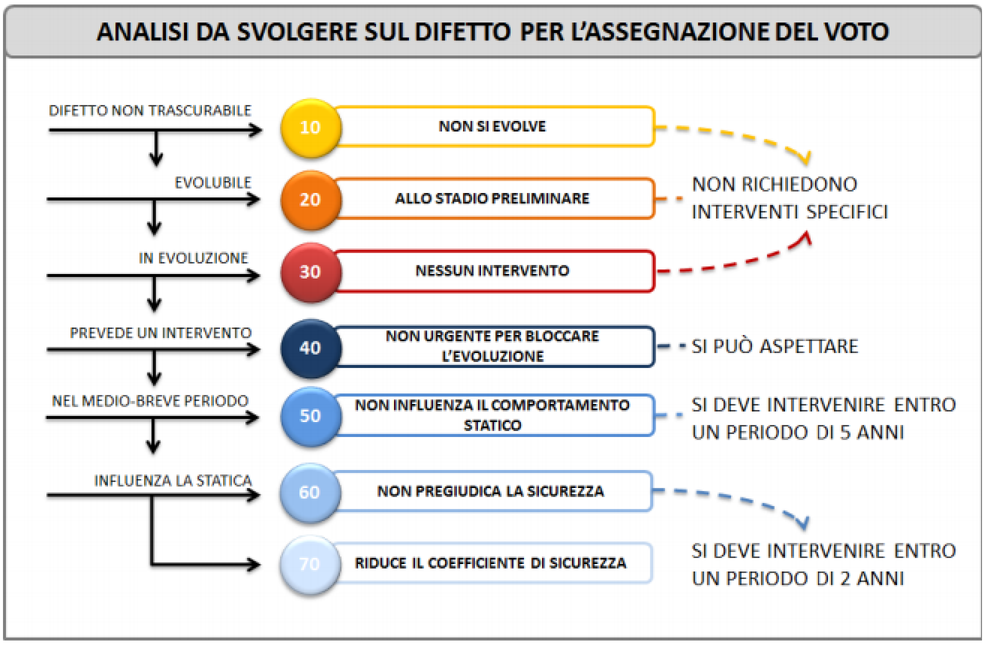


Figure 4.24 – Logic diagram for attributing ratings to the defects according to the 2015 handbook [100]

4.5 Literature review covering BIM for bridge inspections

Thorough research was conducted on the topics of "*BIM*", "*Inspection*", and "*Bridge*" among the papers indexed according to the *Web of Science* [WoS] and *Scopus* databases. The results – 64 from the WoS database and 87 from the Scopus one presented in the Table 4.4 are listed from the most recent publication year [PY] to the oldest, and further organised according to their relevance within the same year – include 116 contributions, divided between "*Conference Proceedings*" [C = 56], "*Journal Articles*" [J = 59], and "*Book Chapters*" [B = 1]. Furthermore, a graphic diagram was drawn up summarising the distribution of publications throughout the world (Figure 4.25).
To a certain extent, all the contributions provide for a tentative formalisation and standardisation in the use of BIM applied to bridges in order to either improve data storage, automatically recognise damage and/or create a visual decision-support tool. Notably, the *conference proceedings* generally present workflows for facility management, supplemented by some additional topics dealt with in greater depth in *journal articles* and some *book chapters*. However, due to their synthetic nature, the methodological approaches presented in the *proceedings* are hardly ever fully explained and the results presented need to be further developed in forthcoming longer treatises. Hence, the focus will be on more-extensive contributions [60] to better capture the trends in the literature review.

Table 4.4 – The papers are listed, from the most recent to the oldest publication year, according to the relevance criteria established by the Web of Science [Wos] and Scopus databases within the same year. The first column contains the *reference number* [REF], followed by the *title of the article*, the *type of publication* – J = *Journal Article*, C = *Conference Proceedings*, B = *Book Chapter* –, the purpose of the contribution, and its year. The *open access* papers (30) are highlighted in yellow, while the *review* ones (11) are in blue; whether a review contribution also has open access (4) will be marked in green. The indexed abstracts introducing the conference proceedings volumes are considered reviews.

REF	Article Title	Country	PT	Purpose	PY
[101]	BIM-based mixed-reality application for bridge inspection and maintenance	South Korea	J	This study targets two key issues: creating a BIM-based model for bridge inspection and maintenance and developing this model in a mixed-reality [MR] platform based on Microsoft Hololens; thus, a MR application called HoloBridge is developed to visualise the stored data concerning bridge inspection and the related damages.	2022
[102]	A Parameter-Driven Method for Modeling Bridge Defects through IFC	China, Australia	J	The research, which was validated on concrete highway bridges, proposes an industry foundation classes [IFC]-based method to document and represent inspection-related information in bridge BIM models, parametrically modelling and spatially placing the shape of detected defects as a support tool for decision making.	2022

[103]	Research on Automatic Visualization Technology of Bridge Disease Information Based on BIM	China	C	This paper proposes an automatic three-dimensional [3D] matching and visualisation expression method of bridge inspection disease information based on BIM technology, additionally designing the disease database to store the information in a time-sharing classification manner.	2022
[104]	Asset Management of Existing Concrete Bridges Using Digital Twins and BIM: a State-of-the-Art Literature Review	Sweden	J	This study presents a state-of-the-art review of the literature on asset management for bridges using Digital twins [DT], which are still incipient in infrastructure management, for the improvement of Bridge management systems [BMS]. It mainly focuses on complex data flow and software compatibility in DT implementation.	2022
[105]	Framework for Developing IFC-Based 3D Documentation from 2D Bridge Drawings	United States of America	J	The present paper proposes a framework for semiautomatically processing 2D bridge drawings from PDF, converting them into 3D information models, and then converting them into IFC files. The results seem to be qualitatively comparable with the 3D models generated employing the current state-of-the-art method while using just 3.33% of the time necessary for the traditional modelling application.	2022
[106]	A Scoping Review of Information-Modeling Development in Bridge Management Systems	Australia	J	In this study, search resulted in a final refined list of 78 journal articles published in the recent decade, categorised into six different topic areas, listed as follows: Review papers and BMS frameworks; Geometrical modelling, design and inventory data; Cost and construction management; Inspection by computer vision approaches and non-destructive tests; Structural assessment [Load Rating and Condition Examination]; Maintenance optimisation and risk-based prioritisation. By analysing the knowledge gaps, limitations, and emergent works for industrial and academic investigators, it comes out that the main focus of BrIM researchers is on new inspection and test methods and maintenance optimisation with particular attention to concrete structures.	2022
[107]	A BIM Based Approach for Structural Health Monitoring of Bridges	China	J	In this paper, a bridge health monitoring system is developed through the combination of BIM and traditional bridge health monitoring that can organise and visualise a considerable amount of sensor data and subsequent structural health information over a prolonged period. A BIM-enabled platform is utilised to develop the proposed visualisation tool for a long-span bridge and enable automated sensor data inventory.	2022
[108]	Mixed Reality Support for Bridge Inspectors	Germany	C	The paper proposes a mixed analogue and digital workflow that includes Mixed-Reality views that can be ready-to-hand for bridge inspectors during their work at and in a bridge. It employs BIM data that contains 3D geometry-data and additional data about the structure, such as previous damage reports.	2022

[109]	Creation of a Mock-up Bridge Digital Twin by Fusing Intelligent Transportation Systems (ITS) Data into Bridge Information Model (BrIM)	United States of America	J	Weigh-in-motion [WIM] systems can currently detect real-time traffic data; however, these data are stored in standalone databases. This research investigates the feasibility of developing a digital twin of a mock-up bridge by integrating WIM data into a BrIM model. The system was validated by first creating a mock-up bridge with affixed weight sensors attached to microcomputers and then developing a BrIM model and passing scaled vehicles over in real time with varying weight capacities.	2022
[110]	Virtual trial assembly of steel structure based on BIM platform	China	J	With regard to the application of BIM in the manufacturing stage, this study proposed an innovative framework that implements the virtual trial assembly [VTA] of a complex steel structure on a BIM platform. In this study, Revit was used as the research platform, and a VTA program prototype based on the Procrustes Analysis algorithm was developed using the built-in Dynamo visual programming plugin. The prototype was developed with two basic functions: geometric inspection and assembly testing.	2022
[111]	Path Planning and Control of a UAV Fleet in Bridge Management Systems	Italy	J	This work proposes the use of autonomous navigation with a fleet of UAVs for infrastructural inspections. Starting from a digital twin, a solution is provided to problems such as the definition of a set of reference trajectories and the design of a position controller, also providing a workflow to integrate a generic Bridge Management System [BMS] with this type of approach.	2022
[112]	Integration and linking of inspection data in digital bridge models	Germany	J	This article describes approaches for processing large image-based data sets into a linked inspection model. It is then shown how annotations in images and orthophotos are used in the context of idealised simulation models and support the process of condition assessment. The BIM model becomes interactive storage for the management of inspection data.	2022
[113]	A BIM Based Framework for Damage Segmentation, Modeling, and Visualization Using IFC	Germany	J	This study focuses on a framework that incorporates semi-automatic damage data acquisition, transfer, and a damage information model for data exchange via IFC; this enables inspectors to use damage data for subsequent analyses and simulations.	2022
[114]	Condition state prediction of engineering structures based on digital twins and inspection data	Germany	J	The paper presents an approach to derive data driven predictions of the condition states of railway bridges based on BIM and digital building models, linked with inspection and SHM data. Machine Learning [ML] methods are applied to the aggregated data of the bridge structures to provide the basis for reliable decisions in maintenance management.	2022

[115]	Existing infrastructure cost effective informative modelling with multisource sensed data: TLS, MMS and photogrammetry	Italy	J	This paper presents a methodology for the generation of a detailed informative model starting from multi-sources integrated data: terrestrial laser scanning [TLS], Mobile Mapping Systems [MMS], and photogrammetry. The enrichment of the informative model with further data coming from load testing and inspection is presented to create a unique informative platform suitable for different end-users involved in maintenance operations.	2022
[116]	Evaluation and decision-making framework for concrete surface quality based on computer vision and ontology	China	J	Combining ontology and computer vision, this application set up a defect identification quantification framework by using ontology reasoning technology to determine de state of conservation of concrete surfaces. Indeed, this proposed framework can automatically identify and quantify defects and infer the causes, responsibility, severity and repair methods of defects. This paper then presents an evaluation and decision-making tool for the assessment of concrete surface quality so as to improve the standardization and intelligence of surface defect inspection and potentially provide reusable knowledge for future examinations.	2022
[117]	Structural health control of historical steel structures using HBIM	Spain	J	In this paper, a methodology based on an HBIM framework is proposed, developing a model of O Barqueiro, located in Galicia (Spain) aimed at structural health monitoring over time. This model collects, in detail, the geometrical shape, material composition, structural configuration, and additional data required for the control and management of the construction. On the other hand, a calibrated structural model, representing the actual overall mechanical behaviour of the structure, is also automatically generated.	2022
[118]	The Implementation Potentials of BIM in Bridge Maintenance Workflows	Austria	C	The present research dealt with the experimental implementation of the BIM method in the field of bridge maintenance and was carried out in cooperation with the municipal department for bridge maintenance in Vienna as part of the “Public Administration 4.0” project. Due to the success of the digitalization process, it was then adapted to store bridge inspection data.	2022
[119]	BIM-Based Organization of Inspection Data Using Semantic Web Technology for Infrastructure Asset Management	Germany	C	In this paper, a concept for applying BIM models for bridge inspection and the subsequent integration of the results into existing asset management systems is presented. The information for inspection and condition assessment is provided as an information container according to ISO 21597, using semantic Web technologies to describe the information for the structural components, the structural conditions, and the detected damages.	2022
[120]	Combined LOD-Definition for Bridge Maintenance and 3D City Maps	Austria	C	By applying BIM in the field of bridge maintenance and inspection, the research project Austrian Public Administration 4.0 has shown that the required Bridge-BIM-models for bridge inspection can also be used in other areas of public administration, such as 3D City Maps. To make this possible, the intersection of the requirements for geometric and semantic information must be defined from both fields. Since there is no semantic information in the LOD-Definition of the Citygml Standard for 3D City Maps, this needs to be elaborated to complete the LOD interface.	2022

[121]	BIM and BMS: Current Status and Challenges	Serbia, Austria	C	The paper discusses the advantages and challenges in BIM-BMS integration. Most BMS do not support geometric representation that render data collection during inspections quite tedious. The introduction of BIM in BMS can substantially facilitate the collection of inspection data and accurately localize monitoring data. Moreover, the exact geometry of bridges can enhance maintenance planning by simulation of structural behaviour of as-is structure under different environmental actions.	2022
[122]	Evaluation of Mixed Reality Support for Bridge Inspectors Using BIM Data Digital Prototype for a Manual Task with a Long-Lasting Tradition	Germany	J	The research project proposes Mixed Reality [MR] and Virtual Reality [VR] prototypes to support bridge structural inspections. A mixed analogue and digital workflow using BIM data ready for bridge inspectors during on-site work is developed. The system is tested on a German autobahn bridge and the results are evaluated. Some of the challenges faced are lacking BIM data for existing bridges and structures and appropriate user-interfaces in this new application domain, or the need to adopt norms and guidelines for public tender.	2022
[123]	Creating digital twins of existing bridges through AI-based methods	Germany	C	This paper aims to propose a segmentation method that is the basis for a parametric modelling approach to enable the semi-automatic geometric modelling of bridges from point cloud data. To this end, metaheuristic algorithms, fuzzy C-mean clustering, and signal processing algorithms are used.	2022
[124]	Digitalization Processes and Bridge Information Modeling for Existing Bridges	Italy	C	In the present work, HBIM methodologies are implemented for the creation of a damage database and new approaches are tested for the application of the guidelines directly on the BIM environment. HBIM models of the dismantled structures of Largo Grosseto bridge have been created using two different methodologies: Parametric modelling and Mesh-to-BIM process, to later upload the damage information previously recovered.	2022
[125]	1st Conference of the European Association on Quality Control of Bridges and Structures, EUROSTRUCT 2021	Italy	C	The proceedings contain 161 papers, focusing on the first "European Association on Quality Control of Bridges and Structures" conference, held at the university of Padua from August 29th to September 1st.	2022
[126]	18th International Road Federation World Meeting and Exhibition, 2021	Dubai	C	The proceedings contain 86 papers. The special focus in this conference is on Road Federation World Meeting and Exhibition. The topics include, among others: Damage Inspection, Structural Evaluation and Rehabilitation of a Balanced Cantilever Bridge with Center Hinges; reinforcement of Scoured Pile Group Bridge Foundations with Spun Micro Piles; repair of Settled Pile Bent Bridge Foundations with Spun Micro Piles; overview of Integral Abutment Bridge Applications in the United States; Construction and Maintenance Using BIM; Demonstrating Connectivity and Exchange of Data Between BIM and Asset Management Systems in Road Infrastructure Asset Management; and so on.	2022

[127]	The measurements of surface defect area with an RGB-D camera for a BIM-backed bridge inspection	Poland	J	Latest generation RGB-D cameras coupled with tabled are used to acquire and then extract the defect area, creating a 3D representation of it. Even though the localisation of the defects was proven not to be that easy the proposed application goes in the direction of a BIM-based Bridge Management System to be used in decision-making process regarding repairs.	2021
[11]	A Digital Information Model Framework for UAS-Enabled Bridge Inspection	United Kingdom, Norway	J	This study has proposed a novel methodology for a digital information model covering data acquisition through to a 3D GIS visualisation environment, also capable of integrating within a bridge management system [BMS]. Unmanned aerial systems [UAS] survey has been integrated in the inspection methodology. It particularly focuses on integrating BIM and GIS to provide an efficient information model, additionally creating two interactive visualisation environments for the coordination of the BMS process.	2021
[128]	Digital Twin Aided Vulnerability Assessment and Risk-Based Maintenance Planning of Bridge Infrastructures Exposed to Extreme Conditions	United Kingdom, China	J	This study has further demonstrated the unprecedented applications of digital twins to sustainability and vulnerability assessments, which can enable the next generation risk-based inspection and maintenance framework. The practical integration of digital twins and bridge risk inspection model has been established, on the case study of Zhongcheng Village Bridge in Zhejiang Province, China, in order to become a more effective information platform for all stakeholders.	2021
[129]	Image-Based Automatic Bridge Component Classification Using Deep Learning	South Korea	J	This study developed an image-based automatic bridge component classification network to reduce the time and cost required for converting the visual information of bridges to a digital model. The proposed method comprises two convolutional neural networks. The first network estimates the type of the bridge based on the superstructure, and the second network classifies the bridge components. Results show that the system automatically classified 461 bridges' components with 96.6% accuracy.	2021
[130]	Digital models for e-conservation: the HBrIM of a bridge along the Aterno river	Italy	J	The paper deals with the e-conservation paradigm and discusses the results of an investigation on the potentialities offered by parametric models of historic bridges. It also checks and validates the introduction of the approach advised by recent National regulations, the LG20, in the framework of the Historic Bridge Information Modelling (HBrIM) combining safety and conservation knowledge instances.	2021
[131]	Synthetic data generation using building information models	South Korea	J	The paper proposes a method for generating high-quality synthetic data that includes the automatic annotation of infrastructure scenes. The method consists of three steps: translating BIM images into real-world images; automatically labelling them using the spatial information contained in the BIM to generate various synthetic datasets; and splicing the selected synthetic datasets together to form the final synthetic dataset. The models trained achieved a precision over 70%.	2021
[25]	Digital twin and its implementations in the civil engineering sector	United Kingdom, China	J	Even though the concept of DT is quite diffuse in the civil engineering sector, a unique definition of it still has to be provided. Thus the review paper analysed 468 articles related to DT, BIM and CPS, to propose a DT definition and its constituents in civil engineering. Focusing on the 134 papers mainly related to Digital Twins, they proceeded to cluster the research to draw up a comprehensive state-of-the-art on the topic.	2021

[132]	A BIM-Based Visual Warning Management System for Structural Health Monitoring Integrated with LSTM Network	China	J	In this paper, a visual warning framework of structural health monitoring is proposed based on the BIM platform. The monitoring data bound with the sensors is stored in the database, and the data is mined to obtain the warning information by the deep learning algorithm long short-term memory [LSTM]; moreover, the BIM elements are associated with sensors to make the monitoring area correspond to the BIM model so that the sensor and monitoring area can be visible on the BIM platform and, through the development of an integrated plug-in, the user interface and the database are connected by back-end controls. Finally, the application also integrates the Internet of Things [IoT] technology to automatically control the light indicators based on real-time sensor data.	2021
[133]	Automatic Identification and Geometrical Modeling of Steel Rivets of Historical Structures from Lidar Data	Spain	J	This work presents a novel methodology that allows the automatic identification and 3D modeling of rivets in iron and steel structures from Lidar data. The proposed methodology has been tested with both laboratory specimens and a full-scale real bridge.	2021
[134]	A semantic modeling approach for the automated detection and interpretation of structural damage	Germany	J	In this paper, an approach is proposed towards a machine-based damage evaluation for damage detection on constructions. First, anomalies are detected, classified and assessed automatically within the calculation process of the photogrammetric point cloud. Then, the detected damages are recorded via web ontology generated as a semantic representation. The inferred information is then used to create damage representations in a structural analysis model. Furthermore, the geometrical data are represented within BIM environment and linked to the semantic and structural data via a Multimodel approach.	2021
[135]	Data modeling based on a 3D BIM standard and viewer system for the bridge inspections	Japan	C	In this paper, a 3D bridge information model based on IFC for the support of inspection, evaluation, and maintenance. Various data, such as text, photographs, point clouds, and measured polygon meshes, relating to the inspection, evaluation, and repair of a bridge are linked to the 3D bridge model also developing a viewer system for the visualization in a VR environment.	2021
[136]	Research on key technology of operation and maintenance management of long span railway steel bridge based on BIM	China	C	Taking as a case study one railway steel bridge, the division levels of bridge structural parts, structural elements and specific components were defined, and the refined BIM model of bridge was established based on the demand of operation and maintenance. The resulting BIM model was ready to store inspection data and provided a suitable basis for the implementation of DT.	2021
[137]	Labor productivity improvement of concrete bridge through utilizing bim and ict	Japan	C	Given the shrinking youth workforce in Japan, BIM has been introduced to improve productivity at construction sites. In this project, a digital twin was used to obtain real-time construction data from the construction site of a four-span continuous prestressed concrete box-girder bridge. Construction management through the 4D system in bridge construction equipment, reinforcement inspection using UAV images, and formwork and construction progress inspection using MR technology were tested by combining BIM and ICT technology.	2021

[138]	Digital Support for Bridge Inspectors through Mixed Reality BIM Data Visualizations	Germany	C	The paper describes an interactive augmented and virtual reality [AR/VR] system that supports bridge inspectors during in-office preparation, on-site inspection, and follow-up work back in the office using BIM data, particularly focusing on the prototype implementation. Findings reveal that several issues in data synchronization and communication techniques need to be considered for proper integration into the entire system.	2021
[139]	Application of bridge maintenance and management system with BIM technology	China	C	This paper, based on the successful practice of the Nanjing No.3 Yangtze River Bridge, describes the application of the maintenance and management system in bridges. The system utilizes BIM, GIS, mobile Internet, cloud and other technical means, and combines the practical needs of bridge maintenance and management and the professional knowledge of maintenance and management.	2021
[140]	From condition to performance assessment of bridges - The challenge	Denmark	C	Projects, such as COST TU1406, propose a transition from condition to performance assessment when prioritising inspection and maintenance. Key Performance Indicators [KPI] could be Reliability, Availability, Safety, Environment and Economy. According to the papers, integrating these KPI's, through population-based BIM modelling of Bridge deterioration, can support a risk-based approach when prioritising maintenance works.	2021
[141]	Augmented reality-based safety inspection framework for safety management in railway bridge and tunnel projects	South Korea	J	This study aimed to formalize a framework specialized for railway site safety inspection by utilizing smart technologies, namely Augmented Reality [AR] and BIM. Additionally, to the projection of 3D models and relevant information directly onsite, this system also enables the reprojection of BIM models reflecting the results of initial safety. Furthermore, remote inspection is implemented to allow for precise safety checks that can be performed in a stable indoor environment.	2021
[142]	Application of bridge construction monitoring management system based on Internet	China	C	A bridge construction monitoring information system based on BIM model management was developed. According to the requirements, the bridge site construction monitoring data is transmitted through the Internet of Things, and the embedded artificial intelligence algorithm is used to realize the automatic processing of monitoring data inspection, error analysis and early warning, and control command calculation. The BIM model is used to supplement the bridge construction management for visualization purposes, improving the overall efficiency.	2021
[143]	Data-driven asset management by the Swedish transport administration	Sweden	C	The paper describes how the Swedish Transport Administration is currently working with BIM implementation into the active BMS national system, mainly focusing on standardisation. Drones can be used to inspect bridges and BIM can be used to store the data from building, maintaining and inspections of bridges. BIM is used for new bridges, but, because of the high demands on persistent formats to store data, the BIM models are still transferred to 2D drawings.	2021
[144]	The digital bridge twin [Der digitale brückenzwilling]	Germany	J	A strategy to achieve complete digital maintenance on infrastructures is the realisation of a digital bridge twin. Based on a three-dimensional BIM model of the geometry, the condition can be detected and determined by combining cyclic results from bridge inspections and other diagnostic evaluations supplemented by real-time monitoring data. Therefore, the paper gives an overview of the concept of digital bridge twins and the potential for geodetic techniques in supporting the transition to digital infrastructure.	2021

[145]	Unmanned Aerial Vehicles as a Tool for Monitoring and Protection of Physical Infrastructure Systems	Slovakia	C	The aim of the paper is to present the possibilities of using unmanned aerial vehicles in selected industrial applications such as inspections in energy, monitoring of traffic flow and transport infrastructure elements, creation of the BIM (Building Information Model) system, etc. The paper contains an overview of the commercial use of UAVs in practice, as well as in security services and operational activities within rescue services.	2021
[146]	Exploring the Application of BIM Technology in Bridge Inspection	China	C	BIM in China is not so frequently used for bridge maintenance, this paper aims at employing BIM to try to overcome the shortcomings of bridge inspections, via primitive experimentation on visualisation and database setting up.	2020
[147]	Integration of Extended IFC-BIM and Ontology for Information Management of Bridge Inspection	South Korea	J	This research aims to establish the benefits of utilising the extended industry foundation class [IFC]-BIM and ontology for bridge inspection information management. The IFC entities were extended to represent the bridge objects, with the final objective being capable of retrieving bridge inspection data via queries from the IFC-BIM model	2020
[59]	State of the art in damage information modeling for RC bridges - A literature review	Germany	J	Based on the analyses of German RC bridges' life-cycle, this paper analyses the requirements which arise from practice and the research done in modeling damage and related information for bridges, especially focusing on the issues related to lack of standardisation and the fallout on data exchange.	2020
[148]	Bridge damage: Detection, IFC-based semantic enrichment and visualization	Serbia, Germany	J	This paper presents an approach for point cloud-based detection of spalling damage, as well as integrating damage components into an as-built BIM via semantic enrichment of an as-built Industry Foundation Classes [IFC] model. Multiview-classification is used and evaluated for the detection of spalling damage features, thus enriching inspection data within the BMS by adding visual representation of the Bridges BIM models.	2020
[149]	Research on Construction of Highway Bridge Quality Engineering Based on BIM Technology	China	C	This research is based on fully investigating the experience of domestic large-scale bridge quality engineering construction, combining the engineering characteristics of highways, and proposing the application of BIM technology to achieve information sharing and collaborative operations in project management.	2020
[150]	Assessment of State-of-the-Art Methods for Bridge Inspection: case study	Poland	J	A state-of-the-art method was implemented, taking into account each step starting from data acquisition and ending on BIM model enrichment. Additionally, the deep learning cracks semantic segmentation algorithm results were compared with human inspections ones.	2020
[151]	Concept for BIM-based maintenance of engineering structures with monitoring systems	Germany	J	The present work lays the foundations for developing a digitally supported maintenance system of railway bridges by the interlocking of BIM and SHM to enable predictive maintenance management and thus improve the reliability of engineering structures over their lifetime.	2020

[152]	smartBridge Hamburg - prototypische Pilotierung eines digitalen Zwillings	Germany	J	Therefore, the Hamburg Port Authority (HPA) has initiated the smartBridge Hamburg project, which prototypically tests the concept of the digital twin using the Koehlbrandbruecke in Hamburg. The paper presents the premises and basic considerations to initiate the implementation of digital twins to conceptually unify the BIM models with analogue and electronic assessment pieces of information so as to provide aggregated data in any forms required by the different user groups.	2020
[153]	RPAS-Based Framework for Simplified Seismic Risk Assessment of Italian RC-Bridges	Italy	J	To connect the UAS technologies' advantages to the seismic risk assessment of bridges, a simplified mechanic-based procedure is described, oriented to map the structural risk in road networks and support prioritisation strategies. Future developments may include automatic algorithms to extract and manage data for BIM storage or to address analytical structural assessment processes.	2020
[154]	Identifying Considerations for Developing SLAM-based Mobile Scan Backpack System for Rapid Building Scanning	South Korea	J	This paper proposes the mobile scan system, framework, and component structure to derive the considerations, analyse the results, and improve scan productivity.	2020
[155]	Optimization on the intellectual monitoring system for structures based on acoustic emission and data mining	China	J	This paper proposes an innovative concept combining Acoustic Emission [AE] and Data Mining [DM] on fog computing and centralized management. Firstly, raw data are collected by the AE sensors system and transformed into fog node for DM, including removing useless data, consolidating, organizing, and visualizing the result. This idea is verified by a systematic experiment and a real-world application on two real bridges for detecting a critical point.	2020
[156]	Construction Method of Cable-Stayed Bridge Based on BIM Platform	China	C	The research method of this paper is to apply BIM technology to the construction, operation, maintenance and management of steel box laminated beam cable-stayed bridge based on Revit, a BIM authoring software. Combined with the experimental research of bridge engineering, the 3D model of the bridge structure was built. The BIM model was used to check the collision inspection of components in the basic components of the bridge, provide accurate engineering quantity statistics of bridge construction materials and define the two-dimensional plane plan.	2020
[157]	BIM-based innovative bridge maintenance system using augmented reality technology	South Korea	B	This paper proposed an innovative BMS that, using a schematic BIM-based information management system, links the model to automated inspection tasks via augmented reality [AR] devices, applied on an existing cable-stayed bridge. An integrated digital model is created to store, manipulate and share the inspection data and maintenance history. On the other hand, the onsite inspection task is timely performed, with the AR device enhancing its precision and performance.	2020

[158]	Application of BIM in Bridge Engineering and Its Risk Analysis	China	C	This article explores the development characteristics of BIM technology in the bridge industry; combined with the current status of BIM in bridge engineering, it is found that it brings greater value in the design, construction, maintenance, and inspection stages. It further discusses risk analysis and countermeasures undertaken via BIM technology based on human resources, process management, economy, technology, and policy environment.	2020
[159]	An automated approach to digitise railway bridges	United Kingdom	C	This paper presents a strategic approach for an effective solution to automating the traditional process of surveying and processing point cloud data, with further automation of implementing an automated bridge generation approach to large and complex cloud data sets. The presented digital method aims at generating a digital asset from the point cloud with the potential to produce BIM models to support surveyors and engineers in identifying defects through various digital means.	2020
[160]	Mobile mapping, machine learning and digital twin for road infrastructure monitoring and maintenance: Case study of Mohammed VI bridge in Morocco	Morocco	C	This work presents a general vision and a justification for integrating DT technology with geospatial data. The paper examines the benefits of integrating 3D GIS data acquired by automated mobile mapping [MMS] workflows for modelling the reality of a major bridge infrastructure in Morocco. This allowed to study the future performance of this bridge structure on virtual twin structures under different environmental conditions.	2020
[161]	State-of-the-art review of bridge informatization and intelligent bridge in 2019	China	J	To reveal the progress and trend in BrIM digitisation, this paper reviews related research worldwide in 2019, with regard to bridge informatization, intelligent inspection, high-performance intelligent materials, and intelligent disaster prevention/mitigation, and proposes prospects of future research opportunities. According to the review, BIM technologies can significantly improve the productivity, performance, and integration of construction, maintenance, and management of bridges, while smart inspection technologies and AI applications continuously enrich bridge monitoring systems, improving accuracy and efficiency.	2020
[162]	Modeling geometry and semantics of physical damages using IFC	Germany	C	This paper presents two different approaches to model physical damages using the Industry Foundation Classes [IFC]. Finally, the modelling concepts are tested with multiple BIM applications. Although the tests show that IFC can model physical damages, current software tools do not support IFC up to its full potential.	2020
[163]	Study and Application of Key Technologies in Intelligent Construction of Railway Continuous Beam Bridge	China	J	According to the characteristics of railway continuous beam bridge project and the key procedure of construction control, this paper proposes the intelligent construction solution of railway continuous beam bridge, and the setting up of an intelligent framework system for comprehensive management and key link management and control. BIM-based construction simulation and scheme optimization of Block 0, high formwork monitoring, prestressed construction automation, and alignment are proposed. The quality traceability of the process is tested on Beijing-Zhangjiakou and Beijing-Xiongan high-speed railways.	2020

[164]	System Identification-Enhanced Visualization Tool for Infrastructure Monitoring and Maintenance	Canada	J	The objective of this paper is to take one step forward from static toward dynamic BIM by representing and visualizing real-time SHM data. The proposed framework features an online visualization of data, real-time system identification and tracking, and efficient decision-making. The application is then validated on a BIM-SHM integrated system representing a steel bridge located in London, Ontario (Canada).	2020
[165]	Development of a Bridge Management System Based on the Building Information Modeling Technology	China	J	A BMS that could help to improve the management for the maintenance of massive bridges in China is proposed. In detail, a collaborative Web-BIM-oriented platform is designed, also introducing portable devices into the system.	2019
[166]	A Study on Integrated Information System for BIM Application of Bridge Maintenance	South Korea	J	In this study, the information items necessary for the safety inspection, valuation, and durability life prediction of the bridges are organised by analysing existing research and guideline. Thus, organising this information for an eventual application for the development of a BIM-oriented management system.	2019
[167]	Research on application of BIM technology in municipal road construction	China	C	Based on the application characteristics and advantages of BIM technology, this paper aims to study some details of BIM technology in municipal road construction. In order for the proposed research to provide technical guidance for their construction and management.	2019
[168]	Improved visualization of infrastructure monitoring data using building information modeling	Canada	J	In this article, BIM is utilised as a promising computing environment and integrated digital representation platform of SHM that can organise and visualise a considerable amount of sensor data and subsequent structural health information over a prolonged period for long-span bridges enabling sensor data inventory. The proposed method can be considered a user-friendly and economic framework for condition assessment and disaster mitigation of structures from long-term monitored data.	2019
[169]	Investigation of the lifetime extension of bridges, using three-dimensional CIM data	Japan	C	Since 2016, Japan has been promoting the digitisation of the construction process. The primary objective is to shift the data format from conventional two-dimensional data to three-dimensional data, which will then be used to unitarily manage the design, construction, maintenance and investigation of bridges, with the ultimate goal being to minimize the burden of future maintenance and management. Thus, a workflow for the maintenance of small bridges via CIM [Civil Information Modeling] is proposed.	2019
[170]	Selected Bearing Problems of Old Railway Bridges Located on Mining Areas in Poland	Poland	C	The article describes how mining exploitation affects bridge bearings and the conditions that bearings should fulfil on mining areas in Poland. The article also draws attention to the necessity of frequent monitoring of bearing condition due to the possibility of sudden damage. Thus, examples of Polish experiences are given, i.e., working SHM (Structural Health Monitoring) system is described to emphasise the need to implement it for monitoring Polish old railway bridges within a BIM environment.	2019

[171]	Unmanned aerial vehicle (UAV) enabled building information modeling for bridge inspection	United States of America	C	An approach to model component-wise damage information of inspected bridges, tested on a Colorado bridge, is presented. Using UAV-enabled photogrammetry and unsupervised machine learning techniques, this system can automatically identify the bridge components from a 3D point cloud with minimal user input; then the BIM model is prepared according to the segmented point cloud, and the damage is mapped onto the corresponding components.	2019
[172]	The future of BIM and Bridge Management Systems	Serbia	C	The paper discusses the BIM requirements both from the owner and operators sides and shows where these deviate from design and construction needs. It presents a conceptual framework for integrating BIM in BMS developed by the authors in recent years.	2019
[173]	Application of BIM Technology in Zhuhai Port Project of Hong Kong-Zhuhai-Macao Bridge	China	C	Taking the Zhuhai Port Project of Hong Kong-Zhuhai-Macao Bridge as an example, the paper analyses the application of BIM technology in large-scale and complex projects. The project adopts BIM technology for management and cost estimation to simulate the plane layout construction, carry out collision inspection of pipelines, and evaluate the installation of large-scale steel roof.	2019
[174]	Design and Development of Digital Operation and Maintenance System for Hutong Yangtze River Bridge	China	J	Relying on the operation and maintenance plan of Hutong Yangtze River Bridge, this work presented one novel and digital operation and top-level maintenance design of large railway bridges. The proposed top-level design involved: the acquisition and management of multi-source information, intelligent structural analysis and condition assessment of bridge structure, and smart maintenance of bridge structure applied to large-span railway bridges. The feasibility of introducing BIM, SHM, electronic inspection terminal, and visual inspection system is also discussed.	2019
[175]	Application of 3D bridge information modeling in the life-cycle of bridges	Italy	C	This paper proposes technologies available to generate, manage, and enrich the bridge 3D model with intelligent information from construction to design and inspection.	2019
[176]	Optical methods and wireless sensors for monitoring of bridges	Sweden	C	In Sweden, six railway bridges have been scanned using infrared scanning [IR], close-range photogrammetry [CRP] and terrestrial laser scanning [TLS] to evaluate the potential of the technologies for BIM and assessment purposes. The wireless sensors monitoring system consists of a base station that receives signals and the node antennas that transmits the signals to the cloud. The results assessment considers the accuracy and quality of the point clouds, time consumption, safety, and traffic disturbance.	2019
[177]	Intelligent, sustainable and integrated system of management of structures	Spain	C	In Spain, the SISGES project was conceived and aimed at developing a smart bridge management system capable of making rational decisions regarding the maintenance and repair of existing structures. The SISGES platform comprises remote inspection technology, which reduces the inspection times and costs while increasing workers' safety; continuous monitoring technologies, registering displacements, vibrations, temperature and humidity; scanning technologies to create three-dimensional models of the structures and BIM technologies to assign each element with an attribute.	2019

[178]	BIM authoring for an image-based bridge maintenance system of existing cable-supported bridges	South Korea	C	The paper presents a pilot BIM-oriented BMS system for a cable-supported bridge. Data management for this BMS is separated into two modules: site inspection system and information management system. Specifically, once the CDE has been created, the information management phase aims at optimising damage detection from the images acquired during on-site inspections and at converting them into vector data to keep the BMS updated for automatised technical report generation.	2018
[179]	Research on Bridge Management System Based on BIM Technology	China	C	The BIM technology is applied in Bridge Management System [BMS]. The first step is to parameterise the bridge structure information during its whole life cycle, including geometric and physical information, load information, detection information, evaluation information and maintenance information of bridge. A final as-built BIM model combines data from the SHM system and the bridge technical condition inspection results to simulate maintenance plans.	2018
[180]	Automatic As-Built BIM Creation of Precast Concrete Bridge Deck Panels Using Laser Scan Data	South Korea, China	J	This study develops a technique to automatically estimate the dimensions of precast concrete bridge deck panels and create as-built BIM models to store the real dimensions of the panels. Noise-filtered scan data has been used to automatically generate the as-built geometry and validate the proposed technique both on a laboratory-scale specimen and on a full-scale precast concrete bridge deck panel, with a resulting accuracy of about 3 mm.	2018
[181]	BIM related workflow for an image-based deformation monitoring of bridges	Germany	C	The paper shows a case study of UAS-based monitoring of bridge pier deformations. An approach for a simplified extraction of basic geometries from 3D point clouds for quantifying deformations generated from aerial images by using Computer Vision methods is introduced to develop a reproducible workflow for change detection and condition documentation within a BIM environment.	2018
[182]	Integrating RC Bridge Defect Information into BIM Models	United Kingdom, Germany, Israel	J	This paper presents an exploratory analysis and as a result, an information model and a candidate binding to Industry Foundation Classes (IFC) to categorise inspection information on RC bridges and to standardise storage of this information in a format suitable for sharing and comparing it between different users and varying requirements. First, types of defects and properties needed for bridge assessment were extracted from existing bridge inspection manuals. Second, the authors modelled the defect entities, their properties, and their relationships, and third, mapped them to appropriate IFC entities.	2018
[183]	Repair and Retrofitting of Bridges - Present and Future	Australia	C	The paper discusses the main challenges for optimum bridge management, proposing a methodology for inspection, monitoring, and asset management. It presents a critical discussion, with possible future developments, on the following topics: BIM; the need for the setting up of a unified database of bridge assets; the requirements for structure repairs, also suggesting the use of 3D printing; and the principal standards for bridge maintenance in different countries.	2018
[184]	Developing Information Model for Multi-Purpose Utility Tunnel Lifecycle Management	Canada	C	A Multi-purpose utility tunnel [MUT] is one of the civil infrastructures in urban areas which accommodates several networks, such as electrical cables, gas, water, and sewer pipes, inside a tunnel. This paper investigates a method for extending BIM to MUT [MUTIM] projects taking advantage of similar developments for other infrastructure systems. The stages concerning design review for checking compliance with standards and constructability and 3D coordination for clash detection and resolution are discussed in further detail.	2018

[52]	Building Information Modeling (BIM) for transportation infrastructure - Literature review, applications, challenges, and recommendations	United States of America	J	This paper aims to provide a comprehensive, up-to-date literature review and critical analysis of research areas regarding BIM for transportation infrastructure to facilitate research and applications in this domain further. The results show that the use of BIM for transportation infrastructure has been increasing, although the research has mainly been focusing on roads, highways, and bridges; additionally, they also reveal a significant need for a standard neutral exchange format and schema to promote interoperability.	2018
[185]	4D beyond construction: Spatio-temporal and life-cyclic modeling and visualization of Infrastructure data	United States of America	J	In this approach, various data categories such as inspection reports, maintenance schedules and costs, operation schedules, and elements' semantics is integrated with infrastructure 3D models also employing 4D technology, thus enabling its spatio-temporal exploration. The introduced technique allows the data visualization via a color-coding scheme and provides customized query and information retrieval support. Therefore the technique, which can also be integrated with degradation models, shows an increase in the accuracy of maintenance tasks by 20-40% and a reduction of their duration by 30-50%.	2018
[186]	SeeBridge as next generation bridge inspection: Overview, Information Delivery Manual and Model View Definition	Israel, Germany, United Kingdom	J	A next-generation integrated bridge inspection system, called SeeBridge, has been proposed. An Information Delivery Manual [IDM] was compiled to specify the technical components, activities and information exchanges in the SeeBridge process, and a Model View Definition [MVD] – bound to the IFC4 Add2 data schema standard – was prepared to specify the data exchange schema to serve the IDM. The development underlines the real potential for automated inspection.	2018
[187]	Creation of "live data" for existing infrastructure	Denmark	C	A recent project concerning the central railway line in Montenegro comprised visual, detailed and special inspection, condition evaluation and action plan for rehabilitation works on all tunnels and galleries. In order to develop a fully digital approach, an initial visual inspection was performed via video recording; then, a laser scanning survey was carried out. A purpose-made inspection database was used for registration of observations on site, so as to generate Action Plans for Rehabilitation directly from data stored in the Inspection Database.	2018
[188]	An information modeling framework for bridge monitoring	United States of America	J	This paper presents an information modeling framework for supporting bridge monitoring applications aimed to extend prior considerations on OpenBrIM standards. Implementation of the framework allows further capture of the information relevant to engineering analysis and sensor networks while employing an open-source NoSQL database system for scalability, flexibility, and performance. The test case utilizes bridge information and sensor data collected from the Telegraph Road Bridge located in Monroe, Michigan.	2017
[189]	Leveraging BIM and Big Data to deliver well maintained highways	United Kingdom; Pakistan; France	J	This paper provides an enhanced understanding of new opportunities created to optimise operations of highway infrastructure using the recent growth in Big Data analytics and data integration technologies. The system architecture designed for this research is translated into a prototype system; however, it needs to be tested and validated by end users to be transformed into a useful solution for the industry.	2017

[190]	Management of the M4 Elevated Section substructures	United Kingdom	J	The M4 Elevated Section in west London is a 1.9 km concrete viaduct structure providing a major arterial route into London. An intervention model bringing together structural assessment, corrosion, and crack monitoring data plus current and future predicted conditions have been developed in a 3D visual platform to enable structural rehabilitation, further assessment and extensive monitoring. Thus, the paper discusses the development of the 3D model, the prioritisation process, deterioration modelling, and the advanced structural analysis used to formulate the strengthening and maintenance programme for the substructures.	2017
[191]	A study on BIM application for the efficient maintenance management of bridge structures	South Korea	J	This paper suggests an improvement plan for the facility maintenance management system [FMMS] through the BIM application of bridge safety inspection. First, the current situation of FMMS-based bridge inspection was analyzed. Second, the improvement requirements were defined, and the current system solution was deduced, defining the requirements for BIM application.	2017
[192]	A PHM system for bridge monitoring on high speed railway	China	C	This paper first proposes the prognostic and health management [PHM] system for bridges on high-speed railway. This new system is a user-oriented tool, providing guidance or information for inspection, repair and maintenance of bridges. The collected data, concerning multi-resource, including design and construction information, and intelligent inspection results, are then visualised via BIM and GIS.	2017
[193]	A review of Building Information Modelling (BIM)-based building condition assessment concept	Malaysia	J	The purpose of this conceptual paper is to study the potential of BIM in building condition assessment practice, by means of a literature review, and covers previous research, guidelines, reports, and other sources that were related to the subject. This framework aims to demonstrate the need to implement Building Condition Assessment to achieve good facility management practices for preventive maintenance, repair, and upgrading work.	2017
[194]	Bridge Information Modeling for Inspection and Evaluation	United States of America	J	A method and prototype implementation for tracking and assessing the structural condition of bridges is presented. Via custom developed add-ins the information about the damage type, amount, severity and location is gathered, to be subsequently analysed to provide performance and load ratings.	2016
[195]	Defining a conceptual framework for the integration of modelling and advanced imaging for improving the reliability and efficiency of bridge assessments	Australia	J	The paper proposes a conceptual framework for the integration of BIM and advanced computing and imaging techniques. Indeed keypoint-based texture recognition applications are developed to defect such as Cracking, corrosion or settlement in bridge components, to be later stored as object's properties into the BIM model developed starting from laser scanning data.	2016

[196]	Application of BIM-based 5D construction technique to Chenglang Bridge	China	C	The paper adopts BIM technology to simulate the construction process of the Chenglang Bridge, realises the project's overall planning, and explores the construction management experience in the application of BIM technology through the entire life-cycle of bridgework. BIM application aims to optimise the construction process, laying the foundation for future implementation in bridgework.	2016
[197]	Virtualizing infrastructure	United Kingdom	C	The paper presents the novel research conducted at the University of Cambridge on inexpensive methods for generating object-oriented infrastructure geometry, detecting and mapping visible defects on the resulting BIM, and automatically extracting spatial defect measurements. The results of these methods are further exploited through their application in Design for Manufacturing and Assembly [DfMA] in order to be further integrated into augmented-reality-mobile inspection tools.	2016
[198]	Structural health monitoring and maintenance aided by building information modelling and repair information tools	United States of America	C	The paper presents both a top-down and a bottom-up approach. The top-down approach starts with a draft Level of Detail (LOD 100) concerning the descriptions of sensor and repair designs, followed by medium-level (200-300) organized representations of sensor data mapped onto BIM structural layouts, and then higher-level analysis and decision-influencing representations. The bottom-up approach aims to develop BIM-SHM framework from field tests on bridges and buildings. Finally, a Repair Information Decision Making [RIMD] tool for concrete structures is presented with the potential to be integrated into BIM.	2016
[199]	Development of new system for detection of bridges construction defects using terrestrial laser remote sensing technology	Egypt, Canada	J	This research represents an automated advance to register laser remote sensing data to compare it with as-built BrIM model of constructed bridges. Experimental work is carried out to confirm the planned method for monitoring the structural defects through a case study, i.e., the Jacques Cartier Bridge in Canada, so as to implement the design and inspection data.	2016
[200]	Improvement opportunity to bridge inspections in Brazil	Brazil	C	This article seeks to identify opportunities for improvement in the inspection of bridges in Brazil. The Bridges Inspection Manual published by the National Bureau of Brazil's Transport Infrastructure [DNIT] was developed in 2004 and is the official reference source for professional training and inspection procedures standardization.	2016
[201]	Design checks and nonlinear response of a full 3D model of a box girder bridge	The Netherlands, Brazil	C	A 17-span double-box girder bridge with a length of 974 meters and width of 16.85 meters in the north of the Netherlands, showing shear cracks, has been analysed using the newly developed "Stiffness Adaptation" [STiffness ADAPtation] method in the DIANA Finite Element program. Thus, a BIM model has been generated through automatic mesh generating procedures starting from the CAD data, presenting a novel approach for designing and assessing structures using 3D finite element analysis.	2016

[202]	Improved Method for Increasing Maintenance Efficiency of Construction Structure Using Augmented Reality by Marker-Less Method	South Korea	J	A SURF algorithm is used to link the 3D objects in the design and construction phases to the maintenance phase. The method could also improve the efficiency of visual inspection on construction structures by implementing the augmented reality technology at the maintenance stage.	2015
[203]	Automated quality inspection of precast concrete elements with irregular shapes using terrestrial laser scanner and BIM technology	China, South Korea	C	This study advances the author's previous work on automated dimension estimation of precast concrete elements so as to include irregular shapes. Once all the point cloud data points have been registered onto different surfaces of the as-designed objects in BIM, the as-built dimensions of the precast concrete element are extracted and compared with the as-design ones in BIM.	2015
[204]	Challenges in generation of as-is bridge information model: A case study	United States of America	C	There are several challenges for researchers and bridge practitioners who intend to create an integrated as-is model based repository. This paper discusses these challenges in detail through a case study on an overpass bridgein the USA. The findings include the issue related to information extraction from documentation, 3D modelling and updating, and 3D model augmentation, for creating as-is bridge information model [BrIM].	2015
[205]	Bridge Asset Management in Hertfordshire - Now and in the future	United Kingdom	C	As of 2015, the approach in Hertfordshire aimed to achieve long-term performance in service levels, resilience, budget certainty and efficiency within an environment of increasing traffic, climate change and ageing infrastructure. Technological developments in automated bridge inspection and photogrammetry were expected to positively impact on bridge stock management; indeed, national initiatives included research on implementation of BIM in Asset Management, better understanding of bridge deterioration and development of a National Bridge Condition Reporting methodology.	2015
[206]	Bridge management system implementation for Italian highways: From Pontis ® towards SIOS (Sistema Ispettivo Opere Sineco) and new generation systems	Italy	C	This article focuses on converting the BMS called Pontis, used by the Italian private company Sineco since 2002, from a well-organised database, to a web based system, capable of bridge management analysis. Sineco employed a BMS and served as support for the development of SIOS [Sistema Ispettivo Opere Sineco], thus the paper further describes the ongoing development of SIOS and its correlation with seismic analysis data and new generation design and inspection systems. Finally, a hint to BIM technology integration is provided.	2014

[207]	2014 International Conference on Materials Science and Computational Engineering, ICMSCE 2014	China	C	The proceedings contain 1116 papers. The special focus in this conference is on Material Sciences and Computational Engineering. The topics include, among others: development of bridge concealment engineering state detection technology; influencing factors of laws of bending force on railway bridge; methods to get template for ultrasonic inspection; the application of BIM technology to improve the installation accuracy of curtain; and so on.	2014
[208]	Visualizing bridge inspection with 2D software	United States of America	C	A true 4D BIM approach remains a challenge in the field due to hardware requirements and user skill demands. A new 2D approach has been implemented with a software system on lightweight digital tablets designed to annotate plan documents and photos. The software captures quantitative and qualitative observations with near real-time cloud-based multi-user synchronization.	2013
[209]	Formulation of a framework for quality assessment of precast concrete based on 3D laser scanning	South Korea, China	C	This study presents a framework for quality inspection of precast concrete components using the 3D laser scanning technique. First, practical guidelines, including detailed inspection procedure, selection of optimized scanner and scan location, inspection criteria, and data storage and delivery system, were formulated; then, the feasibility of the proposed approach was tested on a case study by inspecting the quality of a lab-scale object assumed as a precast concrete component.	2013
[210]	Thermographic analysis from UAV platforms for energy efficiency retrofit applications	Italy	J	In this paper a methodology for automated generation of 3D model of buildings from laser data and integration with thermal images is presented. The developed methodology also allows fusion of Infrared Thermography [IRT] data acquired from different cameras and platforms, i.e., via Unmanned Aerial Vehicle. The proposed methodology is suitable for fast building inspections aimed at detecting the thermal anomalies in a construction.	2013
[211]	Integrated modeling systems for bridge asset management - Case study	United States of America	C	The described approach is based on the integration of existing commercial bridge software, BIM techniques, and other applications to the life-cycle management of existing bridge assets. A case study is presented with an application to a medium-span steel truss bridge.	2012
[212]	2012 Proceedings of the 29th International Symposium of Automation and Robotics in Construction, ISARC 2012	The Netherlands	C	The proceedings contain 96 papers. The topics discussed include, among others: smart-BIM; national guidelines for bridge information modeling and automation; BIM functions for optimized construction management in civil engineering; an integrated system for automated construction progress visualization using IFC-based BIM; automated prediction of condition state rating in bridge inspection; and so on.	2012

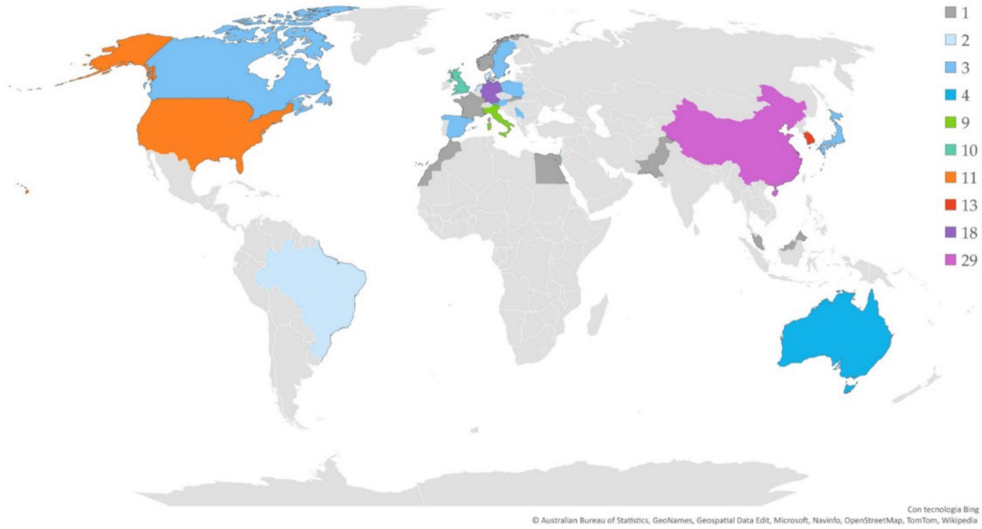


Figure 4.25 – Diagram graphically summarising the distribution of publications worldwide [AoE]

Among the 60 extensive papers concerning BIM, inspections, and bridges, six of them [106,109,130,161,189,199], decided to adopt the acronym BrIM [*Bridge Information Modelling*]. Moreover, only a few explicitly discuss *Structural Health Monitoring* [SHM] [107,114,117,132,151,164,168,174] and *Bridge Management Systems* [BMS] [11,104,106,111,127,148,157,213]. The most generic papers mainly focus on *optimisation* in the design [106,163,189] and construction process [117,134,161,202,210], data *advanced visualisation* [106,107,164,168,174,185] and the setting up of *digital platforms* [101,107,110,115,128,132,165,168,190,210] falling within the BIM 6th Dimension paradigm. Particularly relevant is the next-generation inspection system proposed by Sacks et al. [186], including the *Information Delivery Manual* [IDM] and the *Model View Definition* [MVD] linked to the IFC 4 Add2 standard.

Furthermore, the open exchange formats, i.e., *Industry Foundation Classes* [IFC] and the issues connected with their proper semantization and full integration within the BIM authoring software are addressed [52,102,105,111,113,147,148,182,186].

A particularly interesting theme is the implementation of *Digital Twins* [DT] into the BIM environment [25,104,109,111,112,128,130,144,152]. As a matter of fact, DT implementation cannot disregard the setting up of *sensor networks* [107,109,132,152,155,168,188], connected to the digital models via the so-called *Internet of Things* [IoT] technology [109,132,152].

Equally important is then to employ *Artificial Intelligence* [AI] to sort out data [114,150,161], together with *Data Mining* [DM] [132,155], *Machine Learning* [ML] [113,148], *Deep Learning* [DL] [132,150], and other *automated algorithms*

[133,202]. Namely, various kinds of ad hoc developed algorithms are vital for the implementation of automatic recognition applications from *LiDAR/Laser* survey data [133,154,195] and *photogrammetric* survey data [180,210].
More in general, said automated procedures are applied to *LiDAR* survey data, i.e., *point clouds* [133], *Terrestrial Laser Scanner* [TLS] point cloud [115,195,199], *Mobile Scanners* [154] point clouds, or *photogrammetric* point clouds [115,127,134,150,153,180], calculated from UAS [*Unmanned Aerial Systems*] shots [11,111,112,153], occasionally acquired through differ passive sensors, e.g., *thermo-cameras* [210]. The *semantization* applications developed from survey data generally concern damage detection [25,113,116,134,148,150,161,195]. On the side also a few Scan-to-HBIM practices are included [114,117,151].
Other main topics concern *virtualisation* [193], which can additionally employ *Visual Programming Language* [VPL] [110]. Alternative to the general virtualisation, there are *Augmented Reality* [AR] [141,157,202], *Virtual Reality* [VR] [193], *Mixed Reality* [MR] [101,122], and *Computer Vision* applications [106,116].

Italian applications on bridge digitisation and LG20 implementation

In the past, applications aimed at building up an Italian BMS for the national motorway network have seen private companies translating international protocols to be consistent with the Italian regulation, as in the case of the BMS proposed by Sineco S.p.A.[39]

Sineco selected the AASHTO [American Association of State Highway and Transportation Officials] Bridge Management System – called Pontis – as the bridge management system tool that better suited the italian user necessities. Indeed, they needed a system not only for inventory and inspection data collection, but especially for programming purposes. Therefore, in a 2012 study [214] they reported the description and comparison between the two different inspection methods: the first one being the one applied within Sineco company, and the second one, the AASHTO element level inspection. Since 2002 Sineco and Archimede have been cooperating in Pontis implementation, intended to choose the optimal bridge network maintenance or improvement policies, consistent with Italian agency's usual policies, long term targets and budget constraints on the basis of inspection data recorded by Sineco. Inspections are carried out with the purpose of ascertaining the consistency and safety of structures so as to ensure the structure's state of deterioration. Thus, a great quantity of data is available, obtained from inspection procedures; what Sineco was looking for was a system that could be used both as a database, both as a management tool, with the purpose of predicting future needs and programming and prioritising works and projects.

Furthermore, in a 2014 [206] follow up to the 2012 conference proceeding, Sineco presented the ongoing development of SIOS [*Sistema Ispettivo Opere Sineco*] company and its correlation with seismic analysis data and new generation design and inspection systems. The emphasis was put on the effort performed in converting the Sineco well-organised database to a web-based system, capable of bridge management analysis for engineering applications.

Generally speaking, the problem of the securing ageing infrastructure in Italy, is usually addressed by means of a scan-to-BIM approach. Anyhow the paradigm needs to be re-engineered to o better support infrastructure management. The acquisition of primary data is only the first step of the maintenance workflow. Indeed, even if the adoption of informative content models for structural health monitoring [SHM] for large infrastructures clearly presents important advantages

[39] Sineco S.p.A. is a private limited company that operates in the engineering sector and which controls more than 1200 Km of national motorway network. Sineco collaborates with Archimede S.R.L., an italian engineering company, performing design and engineering consulting and responsible on Pontis italian application [214].

compared with standard management; the adoption of proper tools for such complex infrastructures poses some issues that need to be solved to develop smooth management and maintenance workflows [115].
Thus, italian applications most of the time focuses the accurate informative modelling of the heritage structures and compare the different techniques to determine the best results, such as in the case of Previtali et al. who dealt with the Scan-to-BIM modelling of the Azzone Visconti Bridge [115]. The quality of the 3D models derived from TLS, MMS and photogrammetry surveys is analysed and compared in-depth. The necessity for the BIM to store further data, e.g., loading test results and photogrammetric documentation, is also dealt with, by implementing of a levelling campaign, carried out to evaluate deformations in the loading phase of the bridge under different load configuration. Vertical displacements have been directly correlated to 3D BIM also including links to reports and images with the purpose of faithfully representing the detected reality and consequently increase the reliability of the data extractable from As-Built BrIM models.
Additionally to TLS techniques, *Unmanned Aerial Systems* [UASs] represent a prospect to facilitate in-situ inspections, reducing time, cost and risk for the operators. Indeed, to connect the advantages of the UAS technologies to the seismic risk assessment of bridges, Nettis et al. have proposed a simplified mechanic-based procedure oriented to map the structural risk in road networks and support prioritisation strategies, using as a case study a typical Italian bridge typology, i.e., a six-span RC bridge of the Basilicata region [153].
After the introduction of the LG20 guidelines, one of the first conferences to deal with the topic, among many others concerning bridge safety assessment, was the 1st Conference of the European Association on Quality Control of Bridges and Structures – EUROSTRUCT2021 – that took place from August 29th to September 1st, 2021 at University of Padova, Italy [125].
General discussions on the guidelines concern the necessity of introducing and encouraging the use of SHM to improve the knowledge of a structure; a clear regulatory framework is needed, with standards harmonised among the various countries, that account for the most recent scientific research in this field. To this end, Ormando et al. [215] presented a critical analysis of the main regulations in the world is carried out in the context of monitoring and preliminary suggestions are provided on how SHM may affect the level of knowledge. In detail, the Canadian – Canadian Highway Bridge Design Code (2014) – and the North American – American Association of State Highway and Transportation Officials (AASHTO) Code (2019) – regulations are analysed and compared to the novel LG20 guidelines. On the other hand, De Matteis et al. [216] presented the results of

testing the structural risk assessment procedure envisaged by the LG20 on 75 bridges of Caserta, detecting critical aspects and addressing possible solutions and alternative methods. However, neither Ormando et al. nor De Matteis considered a BIM integration, even though, as yet considered, according to the LG20, the usage of BIM methodology comes as a logical solution to store and manage all information related to the bridge surveillance process and create a unique database [124].
In fact, some particular applications of the LG20 guidelines focused on the case-by-case implementation and manual compilation of relative defectiveness parameters within HBIM models to store data on the state of preservation of case studies related to historic bridges.
A tentative implementation of the LG20 guidelines concerns the HBIM model of the dismantled structure of the Largo Grosseto Bridge, realised using both parametric modelling and a Mesh-to-BIM approach, to be later used as a repository for the damage information previously recollected and organised according to the novel standard [124].
Others applications have been developed by Trizio, Marra et al. and concerned the documentation of the degradation phenomena of the *Ponte delle Pietre* [217] and the *Ponte delle Tavole* [130] masonry bridges from data derived from UAV survey; they subsequently proceeded to set up the defect parameters according to the LG20 describing the type of degradation detected [*Defect*] via the coefficients of extension [K_1 *Extent*], intensity [K_2 *Intensity*] and the weight attributed to the single defect [G *Defect weight*] [217]. The aim of the research was to confirm that the digital model can act as an effective tool for the assessment of the risk factors affecting the infrastructure. Notably, it has been shown that the definition of the *Classes of Attention* [CdA] provided by the Italian Guidelines in the second level of inspection is feasible and can incorporate aspects associated with the preservation of historical infrastructures [130].

4.6 An approach to combining LG20, ASPI, and AINOP requirements

As far back as 2018, ANAS formulated a proposal for the information digitisation and subsequent management of linear infrastructures by drafting the specifications for a BIM special procurement contract [218] which illustrated a *Work Break-down Structure* [WBS][40] for the classification of the individual components of the model to be associated with internationally recognised cataloguing systems - such as UNICLASS and OMNICLASS. It also provides recommendations for the implementation of a plan for the information management [*Piano per la Gestione Informativa* – pGI] of the work covering the contractor's responsibilities during the execution of the works and the specification of as-built modelling activities.

To comply with the laws, decrees, and regulations in force – the 2020 Guidelines [4], the ASPI Surveillance Handbook [99] and AINOP [91] – an inspection method that could combine the cataloguing and assessment requirements in accordance with the various standards has been developed together with the C.U.G.R.I. engineers.

Road structures are classified, according to the ASPI Surveillance handbook [99], into *Global Structures* (which have no interconnection elements with other structures, including joints) and *Partial Structures*.

Three types of *Global Structures* have been identified on the ASPI network (Figure 4.26):

- singular structure with several decks (a) or single deck (b): the decks, separated from each other, share parts or components in common between the two carriageways;
- structure adjacent to another, built in different times (c): there are two separate global structures (without common components) supporting the carriageways;

[40] According to the Project Management Institute's PMBOK Guide [268], a WBS is a deliverable-oriented hierarchical decomposition of the work to be executed by the project team to accomplish the project objectives and create the required deliverables. The WBS organizes and defines the total scope of the project. The WBS subdivides the project work into smaller, more manageable pieces of work, with each descending level of the WBS representing an increasingly detailed definition of the project work. The planned work contained within the lowest-level WBS components, called work packages, can be scheduled, cost estimated, monitored, and controlled. The deliverable orientation of the hierarchy includes both internal and external deliverables.

- a structure adjacent to another, built in the same period (d): there are two distinct global structures (without elements in common, or else when they exist they serve a different roadway) supporting the carriageways.

And three types of *Partial Structures* (Figure 4.27):

- single partial structure (a): coinciding with the global structure in the case of a single deck;
- partial structures – more than one when originally built (b): the cross-section is composed by separate decks;
- partial structures – more than one as a result of road enlargement (c): if the enlargement requires an additional foundation, via new abutments or new piers.

Each *global structure* may contain one or more *partial structure*, which in turn are broken down into *structural sections*, that are subdivided again into *components* (Figure 4.28). The type of *components* that can compose each *structural section* are listed in Table 4.5 and Table 4.6.
In order to be able to identify the construction parts of a bridge in their position, each of them needs to be associated with an identification code, as also required by the LG20. Here follow a schematisation, according to the Surveillance Handbook [99], of the different assets with the respective location (Figure 4.29).

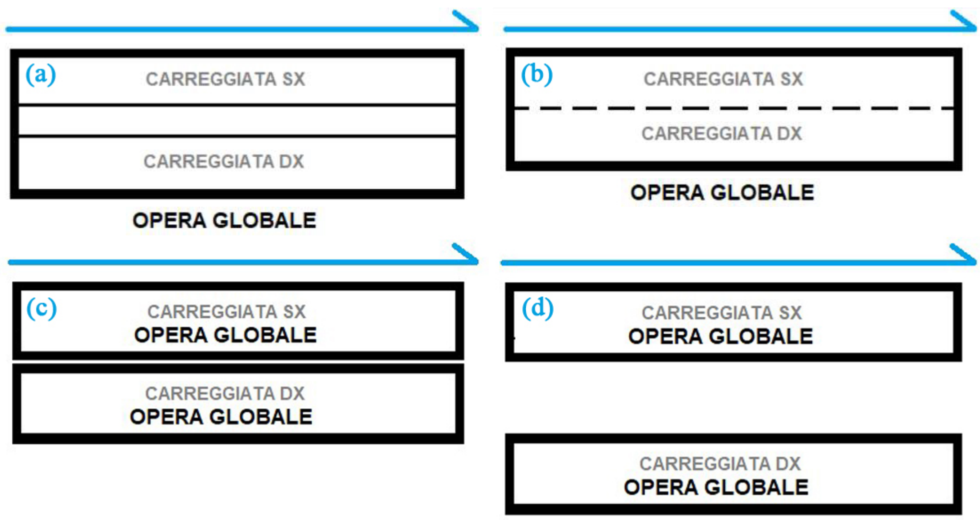


Figure 4.26 – Types of global structures [99]

Figure 4.27 – Types of partial structures [99]

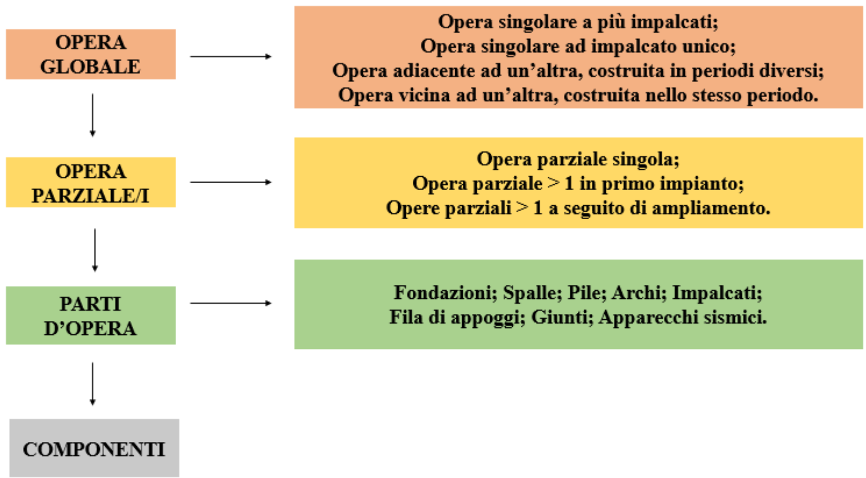


Figure 4.28 – Breakdown of the asset [99]

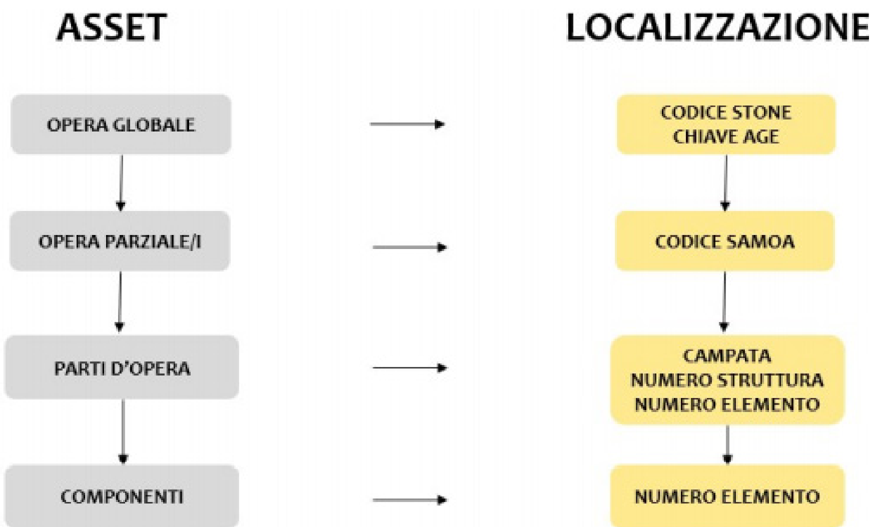


Figure 4.29 – Schematisation of the different assets associated with their respective localization [99]

Table 4.5 – Breakdown of the structural sections – foundations, abutments, piers, arches – into components [99] [MbA]

FOUNDATIONS [FONDAZIONI]	ABUTMENTS [SPALLE]	PIERS [PILE]	ARCHES [ARCHI]
Plinth (including platform) [Plinto (compresa platea)]	Elevation [Elevazione]	Elevation [Elevazione]	Main structure [Struttura principale]
Piles (including pier) [Pali (compresa pila)]	Secondary connecting wall [Paraghiaia]	Pulvinus [Pulvino]	Slab [Soletta]
Wells [Pozzi]	Buttress [Contrafforti]	Cross-connections (including diaphragms) [Interconnessioni trasversali (compresi diaframmi)]	Cross-connections (including diaphragms) [Interconnessioni trasversali (compresi diaframmi)]
Caissons [Cassoni]	Cantilever [Trave cuscino]	Longitudinal interconnections [Interconnessioni longitudinali]	Longitudinal interconnections [Interconnessioni longitudinali]
			Tympanum [Timpano]
			Longitudinal interconnections between piers [Interconnessioni longitudinali tra pile]

Table 4.6 – Breakdown of the structural sections – decks, row of bearings, joints, seismic equipments – into components [99] [MbA]

DECKS [IMPALCATI]	RAW OF BEARINGS [FILA DI APPOGGI]	JOINTS [GIUNTI]	SEISMIC EQUIPMENT [APPARECCHI SISMICI]
Main deck slab [Solettone]	Bearing equipment [Apparecchiature di Appoggio]	King post [Portale o Monaco]	Damper [Dispositivo di Smorzamento]
Beams [Travi]	Plates [Baggioli]	Intermediate slab [Soletta Intermedia]	Seismic retainer [Ritegno Sismico]
Joists [Traversi]	Hinges/Pins [Cerniere di Taglio]	Joint equipment [Dispositivo di giunto]	Isolators [Isolatori]
Webs [Anime]		Screed [Massetto]	
Connectig slab [Controsoletta]			
Rafter [Puntone]			
Secondary slab [Soletta]			

Each asset is then allocated an identification string, following the layout shown below:

XX.YY.ZZZZ.K.J.11.VV.222.YY.333.MAT

XX.YY.ZZZZ.K.J – Global Structure Number
11 – Partial Structure
VV – Structural Section
222 – Structural Section Number
YY – Component
333 – Component Number
MAT – Material Code

This identification code serves not only to identify the individual component in the BIM model but also to assign inspection forms proposed in Annex B of the Guidelines to each element [94]. The identification IDs of the *Structural Sections*, the *Components*, and the *Material* (Table 4.7), as well as the assignment of the forms for each element are outlined in the Table 4.8.
In detail, the forms proposed in the annex B of the LG20 [94] have been assigned to each structural element according to the *Structural Sections*, the typology of the *Component* belonging to the identified Structural Section, the *material* of which that element is made of. Some particular cases such as plinths, foundation rafts and piles need additional specification according to the relative superordinate element – be it, for example, foundation systems for abutments [sp], rather than for pillars [pl] – or the relative structural behaviour, as in the case of arch structures, i.e, main structure, longitudinal interconnections or cross interconnections and diaphragms that may display true arch behaviour rather than beam behaviour.
The specifications provided also comply with the AINOP database requirements, both in terms of the *Basic register information* and the *Specific register data* related to a Viaduct, once the census forms of the LG20 annex A [93] have been filled out. A few small differences can be found just in the format requested for the geographical coordinates of the starting, the middle and the final points used to locate the infrastructure.

Table 4.7 – Outline of the identifier assigned to each structural material

MATERIALS	ID
Reinforced Concrete [Cemento Armato]	CAO
Steel [Acciaio]	ACC
Masonry [Muratura]	MUR
Wood [Legno]	LGN
Prestressed-Concrete [C.A.P]	CAP
Other [Altro]: joints and seismic equipment	NUL

Table 4.8 – Nomenclature of structural sections and components, together with their ID and the Annex B forms to be assigned also according to the material and structural function of each component

STRUCTURAL SECTIONS [PARTI D'OPERA]	ID	COMPONENTS [COMPONENTI]	ID	FORM TEMPLATE NUMBER [SCHEDA] All. B D.M. 20	
FOUNDATION [FONDAZIONE]	FO	Plinti e platee	PP	1,2,3,4,5	
		Pali	PA		
		Pozzi	PO		
		Cassoni	CA		
ABUTMENT [SPALLA]	SP	Elevazione	EL	1,2	
		Paraghiaia	PR		
		Contrafforti	CO		
		Trave cuscino	TC		
PIERS [PILE]	PI	Elevazione	EL	3,4,5,8,9	
		Pulvino	PU	14,15,16,17,18,19	
		Interconnessioni longitudinali	IL	14,15,16,17	
		Interconnessioni trasversali e diaframmi	IT	14,15,16,17	
ARCHES [ARCHI]	AR	Struttura principale	SP	14,15,16,17,18,19	10,11,12,13
		Interconnessioni longitudinali	IL	14,15,16,17	10,11,12,13
		Interconnessioni trasversali e diaframmi	IT	14,15,16,17	10,11,12,13
		Timpano	TI	10,11,12,13	
		Interconnessioni longitudinali tra pile	IP	14,15,16,17	
DECKS [IMPALCATI]	IM	Controsoletta	CS	18,19	
		Puntone	PN	14,15,16,17	
		Anima	AN	14,15,16,17	
		Travi	TR	14,15,16,17	
		Diaframmi	DI	14,15,16,17	
		Solettone	SN	18,19	
		Soletta	SO	18,19	
		Traverso	TS	14,15,16,17	
		Sbalzo soletta longitudinale	SL	18,19	
		Sbalzo soletta trasversale	ST	18,19	
		Interconnessioni longitudinali	IL	14,15,16,17	
RAW OF BEARINGS [FILA DI APPOGGI]	FA	Apparecchiature di Appoggio	AA	6	
		Baggioli	BA	8,9	
		Cerniere di Taglio	CT	14,15,16,17	
JOINTS [GIUNTI]	GI	Portale o Monaco	PM	18,19	
		Soletta Intermedia	SI	18,19	
		Apparecchiature di giunto	AG	7	
		Massetto	MA	7	
SEISMIC EQUIPMENT [APPARECCHI SISMICI]	AS	Amortizzatore	AM		
		Ritegno Sismico	RS		

4.7 Bridge parts classification according to the current Italian regulation

Next, the system of classification and nomenclature of the parts comprising a bridge according to the Italian regulations will be illustrated in detail, accompanied by graphic diagrams extracted from the ASPI Surveillance Handbook [99].

Structure Number

The Surveillance Handbook catalogues bridges, underpasses, and viaducts through a dual coding system:

- a *talking* alphanumeric codification [STONE CODING];
- a computer key [AGE KEY]: generated by the AGE software for each infrastructure.

The so-called STONE code consists of 10 digits according to the scheme:

XX YY ZZZZ K J

The letters refer to the register information of the road structure as illustrated below (Figure 4.30).

Partial structures

Global and partial structures are catalogued in the same way if the latter are single, otherwise they vary in the two digits additional to the STONE code. The code used is referred to as the SAMOA code.

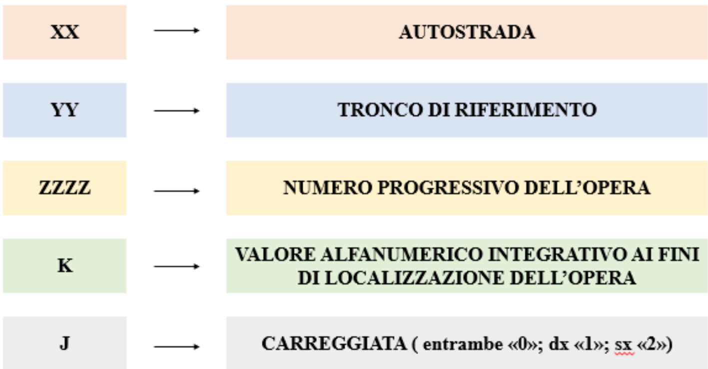


Figure 4.30 – Outline of the STONE Code

Structural Section and Component

As can be seen in Table 4.8, each Structural Section is identified by an alphabetical code consisting of two capital letters, the same applies to Components. The table shows, in the fifth column, for each component the number of the *defect evaluation form* [94] associated with it.

Structural Sections Number and Component Number

The location system envisaged for global and partial structures assumes the identification of the origin system, carried out by positioning the inspector, in the case of underpass structures, with his back to the kilometric origin of the infrastructure, while, in the case of viaducts, with his back to the right abutment looking at the structure with his back facing the kilometric origin of the infrastructure (Figure 4.31).
For the Structural Sections and Components, the convention used by ASPI envisages:

- shoulders pointing towards the origin of the motorway, from origin to destination (increasing progressively);
- numbering proceeding from bottom to top;
- numbering proceeding from left to right.

In particular, the localisation elements are the span, the structure number and the element number. The reference system associated with them (Figure 4.32) provides:

- for the span: progressive increasing values;
- for the structure number: from bottom to top, progressive ascending values;
- for the number of elements: from left to right, from bottom to top, progressive ascending values.

Figure 4.31 – Localisation system [99]

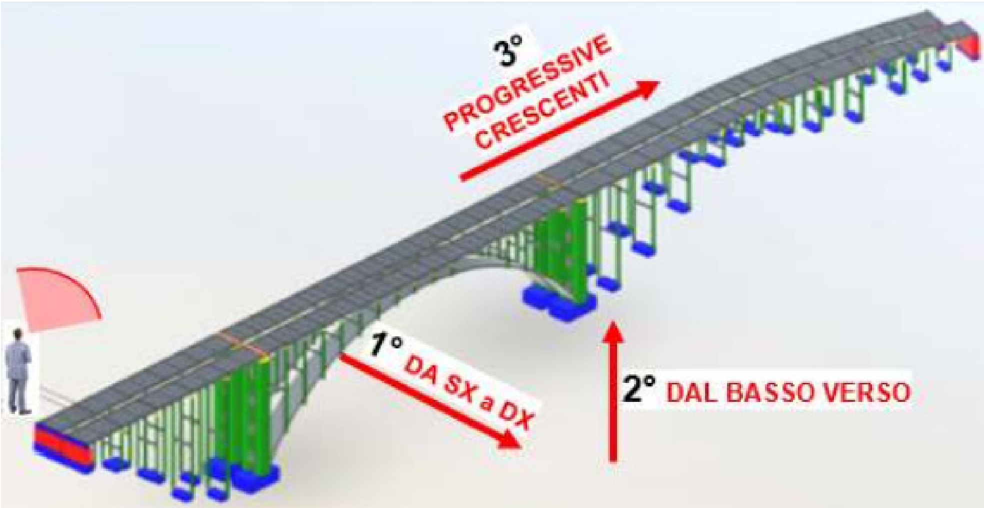


Figure 4.32 – Reference system for the localisation elements [99]

Thus, the convention herein adopted will proceed:

- along the longitudinal direction: progressively increasing;
- along the cross direction: from left to right;
- along the vertical direction: from bottom to top.

Span

Spans are defined as: *"those sections of load-bearing structures that are not restrained at the intrados. The subdivision always coincides with the piers without foundations and if the latter are not present, it coincides with those with foundations"* [99].

Structure number

"The structure number indicates the number of the structure to which each structural section belongs" [99]. An example of span numbering and structure numbering is shown below (Figure 4.33 and 4.34).

Element numbering

The components composing the structural sections have been illustrated earlier (see Table 4.5 and 4.6). A graphical depiction of the components for the different structural sections are shown below with example of possible numbering (Figure 4.35, 4.36, 4.37, 4.38, 4.39, 4.40, 4.41, and 4.42).

The numbering, in this case, as previously explained, will develop from left to right, from bottom to top and increase progressively.

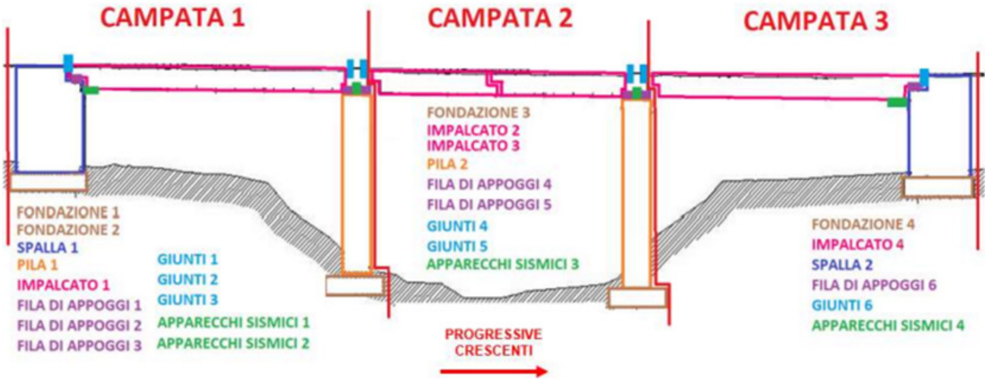


Figure 4.33 – Example of span and structure numbering – Side view [99]

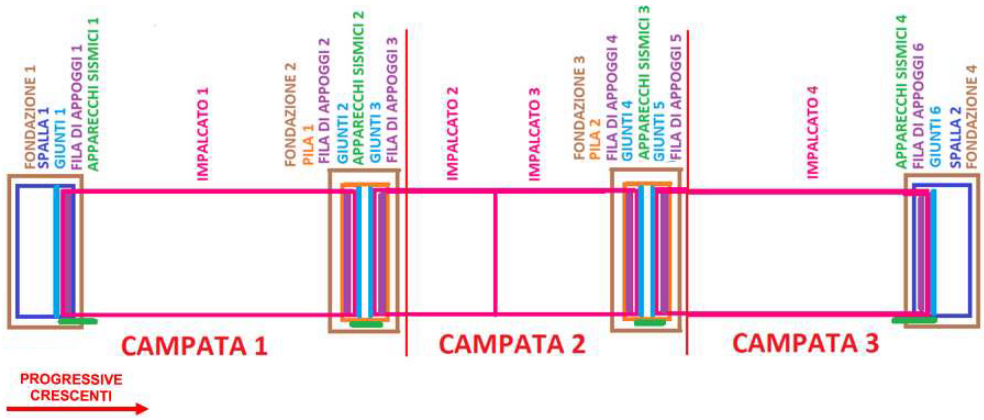


Figure 4.34 – Example of span and structure numbering – Plan view [99]

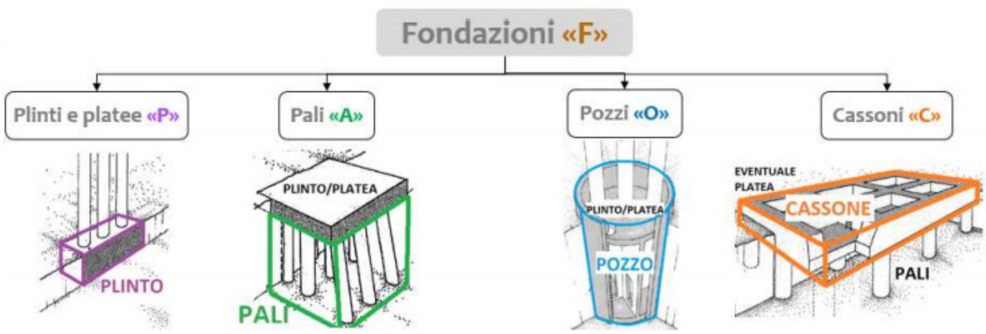


Figure 4.35 – Components of the Foundations [99]

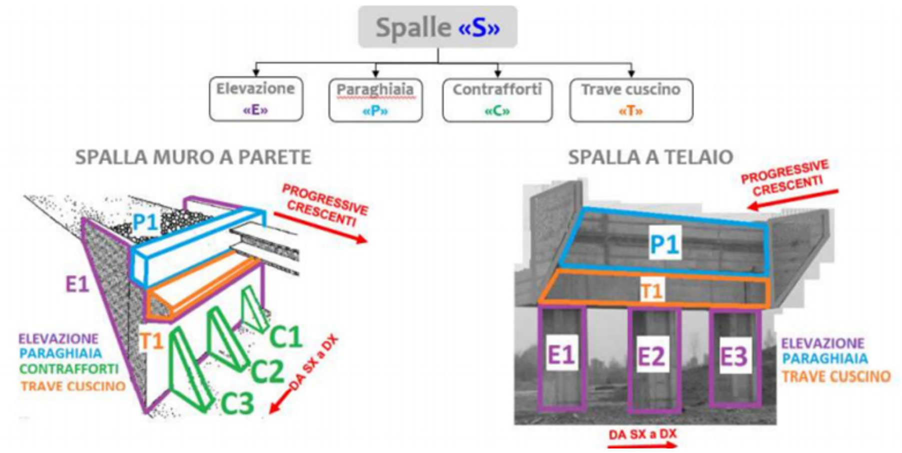


Figure 4.36 – Components of the Abutments [99]

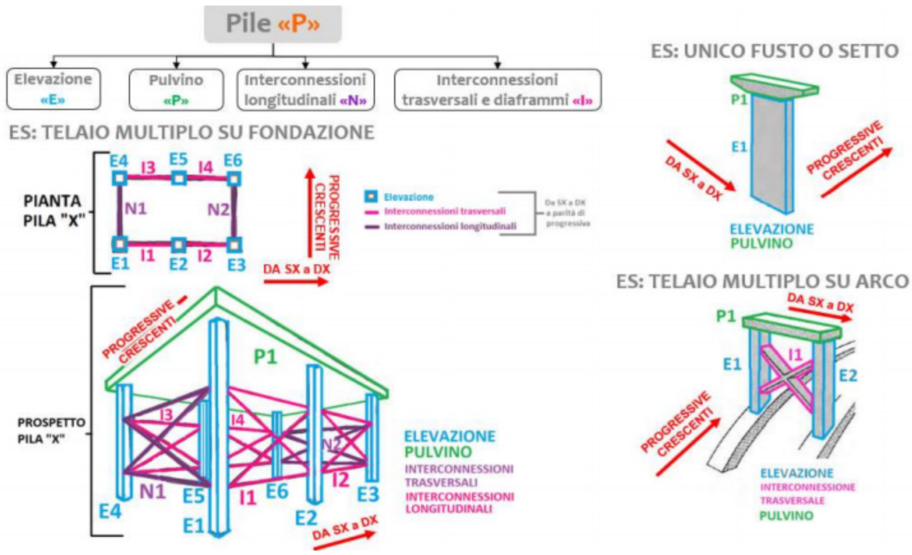


Figure 4.37 – Components of the Piers [99]

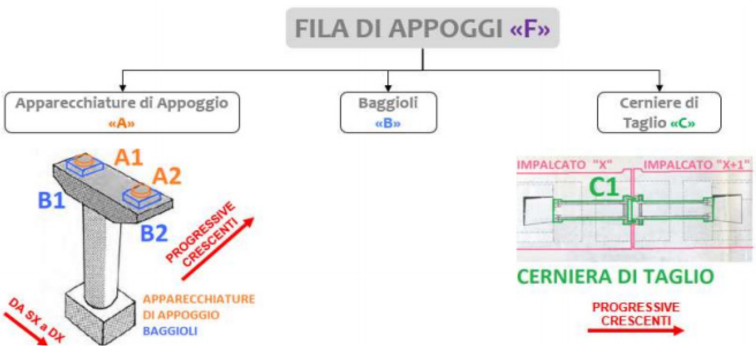


Figure 4.38 – Components of the Bearings [99]

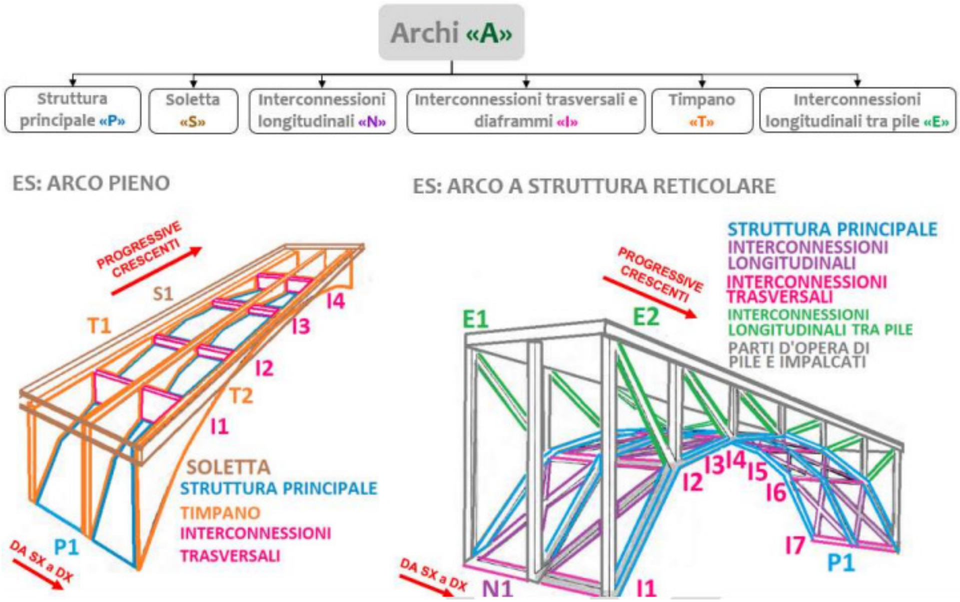


Figure 4.39 – Components of the Arches [99]

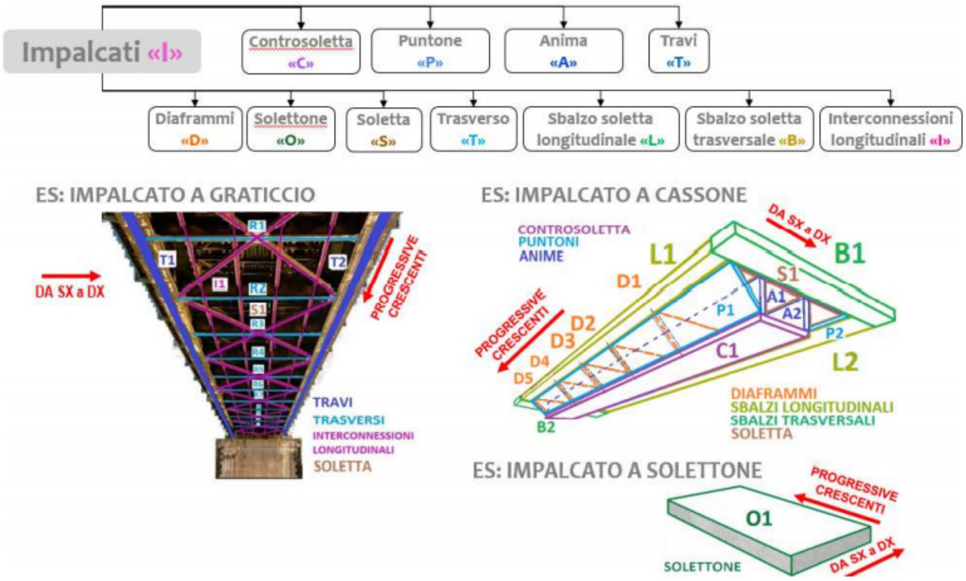


Figure 4.40 – Components of the Decks [99]

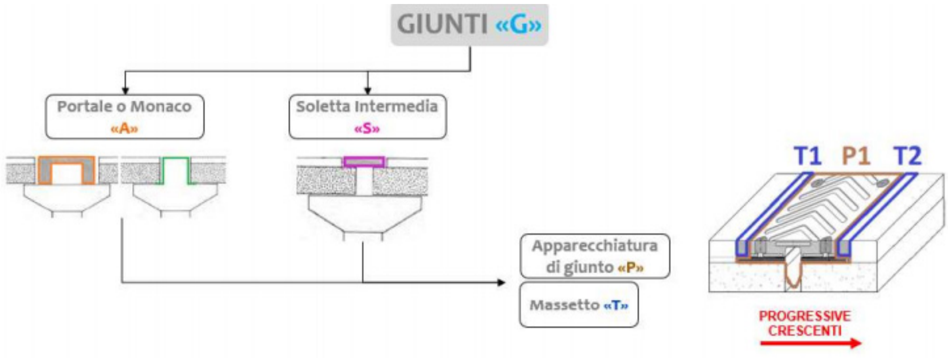


Figure 4.41 – Components of the Joints [99]

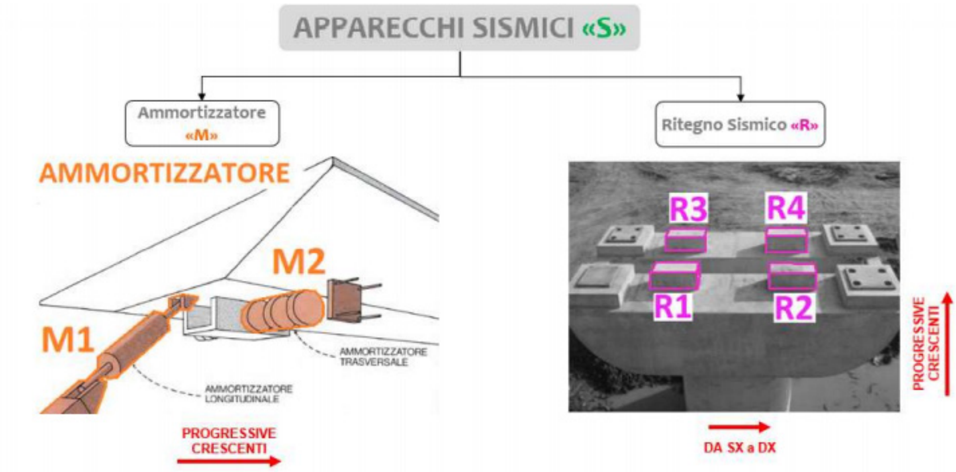


Figure 4.42 – Components of the Seismic Equipment [99]

For components that are part of latticework decks (Figure 4.43), caisson decks (Figure 4.44), cellular arches (Figure 4.45) and truss arches (Figure 4.46), a breakdown into lattices is required. This decomposition is only undertaken if there are cross-sectional elements (transverse, diaphragms and connections) to generate the grid pattern.

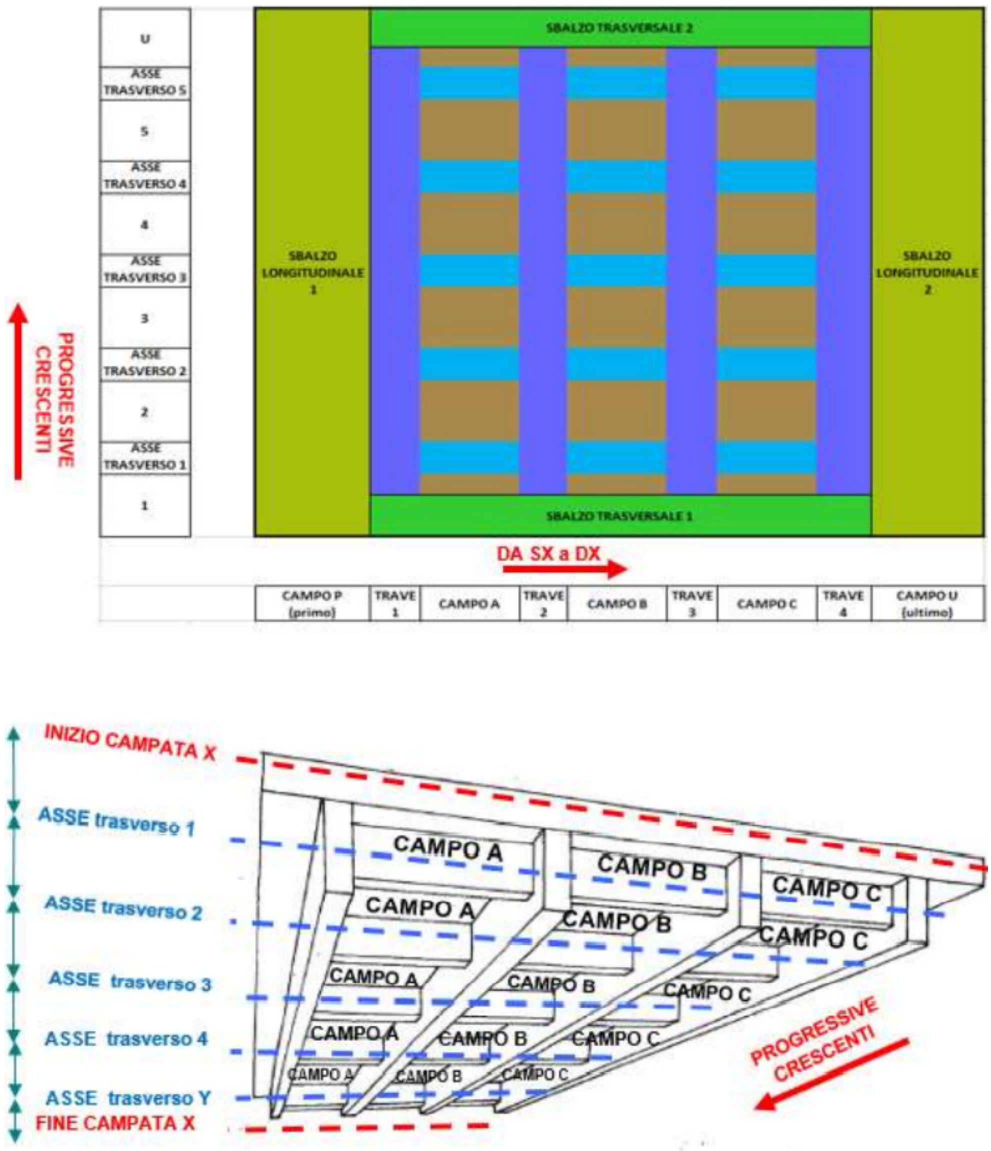


Figure 4.43 – Latticework decks: plan view (up) and perspective view (down) [99]

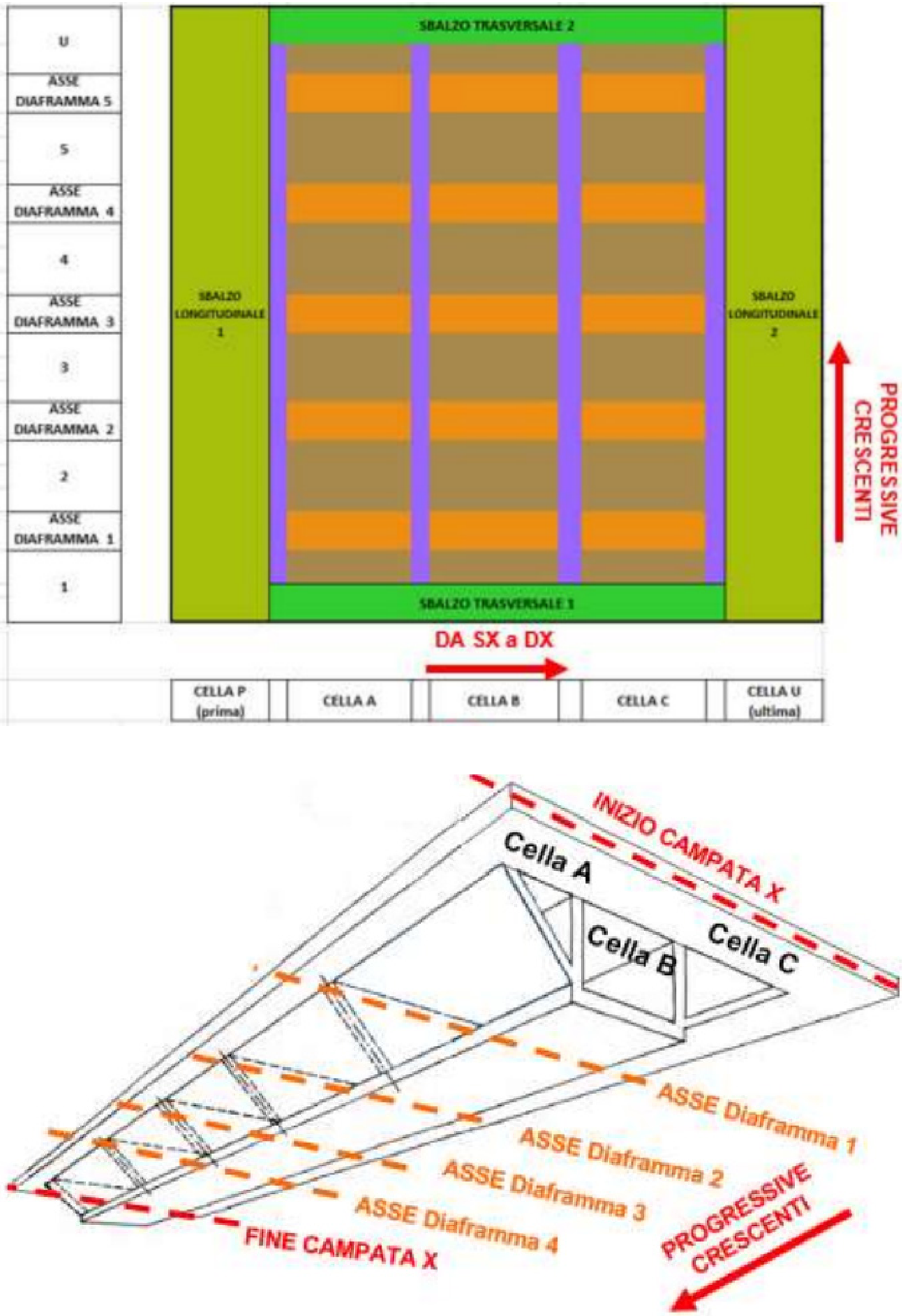


Figure 4.44 – Caisson decks: plan view (up) and perspective view (down) [99]

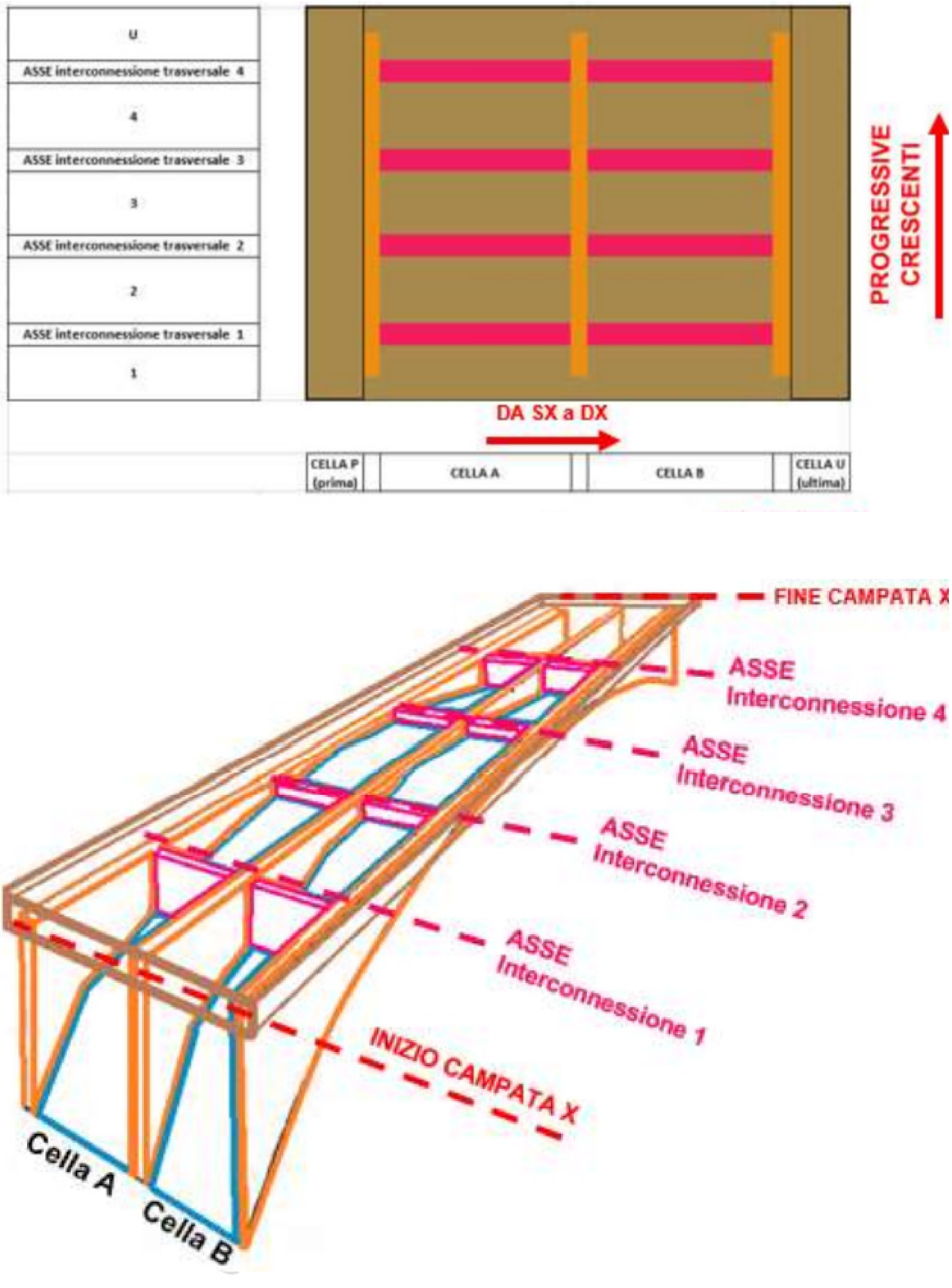


Figure 4.45 – Cellular arches: plan view (up) and perspective view (down) [99]

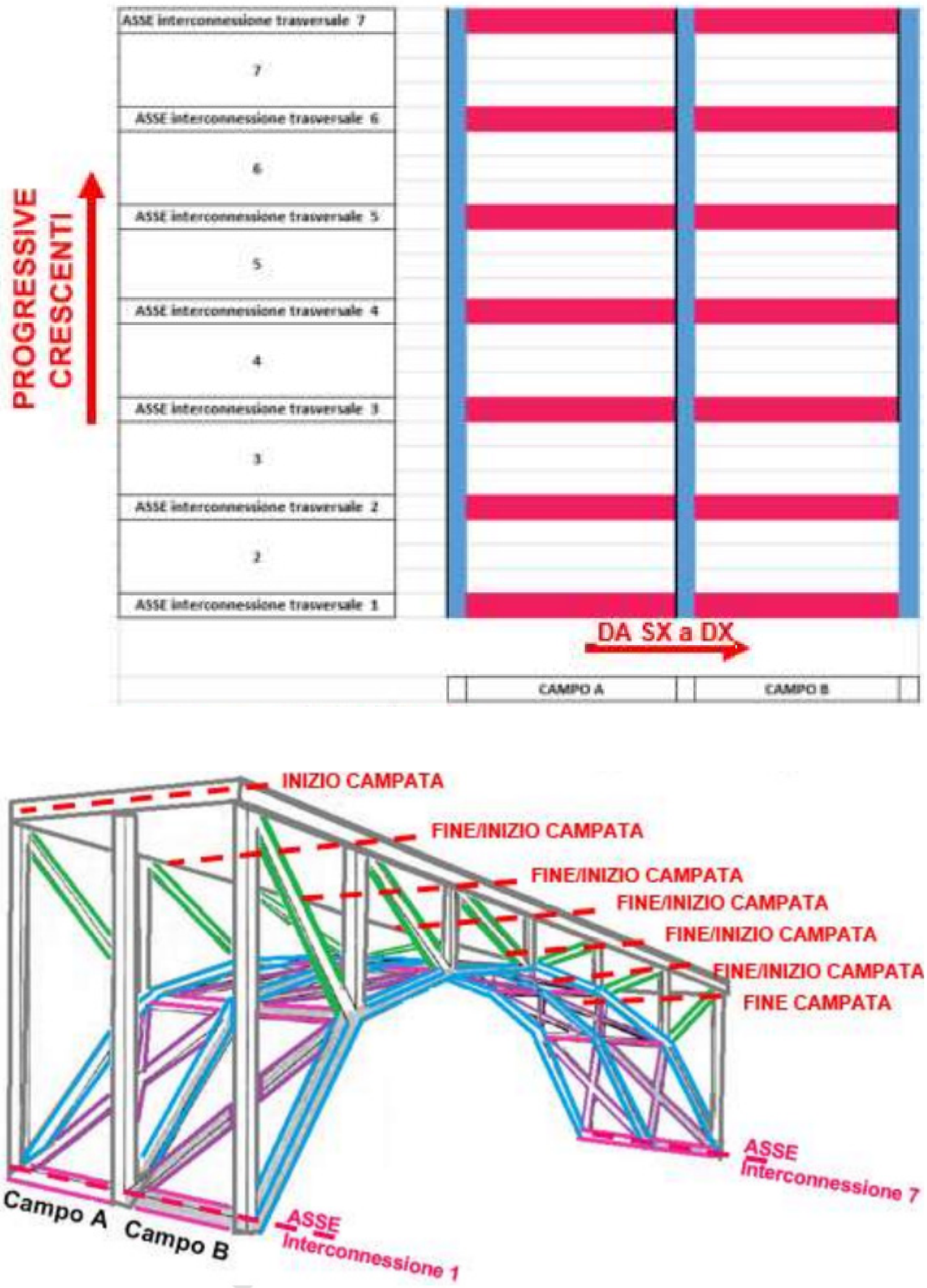


Figure 4.46 – Truss arches: plan view (up) and perspective view (down) [99]

Hollow structures

"In structural terms, the hollow parts of the structures are distinguished into those designed for inspectability, thus typically the internal parts of caisson and pier structures, and those whose internal spaces cannot be inspected, i.e. they include lightweight structural parts" [99].

Depending on the degree of accessibility, they can be subdivided:

- *FA* [*Facilmente Accessibili – Easily Accessible*] *Structural sections*: e.g., caissons, piers, shaft foundations;
- *AC* [*Accessibilità Condizionata – Conditionally Accessible*] *Structural sections*: inspections can be carried out with drones or specialised personnel, e.g., caissons;
- *NA* [*Non Accessibili – designed as Non-Accessible*] *Structural sections*: inspections are only carried out from the outside. In this case is possible to open holes to allow internal inspection by means of drones;
- Structural sections that cannot be considered hollow elements: they are not submitted to internal inspection. It will be up to the Surveillance Contractor to decide, depending on the defect condition, whether an inspection is necessary. This covers the elevation of the frame and portal piers.

Following some types of hollow – therefore inspectable – structures are listed (Figure 4.47 and 4.48).

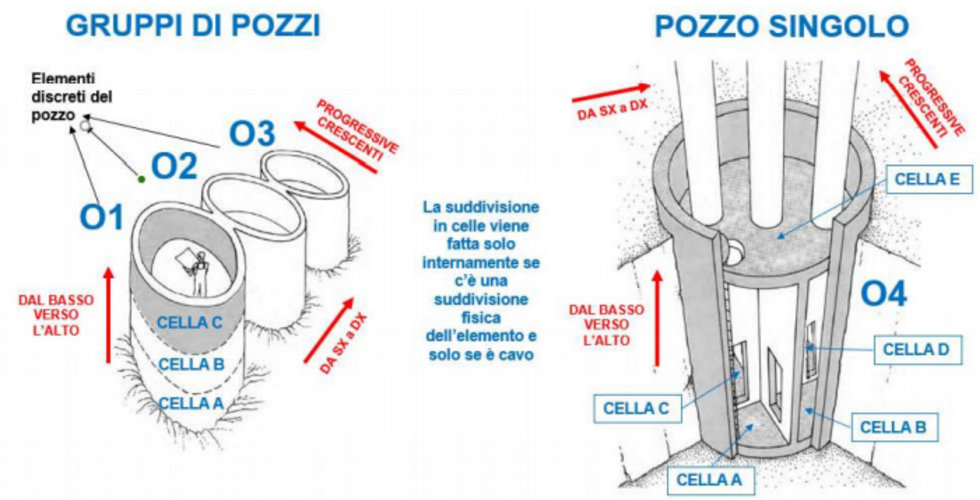


Figure 4.47 – Hollow components localisation system – pier shafts [99]

Figure 4.48 – Hollow components localisation system – caissons, elevation elements, beams, bearings, main structure [99]

5. Updating the current state of knowledge on the Olivieri Viaduct

The first experimental phase involving the updating of the Olivieri Viaduct information database began with a survey campaign of the bridge and the underlying valley in order to produce initial modelling of the infrastructure within its urbanised context, to extrapolate updated technical drawings of the complex system.

The survey campaign was undertaken in the framework of the Project: *CUR_CIS2020* ***Methodologies for the punctual assessment of hydrogeological risk in heavily populated areas and tools for regional development strategies*** *– Application to the case study Strategic Infrastructure Corridor* [*CIS*] *at regional level. Salerno-Cava de' Tirreni – A3 Naples-Salerno motorway section and other downstream road infrastructures*. The project objective concerns procedures to process and integrate various types of 2D and 3D data in a GIS environment: data provided by agencies, acquired from commercial companies and/or derived from topographical and photogrammetric measurement campaigns, useful for 3D modelling of the anthropised territory, in order to generate cartography and DTMs serving as the basis for geomorphological characterisation.

Namely, the survey was carried out by the *geomatics* and *surveying & representation* groups of the *Laboratorio Modelli – Surveying and Geo-Mapping for Environment and Cultural Heritage*, Department of Civil Engineering [DICIV], University of Salerno.

5.1 Case study: the Olivieri Viaduct

The Olivieri viaduct, built between 1954 and 1958 and belonging to the Salerno-Cava de' Tirreni Strategic Infrastructural Corridor (Figure 5.1), has an overall length of 136.80 m; it consists of a hyperstatic R.C. arch structure with a continuous frame deck over the valley and two viaducts. It has two additional continuous-frame spans on the Naples side and six continuos-frame spans on the Salerno side. Expansion joints are located at piers 2 and 12, where the arch springers are. The joints, at the time of construction, were realised by bifurcating the piers at varying heights, thus creating 20 cm thick piers with low stiffness in the span facing the respective abutment. Over the years, the pillars have been replaced by steel exoskeletons composed by 400x200x12 mm, 400x200x10 mm, and 300x200x10 mm box cross-section elements. The spans have a constant width of approximately 7.60 m with local variations in length due to the curvilinear alignment of the viaduct. The deck forms a rigid connection with the abutments and the piers - there are no supporting devices – by means of pass-through reinforcements.

Figure 5.1 – Olivieri Viaduct overview from Google Earth [219]

Figure 5.2 – View of the Olivieri Viaduct [220]

The entire structure (Figure 5.2) – *Maillart* type, i.e., with ribs and piers connected and stiffened using thin slabs – is made of ribbed elements, beams, arch ribs, and pier abutments, coupled, and stiffened by thin reinforced concrete slabs, cast in situ.
Each pier consists of 5 columns stiffened in the cross direction by a connection frame, 12 cm thick; the pillars forming the piers have a variable clear-height; the arch consists of 5 ribs with a variable section height, from 157 cm at the springers to 100 cm at the keystone, connected to each other by a slab, placed at the intrados of the ribs, 14 cm thick; the deck consists of 5 beams connected by a slab of variable thickness from 15 cm at mid-span to 30 cm where it is joined to the outermost beams; the north and south carriageways are staggered in height by 4.30 m and are joined together by a 28 cm thick girder along the bridge alignment, which further provides longitudinal stiffening for the arch and the approach viaducts; finally the foundations are shallow (Figure 5.3, 5.4, 5.5, 5.6, 5.7, and 5.8).

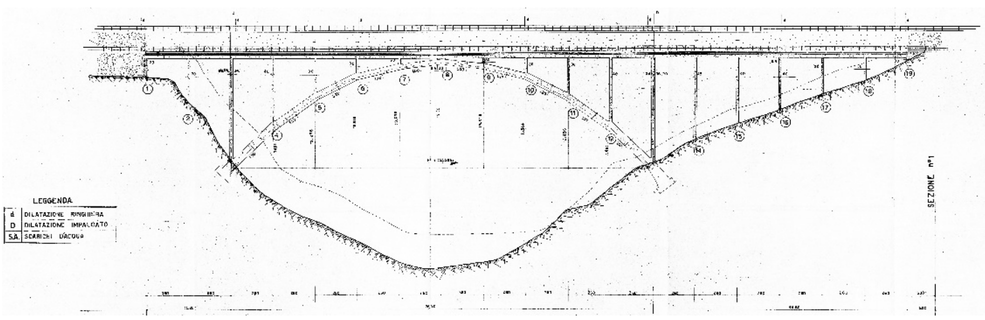


Figure 5.3 – Archival original drawings of the Olivieri Viaduct project: Elevation view [MbA]

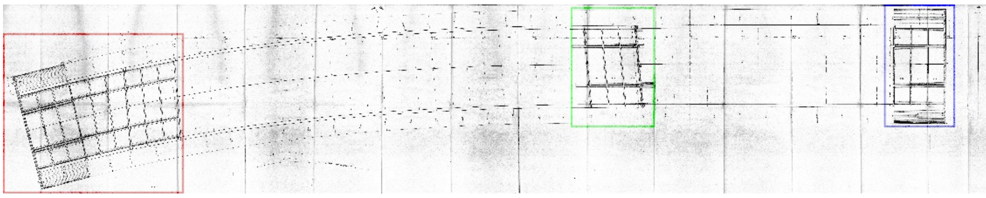


Figure 5.4 – Archival original drawings of the Olivieri Viaduct project: Floor plan view of the Bridge deck [MbA]

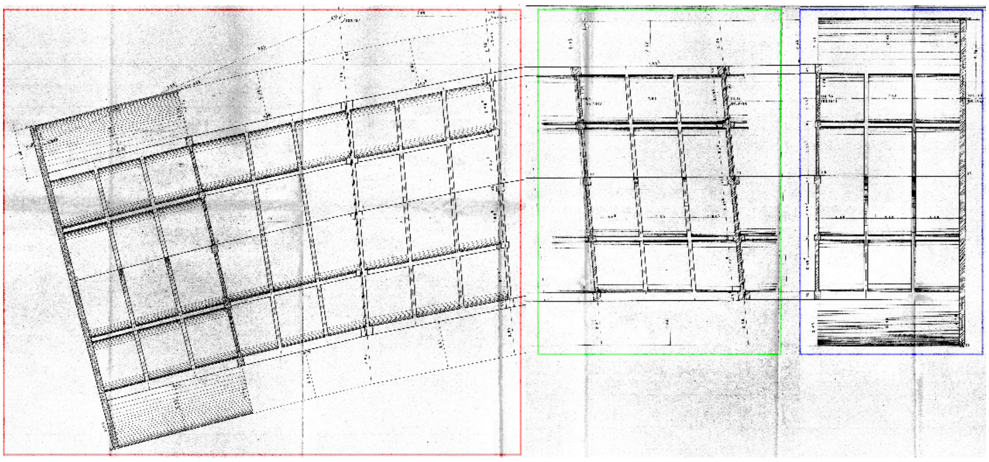


Figure 5.5 – Archival original drawings of the Olivieri Viaduct project: Details of the Floor plan view of the Bridge deck [MbA]

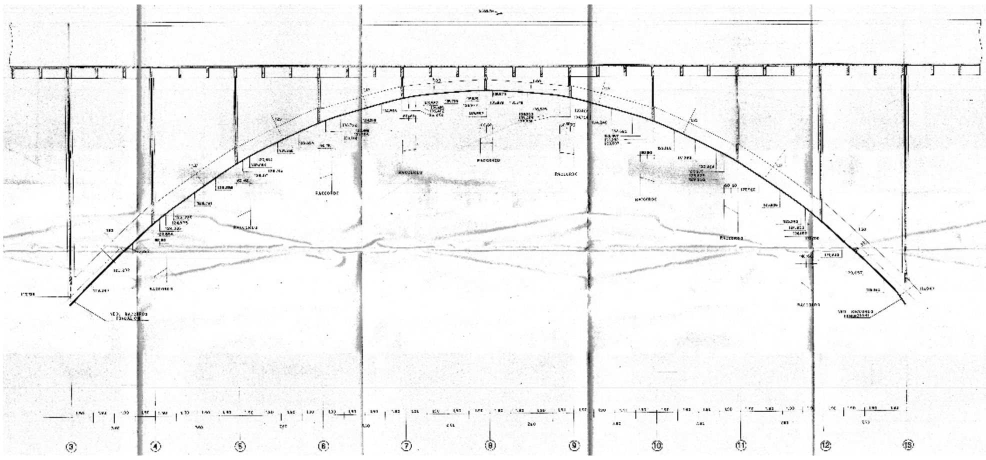


Figure 5.6 – Archival original drawings of the Olivieri Viaduct project: Elevation view of the arched substructure [MbA]

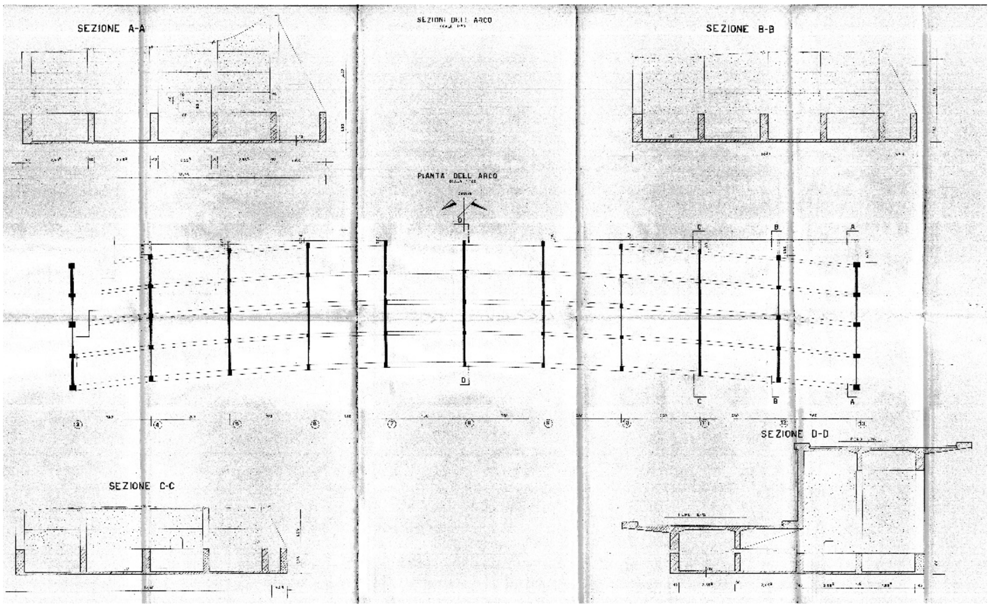


Figure 5.7 – Archival original drawings of the Olivieri Viaduct project: Details and Floor plan view of the arched substructure [MbA]

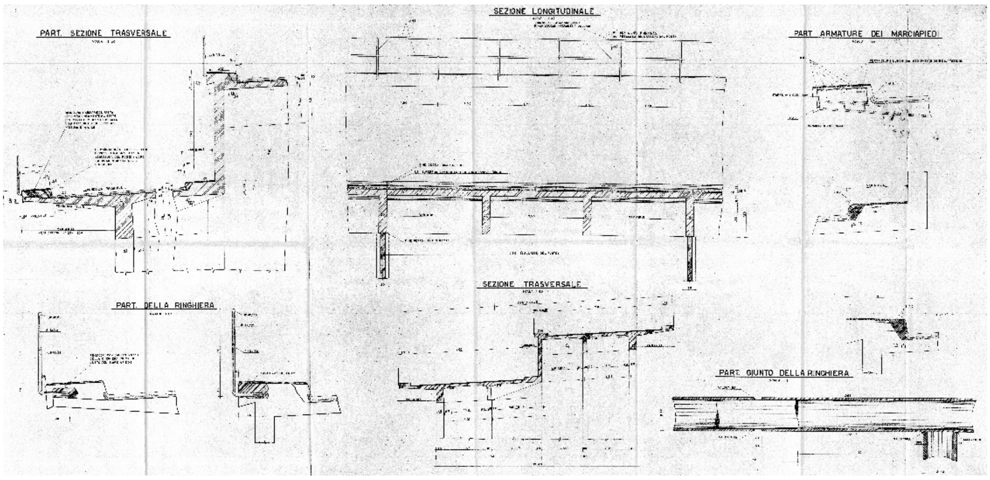


Figure 5.8 – Archival original drawings of the Olivieri Viaduct project: Construction Details of the bridge deck [MbA]

5.2 TLS survey of the viaduct and its surrounding

The survey campaign – 3DS stage of the herein proposed methodology – was carried out by the *geomatics* and *surveying & representation* groups of the *Laboratorio Modelli – Surveying and Geo-Mapping for Environment and Cultural Heritage* as part of the *CUR_CIS2020* project and was aimed at expanding the knowledge base on the geometric characteristics of the Olivieri Viaduct, cataloguing the structural elements, construction materials and external surfaces of each structural element and modelling the valley below as part of a unitary complex system [221].

The surveying activities were performed with a Teledyne Optech Polaris TLS, a pulsed laser using ToF [Time of Flight] technology with ideal characteristics for land surveying but also for short and medium-range applications. The scanner produces a multi-echo laser pulse, capable of generating up to four returns, useful for filtering out vegetation. The nominal accuracy over distance is 5 mm @ 100m (1σ).

A total of 10 measuring stations were set up (8 in the proximity of the Olivieri viaduct and 2 from the SS18 provincial road downstream of the valley as shown in Figure 5.9, left) the layout of the stations was chosen so as to:

- minimise shadows and occlusions;
- have a good overlap between the scans to optimise the alignment process;
- minimise the angle of incidence with the scanned surface;
- ensure a homogeneous spatial density of the points;
- have a good target visibility: a criterion for the choice of scanning positions is the complete visibility of several targets to be used both for the alignment of the scans and for georeferencing. At least 3 targets should be present within each scan [222].

The set scanning resolution is approximately 4mm @100m. For the co-registration and georeferencing of the scans, three flat targets made of high reflectance polymer material were used, mounted on a pole with a spherical and bipod level. The position of the targets was measured with GNSS receivers in the current Italian National Reference System UTM33/RDN2008 (EPSG 7792) with ellipsoidal elevations. In the post-processing phase, the ellipsoid elevations were converted into orthometric elevations using the GK2 grids provided by IGM; the altimetric datum used is ITALGEO2005.

The scans were co-registered and aligned using the proprietary software Teledyne ATLAScan (Figure 5.9, right); the average alignment error of the corresponding points was 4 mm [222].

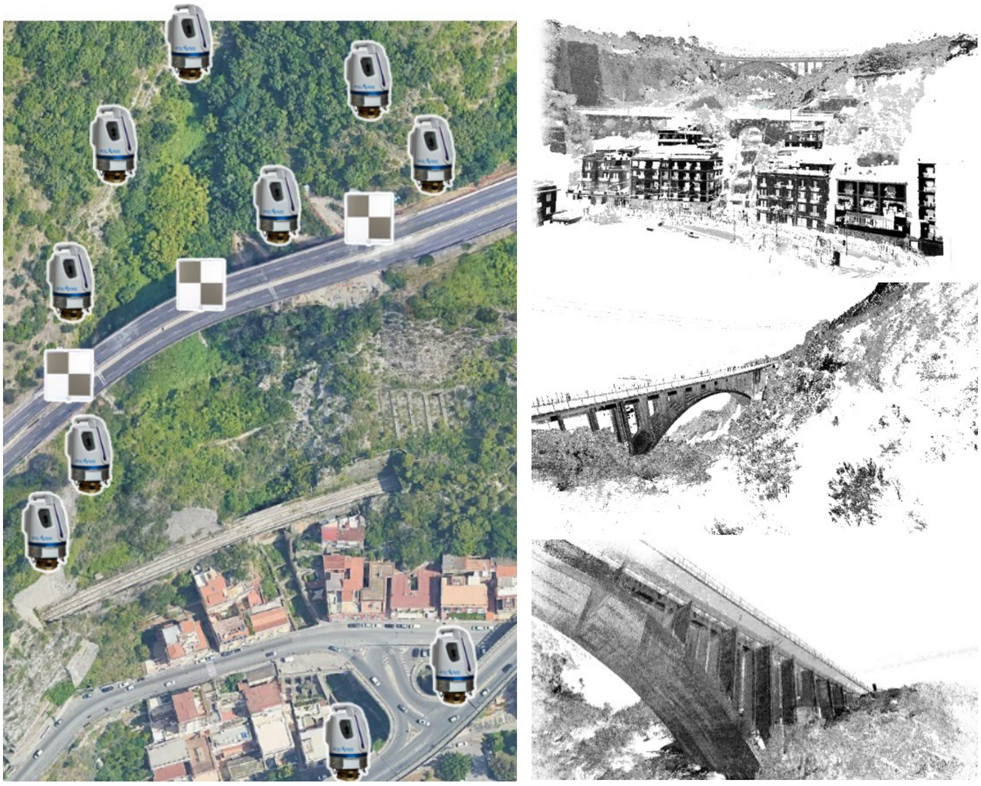


Figure 5.9 – Layout of the 10 surveying stations (left) and views of the aligned and georeferenced point cloud depicting the viaduct and the valley beneath (right) [222]

The objective of this first phase was to realise an integrated BIM and GIS [Geographic Information System] model, combining the strengths of both technologies: the semantic and spatial component of the GIS with the 3D information with a high level of detail, coming from the BIM model, this kind of hybrid informative models are also called GeoBIM [223]. Such a model – falling in accordance with the GEO phase – allows management of the structure and/or infrastructure in a wider and more complete context; therefore, not only at a local level but applicable to works that have a strong impact on the territory and are located in hydrogeological risk areas. The integration of a GeoBIM is carried out through the analysis of some main characteristics: the harmonisation and consistency of data (e.g., estimation of accuracy, geometric and semantic representation, amount of detail, georeferencing); the interoperability of data coming from different sources; the transformation of a set of data into a single standardised format (Figure 5.10).

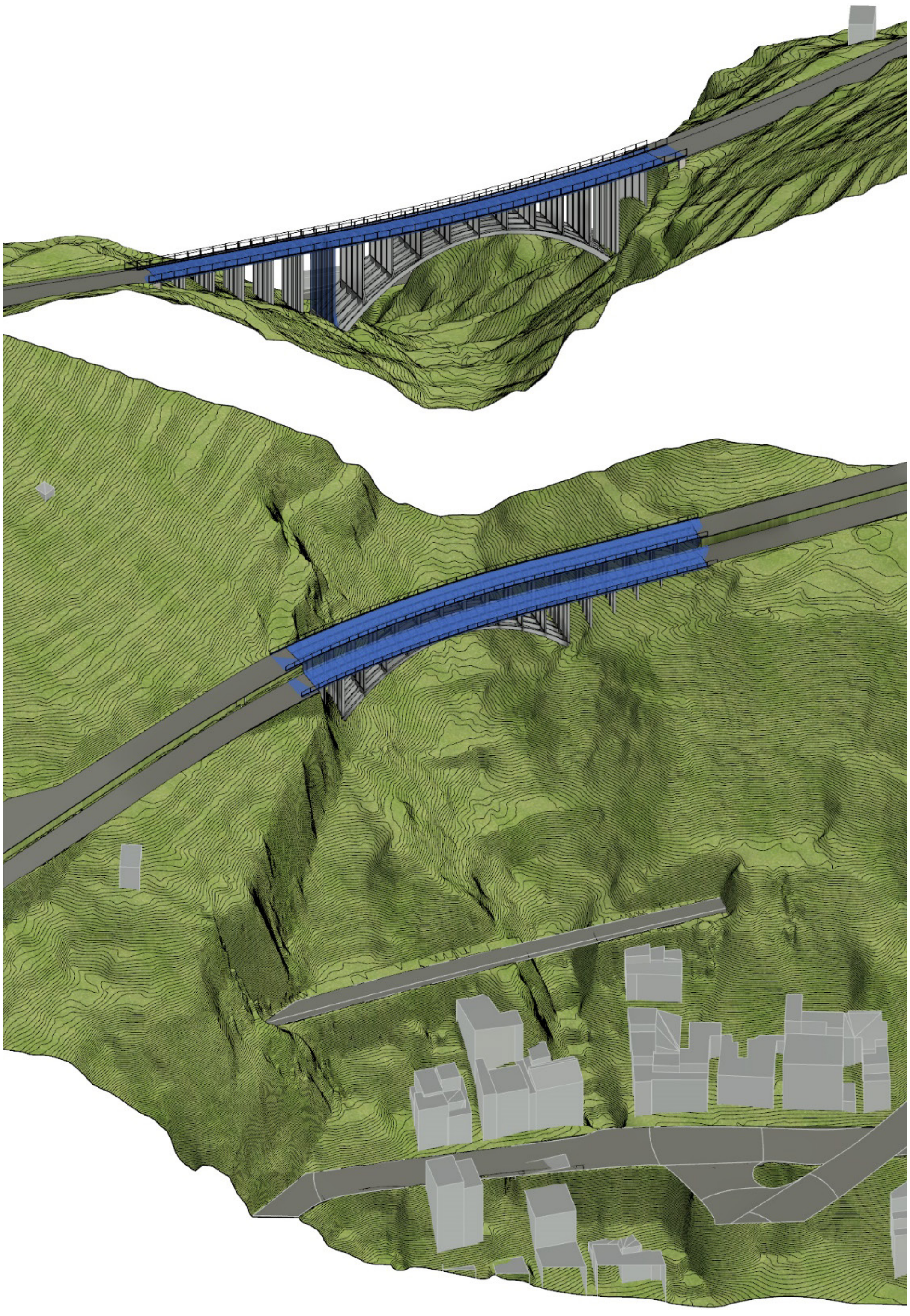


Figure 5.10 – Overview of the integrated GeoBIM model, including the infrastructure, the valley, and part of the urbanised context [AoE]

5.3 Georefencing, federated models setting up, and structural modelling to update the current state of knowledge

The activities incumbent on an infrastructure manager are multiple and include both the up-to-date census of its infrastructure assets and the acquisition of geometric data and the assessment of the state of art [224]. Other interesting activities for the manager may concern the recovery of lost or partially missing design information or the generation of detailed geometric models for the current state of the infrastructure (as-built) to assess any deviations between the actual and design state. The growing interest in the integration of BIM and GIS systems therefore focuses primarily on the import and interoperability of BIM data in a GIS environment and vice versa.

To this end, BIM models of both the infrastructure and the surrounding context were developed and georeferenced from the three-dimensional GIS models of the cartographic base in a common environment in order to organise the information useful to define the entire viaduct: each virtual element was *informed* with all the parameters and characteristics of the structural element [225].

In order to optimise the scan-to-BIM modelling of the infrastructure, it was necessary to segment the point cloud acquired with TLS into six regions (two inherent to the decks and four to the pier zone – Figure 5.11) using the Autodesk ReCap software. In addition to the survey data, the original viaduct project drawings were used to shape the BrIM model. Subsequently, a federated model – FSC phase of the ECO-System methodology – was established in the form of a project with *shared coordinate* settings *published* to the models linked within the Autodesk Revit BIM authoring tool environment (Figure 5.12 and 5.10); it contained both the model of the valley and the representative volumes of the urban context, as well as the BIM model of the viaduct [225].

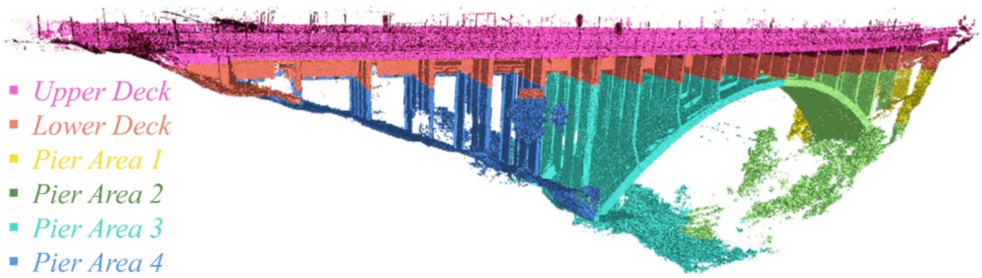


Figure 5.11 – Point cloud segmentation within the Autodesk ReCap Pro environment [225]

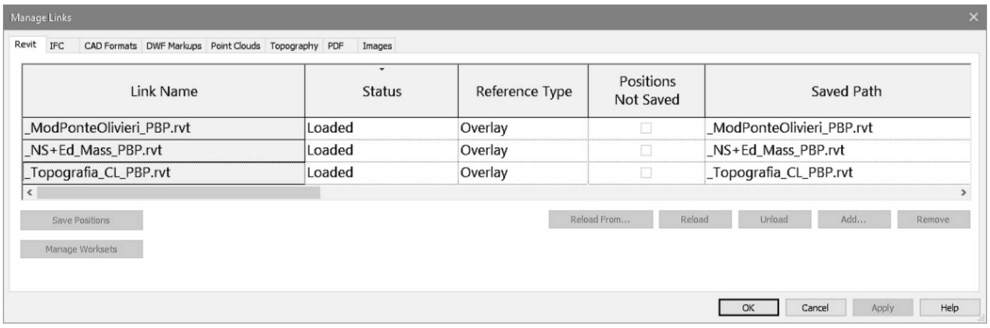


Figure 5.12 – Revit dialog box to manage the sub-projects linked within a superordinate one [AoE]

An initial approximate model of the terrain was developed from the contour lines (*_Topografia_CL_PBP.RVT* in Figure 5.12), proceeding to define in more detail the representative surfaces of the infrastructure system, while the urban context was only reproduced volumetrically within a second Revit file (*_NS+Ed_Mass_PBP.RVT* in Figure 5.12). With specific regard to the structural modelling of the viaduct – STR phase –, since it is mostly composed of non-standardised elements, *ad hoc* parametric families of the various structural parts (i.e., double-highted deck – Figure 5.13, piers composed of pillars and connecting bracing walls and arch with relative ribs – Figure 5.14) were generated within a third project (*_ModPonteOlivieri_PBP.RVT* in Figure 5.12 and Figure 5.15).
Additionally, for the elements of the safety barriers, as they are standardised and regular, semi-automatic modelling procedures were implemented using a VPL script specifically developed via the Dynamo plug-in for Revit (Figure 5.16, 5.17, 5.18, 5.19, 5.20, 5.21, and 5.22).

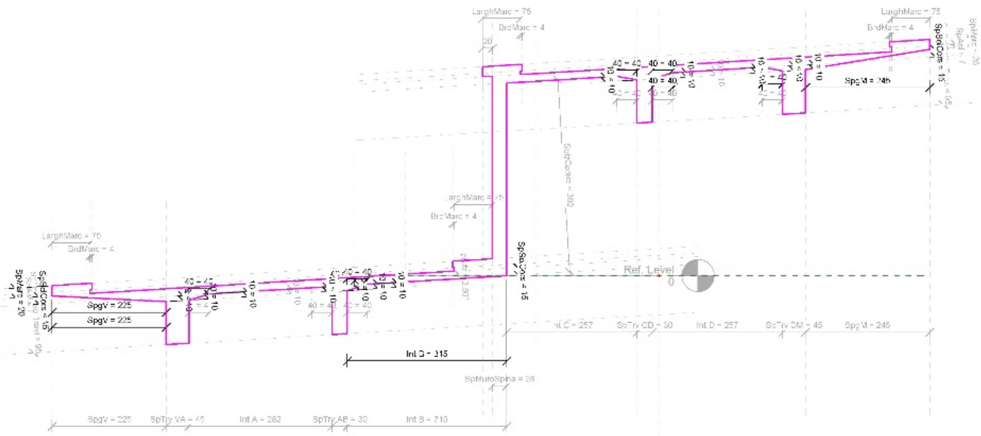


Figure 5.13 – *Ad hoc* parametric family of the bridge deck [AoE]

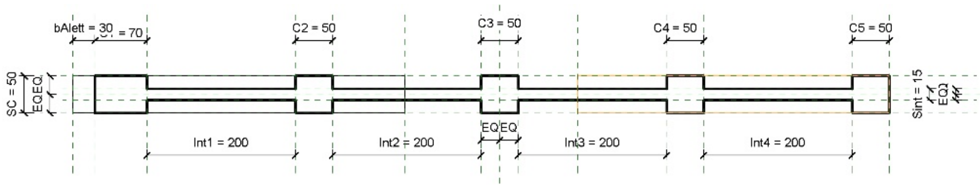


Figure 5.14 – *Ad hoc* parametric family of the bridge piers [AoE]

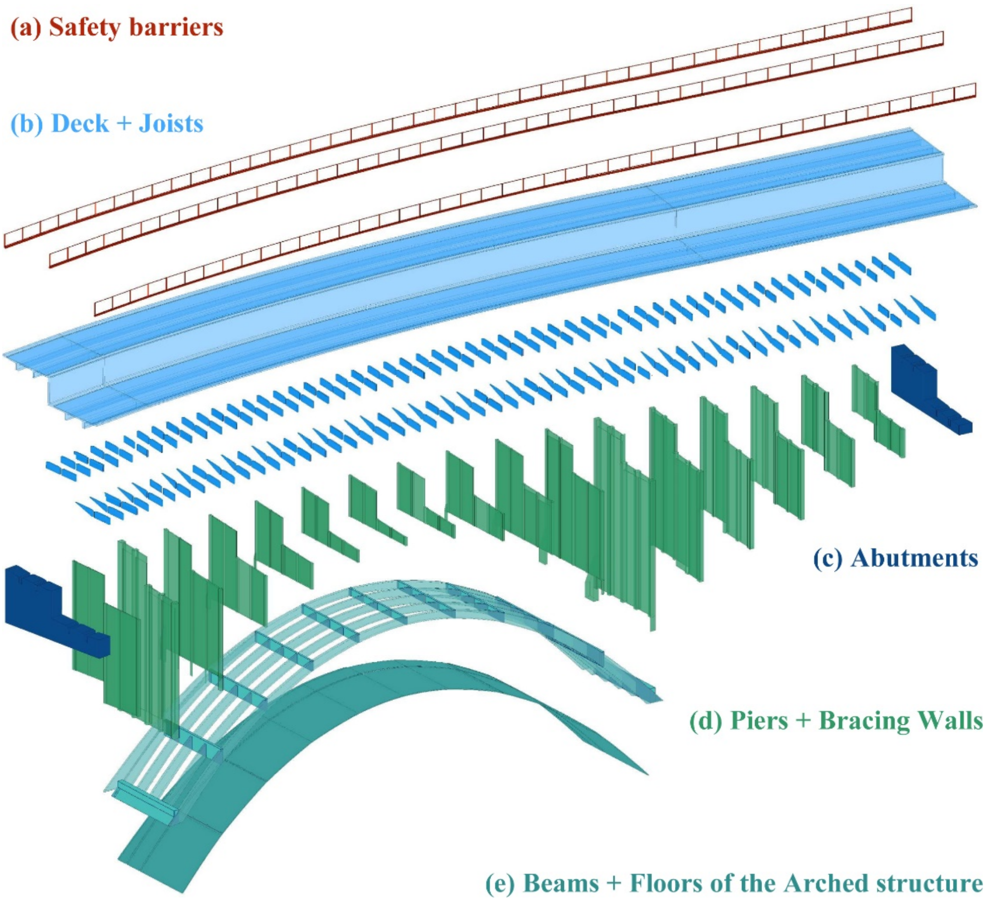


Figure 5.15 – Exploded axonometric view of the structural BrIM model [AoE]

The next phase of the study was dedicated to the optimisation of the workflow dedicated to the integration of BIM and GIS data, when the latter were realised with ESRI tools. In this way, the parametric model produced in Revit is successfully converted into a real GeoDatabase – the recurrence of the GEO phase was aimed at optimising the final procedure.

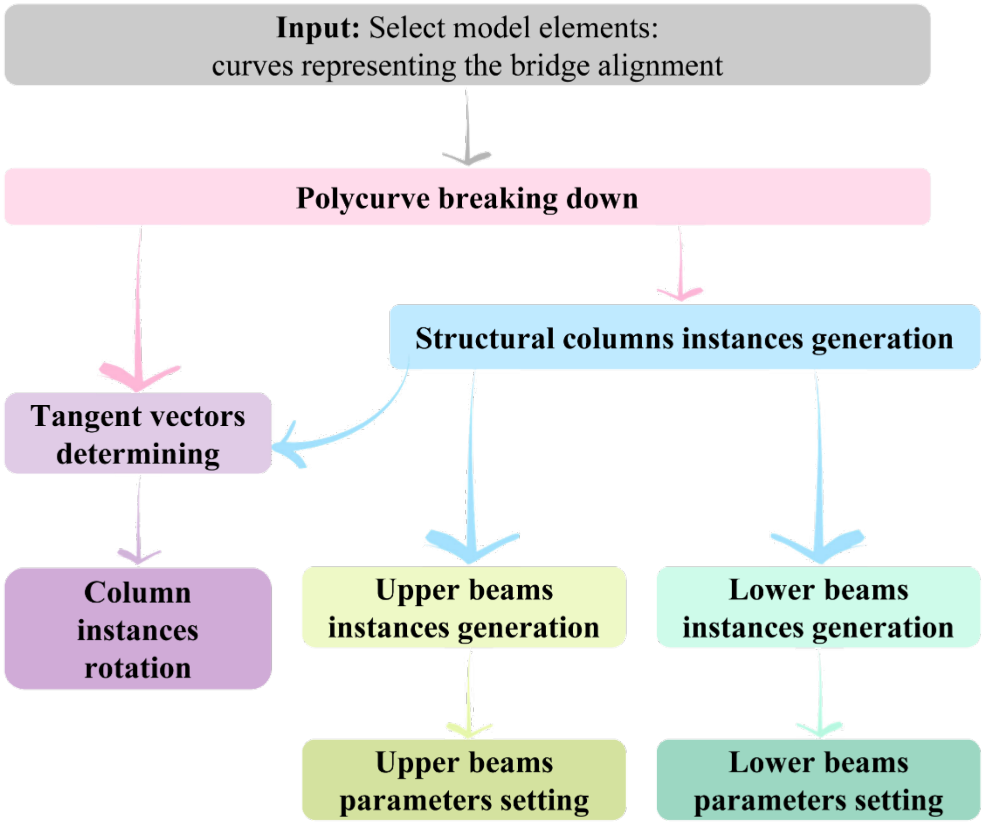


Figure 5.16 – Diagram breaking down the VPL script developed to model the safety barriers [AoE]

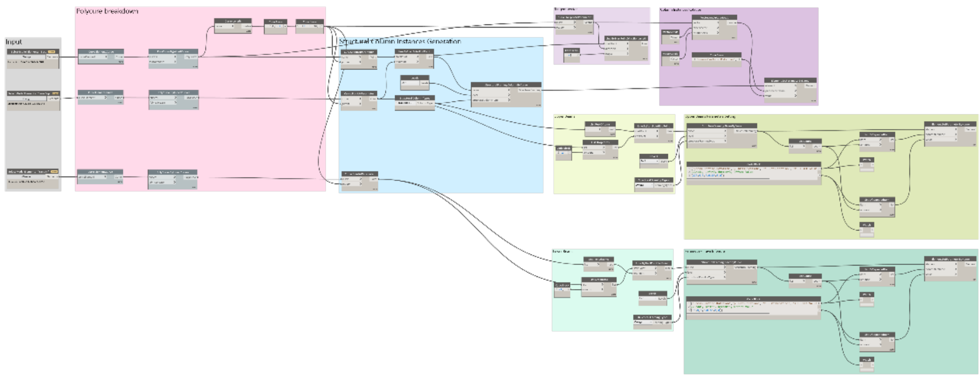


Figure 5.17 – Dynamo VPL script developed to model the safety barriers with the Dynamo environment [AoE]

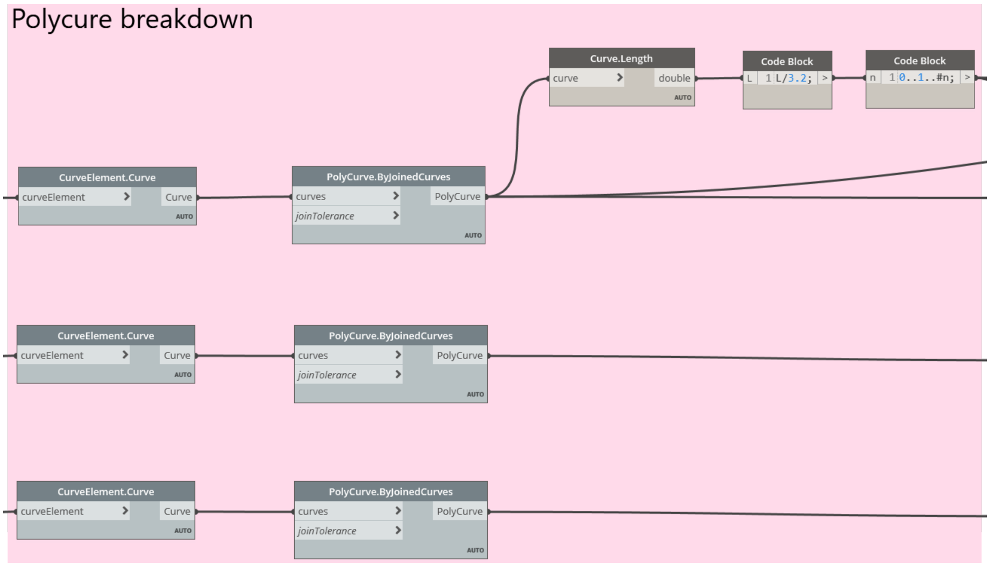


Figure 5.18 – Dynamo VPL script developed to model the safety barriers: Group of nodes dedicated to breaking down the modelled polycurves following the bridge alignment [AoE]

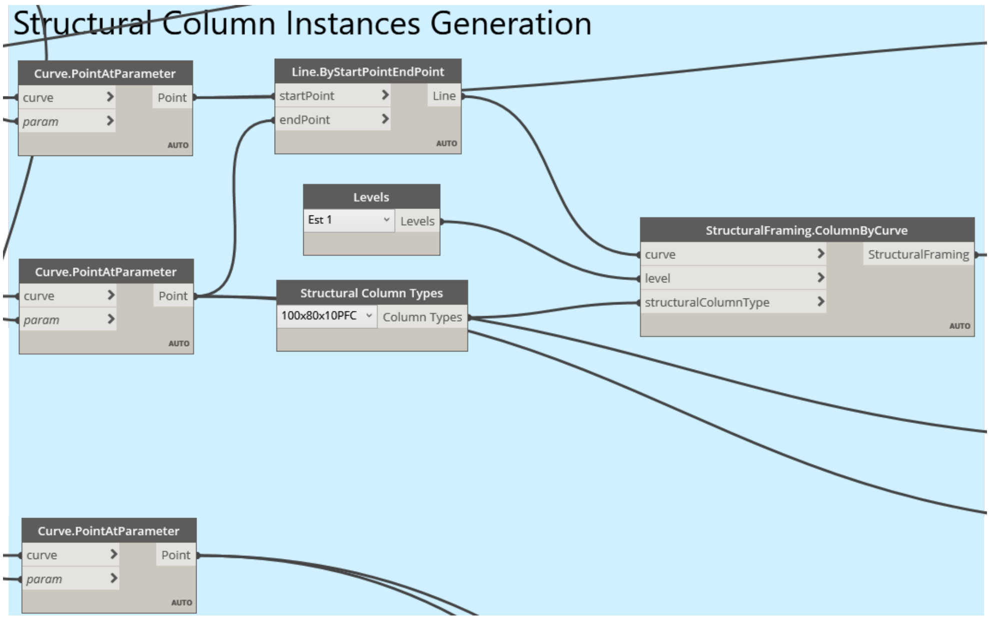


Figure 5.19 – Dynamo VPL script developed to model the safety barriers: Group of nodes dedicated to generating the barriers' structural columns instances [AoE]

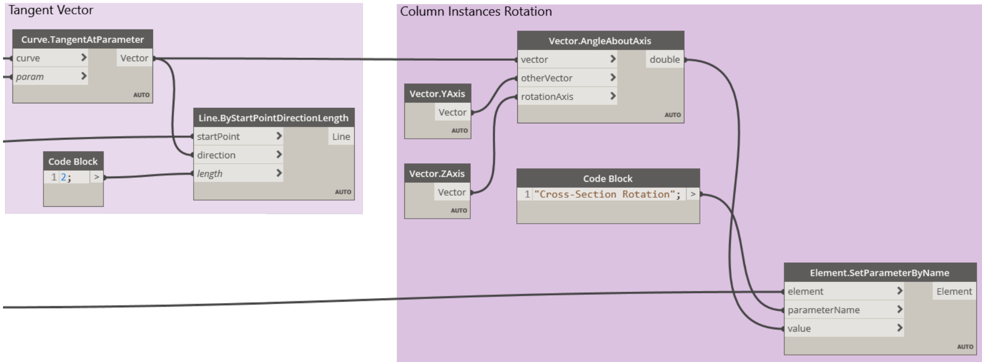


Figure 5.20 – Dynamo VPL script developed to model the safety barriers: Groups of nodes dedicated to rotating the barriers' structural columns instances for orienting according to the bridge alignment [AoE]

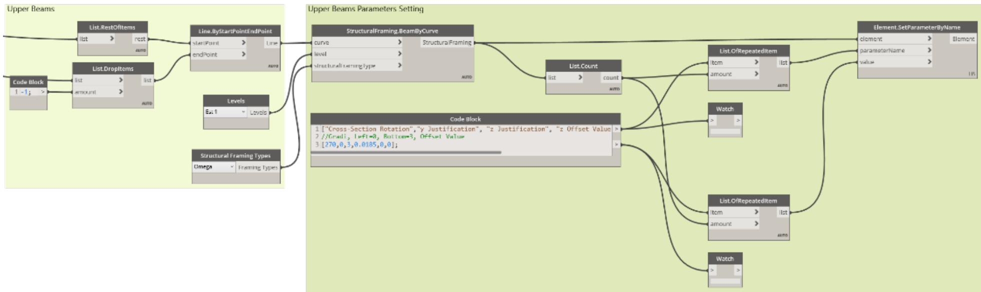


Figure 5.21 – Dynamo VPL script developed to model the safety barriers: Group of nodes dedicated to generating the barriers' upper beams instances [AoE]

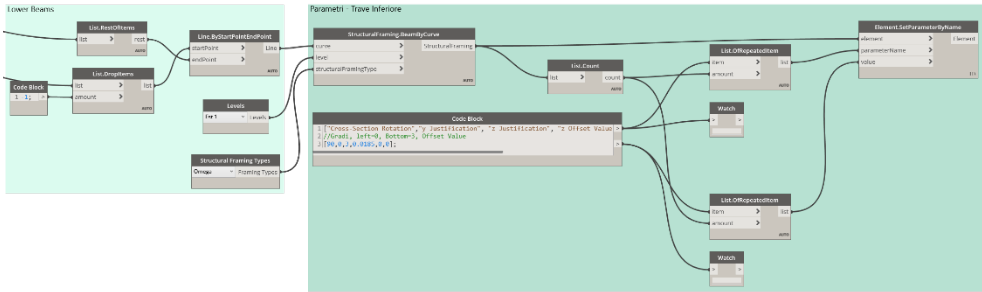


Figure 5.22 – Dynamo VPL script developed to model the safety barriers: Group of nodes dedicated to generating the barriers' lower beams instances [AoE]

Indeed, one of the most evident inconsistencies between BIM and GIS is in the georeferencing of data: BIM designers work in a local Cartesian system while the terrain morphology is referred to a geodetic reference system. In order to integrate the products, a single reference system was adopted, associating the national one in force – UTM33N/RDN2008 – with the main Revit model, which thus acts as a host for the models linked to it, a fundamental step for the *publication*, to the latter, of the same coordinates; this information was acquired semi-automatically from the point cloud and the digital model of the Olivieri Valley. The use of a shared reference system thus made it possible to assemble, after modelling, the three projects developed separately in order to produce up-to-date comprehensive drawings of the integrated infrastructure in its complex environmental system (Figure 5.23 and 5.24).

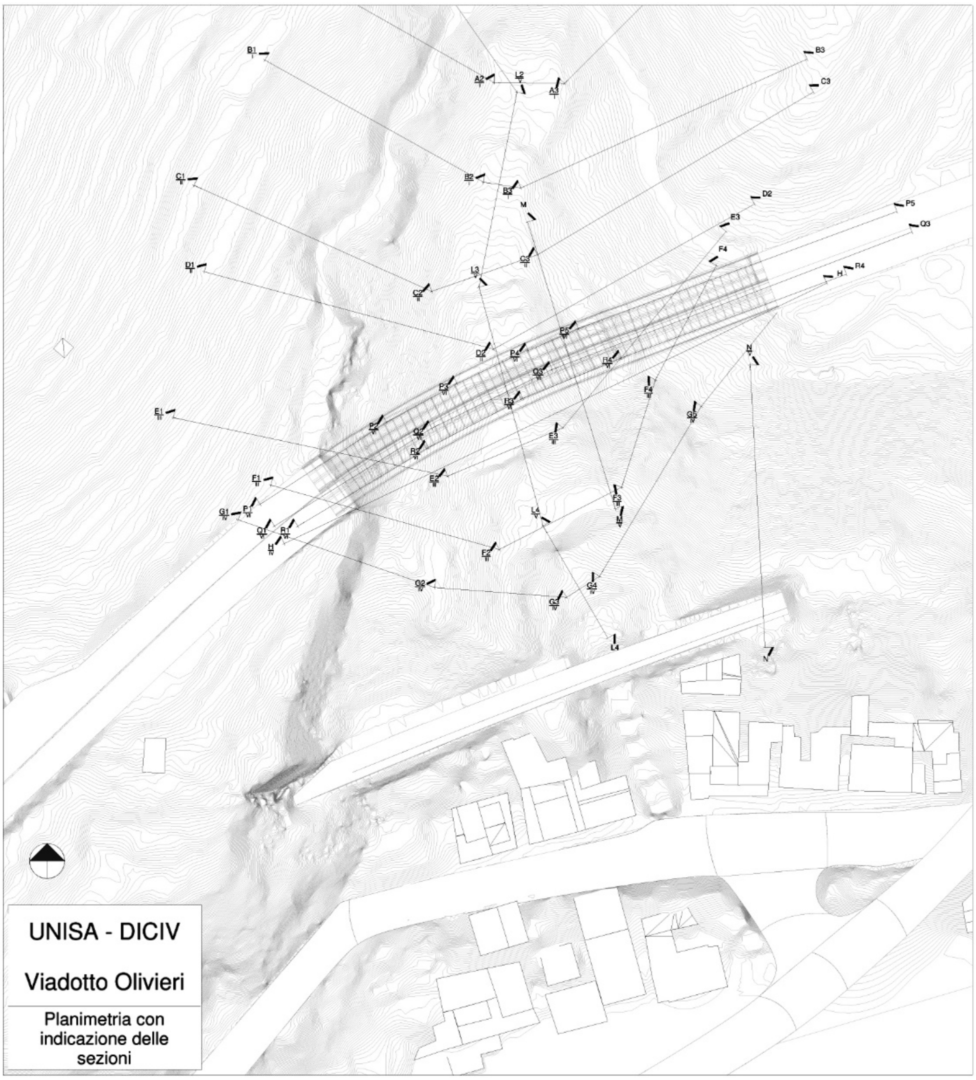


Figure 5.23 – Plan view of the overall environmental system [AoE]

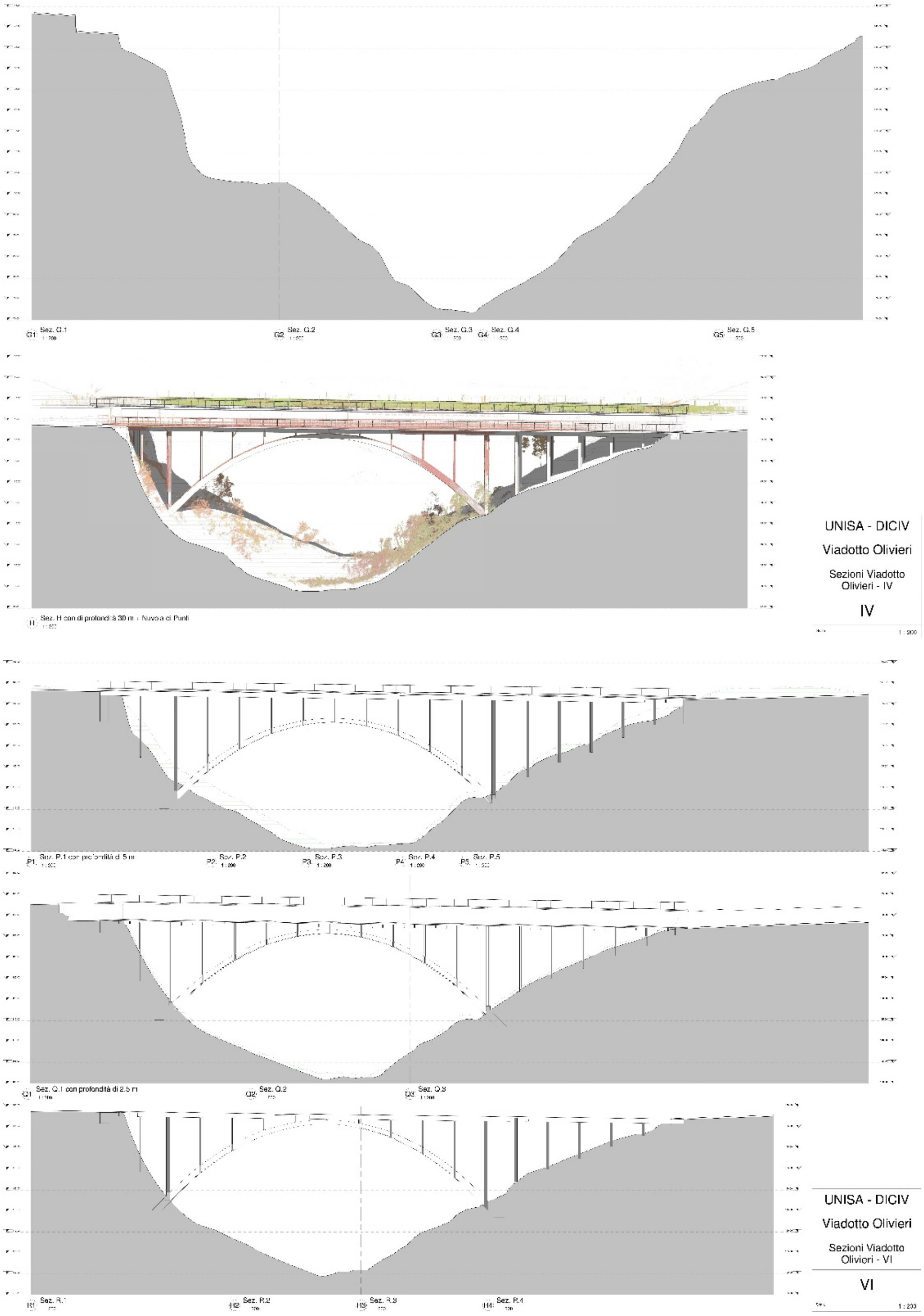


Figure 5.24 – Section views of the overall environmental system [AoE]

6. Pilot case study setting up

Given the relevance of the case study and the experimental research already conducted regarding the updating of the information database concerning the Olivieri Viaduct and the surrounding urban context, it appeared to be the perfect case study to develop an operational methodology for the massive digitisation of both the structural geometry and the relative state of conservation of the infrastructural structures belonging to the category of 'bridges viaducts and overpasses' located along the A3 motorway, within the framework of the C.U.G.R.I[41] [*Consorzio inter-Universitario per la previsione e prevenzione dei Grandi Rischi – Inter-University Consortium for the Forecasting and Prevention of Major Risks*] agreement with the *Autostrade Meridionali* [SAM] company concerning the commissioning of the ***Service for the surveillance of the major infrastructures of the A3 Naples-Pompei-Salerno motorway – in accordance with the circulars of the Ministry of Public Works No. 6736/61 of 19.7.67 and No. 34233 of 25.02.1991 – and related support activities, such as non-destructive technical tests, laboratory tests, etc.***

[41] The *Inter-University Consortium known as the University Centre for the Forecasting and Prevention of Major Risks* [C.U.G.R.I.], established by the Rectors of the University of Naples "Federico II" and the University of Salerno – agreement signed on 15 April 1993 by the Rectors of the Universities of Naples and Salerno, legal status by Ministerial Decree of 14 June 1994 in G.U.R.I. no. 242 of 15 October 1994 – aims to provide organisational, technical and financial support to consortium members, in the field of forecasting and prevention of Major Risks, in particular in the related fields of Earth Science, Geotechnical, Hydraulic, Structural and Industrial Engineering for the general purpose of a planned provision of means for disaster mitigation mainly in soil protection, in accordance with the provisions of these Articles of Association.

Within this framework, the Consortium shall rely as a matter of priority on the collaboration of the Consortium's professors, departments and universities. The Centre has its registered office at the University of Salerno and is under the supervision of the Ministry of Education, Universities and Research, known as MIUR. The Centre has two operating sites, one at the University of Salerno, and the other at the University of Naples. For further information visit the official website: http://www.cugri.it/01_chi_siamo.htm

6.1 C.U.G.R.I. platform for the digitisation of Inspection data

"The surveillance system represents the set of control, inspection and monitoring activities on the structures that the manager of an infrastructure network must carry out in order to ensure the availability, functionality and maintenance of the safety conditions of the infrastructure itself" [4].

Here are the indications, the criteria and the minimum requirements of the procedures adopted by the public and private transport managers on the national territory, keeping in mind the monitoring systems already in use, thereby aiming at standardising the structural safety management activities for the entire national territory.

The purpose is to periodically assess the *state of condition* of the structure itself (diagnosis) regarding *its suitability for the intended use* (structural/foundational integrity, protection from floods and landslides), the *efficiency of the auxiliary apparatuses* and the *estimation of evolutionary trends* (prognosis). All this, together with the analysis of the data collected during the *census* (Level 0), allows the improvement of the knowledge about the structure to reduce the epistemic uncertainties (actions, resistances, models), the updating of the risk classification related to the existence/operation of the structure (current CdA) and, finally, make it possible effective planning of the maintenance/adjustment interventions [226].

The operational tools of the surveillance and monitoring system:

- routine periodic inspections
- extraordinary inspections;
- non-destructive and semi-destructive surveys;
- static load tests and dynamic response surveys;
- instrumental monitoring;
- data analysis and interpretation algorithms;
- representative models of the actual behaviour;
- condition indices and degradation models;
- computational databases [BMS].

"The identification system has the purpose of associating data and information from the surveillance and monitoring system to the different construction elements of the bridge, to the auxiliary equipment, to the deck support apparatuses and in general to those objects whose state of preservation can be observed (or determined through instrumental surveys and measurements) independently from one another and that constitute separate entities from the point of view of the

degradation and damage phenomena suffered and the possible maintenance, replacement and/or restoration interventions" [4].

The structure is defined and identified at Level 0 (*National elements*), but the identification system is further enriched by information from Level 1 and 2 (*Road network elements*), Level 3 and 4 (*Elements composing the structure*).

The decomposition of the bridge into *objects* can be carried out through the construction of BIM models or finite element models on the basis of which data sharing procedures can be activated using BMS software and instrumental monitoring systems. In addition, in order to be able to identify the elements in their position, it is necessary for each of them to be associated with an identification code unique within the structure (Figure 6.1) [4].

"The classification and the assessment and monitoring actions regarding infrastructures, in order to be effective, must be included in an overall management framework, also informative, of the structures so as to guarantee adequate safety levels for the national infrastructural heritage, taking into account the actual needs and the available resources" [4].

These information models, suitably updated in real-time, should then constitute the information skeleton of the National Information Archive of Public Structures [AINOP]. The development of the pilot case was therefore carried out in agreement with the C.U.G.R.I. IT [information technology] technicians who, in parallel, are developing an online monitoring software for the infrastructure, currently under Beta Release, oriented to optimise the visual inspection activities envisaged by the LG20. The objective of the developed BMS-type platform is in fact, the realisation of a structured database that integrates the *register data* of the Italian infrastructural heritage, the updated and updatable information coming from the in-situ inspections and the relative three-dimensional information model imported through open-exchange IFC models.

Figure 6.1 – Structure of the multi-level interconnected identification system envisaged by the LG20 [4]

6.2 Component structural modelling and shared parameters setting up

Following with a more detailed structural modelling phase [STR], the uploadable families that had been previously modelled *ad hoc*, were then edited so that they could be adapted to the indications envisaged by the 2020 Surveillance Handbook [99] and inserted, by breaking them down into components, within the model; starting from the overall families, they were divided into families to fit the description of the components. For example, in the case of the deck, the "*Olivieri Bridge Deck Lanes*" [*Impalcato Corsie Ponte Olivieri*] family (Figure 5.13 and 5.15 – (b)) was broken down into five structural parts in accordance with the ASPI indications (Figure 6.3 – (a)): bottom and top slabs, bottom and top side overhangs, two bottom and two top longitudinal beams sized 45x85 cm and 25x85 cm, longitudinal girder sized 28x365 cm. The joists stiffening the deck have been left as in the original model being already decomposed as required.

With regard to the piers, on the other hand, an ex-novo modelling was carried out since the already existing family "*Olivieri Bridge Pier"* [*Pila Ponte Olivieri*] (Figure 5.14 and 5.15 – (d)) had been modelled as a whole, in accordance with the level of detail required for the previous application on a territorial scale, thus generating five columns and the four connecting bracing walls per each pier (Figure 6.3 – (b)).

The structural column families, called "*Olivieri Bridge Columns"* [*Pilastri Ponte Olivieri*] – which can be loaded from external libraries – were then modelled from pre-existing rectangular cross-section structural columns, modifying their width and thickness and transforming these parameters from type to instance, so that they could be easily adapted to those constructed within a few centimetres tolerance.

On the other hand, the bracing walls connecting and stiffening the piers were modelled using system families, specifically 12 cm thick basic walls (Figure 6.3 – (b)). The cross-sectional dimensions of the piers and the bracing walls were inserted by cross-checking the survey data against the original plans.

For the Arched substructure (Figure 5.15 – (e)), the slab composing it was constructed from scratch using the *Structural Floor* system family, specifically a 12 cm cast-in-place concrete floor; while for the longitudinal beams, the *"Rectangular Longitudinal Concrete Beam – Arch"* family was created; it was modelled for the purpose as a tapered beam, once again parametrising the dimensions of the profiles as instance parameters, to be modified according to the requirements to fit the original ribs of the pseudo-arch (Figure 6.3 – (c)). Once again, the dimensions of the components were cross-referenced against the original

project drawings. The abutments of the Viaduct, modelled as a generic basic wall with 2m filling, were not modified with respect to the original model (Figure 5.15 – (c)). The expansion joints, on the other hand, were obtained as an elaboration from the "*Olivieri Bridge Deck Lanes"* family previously created (Figure 6.3 – (a)).
Since the foundation system was not contemplated in the original GeoBIM model, the foundation elements were located in correspondence with the structural columns of the piers 001, 002, 013, 014, 015, 016, 017, in the form of rectangular isolated elements (plinths) sized 200x145x45 cm, while for abutments 001 and 002 plinths sized 2000x300x45 cm were used.
The foundations of the arch were then modelled completely from scratch as foundation beams from a parametric profile, to which a relative rotation was associated in order to balance the arch's load stresses as prescribed in the original design (Figure 6.3 – (c)).
It is worth emphasising that in order to realise a model, families must be designed as structural elements to begin with.
In order to enrich the modelling, the Revit software allows additional information to be entered through the generation of shared parameters stored in a TXT text file (Figure 6.4), which can, if required, be shared externally to transfer its contents to other projects. In the present case, two sets of shared parameters – the only type of external parameter that can be included in any schedule within the Revit software - were first created: "*IFC*" and "*ASPI Regulation*" [*Regolamento ASPI*]. The former set included *IfcExportAs*, *IfcExportType*, *Site Name* parameters (Figure 6.4 – in red), while the latter contains the identification codes of the Structural Assets provided by the Surveillance Handbook and extensively discussed in sections 4.6 and 4.7 (Figure 6.4 – in yellow).

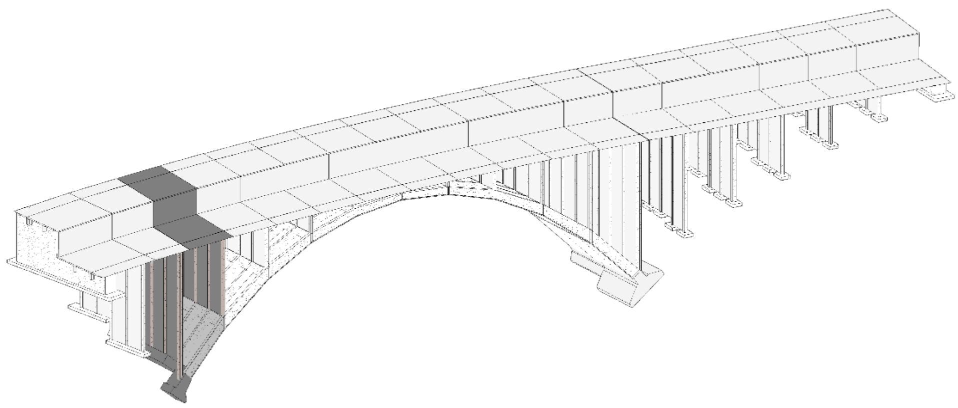


Figure 6.2 – Structural BrIM model of the Olivieri Viaduct broken down into components, with the third *Structural Section* [*Parte d'Opera*] highlighted [AoE]

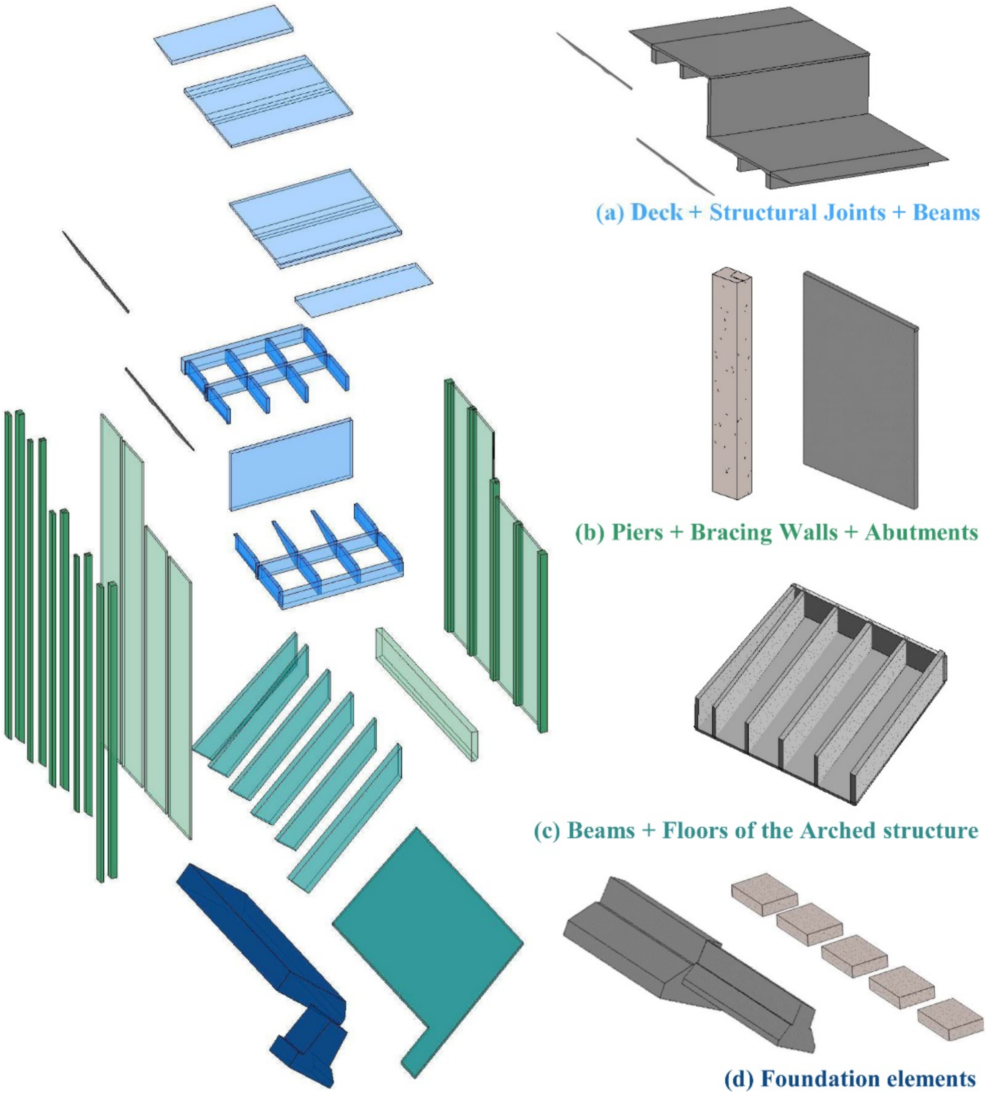


Figure 6.3 – Exploded axonometric view of the structural BrIM model *components* comprising the third *Structural Section* [AoE]

The next step was to create project parameters – which unlike shared parameters, are specific to each project file – from the listed shared parameters, in order to add them to the required categories of elements and to organise them afterwards by means of targeted schedules (Figure 6.5). Subsequently, multi-category and single-category schedules were set up to simplify the compilation of classification parameters.

The project parameters introduced, belonging to the ASPI Regulation (Figure 6.5 – in yellow) and IFC groups (Figure 6.5 – in red), were associated with the categories corresponding to the modelled objects, in detail: Structural Foundations, Generic Models, Walls, Floors, Structural Columns and Structural Frames. The ASPI parameters were entered as *Instances* in order to assign unique values to the individual components and were grouped under the project group *Data* (in order to conveniently organise and retrieve them in the Properties panel as shown in Figure 6.5, left). The IFC parameters, on the other hand, were entered as *Type Parameters* since they were associated with family types, to assign them particular export categories under the BuildingSMART standard and grouped in the IFC Parameters group (Figure 6.5, right). The *Site Name* parameter has been linked to the *Project Information* category and entered once again as an instance parameter. The Layers were then only given allocated the project parameter Structural Section.
It is important to remember that the project parameters must be entered according to the order in which they need to be displayed so as to facilitate their management. Therefore, the parameters have been arranged in the following order:

- *Partial Structure* [*Opera Parziale*];
- *Structural Section* [*Parte d'Opera*];
- *Structural Section Number* [*Numero Parte d'Opera*];
- *Component* [*Componente*];
- *Component Number* [*Numero Componente*];
- *Form Link* [*Link Scheda*] – further explained in section 7.1;
- *ASPI_ID* [*ID_ASPI*] – further explained in section 7.1;
- *Material Code* [*Cod-Materiale*] – further explained in section 7.1.

Only afterwards, three additional shared parameters – further explained in detail in sections 6.4 and 7.1 – are generated automatically by means of an ad-hoc developed script and organised within the shared parameter set "*Schede All.B DM20*" (Figure 6.4 – in green):

- *Typology* [*Tipologia*]
- *Form* [*Scheda*]
- *GlobalStructureCode* [*CodiceOperaGlobale*]

It is worth noting that the infrastructure identifier, defined as *"Structure Number"* [*Numero d'opera*] by the regulations, is inserted as information regarding the entire project in the Revit environment as *"Project Number"*.

```
# This is a Revit shared parameter file.
*GROUP  ID      NAME
GROUP   1       IFC
GROUP   2       Regolamento ASPI
GROUP   3       Schede All.B DM20
GROUP   4       PG_ANALYSIS_RESULTS
*PARAM  GUID                                    NAME                  DATATYPE       DATACATEGORY  GROUP  VISIBLE
PARAM   6303f902-f80c-431f-a606-b2d88882c63b    IFCExportType         TEXT           1             1      1
PARAM   6b3b5c13-d50b-4f1e-9bfe-ecd067113c15    Componente            TEXT           2             1      1
PARAM   21181614-b01f-45c4-b927-0a2e4a1fa04c    Site Name             MULTILINETEXT  1             1      1
PARAM   7d917629-91aa-474f-b370-658dc8df9c75    CodiceOperaGlobale    TEXT           3             1      1
PARAM   638a8135-c8a8-48f9-9baa-1f0045e9b91a    ID_ASPI               TEXT           2             1      1
PARAM   d7bb0644-eade-44c6-8782-325370b108f9    Scheda                TEXT           3             1      1
PARAM   e8b65c47-4c9f-4133-8108-b42148809adb    Dr_2021               NUMBER         4             1      1
PARAM   c9ec9053-a374-4428-889e-e682b32da687    Parte D'Opera         TEXT           2             1      1
PARAM   b8f85c55-05e9-4eba-bbbe-257418450f06    Opera Parziale        TEXT           2             1      1
PARAM   29160c57-b18a-44ec-a954-8fb17d7a4f8c    IFCExportAs           TEXT           1             1      1
PARAM   fe69915e-e387-43e1-941a-e268c5ac786b    Tipologia             TEXT           3             1      1
PARAM   7856fa6a-7a93-41fe-bc9f-6247985aebfe    Cod_Materiale         TEXT           2             1      1
PARAM   4ff02186-b1a5-49be-b474-b4779507e962    Numero Parte D'Opera  TEXT           2             1      1
PARAM   c069519a-b7c3-4cdb-bc4a-bc024315abcb    Link Scheda           URL            2             1      1
PARAM   674949f5-d128-48ca-b826-fa433b08a1b8    Numero Componente     TEXT           2             1      1
```

Figure 6.4 – TXT file storing the shared parameters set up for the proposed application [AoE]

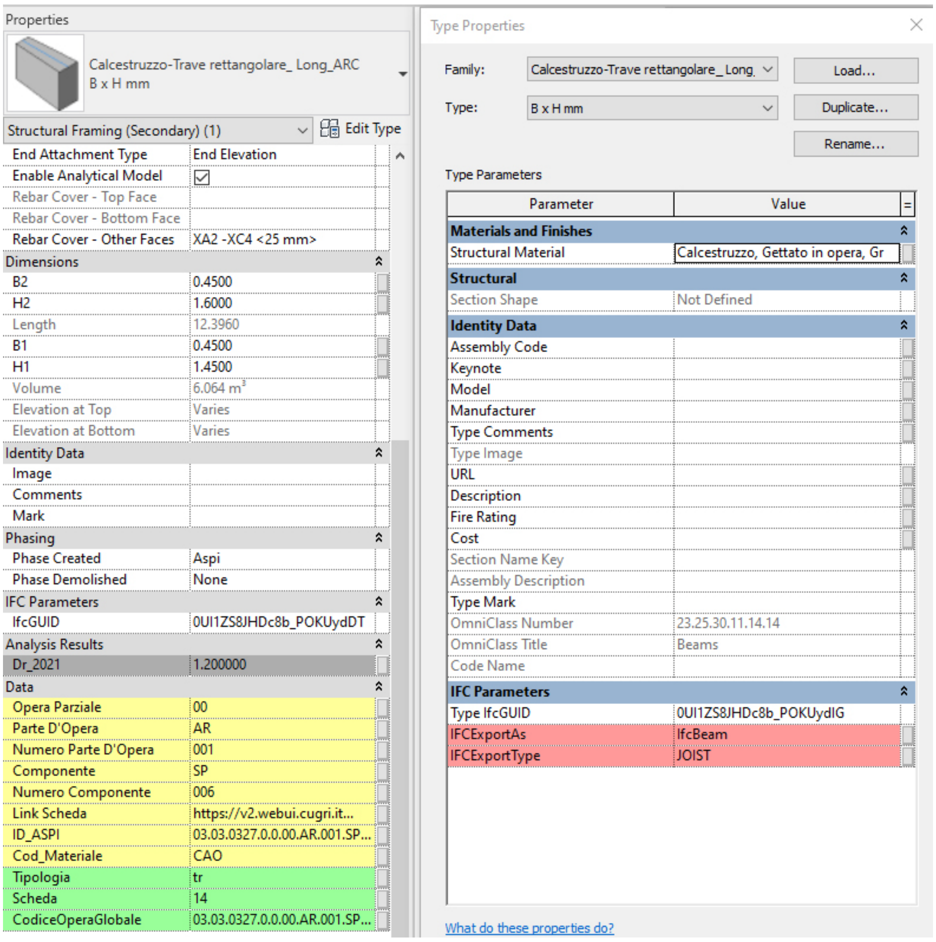


Figure 6.5 – Example of the shared parameter assigned as *project instance parameters* (*Properties* dialog box to the left) and as *project type parameters* (*Type properties* dialog box to the right) to a Joist of the Arched substructure [AoE]

6.3 Olivieri Viaduct classification according to the Italian regulation

The placement of the components on the model follows the overall scheme with the fields identified in accordance with ASPI indications as shown in Figure 6.6. The viaduct plan is shown subdivided into 18 fields, while the four diagrams shown in Figure 6.7 represent the generic X field at different heights to identify the elements comprising the viaduct.
Since the structure is complex, especially along the curvilinear deck, it was decided to represent the individual fields, both in the curved and straight sections of the deck, as linear elements.
In order to adapt the elements of the deck to the real progression of the structure, both the transversal and the longitudinal slope were defined, operating on the element properties and setting appropriate offsets at the insertion level of each element.

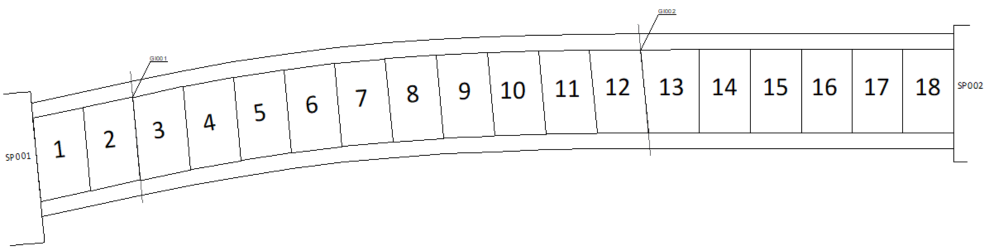


Figure 6.6 – Plan view of the viaduct divided into 18 sections [Developed by the C.U.G.R.I. engineers]

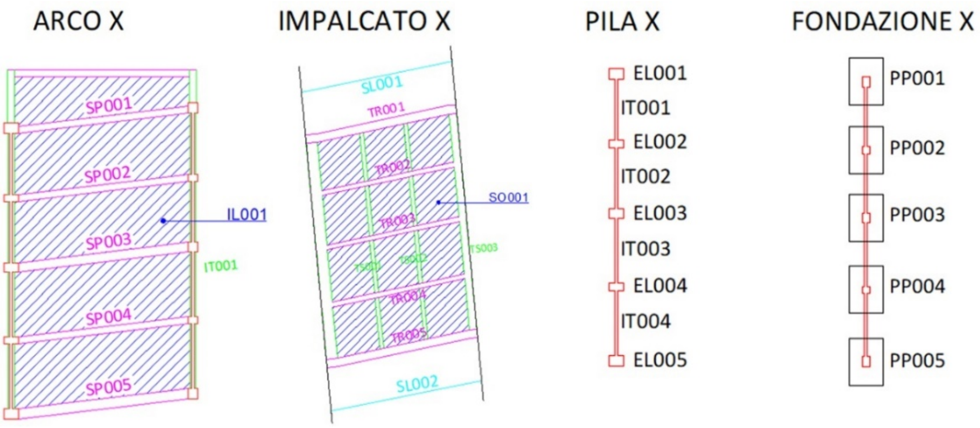


Figure 6.7 – X-Bridge section's diagram at different heights [Developed by the C.U.G.R.I.

engineers]

Reference levels were defined to better place the deck elements:

- *Mountain (top) level* for slab, side overhang, the two longitudinal beams and the three joists of the left-hand lane;
- *Valley (bottom) level* for slab, side overhang, the three longitudinal beams and the three joists of the right-hand lane.

In the case of the piers' vertical elements, different levels were used as base constraints, associating then the columns' upper part to the longitudinal beams of the deck and the bracing walls to the joists of the deck.

To place the arch beams, it was then necessary to properly define the *Reference Levels*, the *Initial Level Offset* and the *Final Level Offset*, while in the case of the slab, the slope was entered through the *Inclination arrow*.

Then, the project parameters – derived from the shared parameters as explained above – were entered so that the elementary components of the viaduct could be thoroughly catalogued according to the requirements of the Surveillance Handbook. Namely, to facilitate the population procedure, *multi-category schedules* were created containing the families of elements and all their specifications, in addition to the ASPI parameters, in order to have an overall control at this information enhancement stage [LOI].

The origin system, upon which the inspector is positioned, coincides with the Naples side of the Olivieri Viaduct. The numbering for the Structural sections and components will therefore be progressive increasing along the directions shown in Figure 6.8:

- for the span: from the Naples side;
- for the number of the structure: from bottom to top;
- for the number of elements: from left to right, from bottom to top.

The identification codes – in terms of ASPI parameters values – of some of the components composing the third Structural Section highlighted in Figure 6.2 and decomposed in Figure 6.3, are summarised in Figure 6.9.

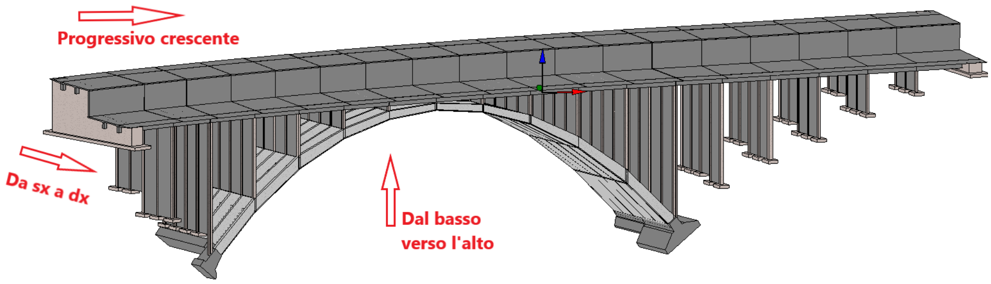


Figure 6.8 – Numbering system used for the Olivieri Viaduct [Developed by the C.U.G.R.I. engineers]

	Deck joint	Deck joint	Deck top slab	Deck bottom slab
Opera Parziale	00	00	00	00
Parte D'Opera	GI	GI	IM	IM
Numero Parte D'Opera	001	001	003	003
Componente	AG	AG	SO	SO
Numero Componente	001	001	001	001
Cod_Materiale	NUL	NUL	CAO	CAO

	Deck overhang	Deck girder	Deck joist	Deck joist
Opera Parziale	00	00	00	00
Parte D'Opera	IM	IM	IM	IM
Numero Parte D'Opera	003	003	003	003
Componente	SL	TR	TS	TS
Numero Componente	002	003	002	002
Cod_Materiale	CAO	CAO	CAO	CAO

	Pier structural columns	Pier structural columns	Pier bracing wall	Arch slab
Opera Parziale	00	00	00	00
Parte D'Opera	PI	PI	PI	AR
Numero Parte D'Opera	002	002	002	001
Componente	EL	EL	IT	IL
Numero Componente	005	005	004	001
Cod_Materiale	CAO	CAO	CAO	CAO

	Arch longitudinal joist	Arch cross joist	Stuctural foundation	Stuctural foundation
Opera Parziale	00	00	00	00
Parte D'Opera	AR	AR	FO	FO
Numero Parte D'Opera	001	001	003	003
Componente	SP	IT	PP	PP
Numero Componente	006	001	001	001
Cod_Materiale	CAO	CAO	CAO	CAO

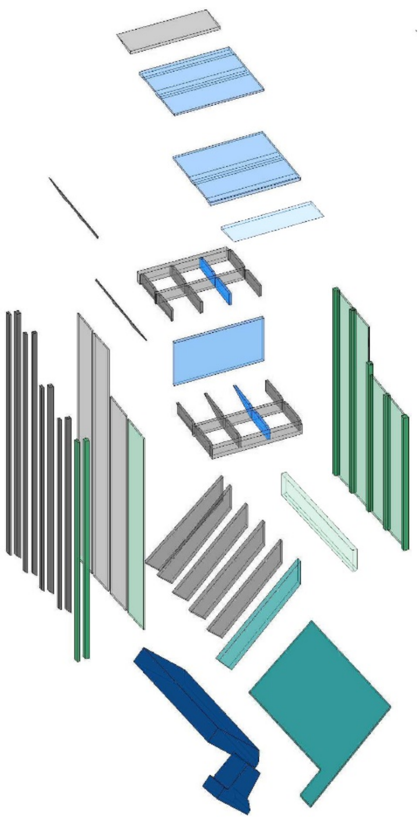


Figure 6.9 – Recap of some of the ASPI identifiers assigned to the third Structural Section's Components [AoE]

6.4 Proposal for a procedural workflow aimed at digitising the infrastructures included in the C.U.G.R.I.-SAM agreement

Following the experimental modelling carried out for the pilot case of the Olivieri viaduct, it was, therefore, possible to define a procedural workflow together with the C.U.G.R.I. counterpart for the optimisation of the digitisation of the A3 infrastructure heritage.
The methodological procedure proposed is currently in its validation process through the application to the other infrastructures included in the C.U.G.R.I.-SAM agreement in order to eventually define a fully functional work breakdown structure [WBS]. Furthermore, the proposed workflow includes a certain degree of optimisation by means of five ad hoc developed VPL scripts (Figure 6.10 and 6.11) explained in detail in chapter 7.
Together, we decided that the first phase involving the modelling and discretisation of the elements would be assigned to the same team of operators (Figure 6.10– in green) who would be later in charge of the in-situ inspections. The same professionals would also transcribe the inspection results within the developed BMS. On the other hand, the model validation and unique assignment of inspection forms to each component will be managed by a supervisor (Figure 6.10 and 6.11– in blue).
It appears clear that BIM-type modelling is not only the product of the demands of the current legislative system but rather constitutes a moment of reflection upon the analysis and discretisation process of the infrastructure under study. The information modelling and component cataloguing phase, in fact, make it possible to understand the functioning of each structural element, in which the structure must be discretised, within the bridge macro-system, revealing in the three digital dimensions any potential issues to be checked during the subsequent in-situ inspection phase.
Before the modelling phase, the existing two-dimensional documentation should optimally be integrated via expeditious three-dimensional surveys to verify the physical asset's actual correspondence with the deposited design. Indeed, as mentioned, the modeller/inspector team is put in charge of discretising the infrastructure according to the current regulations to define appropriately classified intelligent objects.
Following the modelling phase, a supervisor will then validate the realised BrIM models and assign them the uniquely identified inspection forms (*Script 2*).

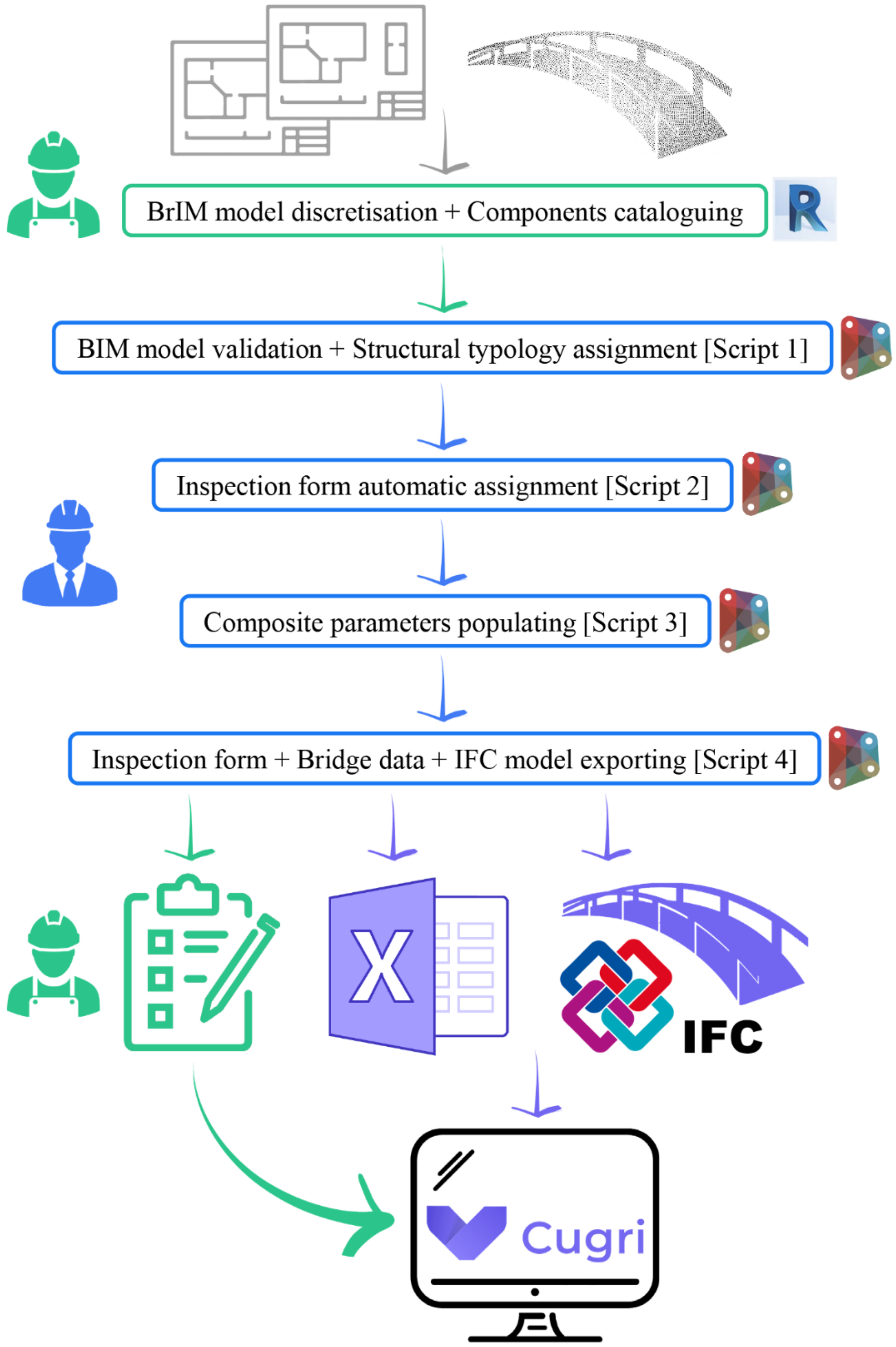


Figure 6.10 – Methodological procedure for the digitisation of the A3 infrastructure heritage:

Exporting stage [AoE]

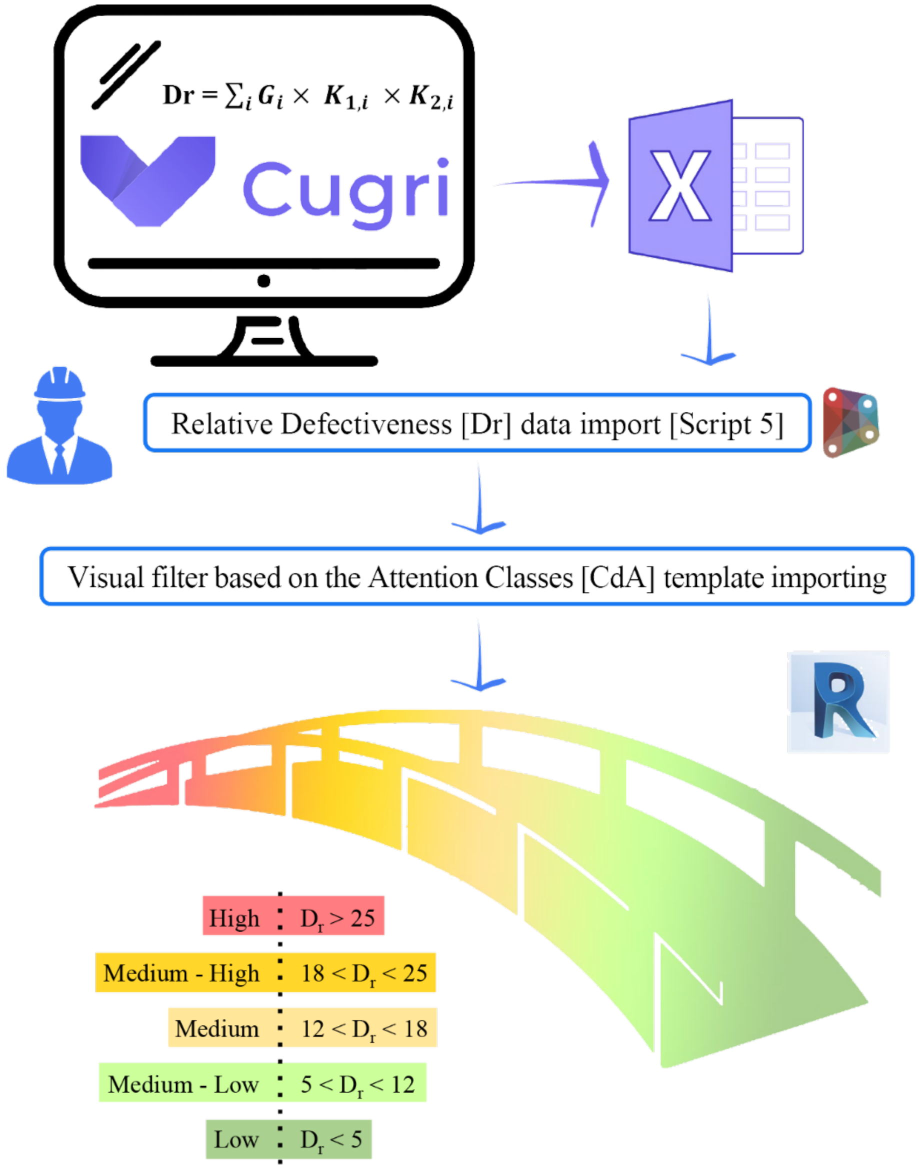


Figure 6.11 – Methodological procedure for the digitisation of the A3 infrastructure heritage: Importing stage [AoE]

As explained in section 4.6, only in the case of those components to which different forms can be assigned due to their multiple possible structural behaviours – as in the case of the arched structure – or their ambiguous relationship to other elemental structural parts – as in the case of plinths - the supervisor will have to fill

in the additional parameter *Typology* [*Tipologia*] – automatically assigned to all categories modelled via *script 1* – before assigning the corresponding inspection forms. The subsequent processes of exporting and *plotting* the information will therefore be managed entirely by the supervisor, supported by the implementation of *scripts 3 and 4*; in particular, they will be responsible for verifying the correct mapping of the structural elements at the time of exporting the model in openBIM [IFC] format.
Since both the export procedures (Figure 6.10) and the reimporting of the inspection results into an editable BIM environment (Figure 6.11) are to be managed by the supervisor, it seemed appropriate to optimise some routines by introducing the VPL scripts mentioned above earlier.

7. VPL Scripts for Level of Information enhancement

The next chapter will detail the validated and optimised procedures for the information exchange concerning both the register and the cataloguing data on the infrastructure, as well as the models in an open format as a basis for further enhancing the level of knowledge concerning the very structure. The bulk of the data thus produced is then organised to be fed into the BMS developed by C.U.G.R.I.'s IT technicians, where it is archived according to regulatory requirements.

In particular, the shared parameters *Form Link* [*Link Scheda*] and *GlobalStructureCode* [*CodiceOperaGlobale*] were introduced. They would respectively contain a working link to the directory of the BMS hosting the inspection form filled in for each component, and a unique identifier for each component, necessary to organise the error-free data feed concerning each component according to the nomenclature, numbering and cataloguing carried out within the BIM environment

A subsequent phase is then envisaged for the re-importation of the data resulting from the detailed inspections – summarised by the *Relative Defectiveness Indicator* [Dr] plotted from the BMS – to the editable BIM environment, Autodesk Revit [LOI enhancement phase]. The BrIM model thus becomes a fully updated repository containing the health status of the infrastructure models through which it is also possible to provide an advanced graphic visualisation of the synthetic data grouped, e.g., into the *Attention Classes* [CdA] imposed by the regulations.

7.1 Automation tools for data export procedures

It was accordingly decided to automate, by developing dedicated VPL scripts, the processes for allocating the monitoring forms, organising the register data, and exporting them; these processes are managed by the supervisor responsible for validating the modellers' work. The resulting information is subsequently used to feed the monitoring platform. To this end, in addition to the basic packages offered by the open tool Dynamo for Revit, a number of additional free packages[42] containing nodes developed and made available by the community of programmers[43] were finalised in order to improve the execution of specific routines, to make up for a few gaps and possibly fix some bugs. Moreover, to solve the issue of replacing the elements within an ordered list with a different attribute of the same element, all of this while maintaining the elements in a given order, a custom node was developed[44]. The code of the custom node – defined *Elements.CorrespondingAtIndex* – is shown below, while its use is marked in red [*] in the scripts it appears in.
The functioning of the scripts will be illustrated graphically, starting with a summary flowchart followed by an overview of the VLP script organised into groups of nodes dedicated to performing a particular operation summarised by the title assigned to each group. Moreover, to facilitate its reading, zooms on each group will be inserted and, where necessary, synthetic images of the input and/or output pieces of information will be shown, too.

Custom node: Elements.CorrespondingAtIndex

The custom node comprises three input and one output lists.
The three *input lists* are listed below:

- *List A*: List whose elements are organised in a given order derived from previous executions, which may contain repeated elements.

[42] The additional free packages used are listed as follows: *Archilab, Clockwork, DynamoText, GeniusLoci, MeshToolkit, Orchid, ReDynamo, Sastrugi, Springs*.

[43] To further investigate the database of additional packages developed for free by the community of programmers and their use, visit: https://dynamopackages.com/ and https://forum.dynamobim.com/.

[44] I would like to thank the PhD Student Lucas Gujski of the *Laboratorio Modelli – Surveying and Geo-Mapping for Environment and Cultural Heritage* for his support in *translating* the intended routine into the *Python Programming Language*, which is the native language used to program the Dynamo nodes.

- *List B*: List ordered according to a different criterion from list A containing in non-repeating sequence the elements of list A in bi-univocal correspondence with the elements of list C.
- *List C*: List ordered according to the same criterion as list B containing per each element of the said list an attribute; it corresponds bi-univocally with the list B.

The *output list D* will thus be characterised by the same number of elements of list A replaced, however, by the corresponding attributes, according to the relationship that exists between the elements of the B list and those of the C list.

Figure 7.1 – Custom VPL node Elements.CorrspondingAtIndex and its Python source code [AoE]

[Script 1] VPL Script for automatic allocation of shared parameters *"Typology"* [*Tipologia*], *"Form"* [*Scheda*] and *"GlobalStructureCode"* [*CodiceOperaGlobale*]

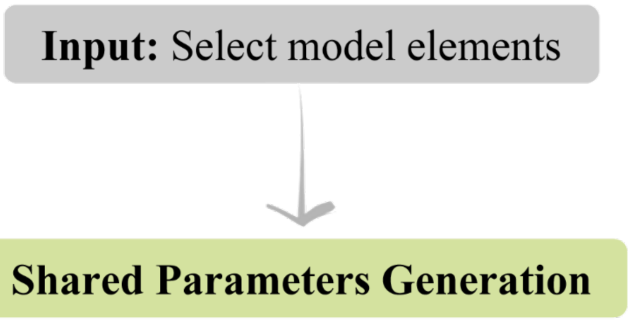


Figure 7.2 – Diagram breaking down the VPL script developed to automatically assign the shared parameters "Typology" [Tipologia], "Form" [Scheda] and "GlobalStructureCode" [CodiceOperaGlobale] to all the modelled elements [AoE]

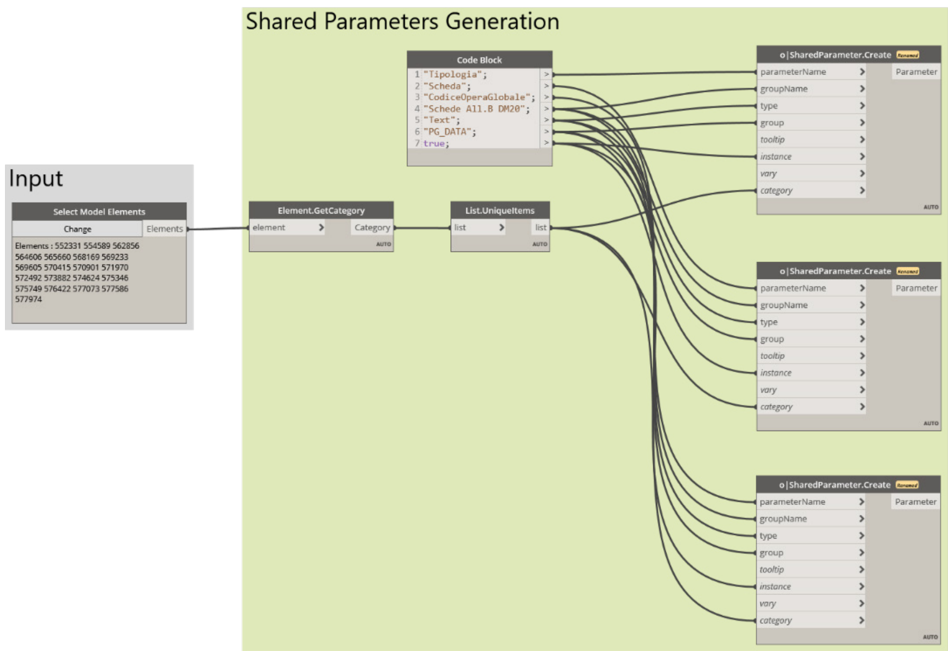


Figure 7.3 – Dynamo VPL script developed to automatically assign the shared parameters "Typology" [Tipologia], "Form" [Scheda] and "GlobalStructureCode" [CodiceOperaGlobale] to all the modelled elements [AoE]

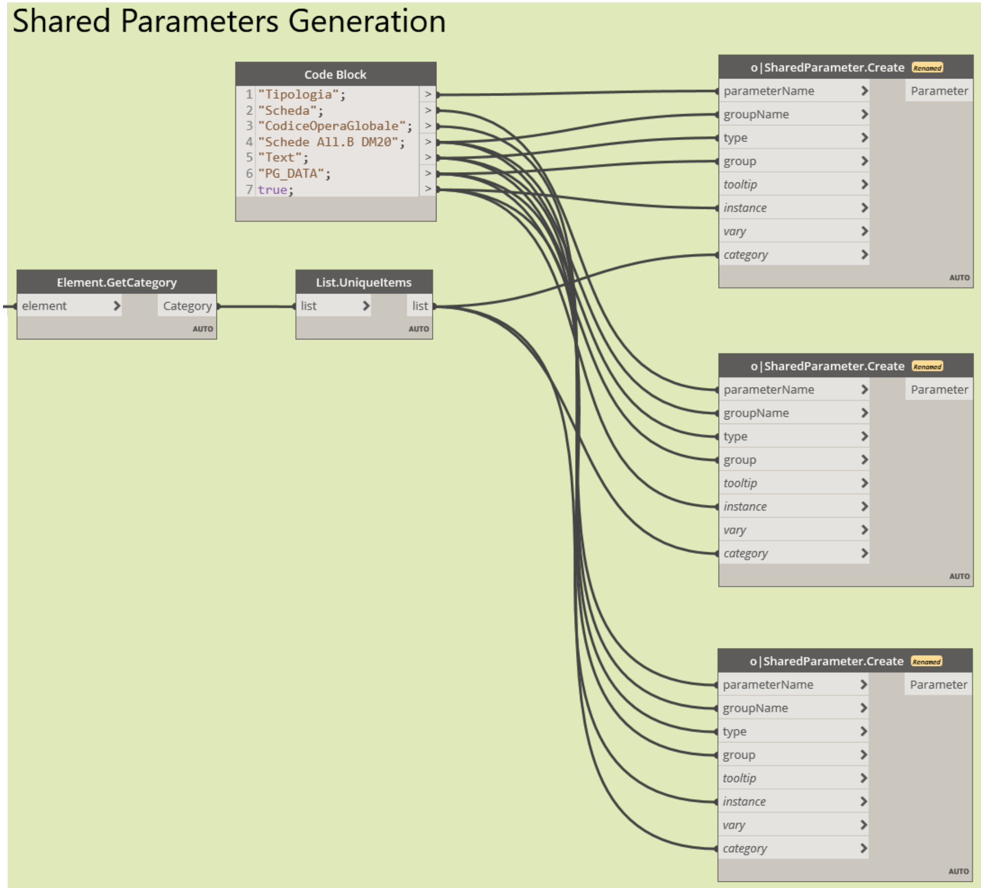


Figure 7.4 – Dynamo VPL script developed to automatically assign the shared parameters "Typology" [Tipologia], "Form" [Scheda] and "GlobalStructureCode" [CodiceOperaGlobale] to all the modelled elements: Group of nodes dedicated to generating the shared parameters within the Revit environment by first adding them to the TXT storing file and then assigning them to the modelled elements [AoE]

[Script 2] VPL Script for the automatic population of the *"Form"* [*Scheda*] parameter according to the Annex B of the LG20 [94]

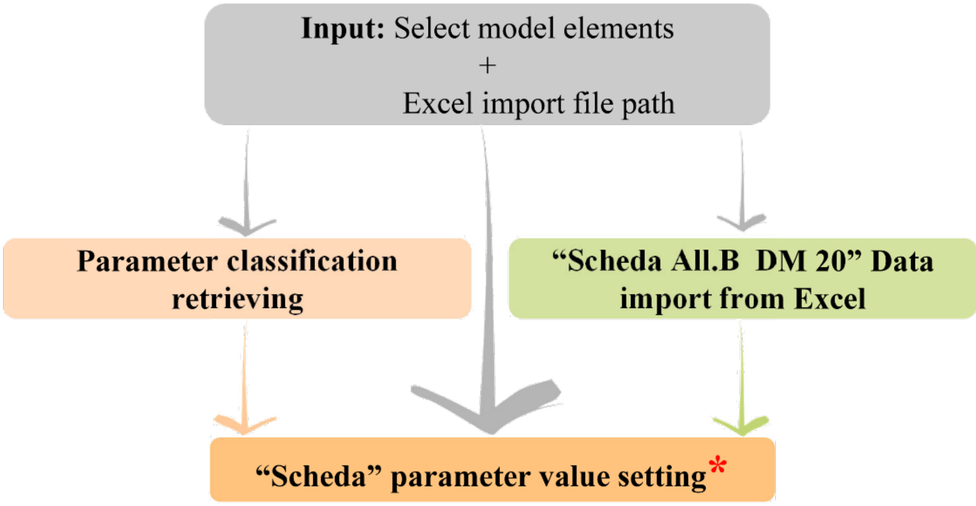


Figure 7.5 – Diagram breaking down the VPL script developed to automatically populate the *"Form"* [*Scheda*] according to the Annex B of the LG20, once the *Typology* parameter has been additionally filled out by the supervisor [AoE]

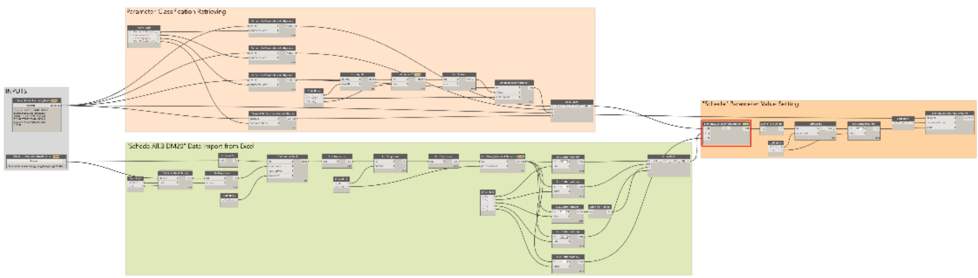


Figure 7.6 – Dynamo VPL script developed to automatically populate the *"Form"* [*Scheda*] according to the Annex B of the LG20, once the *Typology* parameter has been additionally filled out by the supervisor [AoE]

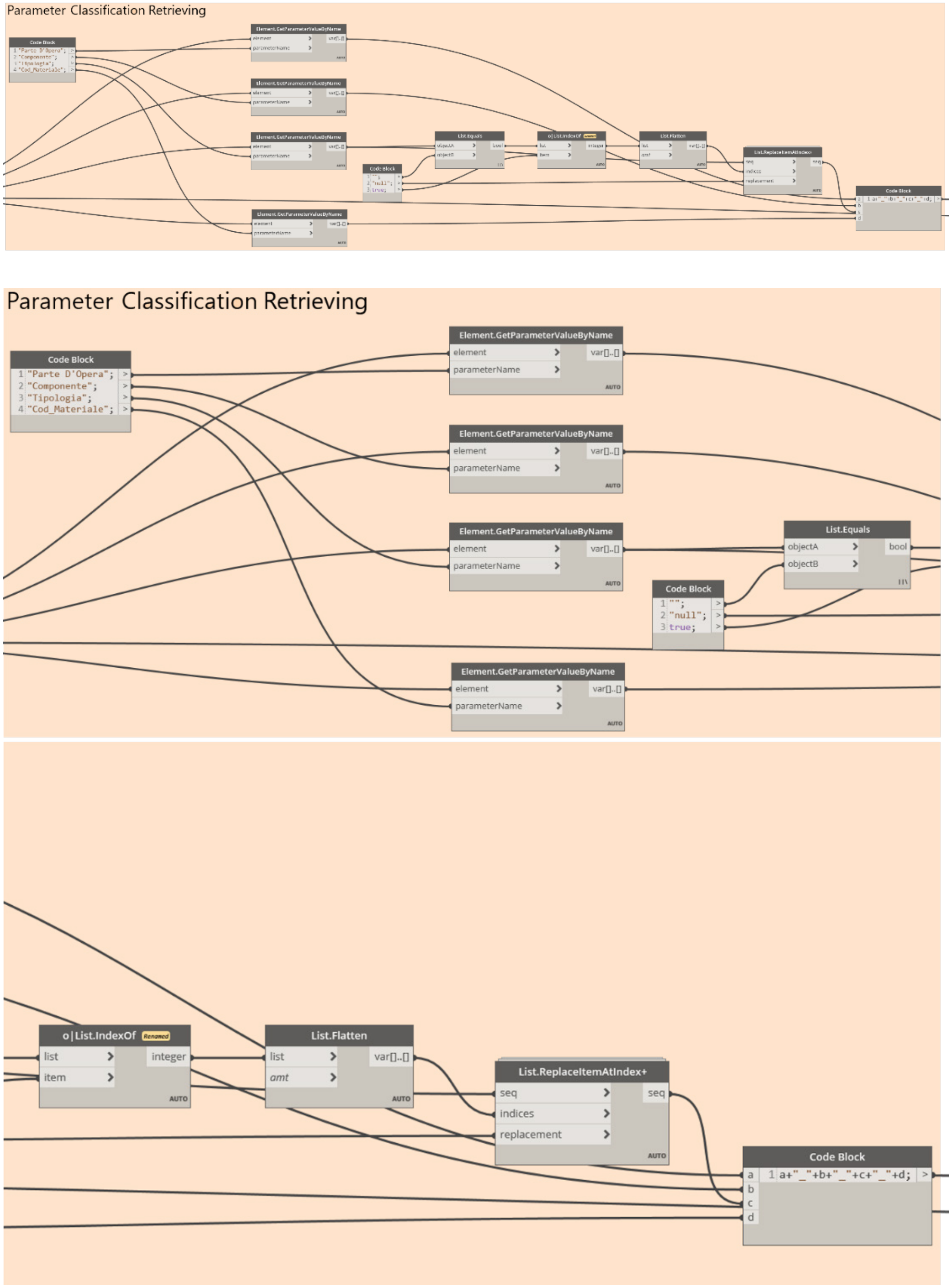


Figure 7.7 – Dynamo VPL script developed to automatically populate the *"Form"* [*Scheda*] according to the Annex B of the LG20, once the *Typology* parameter has been additionally filled out by the supervisor: Group of nodes dedicated to retrieving the classification parameters values [AoE]

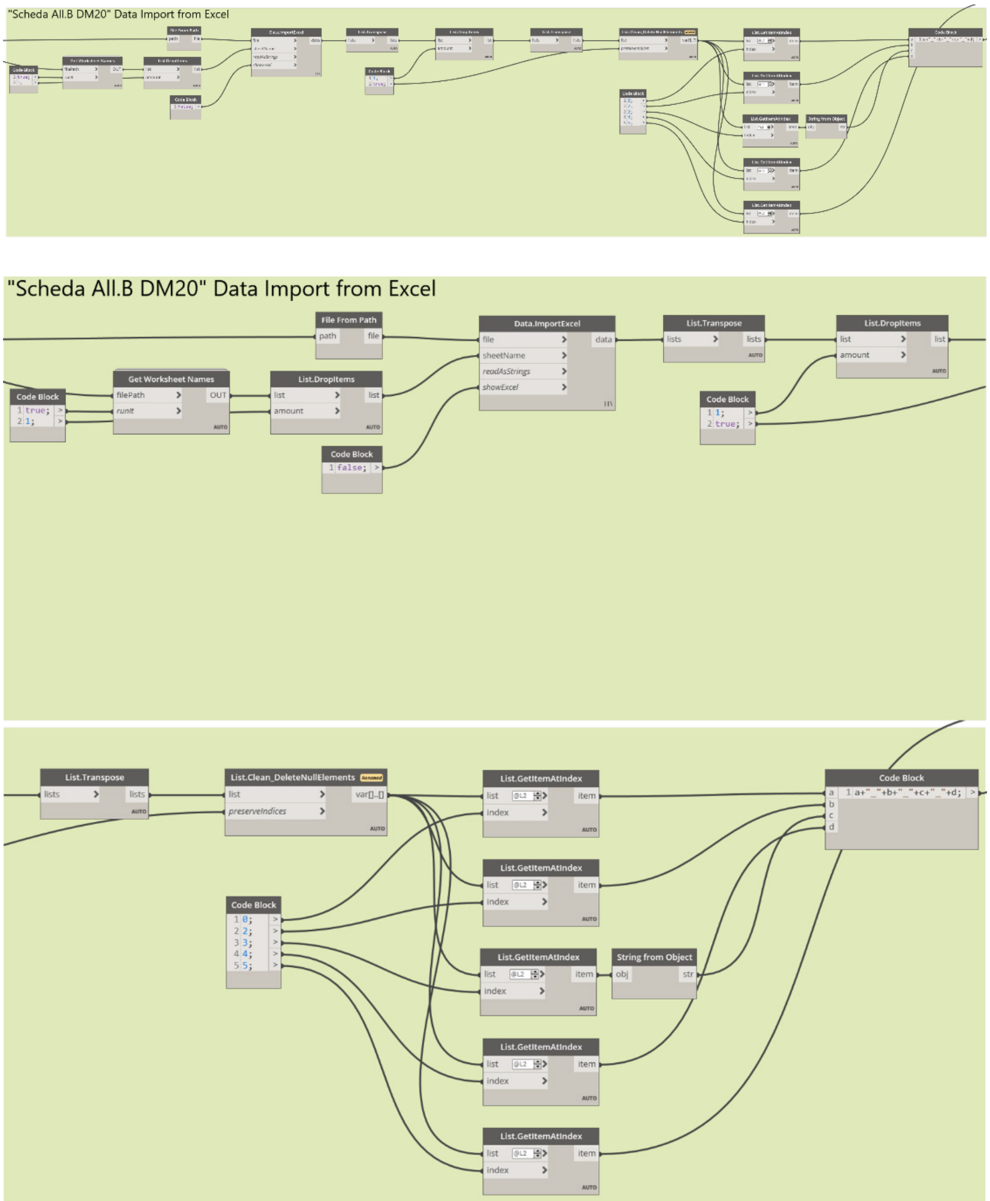


Figure 7.8 – Dynamo VPL script developed to automatically populate the *"Form"* [*Scheda*] according to the Annex B of the LG20, once the *Typology* parameter has been additionally filled out by the supervisor: Group of nodes dedicated to importing the Excel spreadsheet tables as lists that uniquely assign the inspection form's number to the modelled elements [AoE]

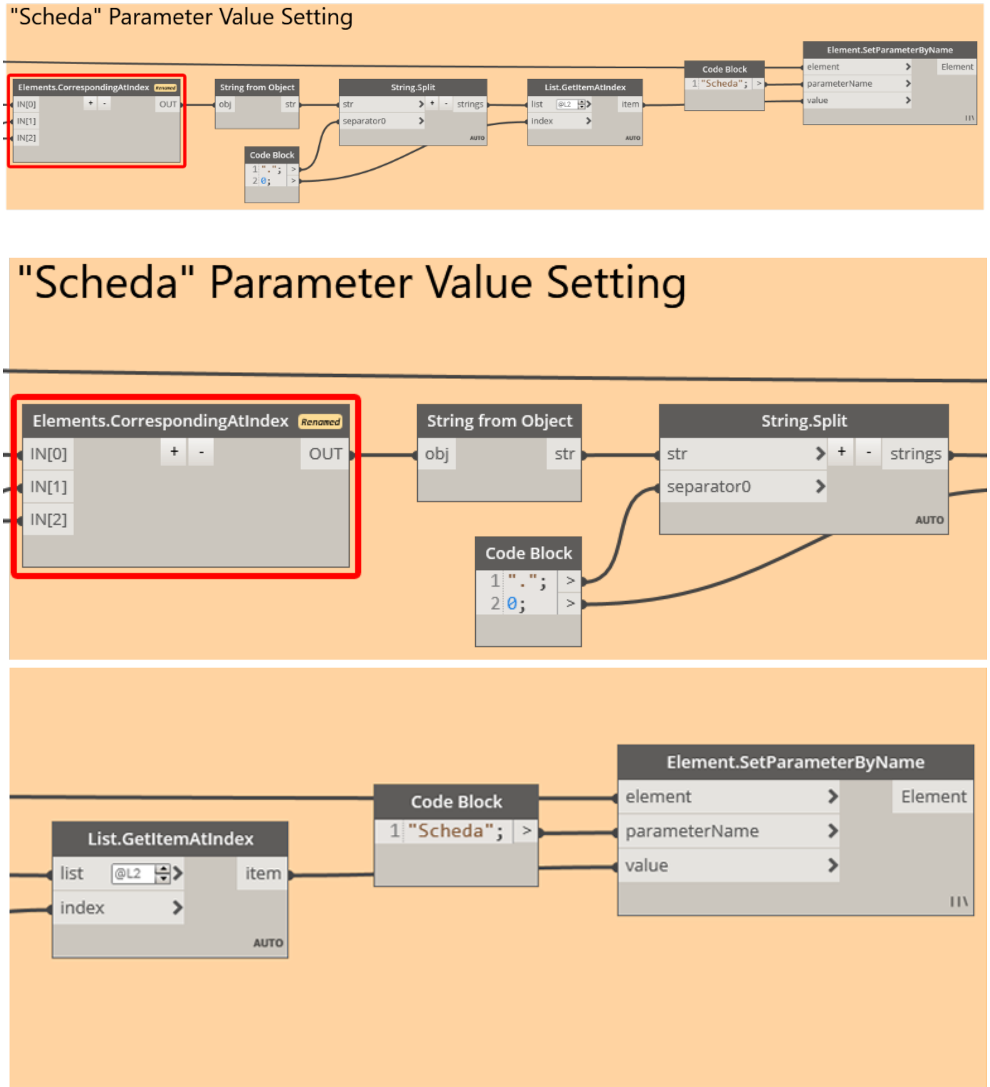


Figure 7.9 – Dynamo VPL script developed to automatically populate the *“Form”* [*Scheda*] according to the Annex B of the LG20, once the *Typology* parameter has been additionally filled out by the supervisor: Group of nodes dedicated to assigning the “Form” parameter values to each modelled element. This group employs the custom node marked in red [AoE]

STRUCTURAL PARTS	ID	COMPONENTS	ID	FORM All. B D.M. 20	
ARCHI	AR	Struttura principale	SP	14,15,16,17,18,19	10,11,12,13
		Interconnessioni longitudinali	IL	14,15,16,17	10,11,12,13
		Interconnessioni trasversali e diaframmi	IT	14,15,16,17	10,11,12,13
		Timpano	TI	10,11,12,13	
		Interconnessioni longitudinali tra pile	IP	14,15,16,17	

ID	COMPONENTS	ID	Typology	Material	FORM All. B D.M. 20
AR	Struttura principale	SP	tr	CAO	14
AR	Struttura principale	SP	tr	CAP	15
AR	Struttura principale	SP	tr	ACC	16
AR	Struttura principale	SP	tr	LGN	17
AR	Struttura principale	SP	sl	CAO	18
AR	Struttura principale	SP	sl	LGN	19
AR	Struttura principale	SP	ar	CAO	10
AR	Struttura principale	SP	ar	MUR	11
AR	Struttura principale	SP	ar	ACC	12
AR	Struttura principale	SP	ar	LGN	13
AR	Interconnessioni longitudinali	IL	tr	CAO	14
AR	Interconnessioni longitudinali	IL	tr	CAP	15
AR	Interconnessioni longitudinali	IL	tr	ACC	16
AR	Interconnessioni longitudinali	IL	tr	LGN	17
AR	Interconnessioni longitudinali	IL	ar	CAO	10
AR	Interconnessioni longitudinali	IL	ar	MUR	11
AR	Interconnessioni longitudinali	IL	ar	ACC	12
AR	Interconnessioni longitudinali	IL	ar	LGN	13
AR	Interconnessioni trasversali e diaframmi	IT	tr	CAO	14
AR	Interconnessioni trasversali e diaframmi	IT	tr	CAP	15
AR	Interconnessioni trasversali e diaframmi	IT	tr	ACC	16
AR	Interconnessioni trasversali e diaframmi	IT	tr	LGN	17
AR	Interconnessioni trasversali e diaframmi	IT	ar	CAO	10
AR	Interconnessioni trasversali e diaframmi	IT	ar	MUR	11
AR	Interconnessioni trasversali e diaframmi	IT	ar	ACC	12
AR	Interconnessioni trasversali e diaframmi	IT	ar	LGN	13
AR	Timpano	TI		CAO	10
AR	Timpano	TI		MUR	11
AR	Timpano	TI		ACC	12
AR	Timpano	TI		LGN	13
AR	Interconnessioni longitudinali tra pile	IP		CAO	14
AR	Interconnessioni longitudinali tra pile	IP		CAP	15
AR	Interconnessioni longitudinali tra pile	IP		ACC	16
AR	Interconnessioni longitudinali tra pile	IP		LGN	17

Figure 7.10 – Input Excel data further detailing, in this case, the typology to determine the appropriate inspection form according to the structural behaviour of the arch elements [AoE]

[Script 3] VPL Script for the automatic population of the composed parameters: *"Form Link"* [*Link Scheda*] – to the C.U.G.R.I. BMS platform –, *"ID_ASPI"*, *"GlobalStructureCode"* [*CodiceOperaGlobale*]

The *"Form Link"* [*Link Scheda*] parameter refers to the structural monitoring software of the *Bridge Management System* [BMS] type that is under development by C.U.G.R.I. – for the moment still in a demo version (Beta Realise). This platform acts as a database for the visual inspections, it was therefore decided to link the filled-in inspection forms related to each component back to the model automatically generating the URL via the dedicated script. An example of a URL identifying the inspection form for the arch longitudinal joist component 00.AR.001.SP.006.CAO belonging to the third *Structural Section* (Figure 7.16) is shown as follows:

https://v2.webui.C.U.G.R.I..it/ispezioni/2021/03.03.0327.0.0.00.AR.001.SP.006.CAO

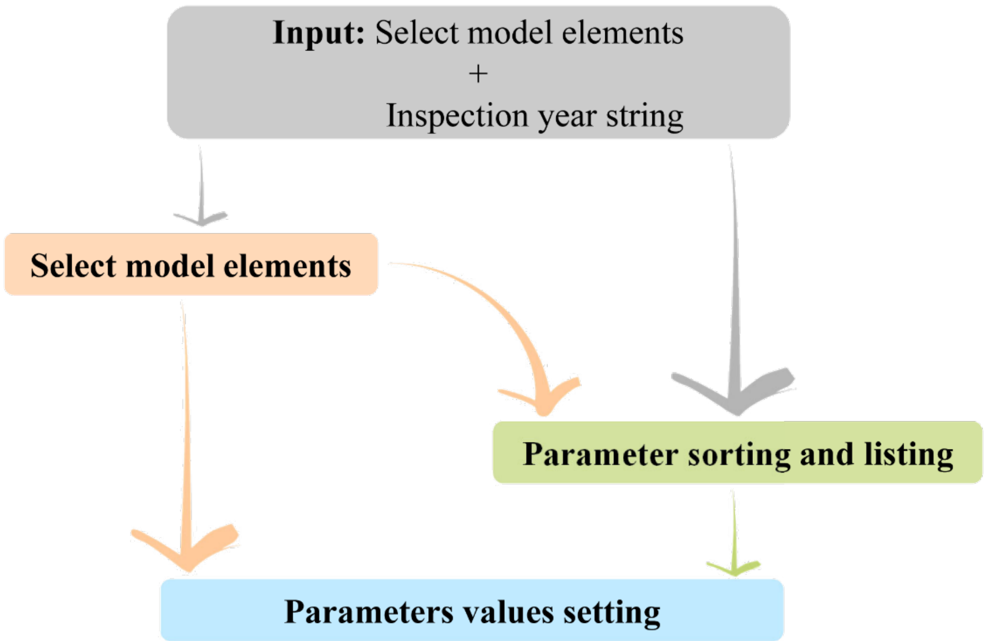


Figure 7.11 – Diagram breaking down the VPL script developed to automatically populate the composed parameters: *"Form Link"* [*Link Scheda*], *"ID_ASPI"*, *"GlobalStructureCode"* [*CodiceOperaGlobale*] [AoE]

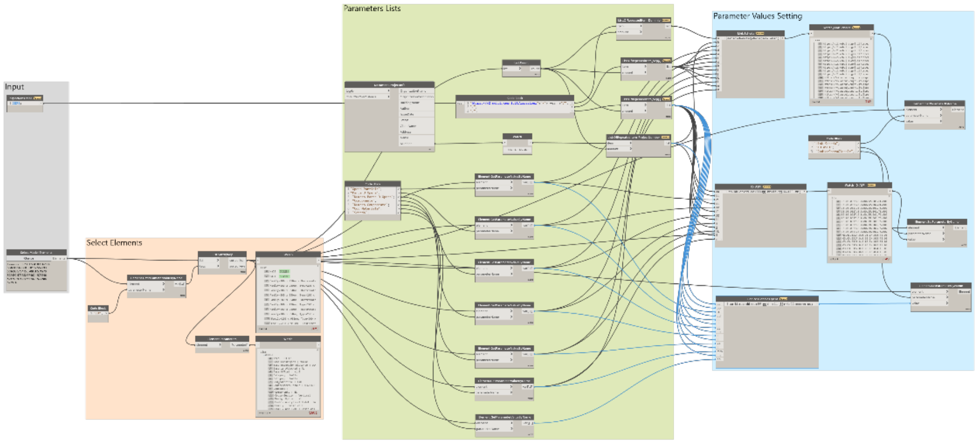


Figure 7.12 – Dynamo VPL script developed to automatically populate the composed parameters: *“Form Link”* [*Link Scheda*], *“ID_ASPI”*, *“GlobalStructureCode”* [*CodiceOperaGlobale*] [AoE]

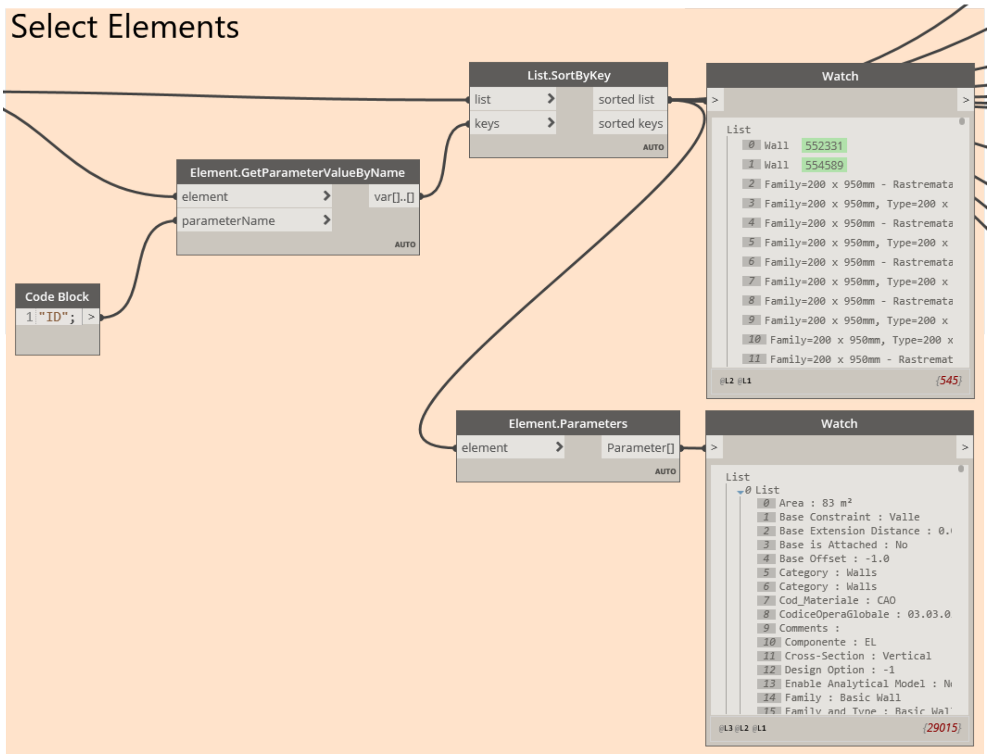


Figure 7.13 – Dynamo VPL script developed to automatically populate the composed parameters: *“Form Link”* [*Link Scheda*], *“ID_ASPI”*, *“GlobalStructureCode”* [*CodiceOperaGlobale*]: Group of nodes dedicated to sorting the selected model elements [AoE]

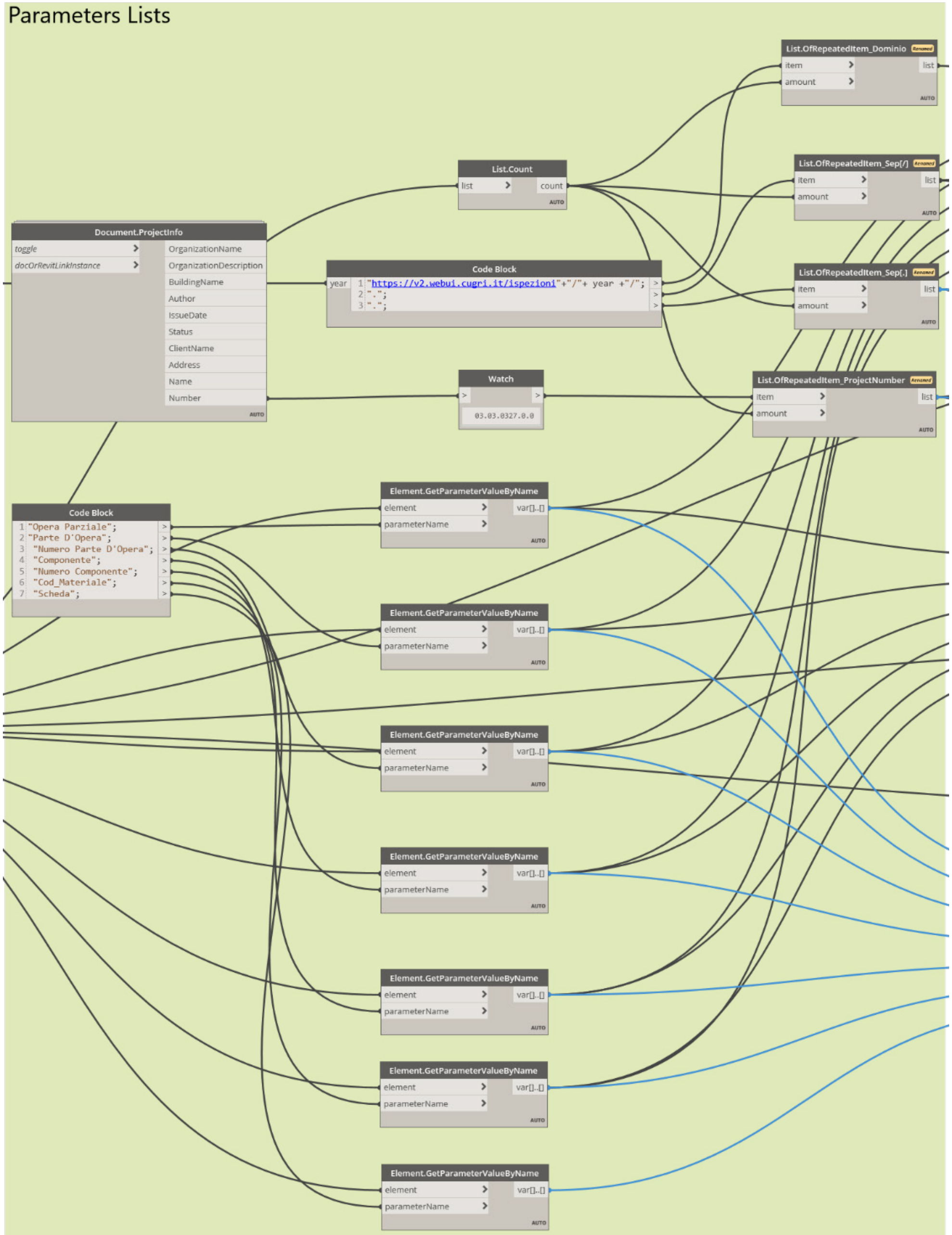


Figure 7.14 – Dynamo VPL script developed to automatically populate the composed parameters: *"Form Link"* [*Link Scheda*], *"ID_ASPI"*, *"GlobalStructureCode"* [*CodiceOperaGlobale*]: Group of nodes dedicated to creating the list of parameters [AoE]

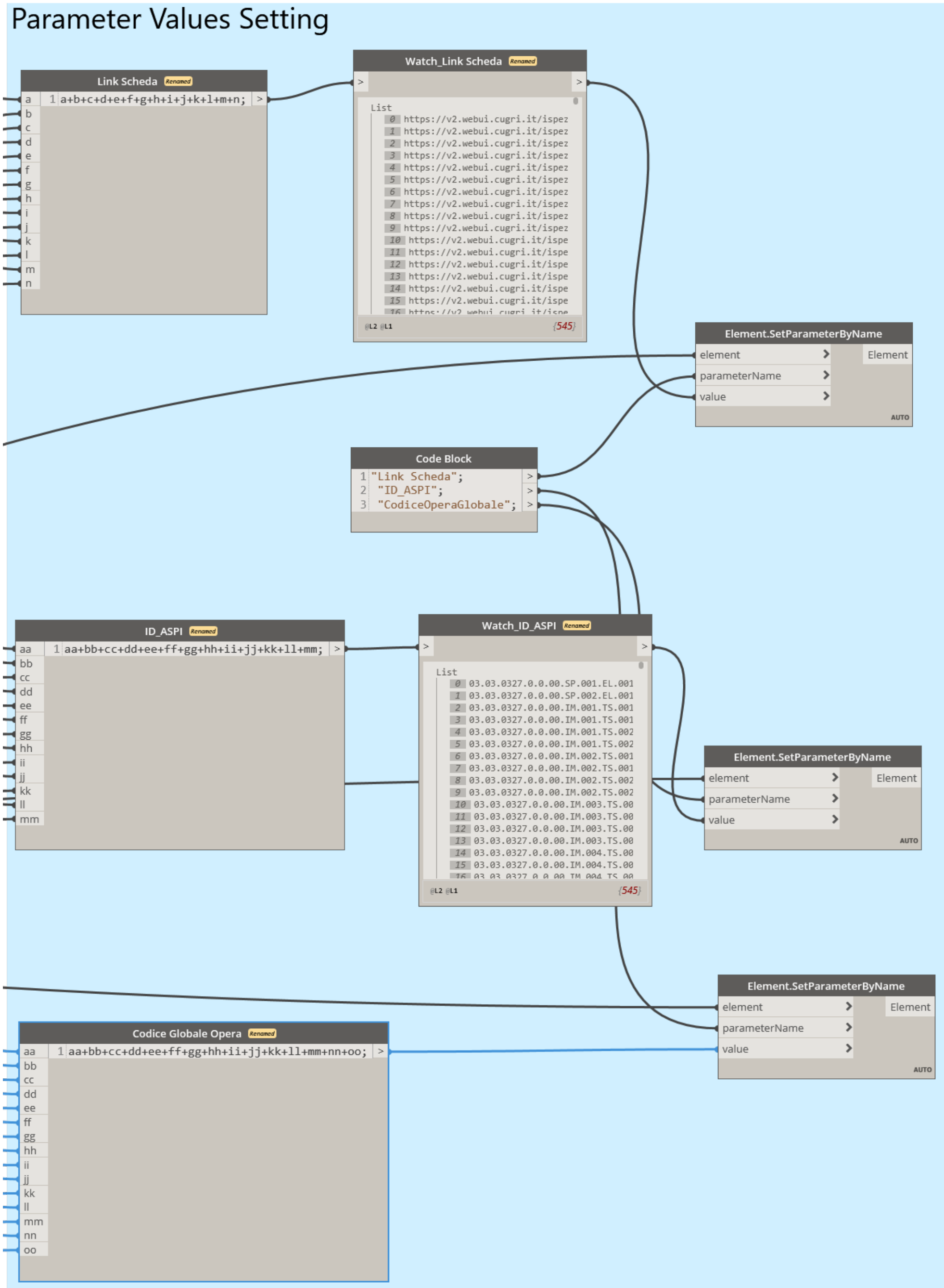


Figure 7.15 – Dynamo VPL script developed to automatically populate the composed parameters: *"Form Link"* [*Link Scheda*], *"ID_ASPI"*, *"GlobalStructureCode"* [*CodiceOperaGlobale*]: Group of nodes dedicated to assigning the parameter values to the selected elements [AoE]

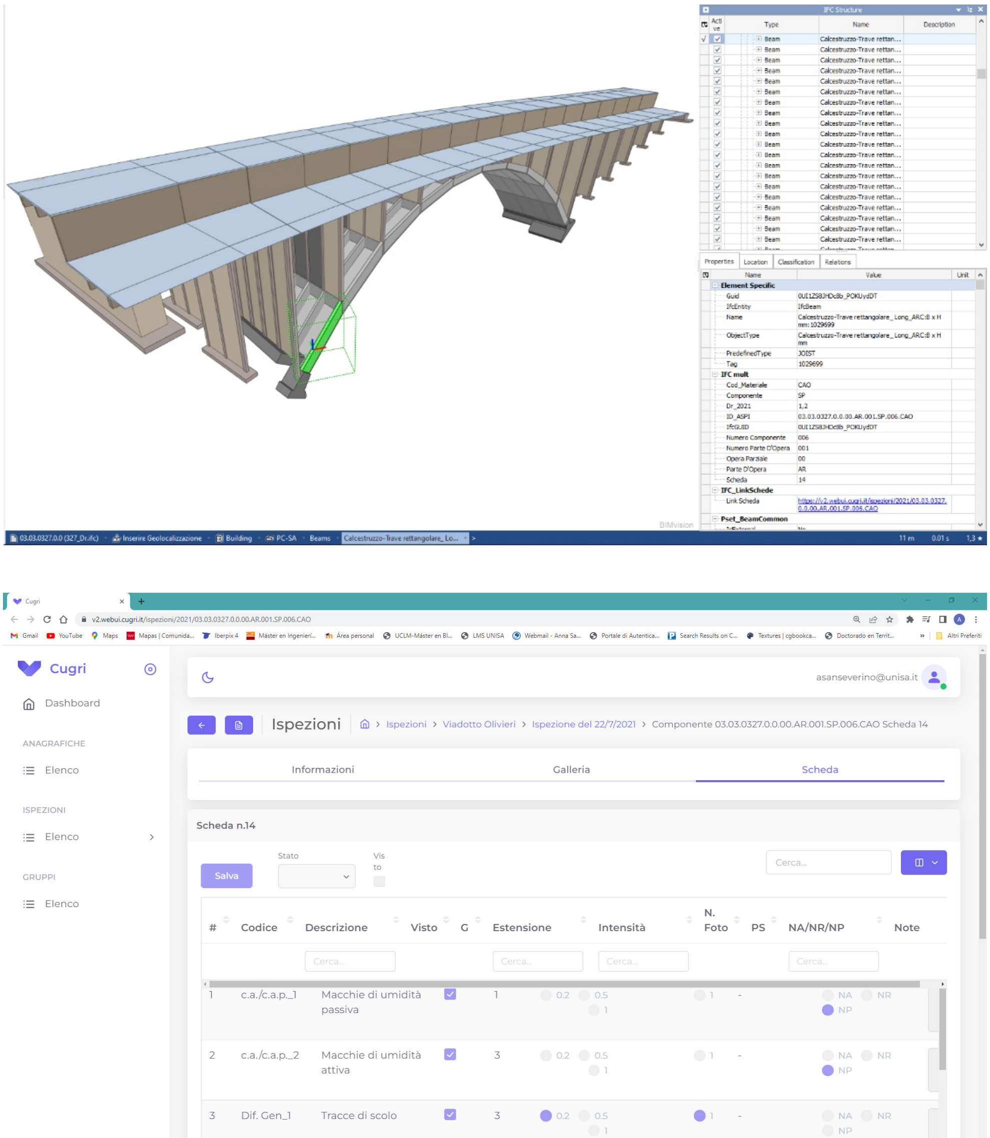


Figure 7.16 – IFC BrIM model of the Olivieri Viaduct with the 00.AR.001.SP.006.CAO component pointed out and screenshot of the C.U.G.R.I. BMS web page corresponding to the URL associated to the [AoE]

[Script 4] VPL Script for plotting *Components'* register data

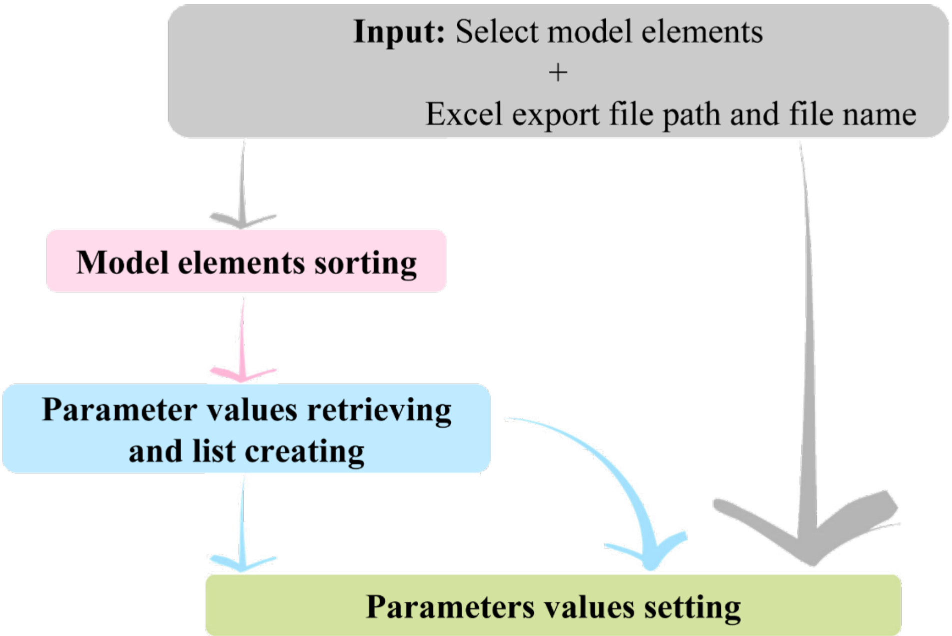


Figure 7.17 – Diagram breaking down the VPL script developed to plot *Components*' register data [AoE]

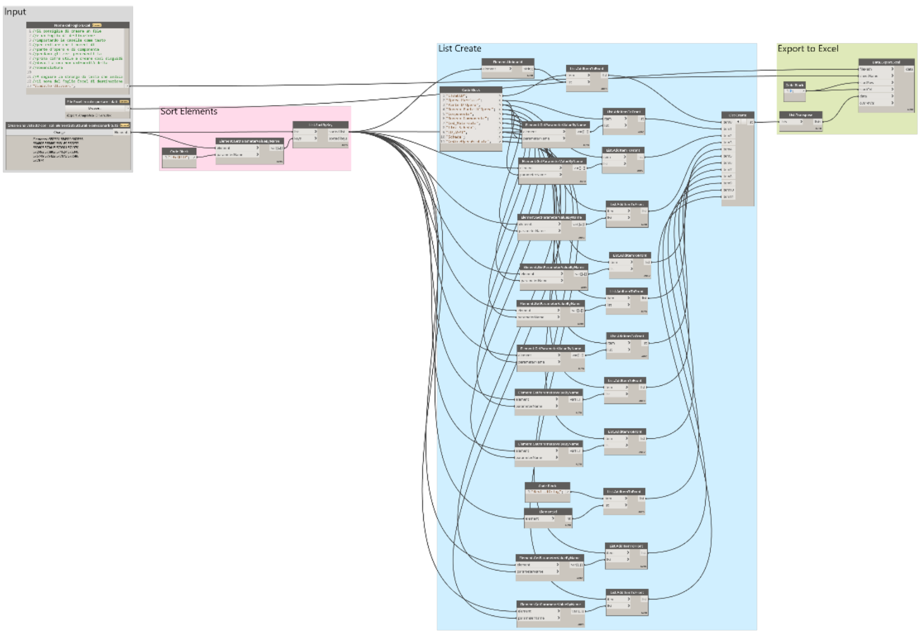


Figure 7.18 – Dynamo VPL script developed to plot *Components*' register data [AoE]

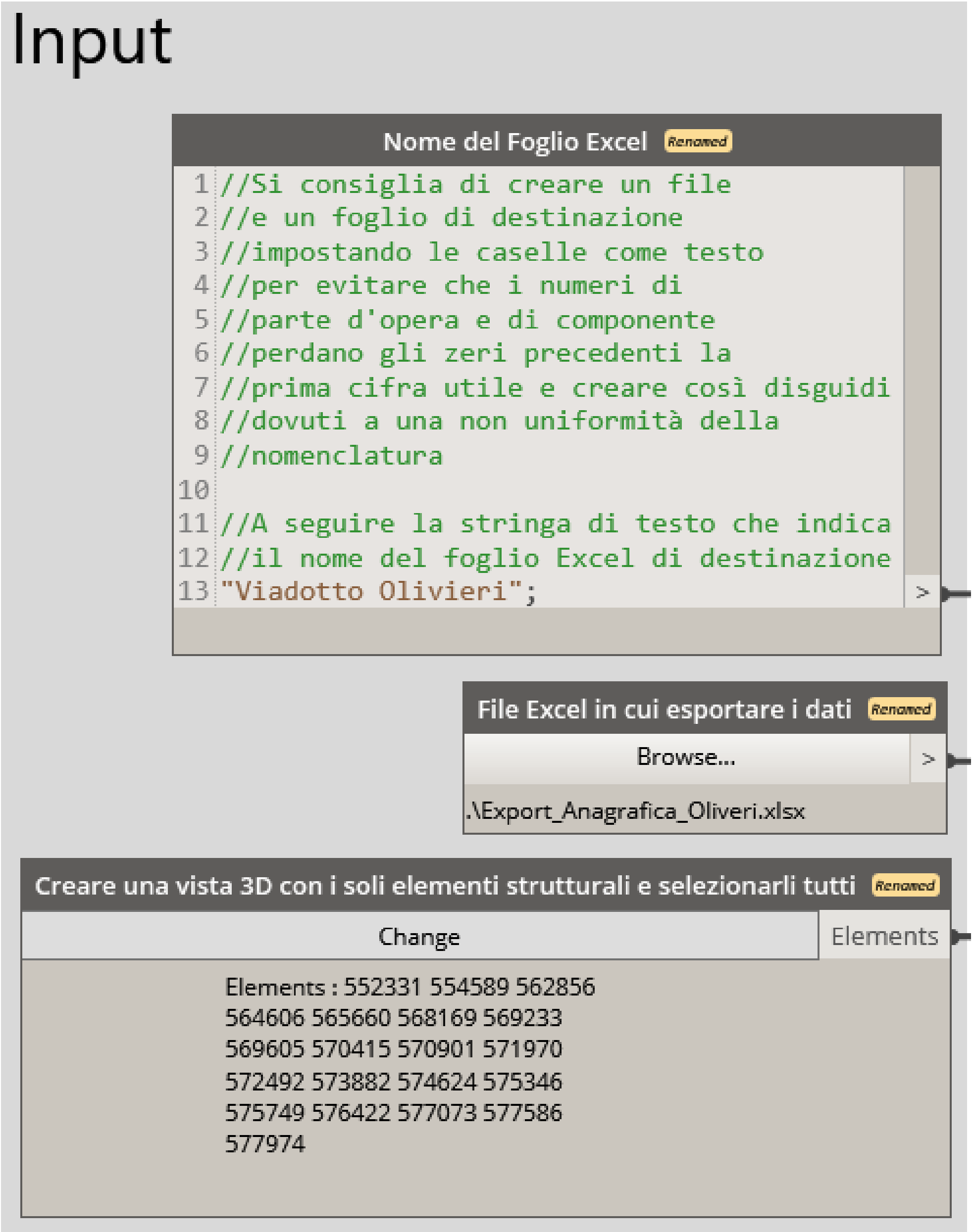


Figure 7.19 – Dynamo VPL script developed to plot *Components*' register data: Group of nodes dedicated to inputting data [AoE]

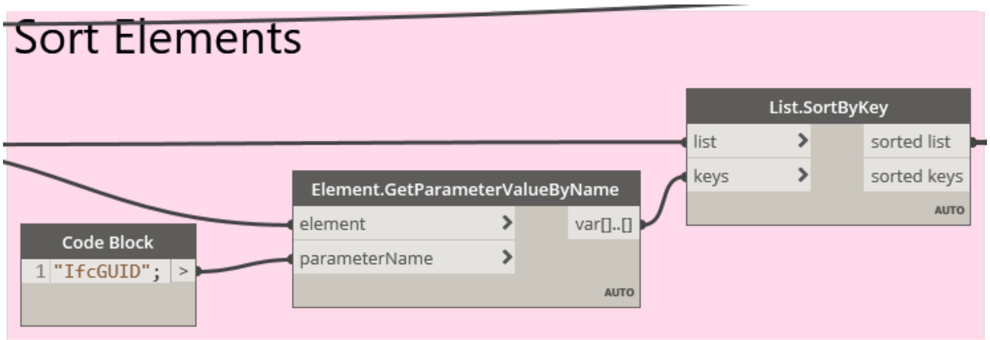


Figure 7.20 – Dynamo VPL script developed to plot *Components*' register data: Group of nodes dedicated to sorting selected model elements [AoE]

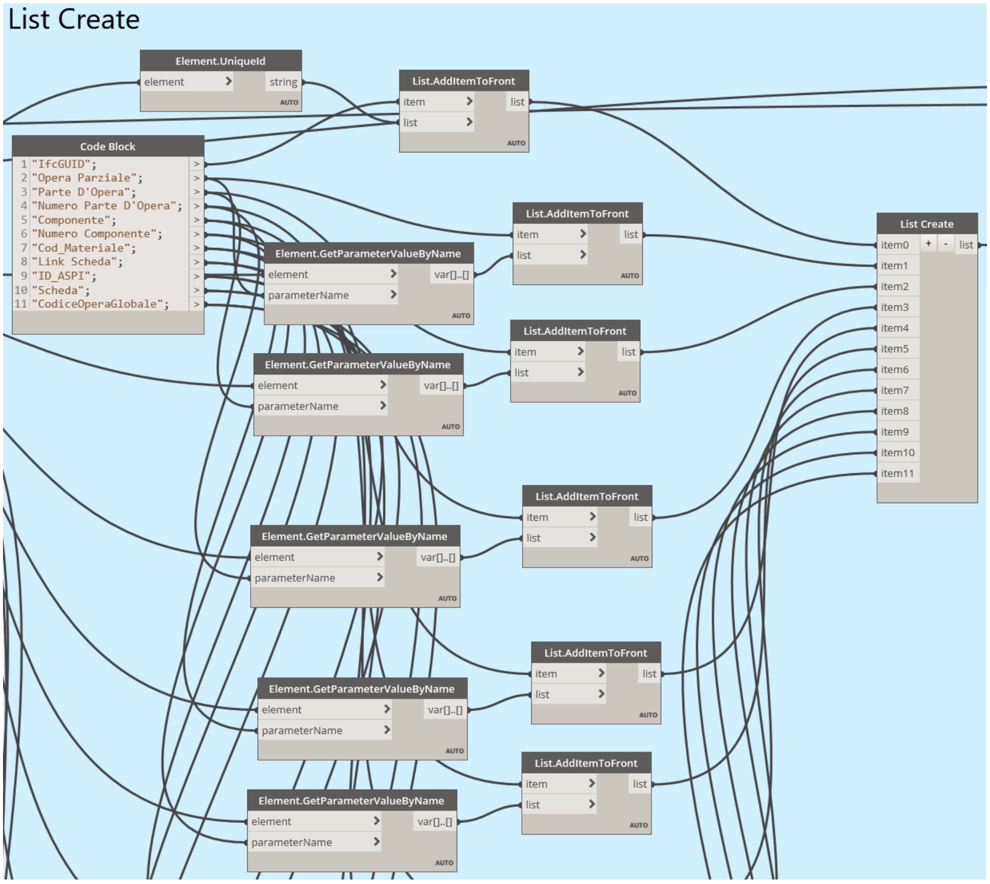


Figure 7.21 – Dynamo VPL script developed to plot *Components*' register data: Extract of the group of nodes dedicated to creating the lists of parameters values to export [AoE]

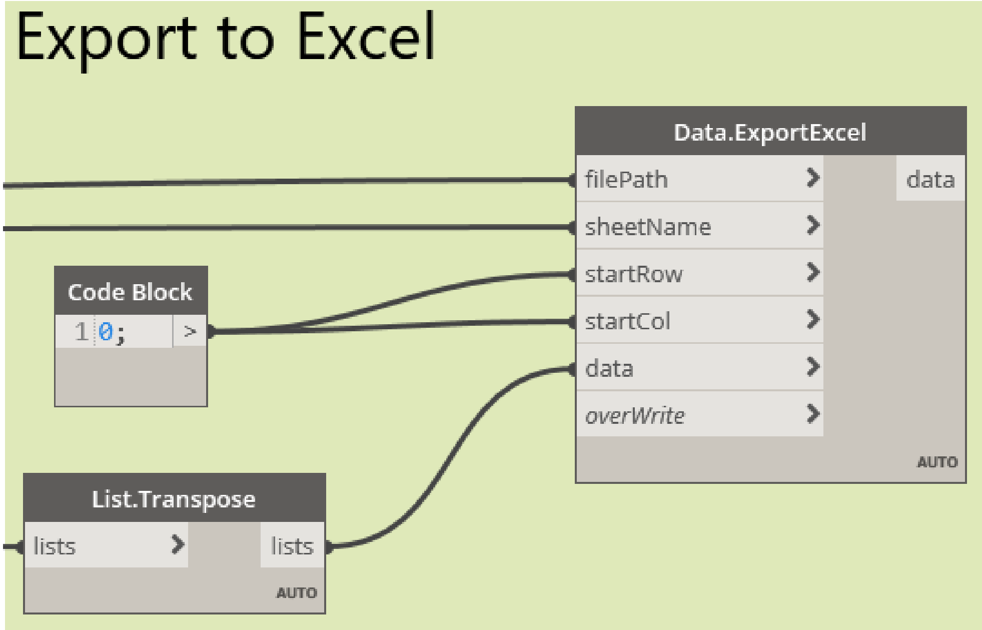


Figure 7.22 – Dynamo VPL script developed to plot *Components*' register data: Group of nodes dedicated to exporting to Excel the lists previously created [AoE]

	IfcGUID	Opera Parziale	Parte D'Opera	Numero Parte D'Opera	Componente	Numero Componente	Cod_Materiale	Link Scheda	ID_ASPI	Scheda	CodiceOperaGlobale
2	3f42deff-ec45-4875	00	AR	006	IT	001	CAO	https://v2.webui.cugri	03.03.0327.0.0.00.AR	14	03.03.0327.0.0.00.AR.006.IT.001.CAO.14
3	00d99f7e-a0df-438	00	IM	007	SO	001	CAO	https://v2.webui.cugri	03.03.0327.0.0.00.IM	18	03.03.0327.0.0.00.IM.007.SO.001.CAO.18
4	01312724-7bc6-4e	00	IM	011	TS	002	CAO	https://v2.webui.cugri	03.03.0327.0.0.00.IM	14	03.03.0327.0.0.00.IM.011.TS.002.CAO.14
5	01312724-7bc6-4e	00	IM	011	TS	002	CAO	https://v2.webui.cugri	03.03.0327.0.0.00.IM	14	03.03.0327.0.0.00.IM.011.TS.002.CAO.14
6	031571f7-819f-443	00	IM	008	SO	001	CAO	https://v2.webui.cugri	03.03.0327.0.0.00.IM	18	03.03.0327.0.0.00.IM.008.SO.001.CAO.18
7	032a60fe-2b74-453	00	IM	007	TS	001	CAO	https://v2.webui.cugri	03.03.0327.0.0.00.IM	14	03.03.0327.0.0.00.IM.007.TS.001.CAO.14
8	032a60fe-2b74-453	00	IM	007	TS	001	CAO	https://v2.webui.cugri	03.03.0327.0.0.00.IM	14	03.03.0327.0.0.00.IM.007.TS.001.CAO.14
9	039b5999-5e0a-43	00	IM	012	TS	002	CAO	https://v2.webui.cugri	03.03.0327.0.0.00.IM	14	03.03.0327.0.0.00.IM.012.TS.002.CAO.14
10	039b5999-5e0a-43	00	IM	012	TS	001	CAO	https://v2.webui.cugri	03.03.0327.0.0.00.IM	14	03.03.0327.0.0.00.IM.012.TS.001.CAO.14
11	039b5999-5e0a-43	00	IM	012	TS	002	CAO	https://v2.webui.cugri	03.03.0327.0.0.00.IM	14	03.03.0327.0.0.00.IM.012.TS.002.CAO.14
12	05984371-fdcc-4cd	00	IM	004	TR	004	CAO	https://v2.webui.cugri	03.03.0327.0.0.00.IM	14	03.03.0327.0.0.00.IM.004.TR.004.CAO.14
13	24214351-cbf0-404	00	FO	009	PP	002	CAO	https://v2.webui.cugri	03.03.0327.0.0.00.FO	03	03.03.0327.0.0.00.FO.009.PP.002.CAO.03
14	24214351-cbf0-404	00	FO	009	PP	001	CAO	https://v2.webui.cugri	03.03.0327.0.0.00.FO	03	03.03.0327.0.0.00.FO.009.PP.001.CAO.03
15	24214351-cbf0-404	00	FO	009	PP	005	CAO	https://v2.webui.cugri	03.03.0327.0.0.00.FO	03	03.03.0327.0.0.00.FO.009.PP.005.CAO.03
16	24214351-cbf0-404	00	FO	009	PP	004	CAO	https://v2.webui.cugri	03.03.0327.0.0.00.FO	03	03.03.0327.0.0.00.FO.009.PP.004.CAO.03
17	24214351-cbf0-404	00	FO	009	PP	003	CAO	https://v2.webui.cugri	03.03.0327.0.0.00.FO	03	03.03.0327.0.0.00.FO.009.PP.003.CAO.03
18	24846447-5c54-46	00	IM	011	SO	001	CAO	https://v2.webui.cugri	03.03.0327.0.0.00.IM	18	03.03.0327.0.0.00.IM.011.SO.001.CAO.18
19	25cb373e-3b72-4b	00	IM	008	TS	002	CAO	https://v2.webui.cugri	03.03.0327.0.0.00.IM	14	03.03.0327.0.0.00.IM.008.TS.002.CAO.14
20	25cb373e-3b72-4b	00	IM	009	TS	001	CAO	https://v2.webui.cugri	03.03.0327.0.0.00.IM	14	03.03.0327.0.0.00.IM.009.TS.001.CAO.14
21	25cb373e-3b72-4b	00	IM	009	TS	001	CAO	https://v2.webui.cugri	03.03.0327.0.0.00.IM	14	03.03.0327.0.0.00.IM.009.TS.001.CAO.14
22	257e299a-0bf7-49e	00	IM	011	SL	001	CAO	https://v2.webui.cugri	03.03.0327.0.0.00.IM	18	03.03.0327.0.0.00.IM.011.SL.001.CAO.18

Viadotto Olivieri | Foglio1

Figure 7.23 – Extract of the Excel data plotted [AoE]

Setting up of the OpenBIM model export

In order to correctly export the model in IFC format, a careful mapping of the elements was carried out by verifying the correspondence respectively between the family categories and types used in Revit and the IFC types and enumerations.
Since it was necessary to set the export categories appropriately, two additional parameters defined below were introduced [227]:

- IfcExportAs: used to define the correspondence between the Revit element categories and the IFC types, e.g., *IfcSlab, IfcColumn, IfcBeam, IfcWall*, and so on;
- IfcExportType: used to define the enumeration of the assigned type suitable for describing the structural behaviour of a specific Revit type, such as *FLOOR, ROOF, LANDING, BASELAB, USERDEFINED, NOTDEFINED* for the *IfcSlabType*.

Additionally, the pre-existing *"Site name"* parameter is used to provide the coordinates to geolocalise the structure in the form of a string of information, according to the format required by the standard. Table 7.1 shows the *IfcTypes* and *IfcTypeEnumerations* assigned to each Revit family type modelled.

Table 7.1 – List of the *IfcTypes* and *IfcTypeEnumerations* assigned to each Revit family type modelled [AoE]

Revit Type	IfcType	IfcTypeEnumeration
Deck overhang	IfcSlab	ROOF
Deck lanes	IfcSlab	FLOOR
Deck longitudinal beams	IfcBeam	BEAM
Deck cross beams	IfcBeam	JOIST
Abutments	IfcWall	SHEAR
Pier bracing walls	IfcWall	PARTITIONING
Pier columns	IfcColumns	COLUMN
Pier foundation	IfcFooting	PAD_FOOTING
Arch foundation	IfcFooting	FOOTING_BEAM
Arch beams	IfcBeam	JOIST
Arch floors	IfcSlab	FLOOR
Joint	IfcDiscreteAccessory	USERDEFINED

The definition for *IfcSlab, IfcColumn, IfcBeam, IfcWall*, according to BuildingSmart, up to the IFC 4.0 release, are provided hereafter.

"An IfcSlab is a component of the construction that normally encloses a space vertically. The slab may provide the lower support (floor) or upper construction (roof slab) in any space in a building. It shall be noted, that only the core or constructional part of this construction is considered to be a slab. The upper finish (flooring, roofing) and the lower finish (ceiling, suspended ceiling) are considered to be coverings. A special type of slab is the landing, described as a floor section to which one or more stair flights or ramp flights connect. May or may not be adjacent to a building storey floor.
A slab may have openings, such as floor openings, or recesses. They are defined by an IfcOpeningElement attached to the slab using the inverse relationship HasOpenings pointing to IfcRelVoidsElement.
A particular usage type for the IfcSlab (Figure 7.24) can be given (if type information is available) by referring to the type object IfcSlabType, using the IfcRelDefinesByType relationship, or (if only occurrence information is given) by using the PredefinedType attribute. Values of the enumeration are FLOOR (the default), ROOF, LANDING, BASESLAB, NOTDEFINED. If the value USERDEFINED is chosen, the user defined value needs to be given at the attribute ObjectType." [228]

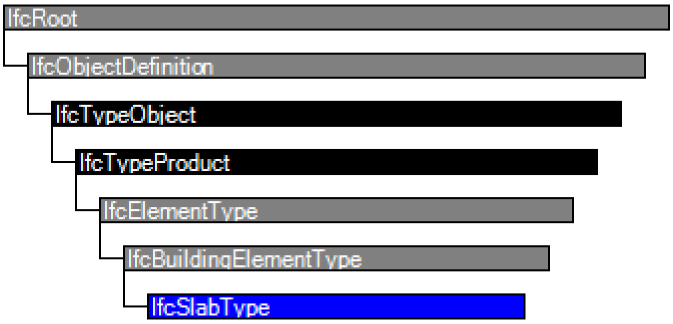
"An IfcColumn is a vertical structural member which often is aligned with a structural grid intersection. It represents a vertical, or nearly vertical, a structural member from an architectural point of view. It is not required to be load-bearing. […] IfcColumn (Figure 7.25) defines the occurrence of any column, common information about beam types (or styles) is handled by IfcColumnType. The IfcColumnType (if present) may establish the common type name, usage (or predefined) type, common material layer set, common set of properties and common shape representations (using IfcRepresentationMap). The IfcColumnType is attached using the IfcRelDefinedByType.RelatingType objectified relationship and is accessible by the inverse IsDefinedBy attribute.
If no IfcColumnType is attached (i.e., if only occurrence information is given) the predefined type may be given by using the ObjectType attribute. Recommended values are column (the default). Recommended values are COLUMN (the default), PILASTER, NOTDEFINED. If the value USERDEFINED is chosen, the user defined value needs to be given at the attribute ObjectType." [228]

"An IfcBeam is a horizontal, or nearly horizontal, structural member. It represents such a member from an architectural point of view. It is not required to be load bearing. […] IfcBeam (Figure 7.26) defines the occurrence of any beam, common information about beam types (or styles) is handled by IfcBeamType. The

IfcBeamType (if present) may establish the common type name, usage (or predefined) type, common material layer set, common set of properties and common shape representations (using IfcRepresentationMap). The IfcBeamType is attached using the IfcRelDefinedByType.RelatingType objectified relationship and is accessible by the inverse IsDefinedBy attribute.
If no IfcBeamType is attached (i.e., if only occurrence information is given) the predefined type may be given by using the ObjectType attribute. Recommended values are BEAM (the default), BRACE, JOIST, HOLLOWCORE, LINTEL, SPANDREL, T_BEAM, NOTDEFINED. If the value USERDEFINED is chosen, the user defined value needs to be given at the attribute ObjectType." [228]

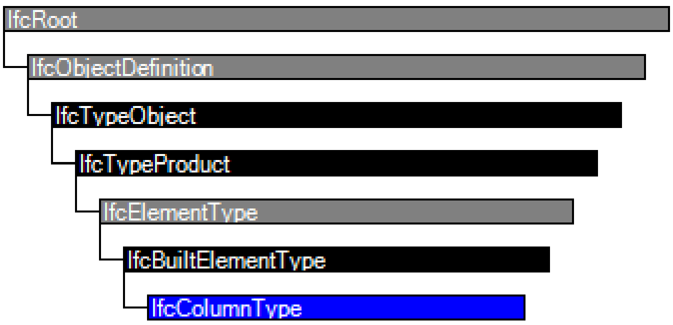
"An IfcWall represents a vertical construction that bounds or subdivides spaces. Wall are usually vertical, or nearly vertical, planar elements, often designed to bear structural loads. A wall is however not required to be load bearing. The IFC specification provides two entities for wall occurrences:
IfcWallStandardCase: used for all occurrences of walls, that have a non-changing thickness along the wall path and where the thickness parameter can be fully described by a material layer set. These walls are always represented geometrically by a SweptSolid geometry, if a 3D geometric representation is assigned. IfcWall: used for all other occurrences of wall, particularly for walls with changing thickness along the wall path (e.g., polygonal walls), or walls with a non-rectangular cross-sections (e.g., L-shaped retaining walls), and walls having an extrusion axis that is unequal to the global Z axis of the project (i.e. non-vertical walls).
IfcWall – or the subtype IfcWallStandardCase – (Figure 7.27) defines the occurrence of any wall, common information about wall types (or styles) is handled by IfcWallType. The IfcWallType (if present) may establish the common type name, usage (or predefined) type, common material layer set, common set of properties and common shape representations (using IfcRepresentationMap). The IfcWallType is attached using the IfcRelDefinedByType.RelatingType objectified relationship and is accessible by the inverse IsDefinedBy attribute. Recommended values are MOVABLE, PARAPET, PARTITIONING, PLUMBINGWALL, SHEAR, SOLIDWALL, STANDARD, POLYGONAL, ELEMENTEDWALL, NOTDEFINED. If the value USERDEFINED is chosen, the user defined value needs to be given at the attribute ObjectType." [228]

For the *Joints*, the type *IFCDiscreteAccessory* and enumeration *USERDEFINED* were used, as it still lacks an appropriate category for its full definition.



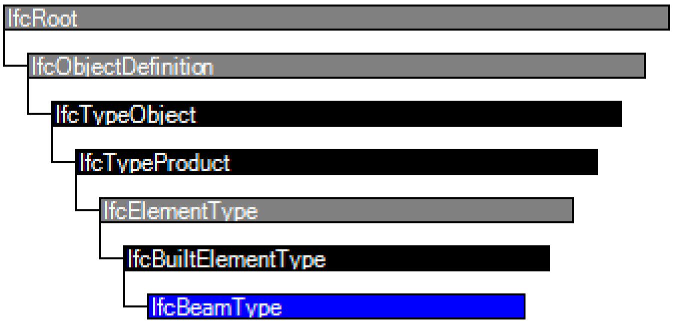
Constant	Description
FLOOR	The slab is used to represent a floor slab.
ROOF	The slab is used to represent a roof slab (either flat or sloped).
LANDING	The slab is used to represent a landing within a stair or ramp.
BASESLAB	The slab is used to represent a floor slab against the ground (and thereby being a part of the foundation). Another name is mat foundation.
USERDEFINED	
NOTDEFINED	

Figure 7.24 – Tree structure and possible enumerations of the IfcSlabType [228]



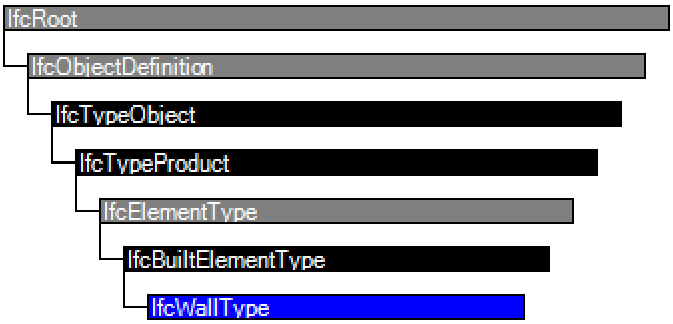
Constant	Description
COLUMN	A standard member usually vertical and requiring resistance to vertical forces by compression but also sometimes to lateral forces.
PILASTER	A column element embedded within a wall that can be required to be load bearing but may also only be used for decorative purposes.
USERDEFINED	User-defined linear element.
NOTDEFINED	Undefined linear element.

Figure 7.25 – Tree structure and possible enumerations of the IfcColumnType [228]



Constant	Description
BEAM	A standard beam usually used horizontally.
JOIST	A beam used to support a floor or ceiling.
HOLLOWCORE	A wide often prestressed beam with a hollow-core profile that usually serves as a slab component.
LINTEL	A beam or horizontal piece of material over an opening (e.g. door, window).
SPANDREL	A tall beam placed on the facade of a building. One tall side is usually finished to provide the exterior of the building. Can be used to support joists or slab elements on its interior side.
T_BEAM	A beam that forms part of a slab construction and acts together with the slab which its carries. Such beams are often of T-shape (therefore the English name), but may have other shapes as well, e.g. an L-Shape or an Inverted-T-Shape.
USERDEFINED	User-defined linear beam element.
NOTDEFINED	Undefined linear beam element.

Figure 7.26 – Tree structure and possible enumerations of the IfcBeamType [228]



Constant	Description
MOVABLE	A movable wall that is either movable, such as folding wall or a sliding wall, or can be easily removed as a removable partitioning or mounting wall. Movable walls do normally not define space boundaries and often belong to the furnishing system.
PARAPET	A wall-like barrier to protect human occupants from falling, or to prevent the spread of fires. Often designed at the edge of balconies, terraces or roofs.
PARTITIONING	A wall designed to partition spaces that often has a light-weight, sandwich-like construction (e.g. using gypsum board). Partitioning walls are normally non load bearing.

PLUMBINGWALL	A pier, or enclosure, or encasement, normally used to enclose plumbing in sanitary rooms. Such walls often do not extent to the ceiling.
SHEAR	A wall designed to withstand shear loads. Such shear walls are often designed having a non-rectangular cross section along the wall path. Also called retaining walls or supporting walls they are used to protect against soil layers behind.
SOLIDWALL	A massive wall construction for the wall core being the single layer or having multiple layers attached. Such walls are often masonry or concrete walls (both cast in-situ or precast) that are load bearing and fire protecting.
STANDARD	A standard wall, extruded vertically with a constant thickness along the wall path.
POLYGONAL	A polygonal wall, extruded vertically, where the wall thickness varies along the wall path. IFC4 DEPRECATION The enumerator POLYGONAL is deprecated and shall no longer be used.
ELEMENTEDWALL	A stud wall framed with studs and faced with sheetings, sidings, wallboard, or plasterwork.
USERDEFINED	User-defined wall element.
NOTDEFINED	Undefined wall element.

Figure 7.27 – Tree structure and possible enumerations of the IfcWallType [228]

Below are the steps to be carried out for a correct export in IFC4 Reference View format from Revit to include also the additional parameters generated ad hoc as IFC attributes. To this end, *floors* [*IFC_ASPI(S)*], *walls* [*IFC_ASPI(W)*], *levels* [*IFC_ASPI(L)*], and *multicategory* [*IFC_ASPI*] schedules, including the added parameters and named to include either *"IFC"*, *"Pset"*, or *"Common"* in their title were previously organised. The essential specifications adopted for the correct setting of BIM model export in IFC4 format are listed as follows.

- General:
  - IFC Version: IFC4 Reference View
  - Coordinate Base: Shared Coordinates
- Additional Content:
  - Export only elements visible in view
- Property Sets:
  - Export IFC common property sets
  - Export schedules as property sets
  - Export only schedules containing "IFC", "Pset", or "Common" in the title
- Advanced:
  - Include IFCSITE elevation in the site local placement origin
  - Store the IFC GUID in an element parameter after exportation.

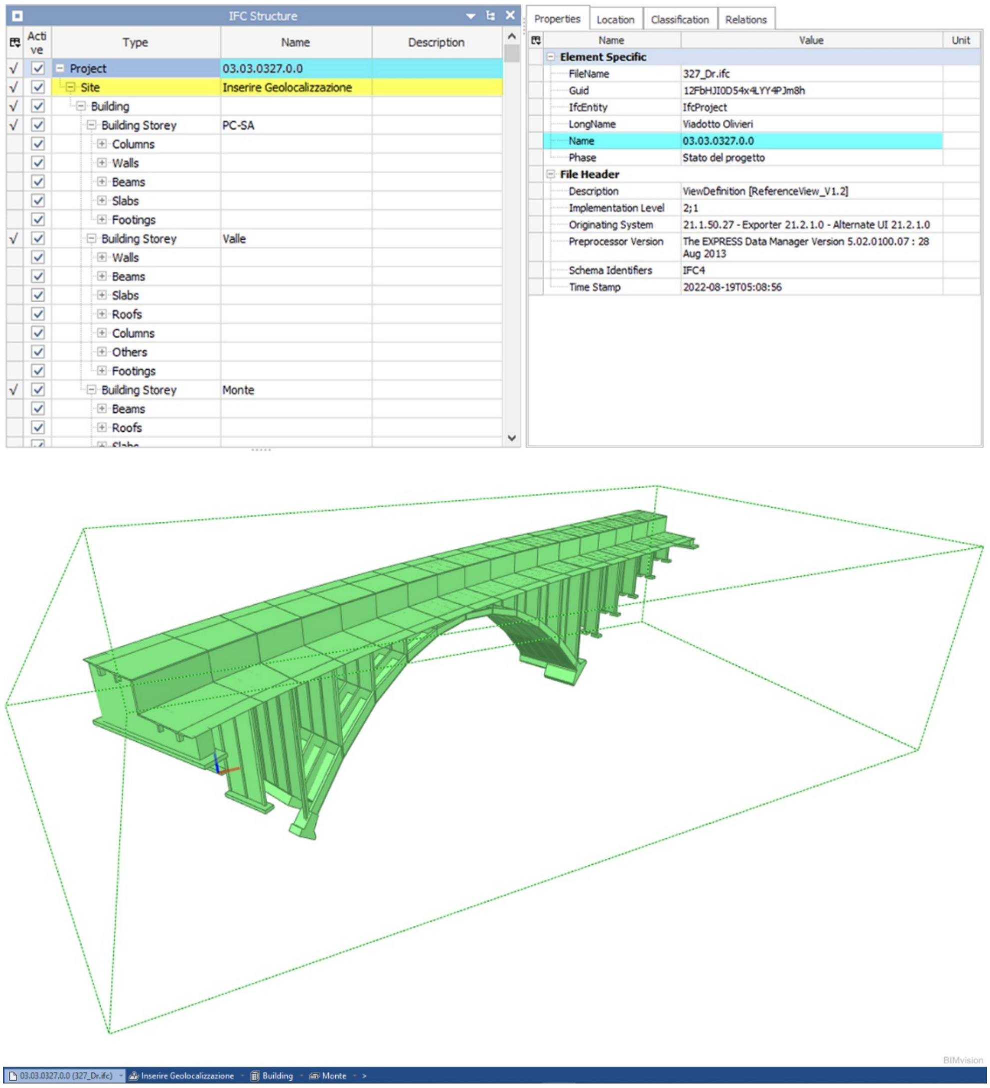


Figure 7.28 – IFC model of the Olivieri Viaduct. As previously mentioned, the *Project Name* parameter (in cyan) has been filled out with the Infrastructure ID – *"03.03.0327.0.0"* according to the *STONE CODING* system – while the *Site Name* (in yellow) has been temporally filled in – *"Inserire Geolocalizzazione"* – waiting for the most suitable geolocalisation data format to be decided [AoE]

7.2 From the C.U.G.R.I. platform to BIM: procedures to import inspection results

With regard to the management of the input information database, both here and in the following case study, Microsoft Excel was the chosen source, as it is a universally recognised and used tool for the relatively simple organisation and filtering of large data sets. Furthermore, it offers the option of cloud sharing and is, on average, considered accessible for any stakeholder, requiring a knowledge of the essential instrumentation that is practically an established standard nowadays.

Filling-in of the defect forms and estimation of the relative defectiveness value for each component

In concrete terms, during a visual inspection (e.g., on the Olivieri Viaduct) a detailed and precise photographic survey is carried out (Figure 7.29 and 7.30) with the aim of identifying and evaluating the defects on each element.
In accordance with Level 1 of the LG20, defect evaluation forms are compiled for all the reachable bridge's constituent components. During the demo phase of the C.U.G.R.I. BMS, the pilot case forms have been filled in both in an Excel format and within the platform, where they are already predisposed with multiple-choice fields.
The compilation is carried out with the help of the defect forms, which can be found in the Annex C of the LG20 (Figure 7.31) [95], containing the defect evaluation criteria, possible triggers, and related degradation phenomena, as well as the values that G, K_1 and K_2 can assume.
In order to make planning more effective, a global numerical index can be used, derived from the combination of the data collected during the visual inspection and reported on the defect forms. Therefore, for each defect found, the product $(G \times K_1 \times K_2)$ is calculated and its relative sum for each component is defined as Relative Defect $\left(D_r = \sum_i G_i \times K_{1,i} \times K_{2,i}\right)$.
The Relative Defectiveness corresponding to the inspections conducted in the year 2021 was then linked to the Revit model of the viaduct by populating a specially created shared instance parameter [*Dr_InspectionYear*]. The Dr values associated to each component are finally displayed graphically via a colouring determined in accordance with the colour ranges associated to the *Attention Classes* [CdA] [4] as shown in Figure 7.32.

Figure 7.29 – Defects affecting the beams and joists of the Olivieri Viaduct [96]

Figure 7.30 – Defects affecting the arch slab and joists of the Olivieri Viaduct [96]

Schede difettologiche **N° difetto: Dif. Gen_1**

Tracce di scolo

Peso del difetto

G = 1 | G = 2 | **G = 3** | G = 4 | G = 5

Estensione k_1	0,2 (appena presente)	0,5 (~50% superficie)	1 (~tutta la superficie)
Intensità k_2	Sempre = 1		

Descrizione

Il difetto si presenta con aree di colorazione diversa dal materiale integro, provocate dal passaggio ripetuto di acqua meteorica sulla superficie degli elementi. Nel caso in cui l'acqua è ancora presente, sono chiaramente visibili macchie di colore scuro e bagnate, altrimenti il passaggio pregresso dell'acqua è denunciato dalla presenza di macchie di colore biancastro legate agli effetti dell'azione chimica dei sali in essa disciolti. Tali macchie ricalcano il percorso intrapreso dall'acqua percolata sulla superficie degli elementi. Tali fenomeni si riscontrano prevalentemente sulle pareti verticali degli elementi strutturali, ma si possono rilevare anche su superfici orizzontali, quali l'intradosso degli sbalzi della soletta dove ristagna l'acqua proveniente dal coronamento.

Cause

La presenza di tracce di scolo è dovuta alla mancanza o all'inadeguatezza del sistema di convogliamento delle acque meteoriche, nonché a carenze del sistema di impermeabilizzazione. Analoghe conseguenze si associano a giunti non correttamente realizzati o manutenuti e a problemi legati ad altri particolari esecutivi, quali l'assenza di gocciolatoi.

Fenomeni di degrado correlati

L'evoluzione del difetto potrebbe portare a **fenomeni di dilavamento/ammaloramento** del calcestruzzo o della muratura, i quali comportano un rapido degrado del materiale con possibile disgregazione dello stesso. Non si devono confondere con le **macchie di umidità passiva** e **attiva**, le quali non derivano da percolazione di acqua sulle superfici ma da infiltrazioni di acqua all'interno del materiale.

Schede difettologiche **N° difetto: c.a./c.a.p._2**

Macchie di umidità attiva

Peso del difetto

G = 1 | G = 2 | **G = 3** | G = 4 | G = 5

Estensione k_1	0,2 (appena presente)	0,5 (~50% superficie)	1 (~tutta la superficie)
Intensità k_2	Sempre = 1		

Descrizione

Il difetto si presenta con aree di colorazione diversa dal materiale integro. In particolare, si tratta di tracce di calcio rilasciate sulla superficie dall'umidità penetrata attraverso il calcestruzzo. A differenza delle macchie di umidità passiva, l'**umidità attiva** è legata a fenomeni di infiltrazione di acqua tutt'ora in corso e si presenta con macchie di colore scuro dovuto al contatto continuo con l'acqua e l'umidità.

Cause

La penetrazione di umidità e di acqua meteorica attraverso il materiale è favorita in presenza di:

- materiali caratterizzati da elevata porosità;
- mancanza o carenze nel sistema di impermeabilizzazione;
- sistemi di convogliamento delle acque assenti, inadeguati o danneggiati;
- imperfetta tenuta dei giunti;
- scossaline assenti o deteriorate.

Fenomeni di degrado correlati

Il progredire di tale fenomeno di degrado potrebbe comportare l'innescarsi di **fenomeni di dilavamento e di ammaloramento** del calcestruzzo, nonché possibili **distacchi di copriferro** con conseguente esposizione delle armature. Tale difetto è diverso da altri fenomeni, quali le **tracce di scolo**, dovuti a scorrimenti superficiali di acqua.

Figure 7.31 – Extract of two filled-in defect forms of the Olivieri Viaduct [96]

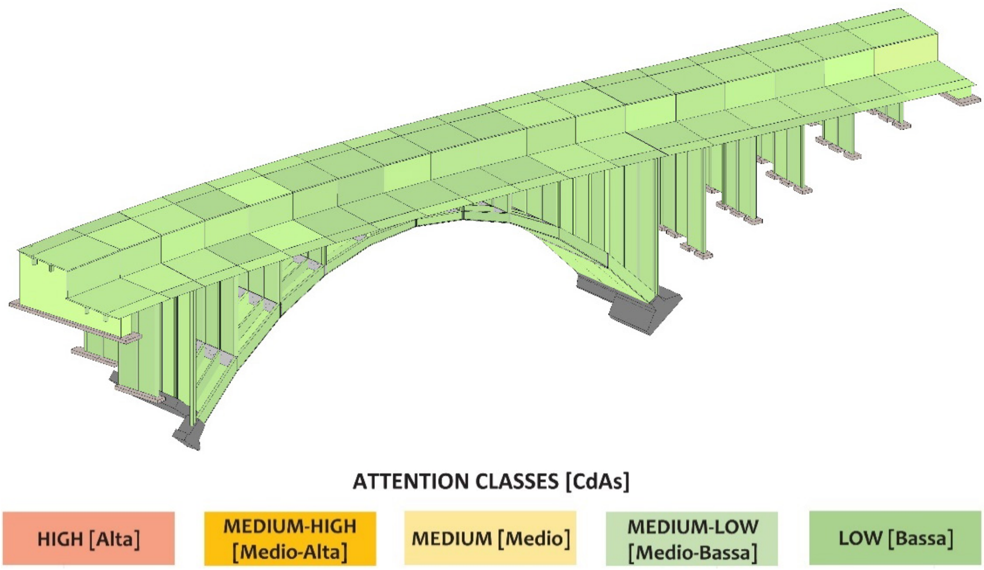


Figure 7.32 – Mapping of the Olivieri Viaduct based on the Dr parameter. It is easy to see that all the elements of the viaduct possess a Low, at most Medium-Low, level of defectiveness [AoE]

[Script 5] VPL script for importing *relative defectiveness* [Dr] data and visualising the results in the BIM environment

Relative defectiveness data are plotted from the BMS once the inspection forms for a given year have been filled in and validated in the form of Excel Spreadsheets. The script developed was therefore designed to create each time a new relative defect parameter linked to the inspection year [*Dr_InspectionYear*] and then populate it with the information regarding the inspection results, searching before between the sheets (indicating the Structural Sections), the identifying for each structural section the value designated for the single component corresponding to a modelled BIM object. The final part of the script was thus implemented to overlay, in a selected view, a visualisation based on the colour scale assigned to the attention classes.

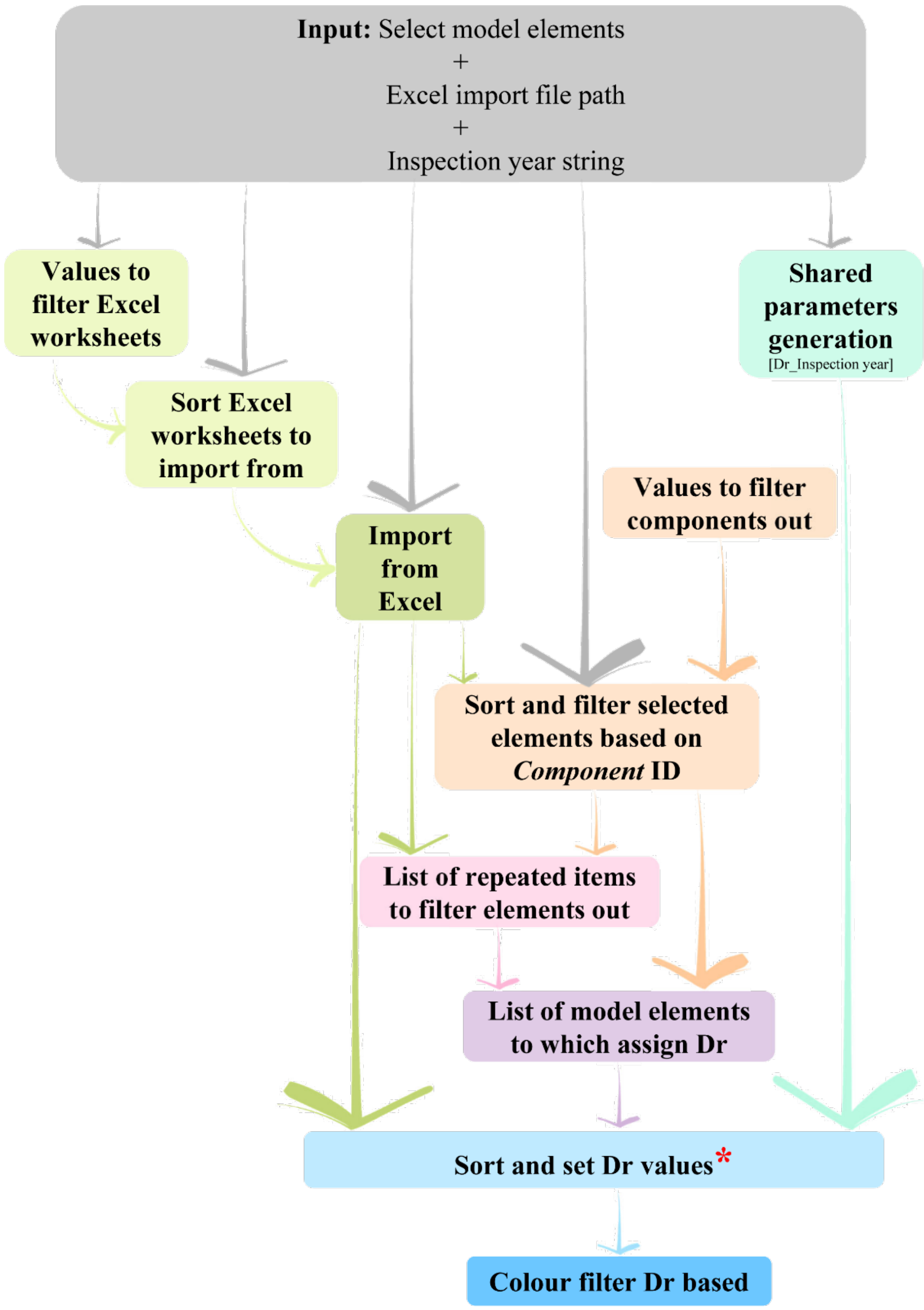


Figure 7.33 – Diagram breaking down the VPL script developed to automatically import *relative defectiveness* [Dr] data and visualise the results in the BIM environment [AoE]

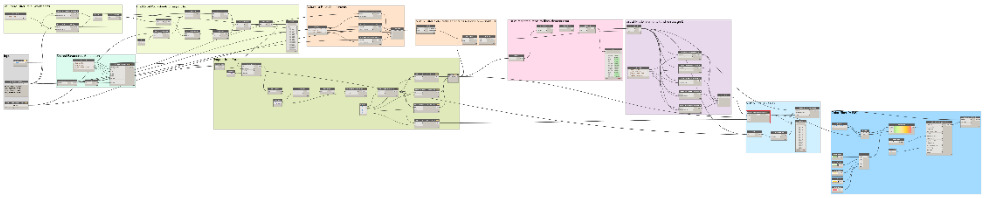


Figure 7.34 – Dynamo VPL script developed to automatically import *relative defectiveness* [Dr] data and visualise the results in the BIM environment [AoE]

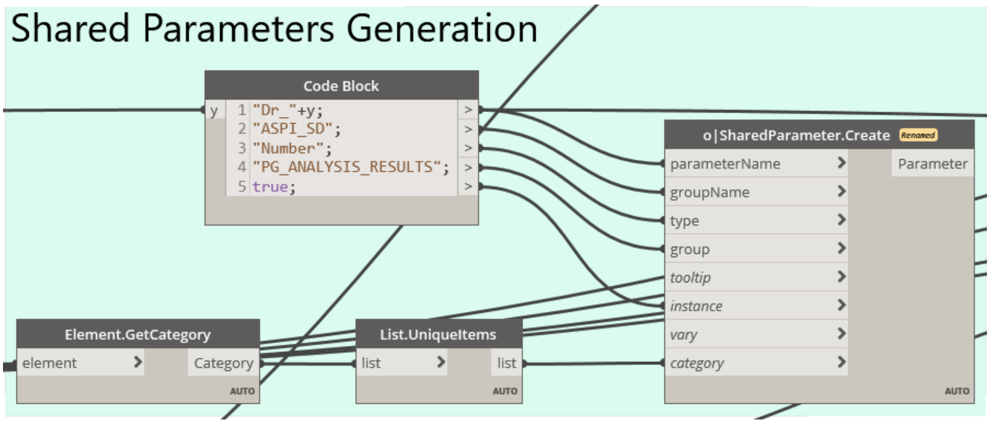


Figure 7.35 – Dynamo VPL script developed to automatically import *relative defectiveness* [Dr] data and visualise the results in the BIM environment: Group of nodes dedicated to generating the shared parameter [*Dr_InspectionYear*] [AoE]

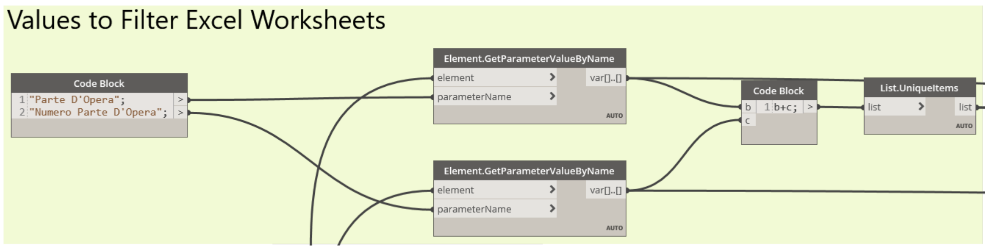


Figure 7.36 – Dynamo VPL script developed to automatically import *relative defectiveness* [Dr] data and visualise the results in the BIM environment: Group of nodes dedicated to filtering *Structural Sections* and *Components* data from the Excel spreadsheet [AoE]

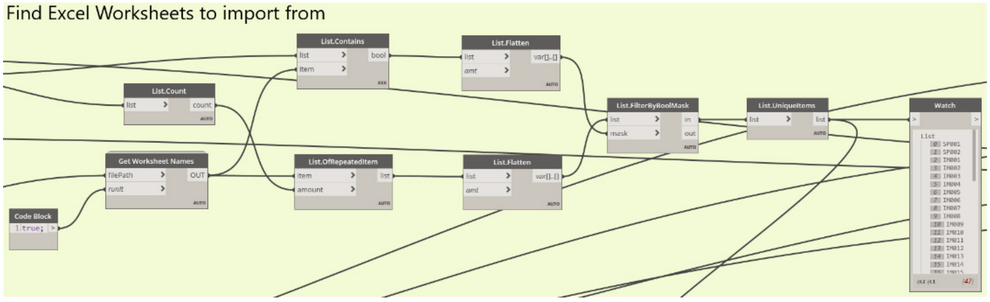


Figure 7.37 – Dynamo VPL script developed to automatically import *relative defectiveness* [Dr] data and visualise the results in the BIM environment: Group of nodes dedicated to retrieving the Excel sheets to import Dr values from [AoE]

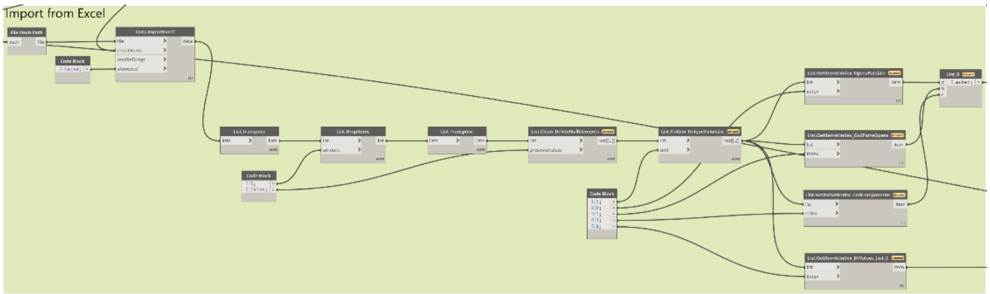


Figure 7.38 – Dynamo VPL script developed to automatically import *relative defectiveness* [Dr] data and visualise the results in the BIM environment: Group of nodes dedicated to importing Dr values corresponding to each *Component* [AoE]

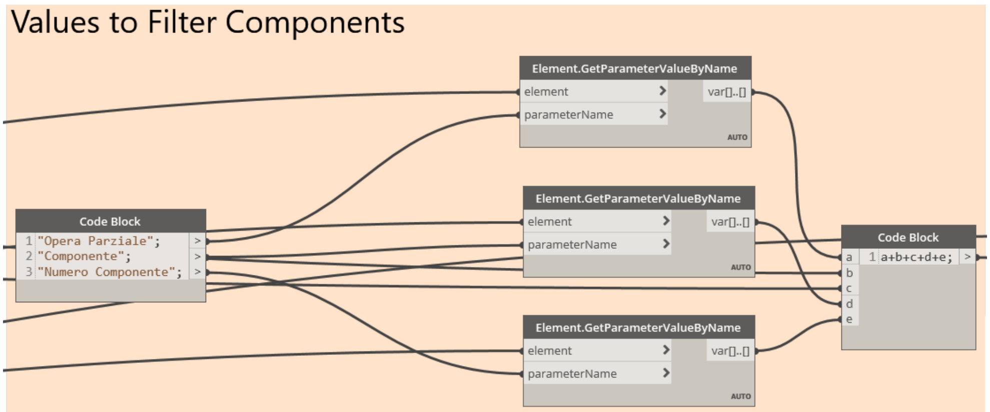


Figure 7.39 – Dynamo VPL script developed to automatically import *relative defectiveness* [Dr] data and visualise the results in the BIM environment: Group of nodes dedicated to filtering BIM modelled *Components* according to their *Structural Section* and their numbering [AoE]

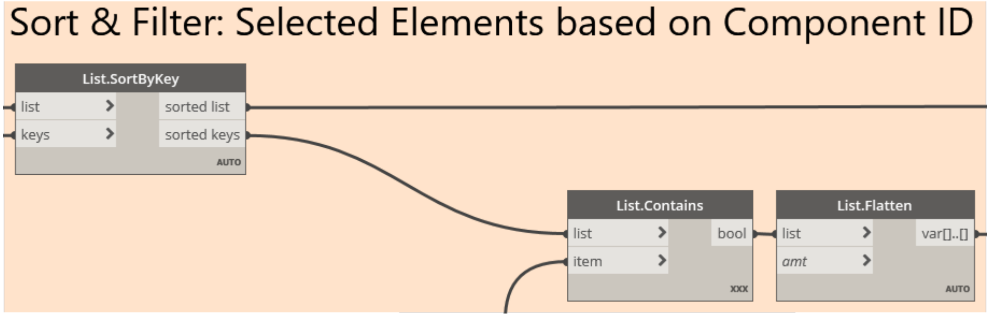


Figure 7.40 – Dynamo VPL script developed to automatically import *relative defectiveness* [Dr] data and visualise the results in the BIM environment: Group of nodes dedicated to sorting and filtering the selected BIM elements according to the *Component* full IDs [AoE]

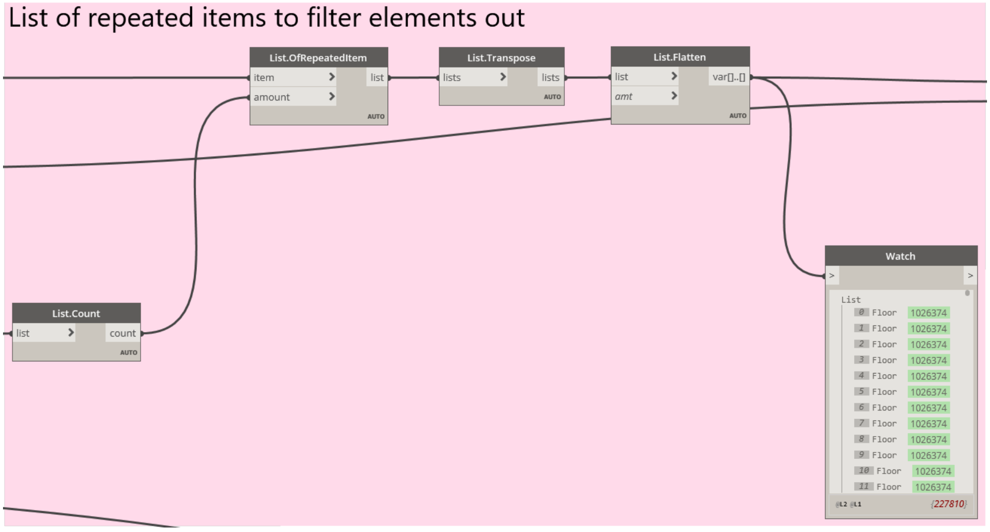


Figure 7.41 – Dynamo VPL script developed to automatically import *relative defectiveness* [Dr] data and visualise the results in the BIM environment: Group of nodes dedicated to generating the list of repeated items used to order the selected elements [AoE]

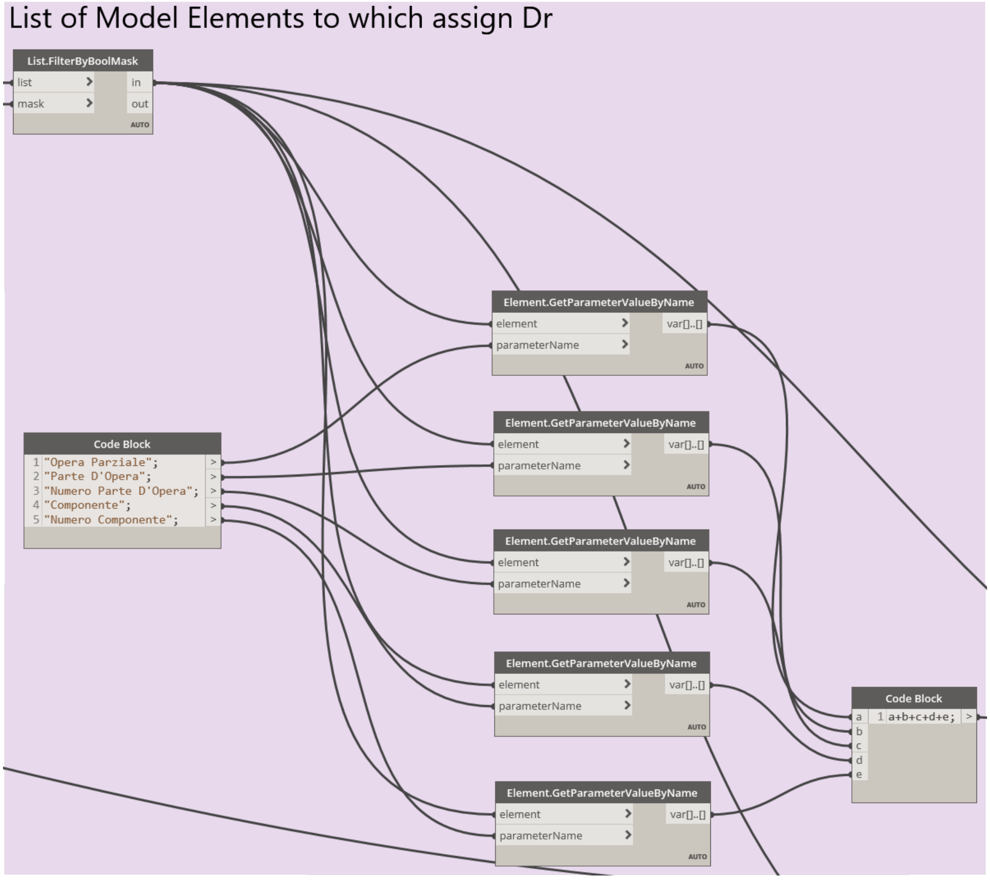


Figure 7.42 – Dynamo VPL script developed to automatically import *relative defectiveness* [Dr] data and visualise the results in the BIM environment: Group of nodes dedicated to generating the list of model elements to which assign the Dr values [AoE]

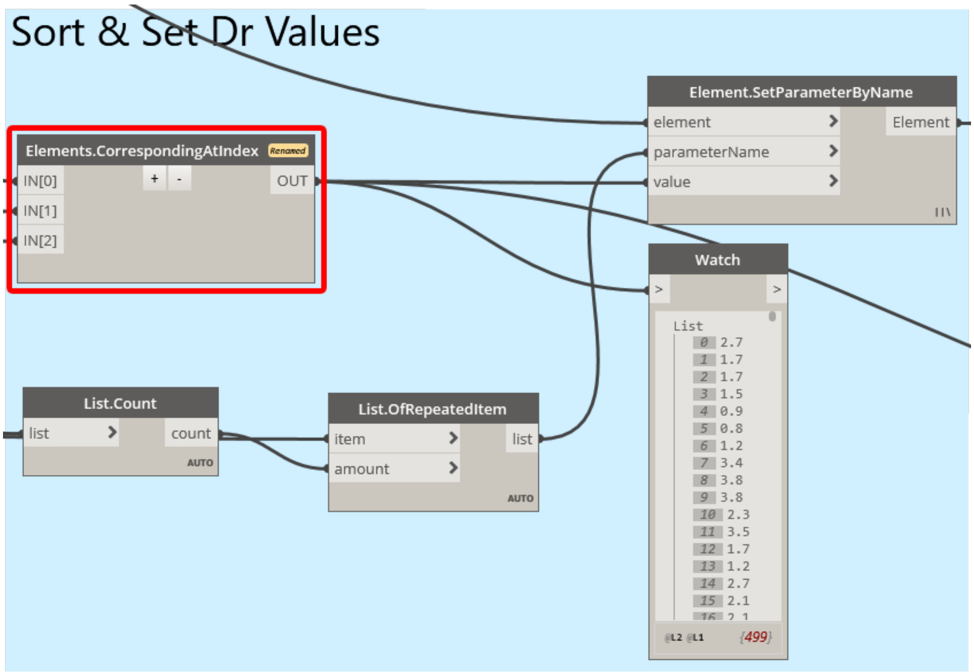


Figure 7.43 – Dynamo VPL script developed to automatically import *relative defectiveness* [Dr] data and visualise the results in the BIM environment: Group of nodes dedicated to sorting and assigning the Dr values to the BIM modelled elemental components. This group employs the custom node marked in red [AoE]

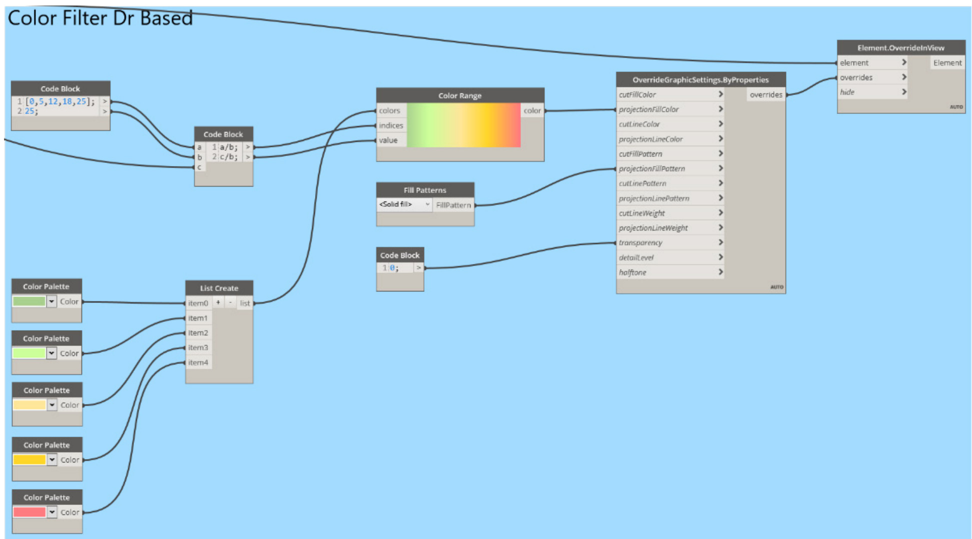


Figure 7.44 – Dynamo VPL script developed to automatically import *relative defectiveness* [Dr] data and visualise the results in the BIM environment: Group of nodes dedicated to setting up the colour filter for a selected view based on the Dr *attention classes'* ranges [AoE]

Part III – Sensor databases: the case study of the Temple of Neptune

8. Integrated 3D survey for the generation of a BIM database

In architecture and civil engineering, maintaining existing constructions is essential for preserving cultural heritage, especially for those constructions exposed to a high degree of degradation [117].
To quote Singh et al., a large amount of raw data resulting from the data logger of these SHM systems require appropriate tools to visualize and diagnose the data systematically. BIM is a powerful data management tool that can be utilized as a base platform to analyze and visualize long-term SHM data. Current BIM-based approaches have the capabilities of facilitating the design, production, and construction management of structures. BIM models in such approaches can serve as static information that contains as-built data [164].
Sharing and integration of such information would facilitate meaningful use of the information and improve asset management, as well as enhance conservative operations and maintenance for public safety. Hence, in many industries, information models and interoperability standards have been developed and employed to facilitate information sharing and collaboration [188].
Traditional approaches, however, are not enough to monitor a large amount of SHM data and conduct systematic decision-making for future maintenance [168].
As a matter of fact, many researchers have already pointed out the necessity to integrate the current *Structural Health Monitoring* [SHM] procedures, including but not limited to *Bridges Management Systems* [BMS], with data coming from sensors, both in terms of measuring instruments connected to a *Digital Twin* of the physical asset via the so-called *Internet of Things* [IoT] and three-dimensional

survey data. Indeed, for preventive and systematic maintenance of structures, periodic visual inspections are essential to detect structural defects at an early stage and to initiate necessary interventions. Modern technologies such as unmanned aircraft systems equipped with high-resolution cameras increasingly support the inspection process and the associated documentation. In addition, processing methods and linked data models allow for effective data management [112].
Generally speaking, the majority focuses on assessing the current state-of-the-art and sporadically proposes applications to practically integrate this kind of database. Namely, several existing studies presented methods to automatise data acquisition and visualisation for inspections, but they lack an open standard to make the gathered data available for other processes. On the other hand, many others discuss data structures for exchanging damage information among different stakeholders. However, those studies do not cover the process of automatic data acquisition and transfer [113].
LiDARs have higher accuracy and density than mobile scanners but require longer registration times and data processing. On the other hand, in interior building space management, relatively high accuracy is not needed, and the user can conveniently move with a mobile scan system or UAS [154]. *Unmanned Aerial Systems* [UAS] offer a significant improvement of inspection and guarantee high-quality images which are essential for reliable inspection results. The gathered data can be georeferenced, which provides the possibility of a highly accurate 3D modelling of structures with a direct referenced visualisation of detected changes or damages [181]. However, as of today, with UAS being a relatively new inspection method, there is little in the way of an existing framework for storing, processing and managing the resulting inspection data within a BIM environment [11]. Therefore, the third part of this thesis endeavours to propose some practical procedures for connecting a sensor-based database to BIM and OpenBIM models for management and maintenance purposes.

8.1 UAS photogrammetric survey

Unmanned Aerial Systems [UASs], known under various names and acronyms, such as Unmanned Aerial Vehicles [UAVs] – although the latter technically correspond to the sole drone supporting the system constituted of both the aerial vehicle and the sensor mounted on it, UAV still is the term most commonly used in literature – and Remotely Piloted Aerial Systems or simply drones [229], to name a few, are aircraft without a pilot on board, that are being continuously miniaturized and have become widely accessible for commercial use [230–232]. In the last years, thanks to recent technological developments, remotely controlled aerial vehicles are increasingly used in support of geophysical surveys, enabling reliable 3D models [233–235]. UAS-based data collection is becoming increasingly cost-effective due to increased precision and accuracy and the ability to cover large areas inaccessible by land, with shorter flights and faster acquisition planning [236]. In particular, aerial photogrammetry from UAS has been used extensively in archaeology and cultural heritage for the documentation and 3D mapping of sites, thanks to innovative low-cost systems and high-resolution digital cameras [237,238], enabling the construction of 3D models with photorealistic textures [239].

8.2 Mesh-to-BIM application and PBR material for enhanced visualisation

In an effort to broaden the topic already addressed in section 1.4, it is worth adding a few considerations regarding Mesh-to-BIM applications, specifically, and the progress made in this field towards implementing innovative techniques for achieving advanced visualisation every day closer to the real-world experience.
Although the practice of BIM modelling the existing asset is becoming increasingly common, there still lacks a direct connection between the rich graphic geometrically accurate data surveyed on-site and the discretized synthesis that even an as-built type of model is capable of storing and reproducing. In other words, a BIM model often feels like too much of an abstraction of the real world, thus, its practical use as a support tool for refurbishment purposes becomes quite limited if not almost inexistent. Hence, it is more than ever necessary to test – as some researchers have proposed – novel procedures capable of making rich-textured photogrammetric outputs dialogue with apparently stone-cold BIM models, e.g., by *projecting* full-sized orthoimages onto the surfaces of model sub-components. On the other hand, Werner Heisenberg would point out that *"quantum physics tells us that nothing that is observed is unaffected by the observer"*; thus, a mere projection of orthoimages onto parts of a model, is most likely not sufficient for us, i.e., the observers and the assigned operators on the built heritage, to fully understand the nature of each crack and each spot that may plague the object of study. Here is where the *Physically Based Rendering* materials may come in handy: they indeed represent a way of shading and rendering capable of simulating a more accurate representation of how light interacts with surfaces, by employing a number of *ad hoc* additional raster images, defined as maps [240]. Furthermore, *Physically Based Rendering* [PBR] techniques have recently joined the photogrammetric workflow to enhance surface information [LOI enhancement stage] provided by the texture mapping process, creating photorealistic, effects for their visualisation. In a PBR pipeline, the most common textures generated for simulating the properties of the physical object are usually [241] (Figure 8.1):

- *Albedo map* or *Diffuse map*: this texture contains the base colour information of the surface or the base reflectivity when texels are metallic. Compared to the diffuse map, the Albedo map does not collect any lighting information. Shadows and reflections are added subsequently and coherently with the visualisation scene.

- *Normal map*: this texture map contains a unique normal for each fragment to describe irregular surfaces. Normal mapping is a common technique in 3D computer graphics for adding details onto simplified models. Together with the *Height map* – a black and white texture map used to enhance protrusions and recesses – the Normal map provides a more accurate reproduction of the surface's relieves (Bump).
- *Metallic or specular map*: this black and white map, acting as a mask, represents whether each texel is metallic or not.
- *Roughness map* (as opposed to *smoothness map*): this texture map defines how rough each texel is, influencing the light diffusion and direction, while the light intensity remains constant.
- *Ambient Occlusion* [AO] *map*: this map is used to provide indirect lighting information, introducing an extra shadowing factor for enhancing the geometry surface. The map is a grayscale image, where white regions indicate areas receiving all indirect illumination.

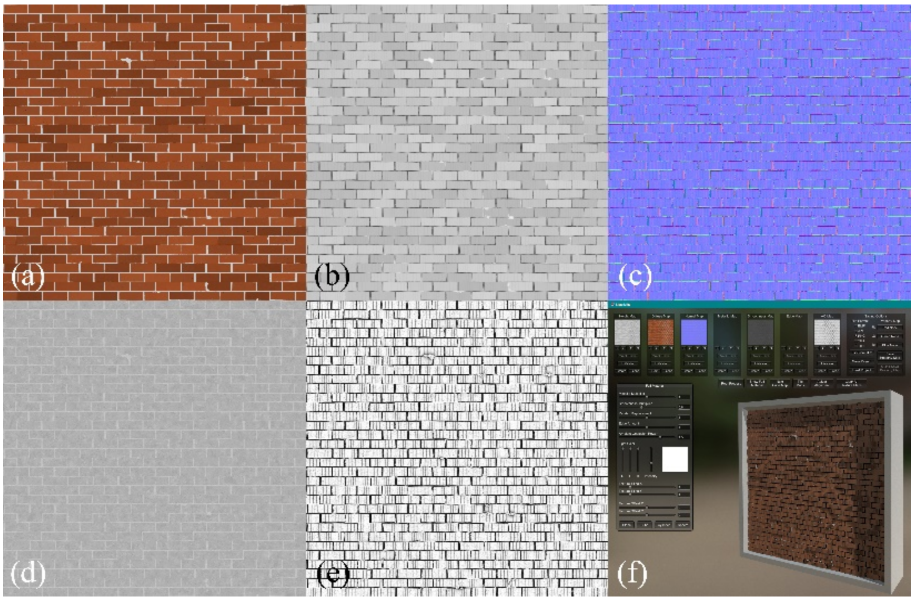


Figure 8.1 – Example of a PBR generic brick wall: (a) *Diffuse map*; (b) *Height map*; (c) *Normal map*; (d) *Roughness map*; (e) *Ambient Occlusion map*; (f) Physically realistic visualisation within the *Materialize*[45] standalone open tool [AoE]

[45] *Materialize* is a standalone tool for creating materials to use in games from images. It allows generating an entire material from a single image or importing the already existing

8.3 How to bridge the gap in the Scan-to-BIM applications

It then appears clear that, in applying the BIM approach to built heritage, one of the main difficulties is that it is not always possible to identify standard constructive rules for architectural elements. It depends on the complexity of the architecture, its details, the goal of the BIM, and the relevance of the architecture, without forgetting the corresponding economic effort [242]. Thus, although the long-term aim of BIM modelling is to standardise the elements as much as possible when the object to be modelled is typically unique, as in the case of the urban context, the aim becomes to propose a practical methodology for the systematisation of the process so at to enable its future reproduction it in the most authentic way. As a matter of fact, the analysis of state of the art reveals a lack of reliable protocols/systems for the realisation in a BIM environment of those elements of the built heritage characterised by a relevant historical, cultural, and economic value and by a recognisable unicity [3].

Therefore, as part of the overall systematic methodology of the Scan-to-BIM approach for the standardisation of digitisation procedures proposed in this thesis work, two innovative procedural practices are presented in the following pages (Chapter 11), aimed at importing, at different scales of detail, operability, and modifiability, textured photogrammetric meshes of the urban context as well as detailed areas of interest within a BIM environment. The purpose is indeed to move in the direction of filling the gap between the type of detail a survey can achieve, precisely a photogrammetric one when talking about colourimetric data, and what can be reproduced in a BIM environment when it comes to distinctive, rather than unique, features such as the urban context or detailed elements, such as damaged areas [LOI enhancement] thus, laying the foundation of a metaphorical eco-systemic monitoring environment for the management of the built heritage [3].

textures to generate other physical maps for the chosen material. For further information concerning *Materialize*, please visit: https://boundingboxsoftware.com/materialize/.

9. The case study monitoring system

Besides the historical relevance of the case study proposed below, the case study of the Temple of Neptune – at Paestum, one of the best-preserved artefacts of Greek origin in Italy – has been chosen for the possibility of carrying out experimental applications starting from the already rich existing database built up over more than a decade. Furthermore, additional information coming from the innovative seismometric monitoring system – whose measuring points are placed on the cornice of the external colonnade of the Temple of Neptune and data collection manholes near the stylobate – has been subsequently implemented. The first laser scanner survey crucial herein for scan-to-BIM modelling dates back to 2011 [243]. The knowledge of the site was then variously updated mainly with photogrammetric surveys oriented to the acquisition of material data, the most up-to-date of which, designed to acquire both the temple and the surrounding context with a good level of detail, was then carried out in 2017 [244]. The subsequent photogrammetric survey carried out in 2020 was, in turn, focused on the survey of the area surrounding the temple of Neptune, having been requested due to the new excavations made upon the placement of the seismometric monitoring system (Figure 9.1) [245].

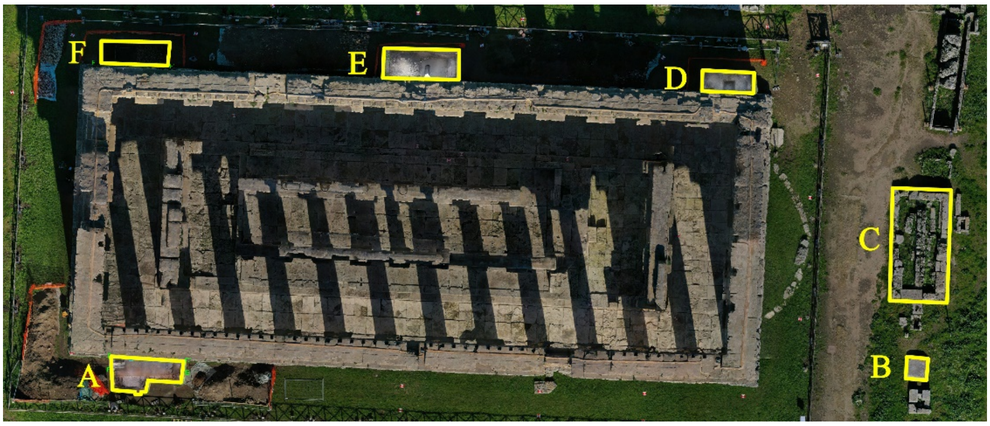


Figure 9.1 – North-oriented plan view showing the six additional sampling points identified during the placement of the dynamic monitoring system on the Temple of Neptune [245]

The monitoring system network consists, among other specific equipment, of experimental measurement instruments – *UNISA Folded Pendulum* [246], seismometers developed and patented by the *Research Group in Applied Physics* of the University of Salerno engaged in the study of gravitational waves – set in place under the supervision of the scientific coordinators: professor Luigi Petti (Department of Civil Engineering – University of Salerno) and the director of the *Archaeological Park of Paestum and Velia* archaeologist Gabriel Zuchtriegel.

9.1 Case study: the Temple of Neptune

The ancient city of Paestum preserves ruins of Greek and Roman times and three remarkably well-preserved Doric temples. Indeed, Paestum is one of Italy's most important archaeological sites and was included in the UNESCO World Heritage list in 1998. The ancient city of *Poseidonia* was founded around 600 BC by Greeks from Sybaris and it presents an urban space divided into sacred, public and private areas. The city's central area was designated for public use and during the Greek period was occupied by the agorà. In the North was located the sanctuary of Athena (ca 500 BC) later known as the temple of Ceres. Instead, the so-called *Basilica* (ca 550 BC, it was the earliest of three temples) and the temple of Neptune (ca 450 BC) were placed in the South. At the end of the 5th century BC *Poseidonia* was defeated by the Lucani, a population of Samnite origins, who replaced the Greeks in the government of the city. The conquest of Lucani did not introduce changes in the organisation of urban cities, just adding the defensive wall. Then, in 273 BC the city became a Roman colony, taking the name of Paestum. The most important transformations of this period involve the organisation of the urban space: the Forum was built and the prominent Greek public monuments (*agorà, ekklesiasteiron* and *heroon*) were destroyed (Figure 9.2).

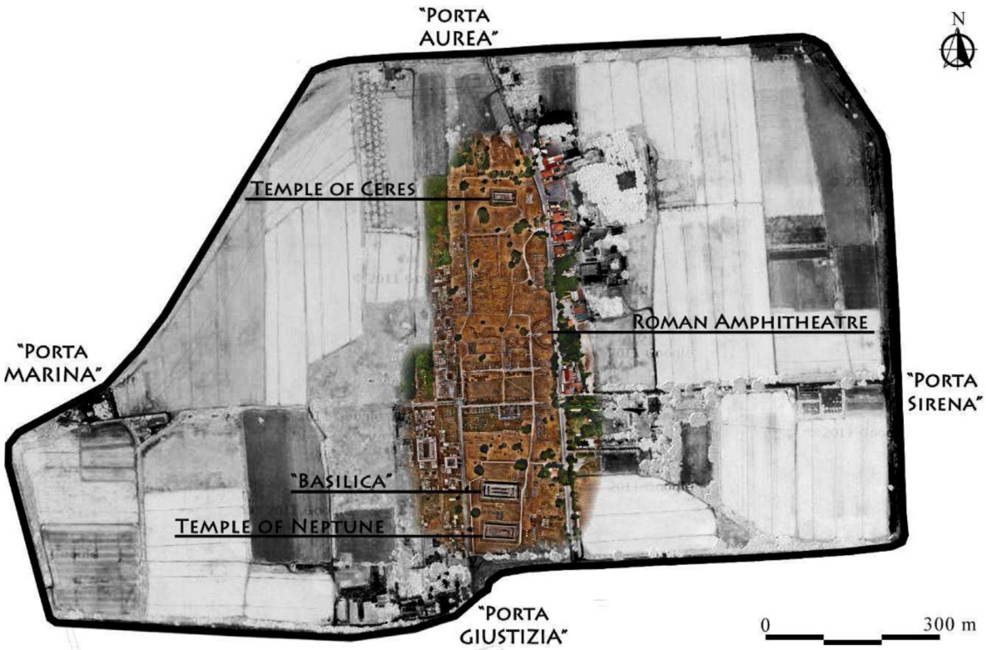


Figure 9.2 – Plan of the Paestum Archaeological zone [243]

Subsequently, the city was abandoned during the Middle Ages and the archaeological area remained submerged under marshes and brushwood for a long time. With the rediscovery of temples in the 18th century, thanks to travellers embarking on the so-called *Grand Tour*, Paestum came into knowledge again and the temples became an attraction for the world. Therefore, systematic archaeological investigations started at the beginning of the last century, and they are still on-going [243] (Figure 9.3).

Near the Basilica, on a slight rise, stands the most beautiful and best preserved of the three Doric temples: the Temple of Neptune. The monument dates back to the mid-fifth century BC; attribution to Neptune is due to 18th-century scholars who believed the building was built in honour of the god Poseidon-Neptune, who gave the city its name. Recent studies attribute it instead to Apollo, in his role of a physician. The temple is of the peripteral type and stands on a three-stepped base on which a colonnade of 6x14 Doric columns (24.14x59.88) stands – 6 columns on the east and west-facing façades and 14 on the northern and southern-facing longitudinal sides. The columns of the outer colonnade, almost 9 metres high, are tapered at the top and have a swelling (*Entasis*) in the middle of the shaft; these are characterised by 24 flutings instead of the canonical 20. On the abacus (the element that completes the capital) rests the architrave embellished with projecting decorations. The upper part, characterised by triangular tympana, forms the typical Doric frieze. The roof, now collapsed, consisted of an internal wooden ceiling and a roof covered with terracotta tiles. Important for the dating of the temple are certain features such as the slight curvature of the staircase, the barely perceptible inward inclination of the columns and the very slight downward curvature of the entablature of the two fronts. Inside, a high step marks the passage from the *prònaos* (the front vestibule), composed of two columns between pillars, to the *naos* (the cell that constitutes the core of the temple intended to house the divine simulacrum). The cell, elevated, is divided into three naves by two rows of double-order columns – characterised by 20 flutings, those at the bottom, and 16 flutings, those at the top – on which the roof trusses were placed (Figure 9.4). Opposite the *prònaos* is the *opistòdomos* (rear vestibule). In front of the temple are the remains of two bòmoi for sacrifices. To the east of the temple, vestiges of the altar have been found, preserved only in the foundations; meanwhile, in the 1st century BC a new altar was built closer to the east front, a sign of the vitality of the cult even among the Romans [247,248].

Figure 9.3 – *"Raindrops fall while we walk among the Paestum ruins, where a temple stands out, white, pure and perfect, from the soft masses of the Mediterranean scrub. Column drums in the foreground gain strength from that same purity and, resting on the ground, transform the clearing into an open-air museum"*. Quote and drawing by Sandro Parrinello [249]

Figure 9.4 – *"Sitting on the ground, leaning with our backs against a column, we endeavour to describe the double order of columns that characterise the Naos of the Temple of Neptune. The grandiose majesty of the architectural elements overpowers any attempt to balance the space in the drawing sheet, the task is arduous, it requires "distorting" the point of view slightly, it requires dedication and all the time necessary to render that action of transposing thoughts, a language of signs. A moment of pure pleasure. Paestum, interior of the Temple of Neptune"*. Quote and drawing by Francesca Picchio [250]

9.2 A TLS-photogrammetric integrated database

As previously mentioned, an integrated three-dimensional database – 3DS phase of the overall scan-to-BIM methodology proposed therein – is fundamental to digitising the built heritage. Indeed, while a Terrestrial Laser Scanning survey is surely more detailed and possibly more accurate than a photogrammetric one, the latter often makes it possible to fill the gaps in the laser point cloud, occurring in those areas unreachable from the ground, like the top of the roofs, while also enriching the material and colourimetric datum.
As a matter of fact, the roofs of the Temple of Neptune, missing in the 2011 TLS point cloud, were integrated using the 2017 dataset once the laser point cloud had been updated and georeferenced in the same geographic coordinate system used for the UAS survey. The resulting integrated point cloud has then become the base for the monument's Scan-to-BIM structural modelling [STR phase]. Since the laser point cloud was also lacking chromatic information, the orthoimages of the main façades produced from the 2017 UAS survey were likewise helpful to better read the decomposition of the *Doric columns* into their constituent *drums*.
Subsequently, both the 2017 and the updated 2020 UAS survey were employed for image-based elaboration with the aim of recreating in the most accurate way possible the temple surroundings, further including a detailed and fully parametric reproduction of some of the newly sampled areas – particularly the A, C, and D areas shown in Figure 9.1.

The 2011 Terrestrial Laser Scanning survey

The 2011 survey of the Temple of Neptune formed part of the research activities of the *Paestum Project*, in which the 3DOM [*3D Optical Metrology*] group of the *Fondazione Bruno Kessler* (https://www.fbk.eu/it/ – Trento, Italy) participated in collaboration with the Department of Civil Engineering of the University of Salerno. The project concerned the survey and three-dimensional restitution of the Paestum Archaeological Park for documentation, preservation, and valorisation purposes.
The acquisitions of the Temple of Neptune were carried out using the *Leica Geosystem phase-based HDS 7000 laser scanner* (which is now out of production) provided by the 3DOM group, who also surveyed the monument (Figure 9.5, left). The positions of the different scans have been organised to cover the entire volume of the monument, taking account of shadows, obstacles and undercut. The geometric resolution of the scans has been chosen depending of the distance instrument-object in order to ensure a sampling fairly constant

and sufficient to reconstruct all the necessary architectural details and degrade. The nominal resolution for the nearest stations and for all scans of the inner Temple of Neptune was set to 0,018° (one point for every 3 mm at a distance of 10 m). In contrast, for the most distant scanner position, a higher resolution, equal to 0.009° (1,6 mm at 10 m), was chosen [243].

From the 48 resulting scans – 26 inside the temple and 22 outside – a registered point cloud with more than 500 million points was obtained (Figure 9.5, right, and Figure 9.6). However, on updating the point cloud, available only in the structured albeit-non-native RCP format, 5 of the external scans – recording more the surroundings than the temple – were discarded to lighten the final point cloud. With the structured point cloud within the Autodesk ReCap Pro environment, it was possible to update its reference system, assigning the corresponding coordinates to natural points homologous to those recognised in the 2017 TLS survey. Then for management purposes, the already integrated cloud was decimated, keeping a 3 mm spacing between consecutive points, into three macro-areas, generated as new scan locations, corresponding to the inner temple, the external colonnade, and the surroundings (Figure 9.7).

Figure 9.5 – TLS acquisition via the *Leica Geosystem HDS 7000 laser scanner*, to the left [243], **and a perspective view of the resulting point cloud, where each scan is highlighted in a different colour, to the right [AoE]**

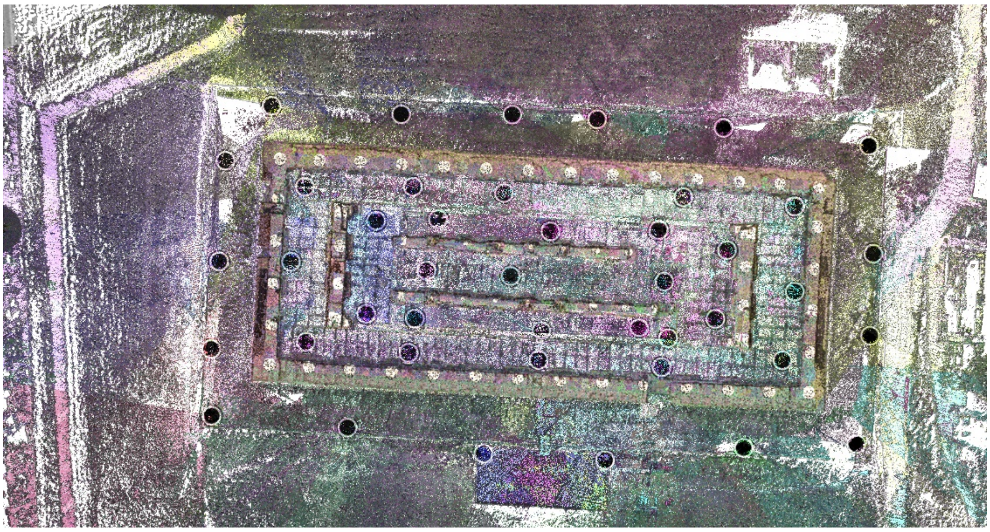


Figure 9.6 – Plan view of the TLS point cloud, where each scan is highlighted in a different colour and the acquisitions' location are identified by black circles [AoE]

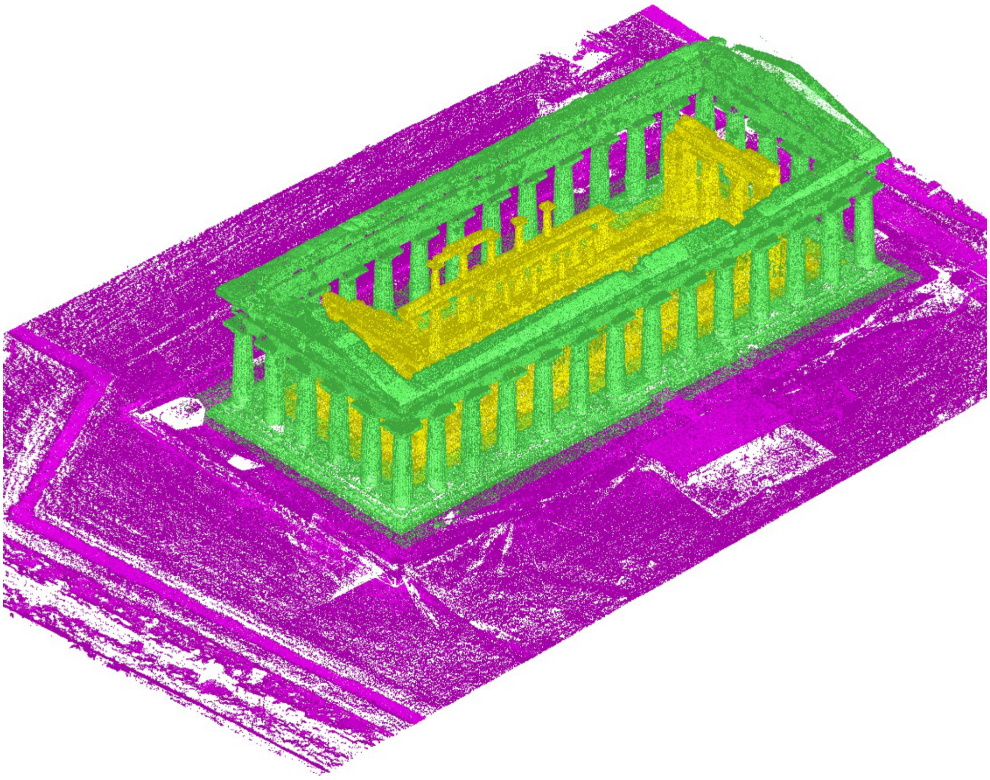


Figure 9.7 – Integrated point cloud divided into three new sampled scan locations: the inner Temple in yellow, the external colonnade in green and the surroundings in purple [AoE]

The 2017 and 2020 Unmanned Aerial System surveys

Both aero-photogrammetric acquisition campaigns were conducted by the *surveying & representation* group of the *Laboratorio Modelli – Surveying and Geo-Mapping for Environment and Cultural Heritage*, Department of Civil Engineering, University of Salerno – setting different input parameters depending on the objective of the survey. In particular, a few experimental analyses have been carried out on the 2017 dataset, such as the one by Gujski et al. ***on "Machine learning clustering for point clouds optimisation via feature analysis in cultural heritage"*** [244], from which the survey specifications reported as follows have been extracted.

As previously mentioned, the 2017 aero-photogrammetric survey was aimed at bot updating the knowledge on the Temple of Neptune and the surrounding environment, thus, a mixed type of photogrammetric acquisition was chosen: the nadiral images were acquired through the generation of a flight plan designed in the DJI Ground Station environment, while for the oblique images - necessary for the 3D reconstruction of the entire Temple and for the restitution of the orthophotos of the elevations - a manual piloting mode was adopted. For both phases, the acquisition was performed in automatic timelapse (2 sec interval). The UAV used is a *hexacopter* assembled with a 3-axis gimbal and the installation of a *Sony Alpha 6500 camera* (sensor size 23.5 x 15.6 mm, 6000 x 4000 pixels, pixel size 3.92 μm, focal length 16 mm). During the flight operations, access to the Temple and the area nearby – security buffer – was closed to the public for a period of 2 hours. The nadiral flight was from North-East to South-West, with a height from the take-off plane of 35 m, which resulted in a ground cover of 51.4 x 34.1 m. In total – from the flight plane only – 185 nadiral images were acquired. The manual flight for the oblique images was planned by carrying out two strips for each side of the Temple: the first was carried out with the camera tilted at 45° - with an average flight altitude of 17.5 m from the take-off point – so that each photogrammetric shot would take a percentage of the frame of the upper part of the Temple, so as to overlap with the nadiral images, as much as the external part of the columns; the other strip at a lower altitude – an average of 13.5 m from the take-off plane – has instead planned a horizontal optical axis of the camera, to guarantee an overlap of the photogrammetric shot with the images acquired in the first strip of between 60 and 80%. Finally, a set of images were acquired at a higher altitude – between 45 and 55 m – to facilitate the matching process in the processing phase. A total of 908 images were processed for the generation of the 3D model (185 nadiral images obtained from the flight plan and 723 oblique images obtained in manual mode) with an average *Ground Sample Distance* [GSD] of 7.78 mm/px and for a total surveyed area of 0.8 hectares. The choice to also acquire oblique images is necessary for the implementation of texture information on vertical elevations, and simultaneously increases the accuracy of the photogrammetric survey [251].

The images were processed with Agisoft Metashape software (Figure 9.8). The workflow implemented is as follows: in the *Align Photos* phase, the parameters were set: *Accuracy = High*, *Key point limit = 60,000*, *Tie Point limit = no limit*, obtaining a *Sparse Cloud* of 2,626,415 *points*. In the generation of the *Dense Cloud* the parameters used were: *Quality = High*, *Depth filtering = Disable*, obtaining a *Dense Cloud* of 56,150,877 *points*. In the *Build Mesh* the parameters set are *Surface Type = Arbitrary*, *Source Data = Dense Cloud*, *Face Count = Medium*, generating a polygonal model with 5,230,012 *triangles*. Finally, in *Build Texture* the parameters set are: *Mapping Mode = Generic*, *Blending Mode = Mosaic*, *Texture size = 4096 x1* (enabling Enable hole fitting). A GNSS network consisting of 11 *Ground Control Points* [GCPs], staggered altimetrically, was designed to support the georeferencing and accuracy assessment of the generated model. The GCPs were materialised on the ground using photogrammetric targets and topographic pegs. The reference system adopted is UTM/ETRF00 with orthometric heights – Projected coordinate system *WGS 84/UTM zone 33N* identified as *EPSG: 32633*. The precision achieved in planimetry is on average subcentimetric while in altimetry it is about 2.5 cm.

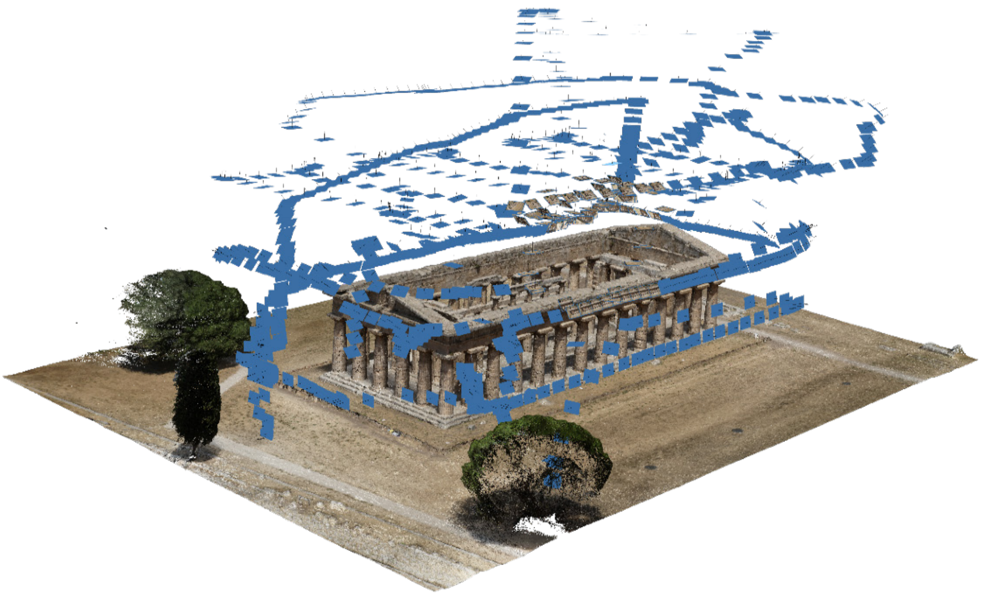


Figure 9.8 – Overview of the 2017 UAS survey within the Agisoft Metashape environment [AoE]

For the 2020 UAS survey, aimed at updating the knowledge concerning the temple surroundings and the novel seismometric monitoring system, the drone used was a *DJI Phantom 4 Pro* – equipped with an integrated *20 Megapixels camera* with a 1" CMOS sensor (5472 × 3648 pixels, Field of View [FOV] of 84°, Focal Length of 8.8 mm, Pixel Size of 2.41 µm).
The photogrammetric shots were carried out both with a flight plan – 353 takes, creating a final square grid for the nadiral images – designed using the DJI Ground-Station software package, and in manual mode – 200 oblique shots. A total of 553 photogrammetric shots were acquired with an average GSD of approximately 7.41 mm/px, for a total surveyed area of approximately 3 hectares.
The workflow implemented in Agisoft Metashape (Figure 9.9) is as follows: in the *Align Photos* phase, the parameters were set: *Accuracy = High*, *Key point limit = 40,000*, *Tie Point limit = 4,000*, obtaining a *Sparse Cloud* of 411.312 *points*. In the generation of the *Dense Cloud* the parameters used were: *Quality = Medium*, *Depth filtering = Disable*, obtaining a *Dense Cloud* of 62,515,870 *points*. In the *Build Mesh* the parameters set are *Surface Type = Arbitrary*, *Source Data = Dense Cloud*, *Face Count = Medium*, generating a polygonal model with 12,503,118 *triangles*. Finally, in *Build Texture* the parameters set are: *Mapping Mode = Generic*, *Blending Mode = Mosaic*, *Texture size = 4096 x1* (enabling Enable hole fitting). In order to control the metric error and georeference the point cloud in the EPSG: 32633 coordinate system, 9 GCPs were measured in nRTK [*Network Real-Time Kinematic*] mode by means of a *Geomax Zenith 25 receiver*. GCP measurement accuracy is lower than 2 cm range in planimetry and 1.4 cm in altimetry for a total error of about 2.7 cm.

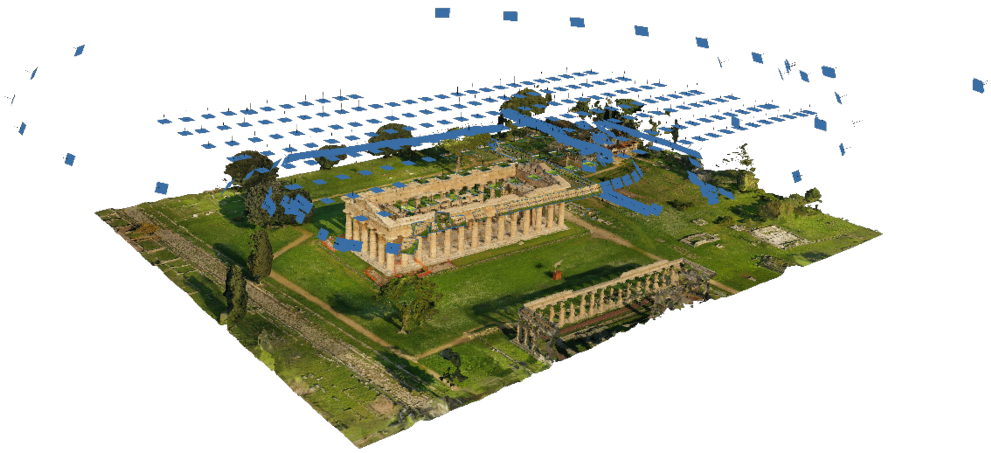


Figure 9.9 – Overview of the 2020 UAS survey within the Agisoft Metashape environment [AoE]

For the sake of clarity, in the following Tables 9.1 and 9.2 are summarised the main input and output data for both UAS surveys.

Table 9.1 – Input data of the 2017 and 2020 UAS surveys

Survey year	Total images	Nadiral shots [Flight plan]	Oblique shots [Manual mode]	GCPs	GCP Accuracy [Planimetry]	GCP Accuracy [Altimetry]
2017	908	185	723	11	*Subcentimetric*	2.5 cm
2020	553	353	200	9	1.4 cm	2.7 cm

Table 9.2 – Output data of the 2017 and 2020 UAS surveys

Survey year	GSD	Quality & Filtering setting	Dense point cloud	Mesh model	Texture size
2017	7.78 mm/px	*High & Disabled*	56,150,877 points	5,230,012 triangles	4,096x4,096
2020	7.41 mm/px	*Medium & Disabled*	62,515,870 points	12,503,118 triangles	4,096x4,096

9.3 The inertial seismometers monitoring system

The detailed discussion regarding the monitoring network installed on the Temple of Neptune was developed based on the technical specifications provided in the scientific report produced by Petti et al. [245] and on the general considerations made by Lamberti, in his master's thesis on ***"Innovative methodologies and procedures for monitoring monuments"*** [252], in which he carries out an in-depth analysis of the signals coming from the seismometers placed in the archaeological park of Paestum and their deconvolution.

The monitoring network consists of highly sensitive and precise mechanical and electronic instrumentation, mounted on several levels and in various strategic points of the monument. The interconnection between the devices allows simultaneous readings and real-time data storage of the structure's vibrations in response to environmental vibrations.

This system is part of a wide-ranging project to protect and preserve the Temple and will allow for the enrichment of the knowledge framework on the asset [46]. From the study of seismometric recordings of the structure's vibrations and the application of dynamic identification methods to the acquired data, it will be possible to investigate different aspects, such as the reconstruction and analysis of the response to different forcings, varying in intensity and type. It will allow the dynamics of the structure to be monitored, controlling its evolution over time.

[46] The monitoring project on the Temple of Neptune is part of a programme of research activities of the *Archaeological Park of Paestum and Velia*, carried out in collaboration with the Department of Civil Engineering [DICIV] of the University of Salerno [UNISA]. The scientific coordinators of the project are the director of the *Paestum and Velia Archaeological Park* Gabriel Zuchtriegel and Professor Luigi Petti.

The monitoring project was financed with the help of private supporters through the Ministry of Culture's *ArtBonus platform*, with donations from two important patrons, *D'Amico D&D Italia Spa* and *Sorrento Sapori e Tradizioni Srl*, and other minor donors, who joined the *ArtBonus project "The Temple of Neptune moves – take part in a unique journey!"* [*Il tempio di Nettuno si muove – partecipa ad un viaggio unico al mondo!*].

The monitoring system was designed by arch. Antonella Manzo, head of the UNESCO Office of the Archaeological Park, in collaboration with Professor Luigi Petti of the DICIV - UNISA; the work was directed by arch. Luigi Di Muccio of the ABAP Superintendency of Caserta and Benevento.

The University of Salerno's *datacenter*, in agreement with the Archaeological Park, will allow research organisations from all over the world to access the data, subject to a no-cost agreement. In the meantime, part of the data is freely accessible in real-time on the page of the institutional site of the Archaeological Park of Paestum and Velia: https://museopaestum.cultura.gov.it/monitoraggio-sismico-del-tempio-di-nettuno/ [269]

The main components of this monitoring system are:

- Sensors for measuring the displacements of the Temple
- Analogue/digital conversion system of the signals acquired by the sensors
- Systems for transmitting, managing and sharing the archived data.

The process of studying and analysing the dynamics of the monument begins at the measurement points. To this end, in the design phase, strategic points were identified, interesting for the evaluation of the dynamic response to environmental forcing, where uniaxial sensors, configured as seismometers, are installed.

The outputs of these devices are electrical signals, so in order for *Digital Signal Processing*, computerised data storage, and analysis of structural dynamics to be feasible, it is necessary to convert the signals into digital format. For this purpose, a network of acquisition modules, known as DAQ [*Data Acquisition System*], installed at several measuring points, receive as input and transform the outputs of the seismometers. These devices carry out an initial processing of the signals and are interconnected by means of a local network, wired with Ethernet cables, which permit a series connection scheme.

The data set, packaged and digitised, converges towards the central acquisition and control unit of the entire monitoring system, installed in the *Archaeological Park Museum* offices. A *rack* cabinet hosts the technological equipment essential to the operation of a computerised workstation. In this, the execution of dedicated software ensures the management of the entire system, such as the activation of sensors, real-time display of signals being acquired as well as the archiving of the recordings of the Temple's displacements.

In the interests of data sharing, the live acquisition carried out by the system's active seismometers is transmitted in video streaming [253].

In order to minimise the problems of interference and alteration of the acquired data along the path between the Temple and the central unit, as well as the amount of data to be transferred, a cabinet known as a *Totem-Leggio*, is installed near the monument. The latter contains *Ethernet*-fibre-optic cable switch devices for the *DAQ-Central Unit* connection and instrumentation for the power supply and control of the electrical energy delivered to the measurement points, protecting them from any power fluctuations or disconnections that might jeopardise their integrity and proper functioning.

The final configuration of the architecture of the monitoring network is the result of a series of options and choices optimised over the course of the various project phases that followed and that in the first months of 2021 allowed the implementation of a system composed of the main elements listed in Table 9.3.

Table 9.3 – Main components of the monitoring network placed upon the Temple of Neptune

Description	Model type	Quantity	Main characteristics
Uniaxial Horizontal Seismometer	SE – 10H	22	LVDT readout system – Spectral sensitivity (<10-8m/√Hz) in band (100 mHz - 100 Hz)
Uniaxial Vertical Seismometer	SE – 10V	4	LVDT readout system – Spectral sensitivity (< 10-8m/√Hz) in band (100 mHz - 100 Hz)
FieldDaq Acquisition Module	FD - 11603	5	8 input channels – Voltage ±10.5 V – Resolution up to 24 bit – Simultaneous sampling rate up to 100 kSamples/s
Data Acquisition, Visualisation and Archiving Software	-	-	Software for signal acquisition, real-time display and archiving on HHD

Figure 9.10 depicts a perspective view of the state of the art, in which the monitoring system is emphasised by means of an illustrative graphic diagram, thus enabling the positioning and connection of all devices to be quickly identified.

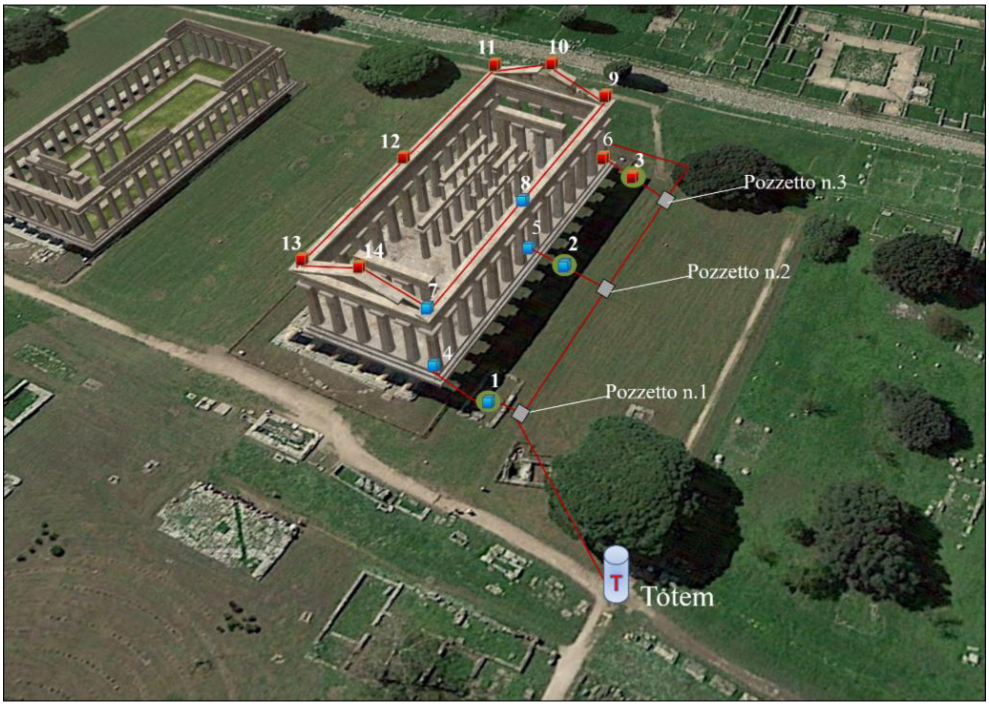


Figure 9.10 – Overview of the schematised monitoring network [245]

The measuring points of the monitoring network are the elements placed in direct contact with the Temple and where the seismometers, acquisition units and electrical connection devices are installed. The initial project envisaged 14 of them, divided as showed in Table 9.4.

Table 9.4 – List of the measuring points initially envisaged for the monitoring system set up and their eventual installation

Quantity	Location	Designation	Eventual installation
3	Underground, adjacent to the foundation, laying surface	1 – 2 – 3	Yes
3	Crepidoma	4 – 5 – 6	No
8	Temple top, cornice	7 – 8 – 9 – 10 – 11 – 12 – 13 – 14	Yes

Of the 14 initially planned measuring points, the first three were actually placed in the ground facing the foundation laying surface and the last eight (from 7 to 14) on the cornice of the temple, while those initially planned on the crepidoma were left out.
The assembly of the devices proved not to be easy, in particular, the different locations required a variety of technological expedients. For example, in order to protect the measuring points installed on the crowning from atmospheric agents - such as rain or wind gusts, sources of potential disturbance to the measurements - but also from birds - which could damage the devices - it was decided to mount them inside plexiglass boxes. Instead, the underground measuring points were installed inside concrete manholes, thus ensuring that the excavation could remain clean and easy to inspect.
The sensor base also plays a key role. As it must provide a common hard surface for the measuring point sensors, it is made of a thick granite plate. In addition, adjusting screws and a spherical spirit level, attached to the body of the sensors, allow their levelled installation.
The instrumentation installed includes:

- Uniaxial sensors, i.e., seismometers of the UNISA Folded Pendulum type[47], distinguished in: Horizontal (model SE-10H) and Vertical (model SE-10V)

[47] The dynamic behaviour of the Temple is monitored by means of a network of seismometers: monolithic mechanical oscillators belonging to the *UNISA Folded Pendulum* category [246]. The prototypes of these sensors were developed by the *Research Group in Applied Physics* at the University of Salerno – which specialises in the study of gravitational waves – and promoted by a start-up and academic spin-off *Advanced Scientific Sensors and Systems s.r.l.* For more information visit: https://www.adv3s.com/en/homepage/.

- Modular acquisition control units, DAQ (FieldDAQ™)
- Any junction boxes, cable connection systems and fasteners necessary.

In Figure 9.11 the measurement points are represented with different symbols. The discriminating factor is the number of sensors installed at the individual measuring point, in relation to which the ability to detect the displacement components exhibited by the structure changes. In fact, introducing a reference system of the type $\{xyz\}$, with axes directed in the following way:

- Axis x parallel to the longitudinal axis of the Temple, East-West direction
- Axis y parallel to the transversal axis of the Temple, North-South direction
- Plane xy perpendicular to the direction of the force of gravity

It is possible to distinguish the measurement points into two types of configurations: Biaxial (with x and y components) and triaxial (including the z component).

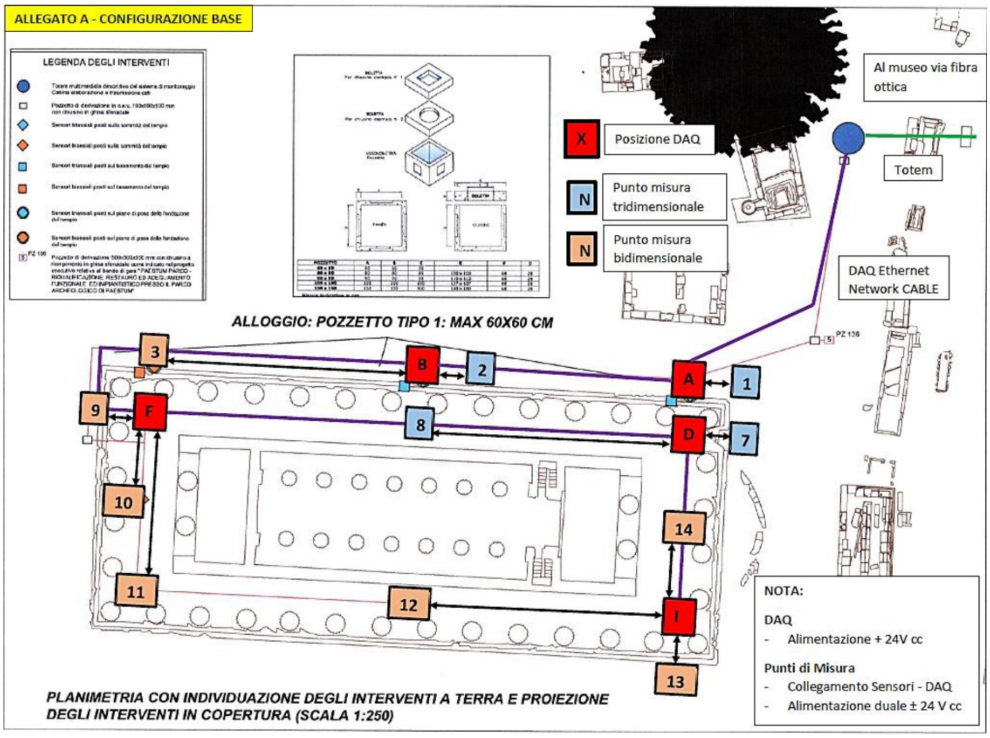


Figure 9.11 – Plan view showing the designation of the 11 measuring points, the DAQ modules and their connections [245]

In addition to the progressive numbering of the measuring points, it was necessary to introduce a specific designation for the signal acquisition channels, which come out of the seismometers installed at the measuring points, differentiating them according to the displacement component detected:

- Odd number + Final letter H: horizontal sensor oriented along the x axis
- Even number + Final letter H: horizontal sensor oriented along the y axis
- Number + Final letter V: vertical sensor oriented along the z axis.

Figure 9.12, therefore, details the measuring points distinguished according to type, components of the detected displacement and presence or absence of DAQ – identified respectively as A, B, D, F, and I –. This information, fundamental for the subsequent MEP modelling phase, has also been reported in Table 9.5 for clarity.

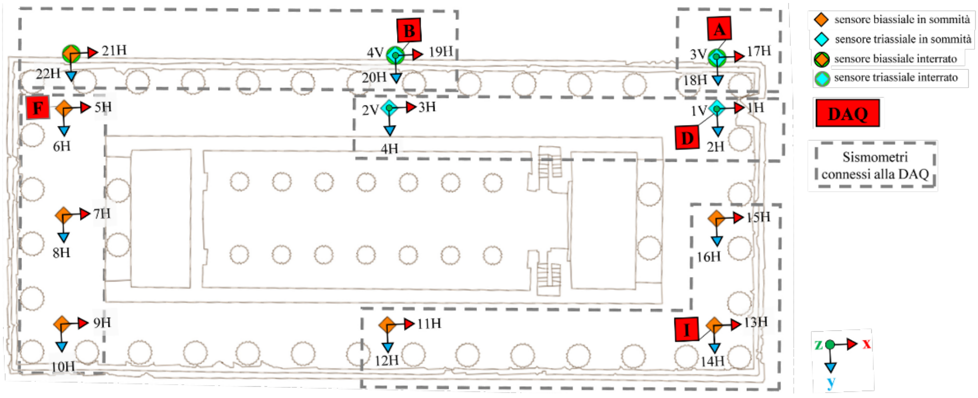


Figure 9.12 – Installed seismometers and identification of the signal acquisition DAQ module [252]

Table 9.5 - A detailed list of the measuring points distinguished according to type, components of the detected displacement and presence or absence of DAQ

Measuring point	Typology	DAQ	Displacement components detected - Seismometer acquisition channel		
			x	y	z
1	3D	A	17H	18H	3V
2	3D	B	19H	20H	4V
3	2D	-	21H	22H	-
7	3D	D	1H	2H	1V
8	3D	-	3H	4H	2V
9	2D	F	5H	6H	-
10	2D	-	7H	8H	-
11	2D	-	9H	10H	-
12	2D	-	11H	12H	-
13	2D	I	13H	14H	-
14	2D	-	15H	16H	-

10. Structural BIM modelling

Given the issues connected with employing a topographic coordinates system within a BIM environment, already addressed in section 2.3, in order to set up the shared environment [FSC] for the Monitoring ECO-System of the Temple of Neptune, it was necessary to perform a translation from the global to local reference system was both on the photogrammetric point clouds – directly within the Agisoft Metashape environment by subtracting a fixed quantity to the x, y, and z values of the GCPs – and on the integrated point cloud used as a reference for the subsequent Scan-to-BIM application.

Indeed, due to BIM working with a cartesian reference system, upon linking a georeferenced RCP point cloud to a Revit project, it will be automatically moved closer to the new internal origin, obliterating the previous coordinate values. On the other hand, when the generation of the BIM instances is forced in place using VPL scripts, in order to keep the geographical coordinates, approximation failures occur in the reprojected objects, above all in the case of meshes (Figure 10.1 and 10.2) and visualisation and modelling issues will arise afterwards.

To avoid losing these pieces of information, the integrated point cloud was then exported in a E57 format, and rigidly translated of the same quantity later used for the UAS point clouds, equal to:

- 4,474,384.0000 in the N/S direction (y axis in the Revit reference system)
- 500,514.0000 in the E/W direction (x axis in the Revit reference system)
- 62.5000 in altimetry (z axis in the Revit reference system)

Once the point cloud had been imported back into the Autodesk ReCap environment, it was finally possible to link it correctly into a Revit project without changing its three-dimensional location. Eventually, by just assigning the quantities previously defined as the *Project Base Point* [PBP] new coordinates, the RVT project set up for the structural modelling phase was already georeferenced [GEO phase].

Consequently, the organisation of the shared environment [FSC phase] within a superordinate RVT project was performed according to the following procedure:

- The superordinate model is georeferenced using the coordinates previously established for the PBP – in this case (500,514.0000; 4,474,384.0000; 62.5000).
- Then the submodels are linked into the shared environment using, only for this first time, the Project Base Points as a reference.
- Finally, the shared coordinates are published back to the submodels to be stored as their new internal origin.

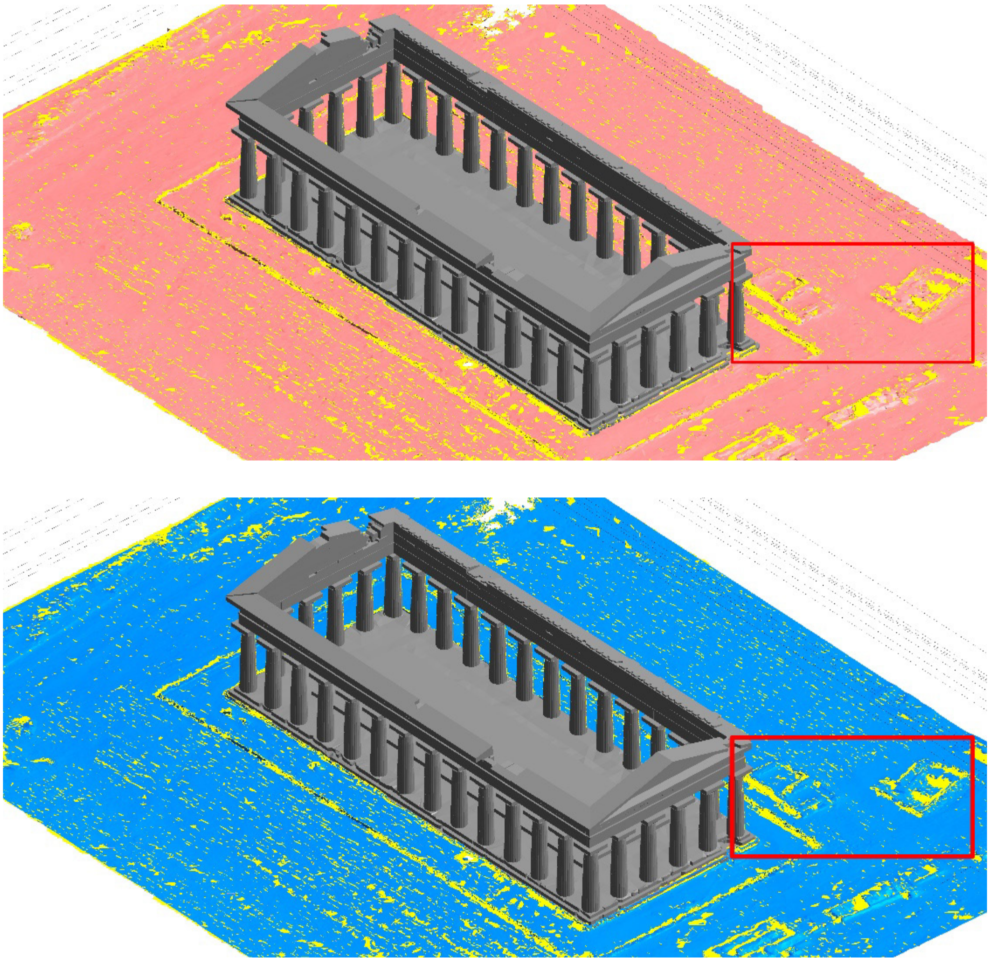


Figure 10.1 – Differences highlighted in yellow, between the same mesh imported as Revit instance. It was generated in the first case (upper, in pink), keeping the geographical coordinates, while in the second case (lower, in blue) using a local reference system [AoE]

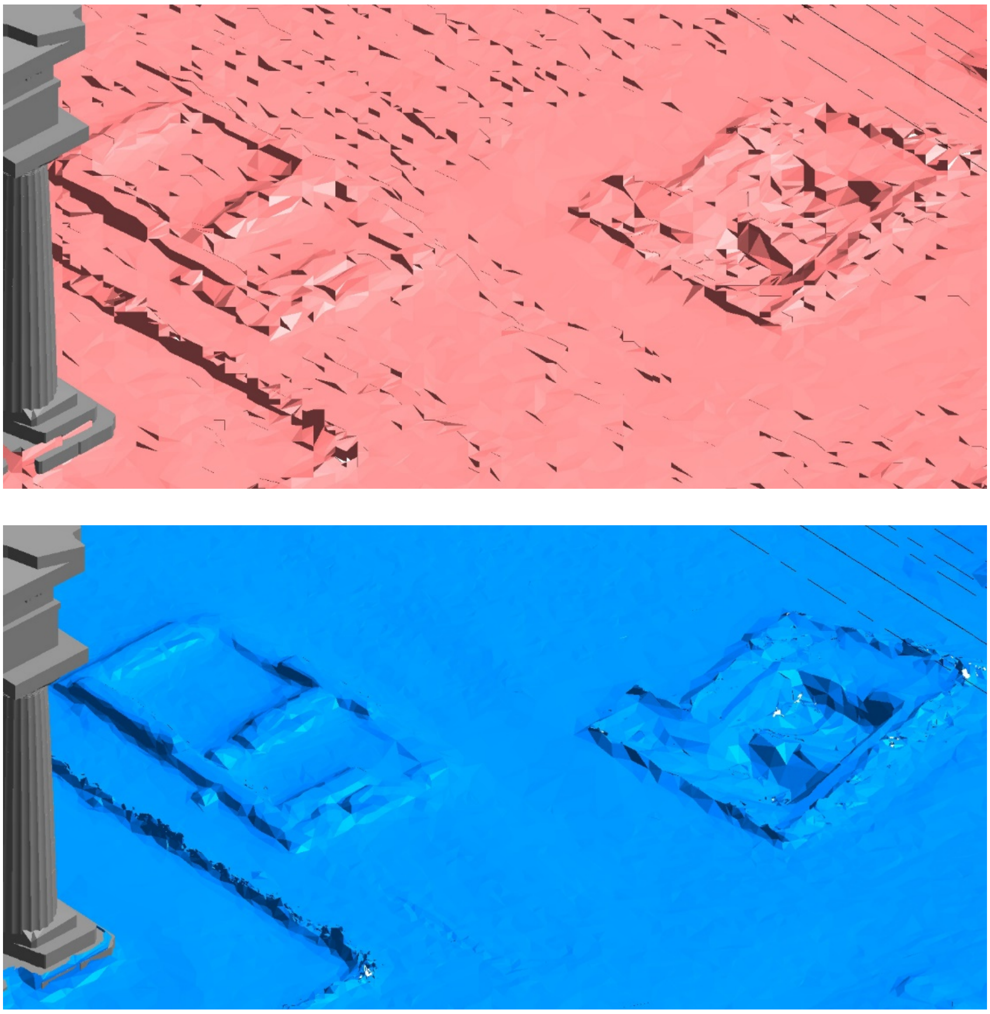


Figure 10.2 – Detail of the same mesh generated as Revit instance, the first time keeping the georeferenced coordinates (upper, in pink) and the second time employing a local coordinate system (lower, in blue) [AoE]

10.1 Integrated point cloud management

The term semantic segmentation (or simply classification) for point clouds refers to the grouping of similar data into subsets (called segments) that have characteristics/features (i.e., geometric, radiometric) useful to distinguish and identify in classes the different parts of the point cloud [254].
The semantic subdivision of 3D data leads to a hierarchy that facilitates data access, decision-making, and design processes. In addition, it can be preparatory to successive applications such as the reconstruction phase of simplified 3D models, such as CAD or BIM. At the same time, working with a classified point cloud could speed-up architecture's analysis and learning, maintenance operations or conservation plans, removing the complicated and time-consuming scan to BIM processes. In fact, the ability to convert the point cloud into an abacus of semantically enriched segments allows them to be associated with morphological and material details and used to define areas, volumes, and masses (if materials are homogeneous) [30].
Incidentally, experimental segmentation, employing machine learning algorithms, of the laser dataset available for the Temple of Neptune have already been conducted, among others by Fiorillo et al. (Figure 10.3) [243] and Teruggi et. (Figure 10.4) [30].

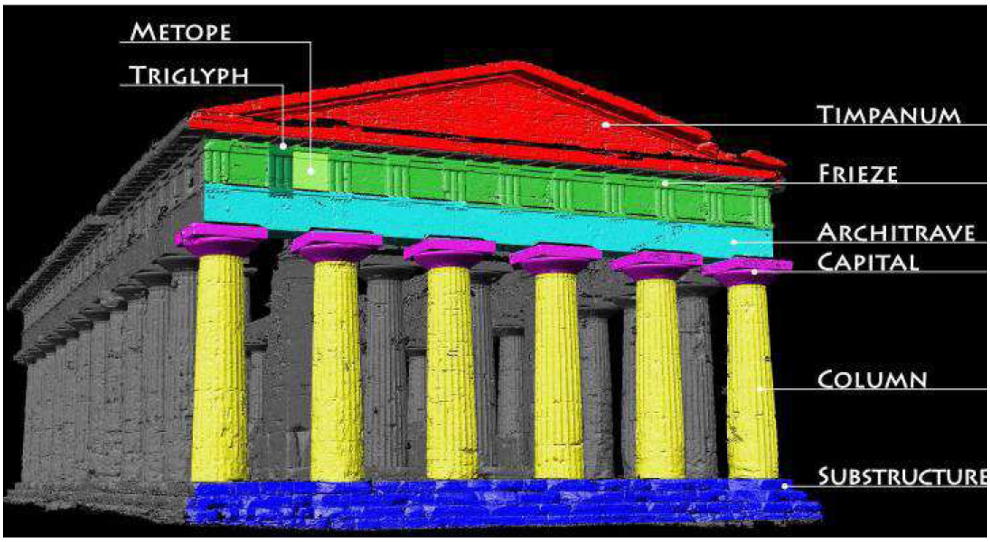
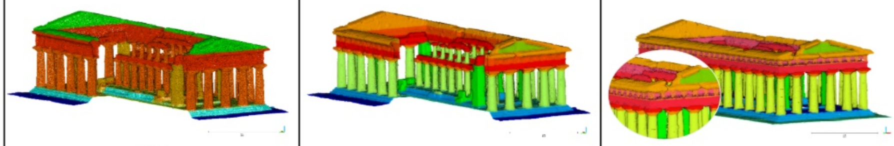


Figure 10.3 – First experimental segmentation of the laser point cloud of the Temple of Naptune, carried out by Fiorillo et al. in 2011 [243]



	LEVEL 1	LEVEL 2	LEVEL 3
Classes	Grass Crepidoma Floor Column Wall Trabeation Pediment	Shaft / Echinus / Abacus Architrave / Frieze Cornice/ Tympanum	Triglyph / Metope
Point number	462,649	2,209,521	32,470,628
Resolution (cm)	10	5	1.5 (Full resolution)
Number of classes	7	11	12
Overall Accuracy (%)	96.40	92.04	97.80
F1 score (%)	96.22	92.13	97.77

Figure 10.4 – Temple of Neptune: classification levels, metrics, and point cloud resolutions at each level (upper) and Multi-Resolution access to the first level of classification (lower), performed and reported by Teruggi et al. in 2021 [30]

As far as the present application is concerned a manual segmentation of the integrated point cloud was performed within the Autodesk ReCap Pro Environment so as to facilitate its management during the subsequent modelling process. The *external colonnade sampled scan* (Figure 9.7 – in green) and the *inner temple sampled scan* (Figure 9.7 – in yellow) were additionally broken down respectively in eight and four *regions*, as shown in Figure 10.5. Namely, the *external colonnade* was decomposed into its four façades: *North* and *South* facing *longitudinal Sides* and *East* and *West* facing *transversal Sides*. In addition, the corner columns were further isolated together with the structure above into four more *regions* identified as *NE* [*North-East*] *Edge*, *SE* [*South-East*] *Edge*, *SW* [*South-West*] *Edge*, and *NW* [*North-West*] *Edge*. The *inner temple* area was then divided into four regions as follows: the *North* and *South* facing *Sides of the Naos*, the East facing *Prònaos area* and the West facing *Opistòdomos area*.

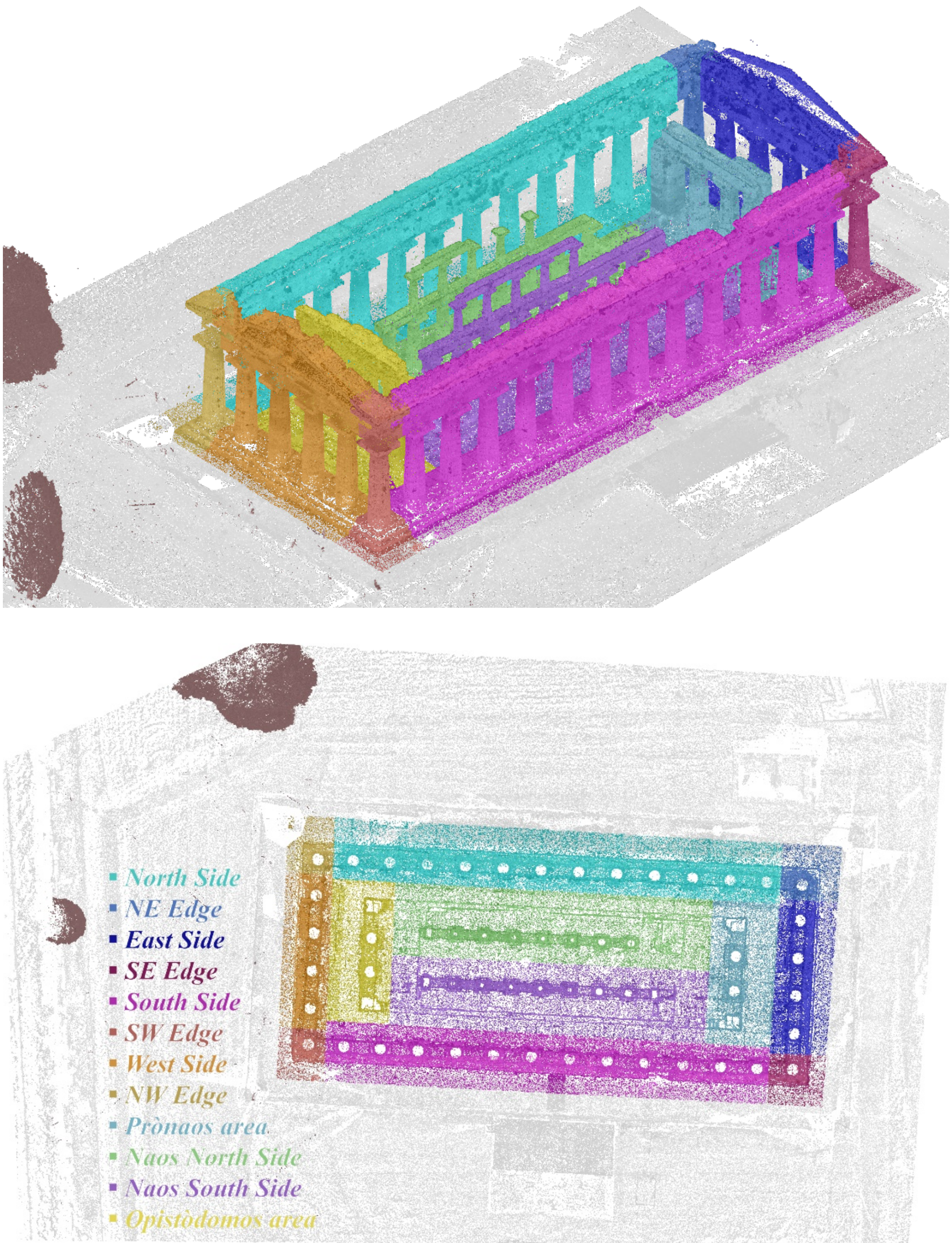


Figure 10.5 – 3D (upper) and plan (lower) views of the integrated point cloud manually segmented into twelve regions listed to the left [AoE]

10.2 Temple structural element analysis and BIM object database setting up

Even though, a manual segmentation of the point cloud fulfilled the purpose of facilitating the Scan-to-BIM modelling process, the results of the machine learning applications were taken into account during the analysis phase of the structure; this analysis was preliminary to its decomposition into elemental components with the aim of generating the dataset of BIM families modelled *ad hoc*, from scratch, and entirely parametric.

In detail, the temple of Neptune can be subdivided into four subparts (Figure 10.6), from the ground level to the top, listed as follows:

- The *Crepidoma*: made of three overlapped slabs, gradually smaller, named *Stereobate* (the broader slab placed directly on the ground) and *Stylobate* (which includes both the second and the third slab), as depicted in Figure 10.6.
- The columns: in the case of this particular temple, as for the Athenian *Partenone*, they have no basis, being directly placed over the Seterobate, for the external colonnade, and over an additional overlapped slab those internal ones enclosing the *Naos*. A typical *Doric column* is then composed of a *Shaft* and a *Doric Capital* above it. As already mentioned in section 9.1, the external colonnade's columns were carved with 24 flutings, while the columns of the *Naos* were realised with 20 (the lower row) and 16 (the upper row) flutings (Figure 10.7, 10.8, and 10.9).
- The *trabeation*: composed of the *Architrave* or *Epistyle* and the *Frieze* area, (which used to host a succession of *Metopes* alternated with *Triglyphs*).
- The remaining upper part of the temple was originally shaped to accommodate the roof structure, which consisted mainly of triangular wooden trusses. Therefore, the surviving portions consist of a predominantly horizontal *Cornice*, slightly inclined outwards, intended to support the trusses, surmounted on the east and west sides by a triangular *Tympanum* (also once decorated) and a *Raking cornice*. Finally, some tiles have survived to this day (Figure 10.11).

An initial analysis phase was therefore conducted mainly by graphically breaking down the structure of the temple into its elemental components through a series of sketches (Figure 10.6, 10.7, 10.8, 10.9, 10.10, and 10.11) aimed at identifying the geometric generators of each structural element.

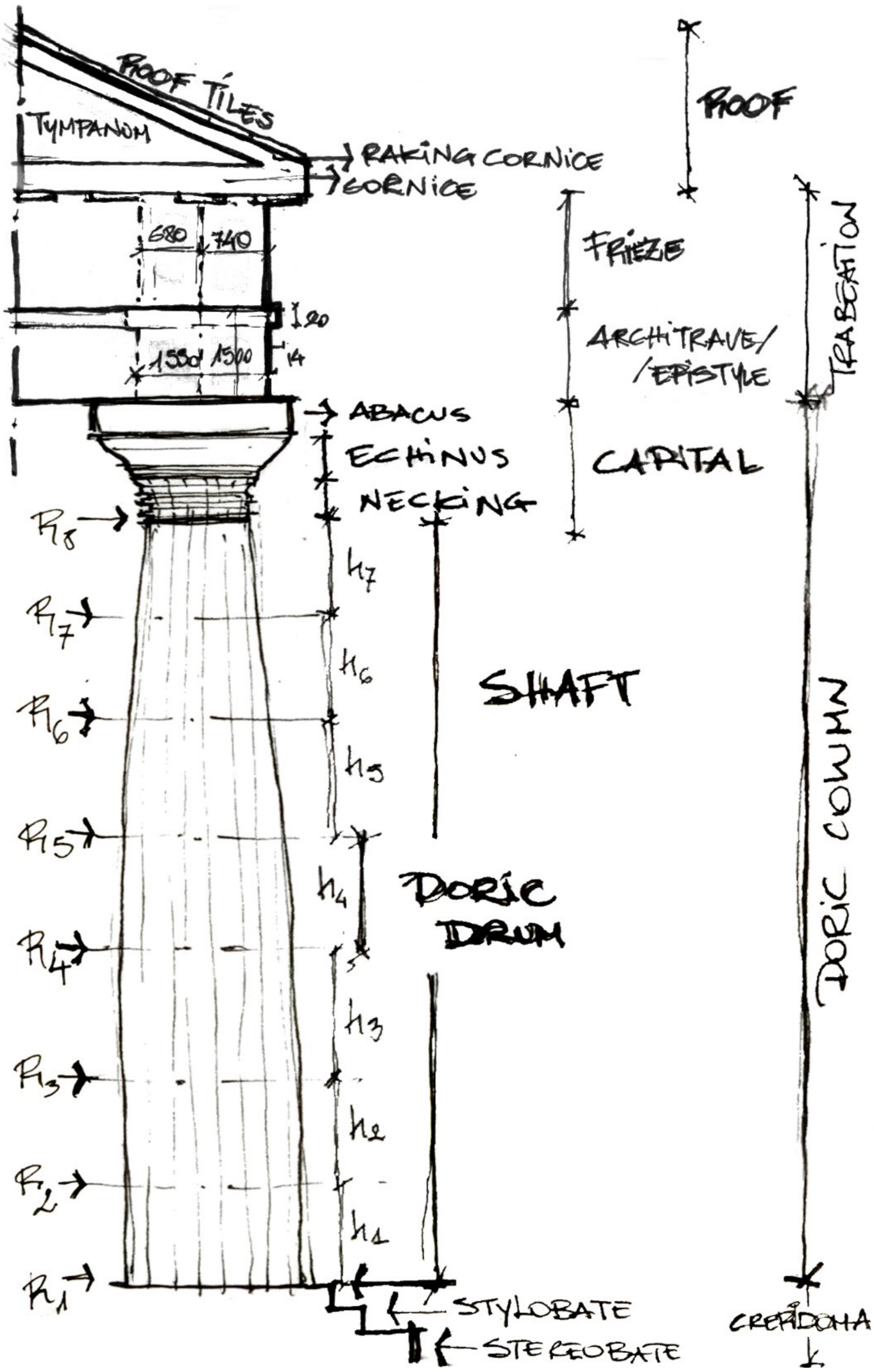


Figure 10.6 – Study sketches: the Doric Temple of Neptune components [AoE]

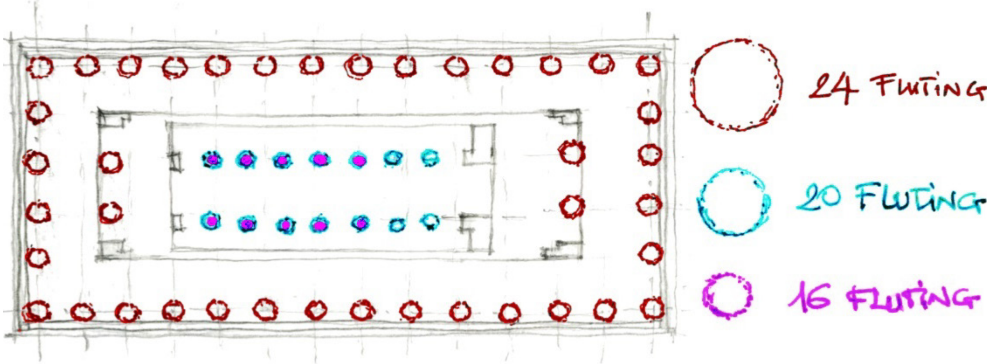


Figure 10.7 – Study sketches: the Temple of Neptune *Doric Columns* disposition [AoE]

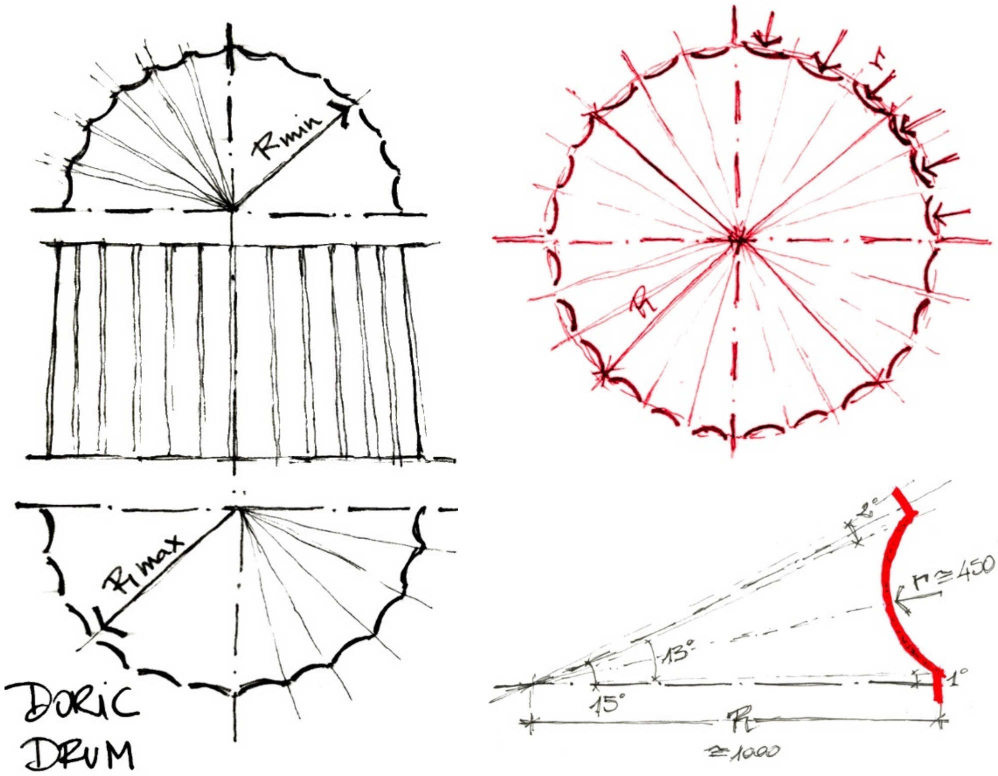


Figure 10.8 – Study sketches: *Doric Drum* (left) and *Drum* generator profile (right) with 24 flutings [AoE]

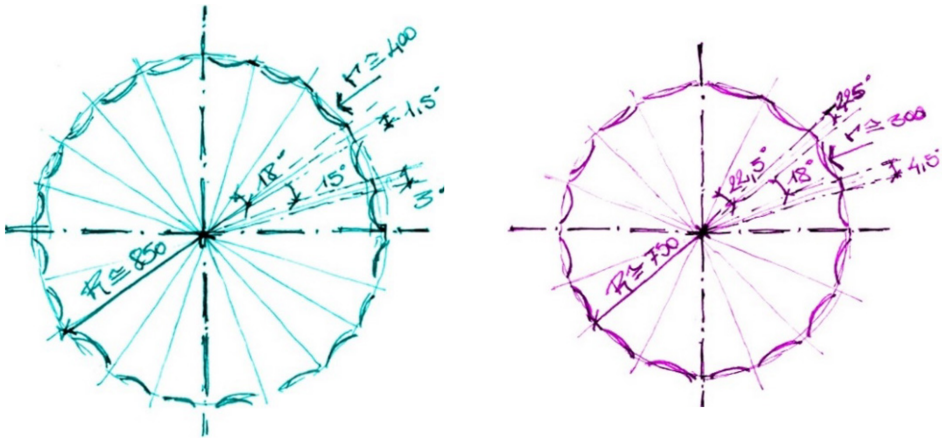


Figure 10.9 – Study sketches: *Drum* generator profiles with 20 (left) and 16 (right) flutings [AoE]

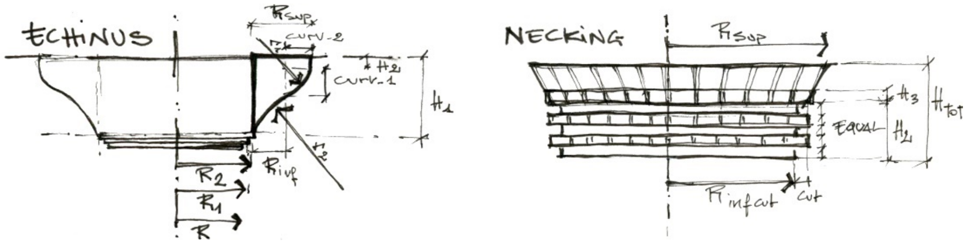


Figure 10.10 – Study sketches: *Echinus* (left) and *Necking* (Right) geometric generation [AoE]

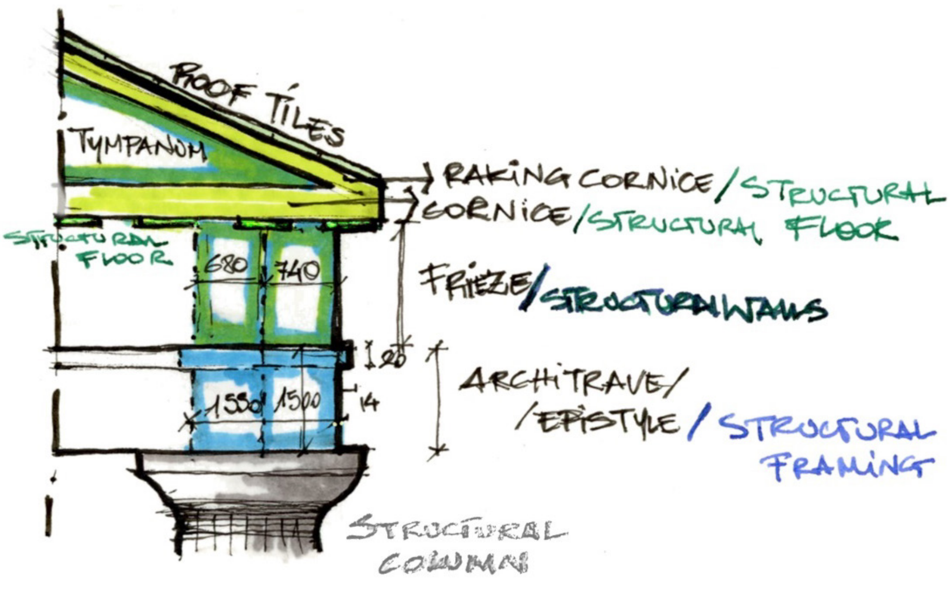


Figure 10.11 – Study sketches: Temple of Neptune *Trabeation* and *Roof* structure with first *Revit categories* assignation [AoE]

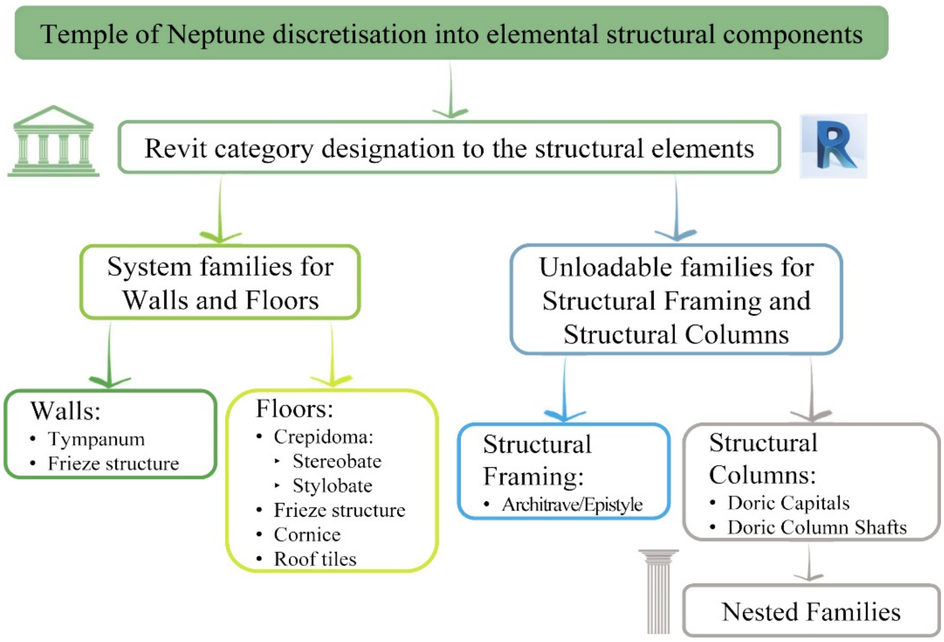


Figure 10.12 – Scheme explaining the Temple of Neptune discretisation into its elemental components and *Revit categories* assignation [AoE]

This phase was followed by a synthesis step characterised by the designation of the appropriate Revit Category to each sub-component to be modelled. The scheme in Figure 10.12, shows the Category chosen for each component according to its characterising structural behaviour: *System families Floors* for the mainly horizontal elements with two equally prevailing dimensions; *System families Walls* for the mainly vertical elements with two equally prevailing dimensions; *Uploadable families of Structural framing* for the mainly horizontal elements with one prevailing dimension; and *Uploadable families of Structural Columns* for the mainly vertical elements with one prevailing dimension and for the punctual elements (i.e., the *Capitals*).

The Structural Framing elements, i.e., the internal and the external beams constituting the *Architrave*, were modelled as a horizontal extrusion after an *ad hoc* parametrised profile, generating two types within the same family (Figure 10.26).

As illustrated by the scheme in Figure 10.13, the Revit objects modelled as structural columns, i.e., the *Doric Shafts* and the *Doric Capitals*, had then to be modelled as a particular type of family, the so-called *Nested Families* (Figure 10.14). They are, indeed, made up of sub-parts that are modelled and parameterised aside for their subsequent incorporation into the main family. It is important, at this stage, to also associate the parameters of the sub-parts with parameters specifically designed in the main family (Figure 10.24 and 10.25) so as to be able to manage them once imported into a Revit project. Namely, three *Doric shafts* have been envisaged, each corresponding to the 24, the 20, and the 16 flutings columns. Then, having found that the temple columns present an irregular number of *Drums* – probably due to the uncertainties associated with working with travertine –, it was considered necessary to model:

- five shafts with 24 flutings (containing from four to eight *Drums* to cover the entire 8-meter height of the shafts – Figure 10.15 and 10.18);
- three with 20 flutings (containing from three to five *Drums* – Figure 10.16);
- three with 16 flutings (containing from four to two *Drums* – Figure 10.17).

The *nested Drums* were modelled after three *ad hoc* parametrised profiles as extrusions (Figure 10.19 and 10.20) and the same profiles were used to separately shape the *Necking* of the three types of *Capitals* (Figure 10.21 and 10.25). Indeed, the Capitals families are composed of three subparts (Figure 10.14, right): the *Abacus* (modelled directly in the main family), the *Echinus* (modelled aside as a revolution of a parametrised profile around the *z* axis – Figure 10.22), and the *Necking* (to which a rotation parameter *"phi"* was assigned in order to fit the shaft eventually rotated placement while still preserving the alignment of the *Abacus* to the *Architrave* – Figure 10.23 and 10.24).

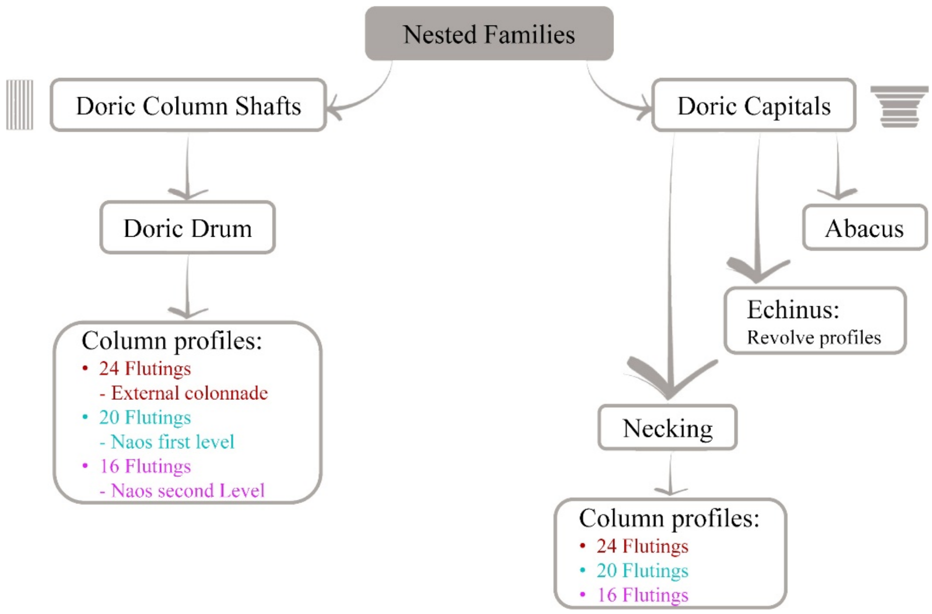


Figure 10.13 – Scheme explaining the breaking down of the *Doric Shafts* and their *Capitals* when modelling the *Nested Families* [AoE]

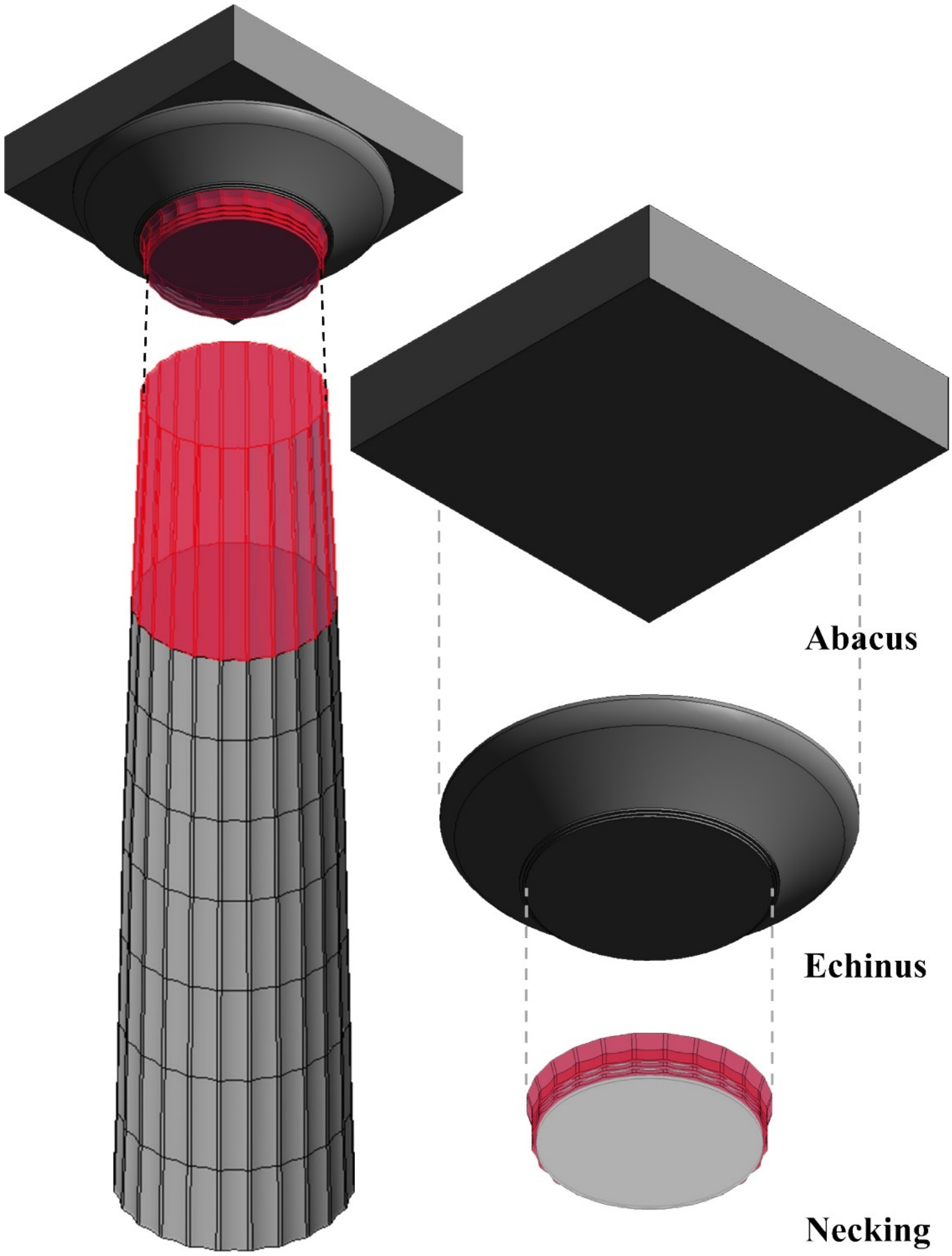


Figure 10.14 – Example of a *Doric Column* composed of eight *Drums* with 24 flutings (left) and decomposition of its *Capital* into subcomponents [AoE]

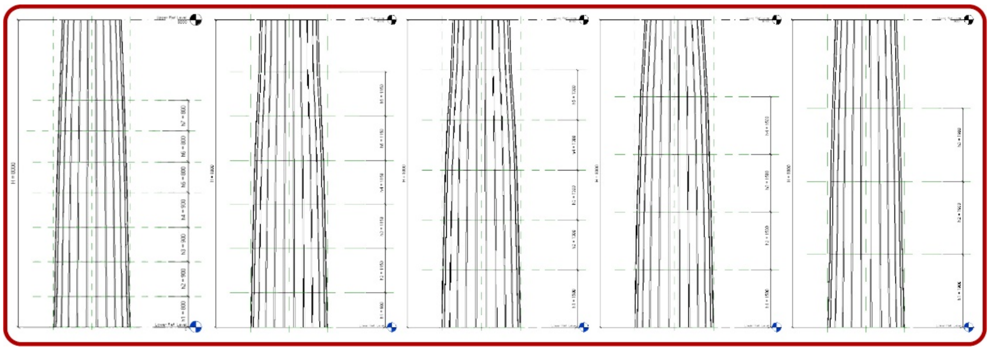


Figure 10.15 – *Structural Shafts* composed respectively of eight, seven, six, five, and four *Drums* with 24 flutings [AoE]

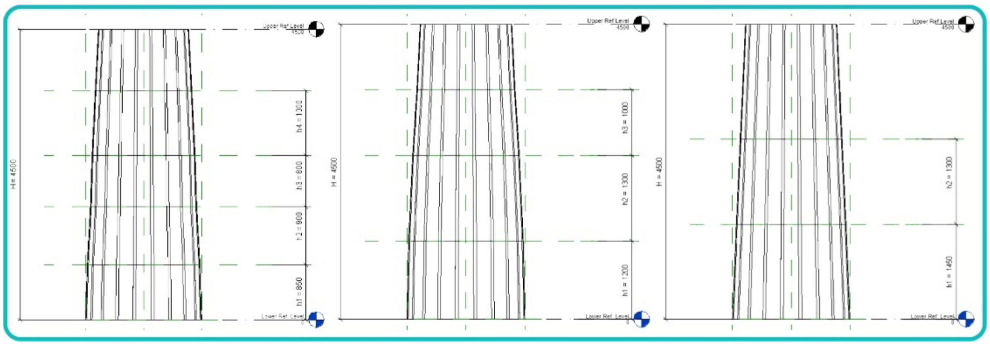


Figure 10.16 – *Structural Shafts* composed respectively of five, four, and *Drums* with 20 flutings [AoE]

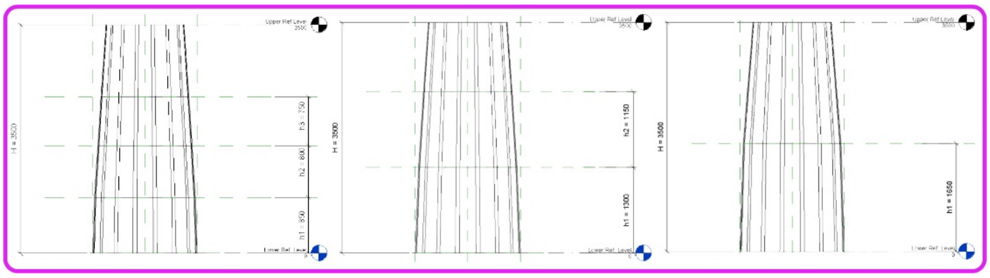
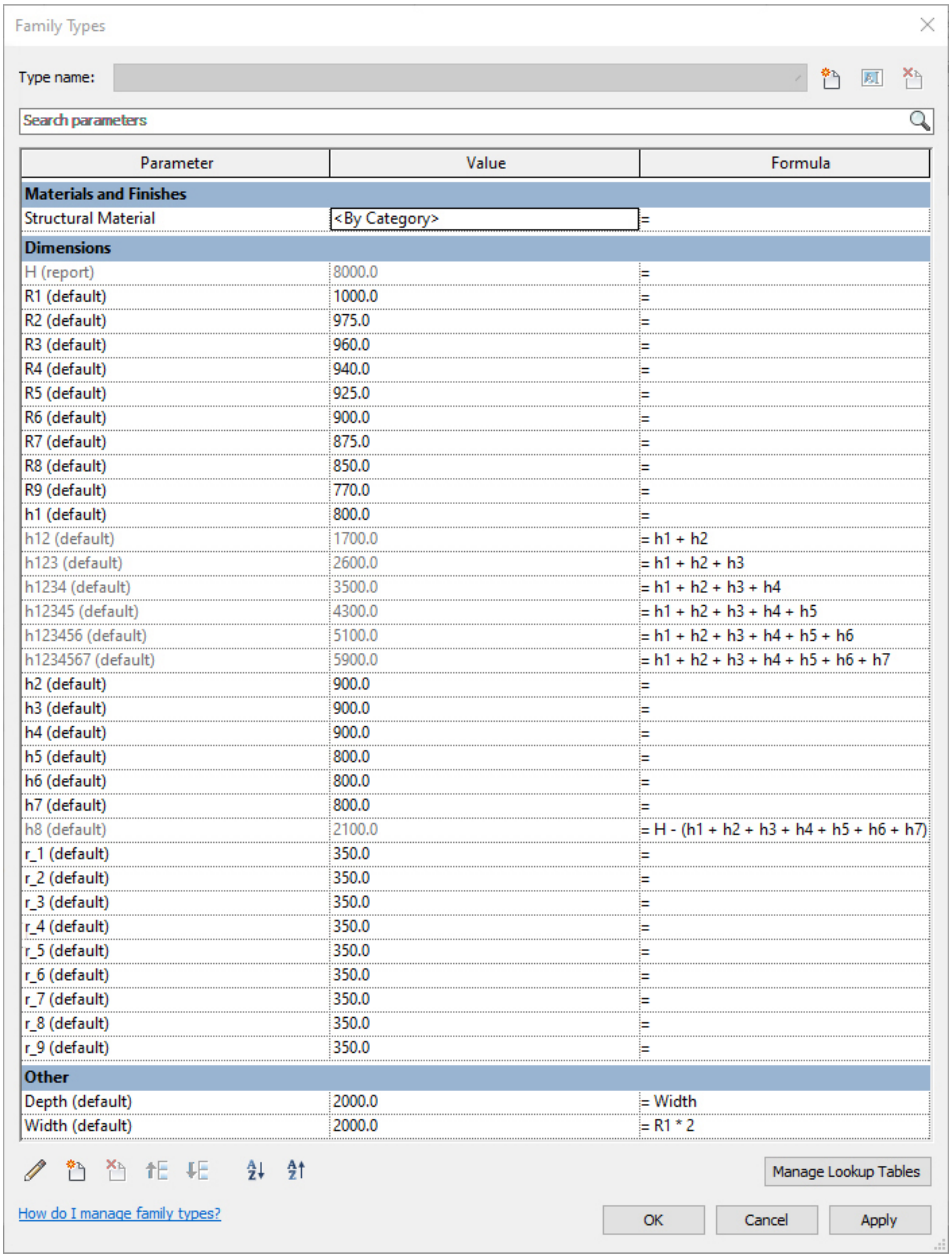


Figure 10.17 – *Structural Shafts* composed respectively of four, three, and two *Drums* with 16 flutings [AoE]



Parameter	Value	Formula
Materials and Finishes		
Structural Material	<By Category>	=
Dimensions		
H (report)	8000.0	=
R1 (default)	1000.0	=
R2 (default)	975.0	=
R3 (default)	960.0	=
R4 (default)	940.0	=
R5 (default)	925.0	=
R6 (default)	900.0	=
R7 (default)	875.0	=
R8 (default)	850.0	=
R9 (default)	770.0	=
h1 (default)	800.0	=
h12 (default)	1700.0	= h1 + h2
h123 (default)	2600.0	= h1 + h2 + h3
h1234 (default)	3500.0	= h1 + h2 + h3 + h4
h12345 (default)	4300.0	= h1 + h2 + h3 + h4 + h5
h123456 (default)	5100.0	= h1 + h2 + h3 + h4 + h5 + h6
h1234567 (default)	5900.0	= h1 + h2 + h3 + h4 + h5 + h6 + h7
h2 (default)	900.0	=
h3 (default)	900.0	=
h4 (default)	900.0	=
h5 (default)	800.0	=
h6 (default)	800.0	=
h7 (default)	800.0	=
h8 (default)	2100.0	= H - (h1 + h2 + h3 + h4 + h5 + h6 + h7)
r_1 (default)	350.0	=
r_2 (default)	350.0	=
r_3 (default)	350.0	=
r_4 (default)	350.0	=
r_5 (default)	350.0	=
r_6 (default)	350.0	=
r_7 (default)	350.0	=
r_8 (default)	350.0	=
r_9 (default)	350.0	=
Other		
Depth (default)	2000.0	= Width
Width (default)	2000.0	= R1 * 2

Figure 10.18 – Example of the parameters of the *Structural Shaft* family composed of eight *Drums* with 24 flutings [AoE]

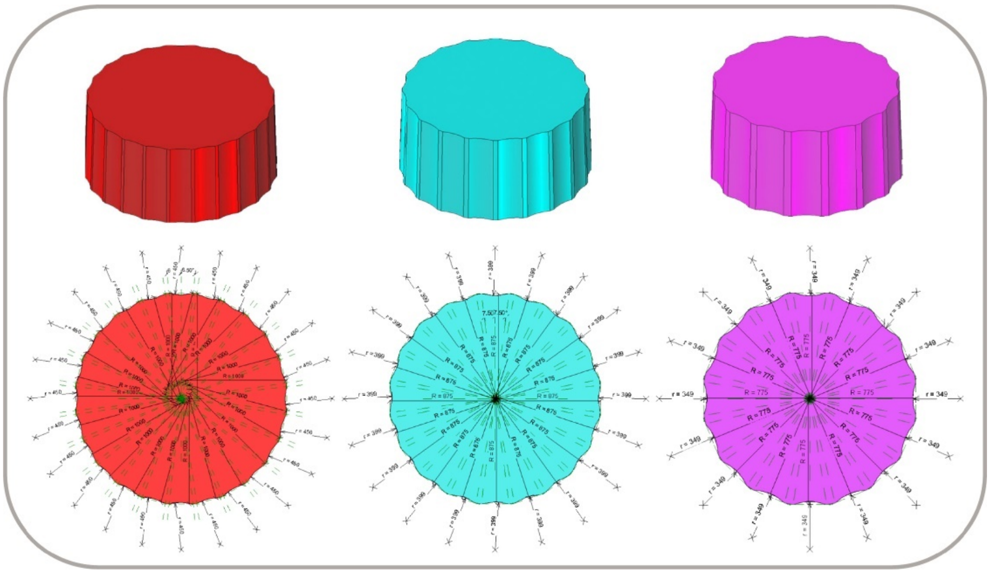


Figure 10.19 – The three types of *Doric Drums* (upper) created and their generator profiles (lower), respectively with 24, 20, and 16 flutings [AoE]

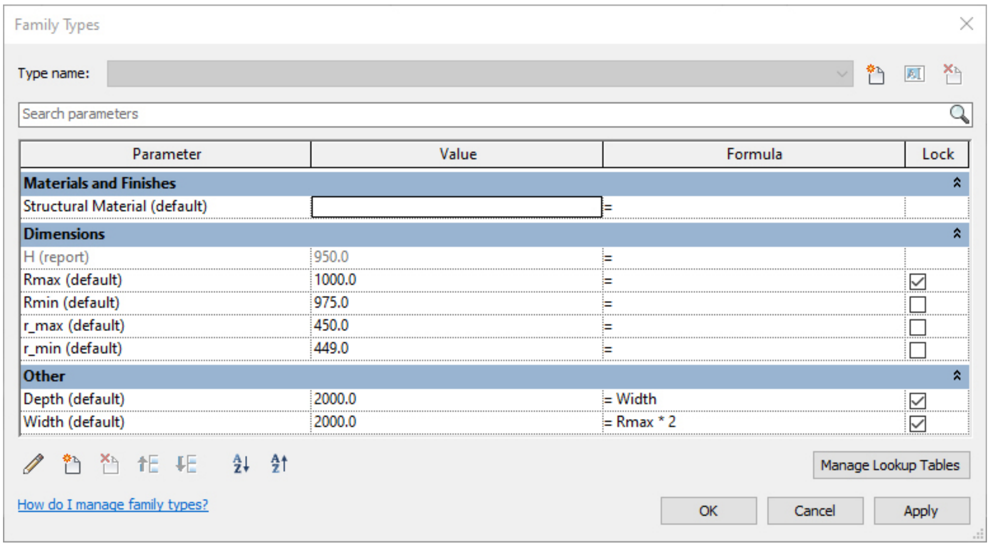


Figure 10.20 – *Doric Drum* family parameters [AoE]

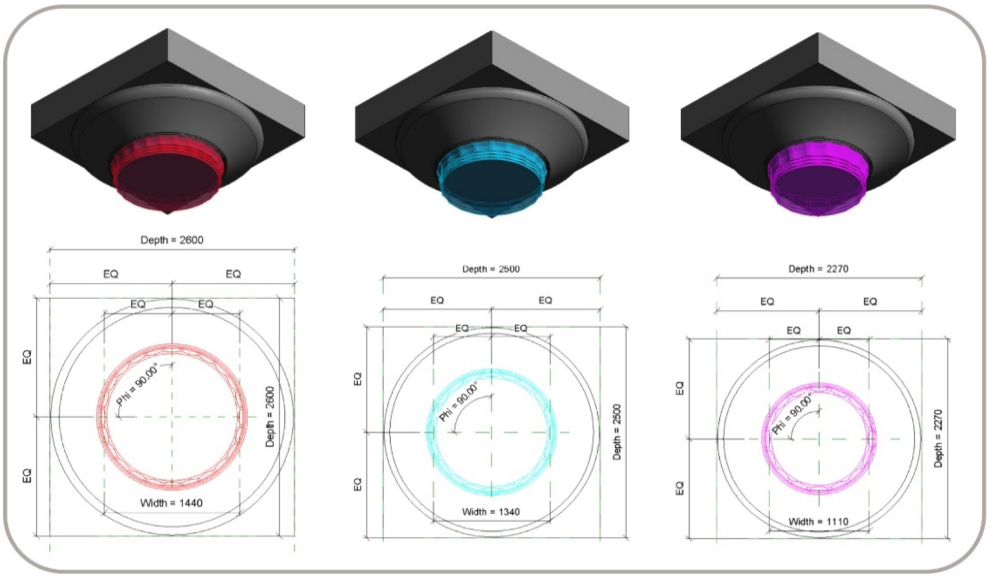
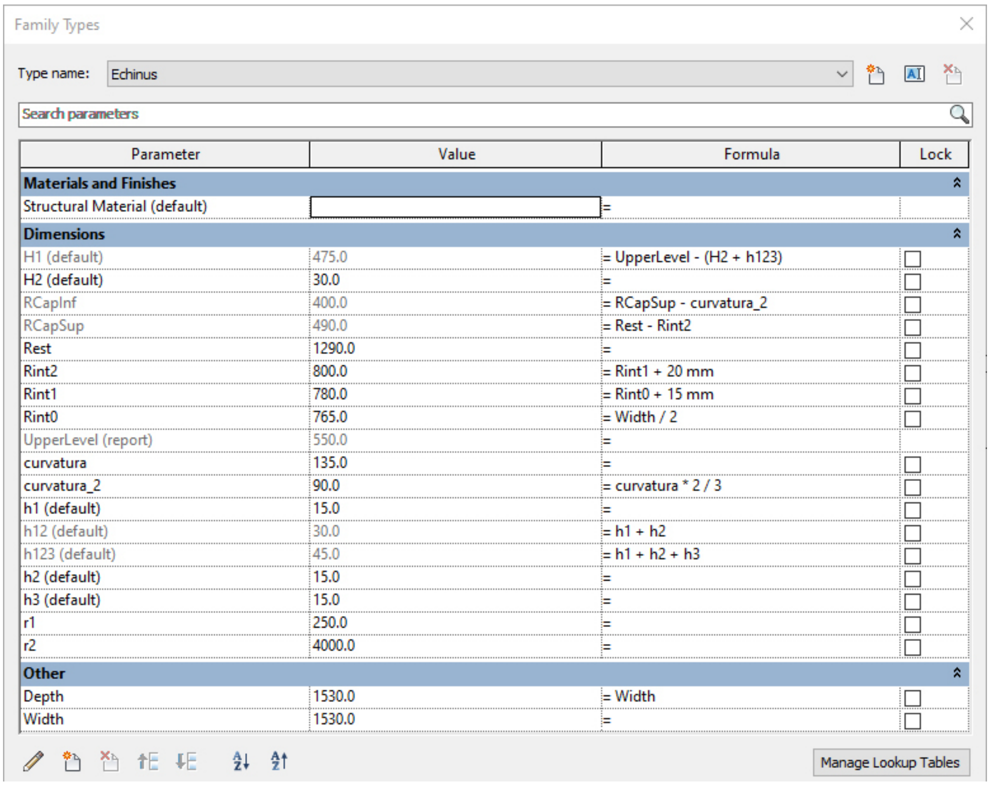


Figure 10.21 – The three types of *Capitals* generated, respectively with 24, 20, and 16 flutings [AoE]


Family Types

Type name: Echinus

Search parameters

Parameter	Value	Formula	Lock
Materials and Finishes			
Structural Material (default)		=	
Dimensions			
H1 (default)	475.0	= UpperLevel - (H2 + h123)	☐
H2 (default)	30.0	=	☐
RCapInf	400.0	= RCapSup - curvatura_2	☐
RCapSup	490.0	= Rest - Rint2	☐
Rest	1290.0	=	☐
Rint2	800.0	= Rint1 + 20 mm	☐
Rint1	780.0	= Rint0 + 15 mm	☐
Rint0	765.0	= Width / 2	☐
UpperLevel (report)	550.0	=	
curvatura	135.0	=	☐
curvatura_2	90.0	= curvatura * 2 / 3	☐
h1 (default)	15.0	=	☐
h12 (default)	30.0	= h1 + h2	☐
h123 (default)	45.0	= h1 + h2 + h3	☐
h2 (default)	15.0	=	☐
h3 (default)	15.0	=	☐
r1	250.0	=	☐
r2	4000.0	=	☐
Other			
Depth	1530.0	= Width	☐
Width	1530.0	=	☐

Manage Lookup Tables

Figure 10.22 – *Echinus* family parameters [AoE]

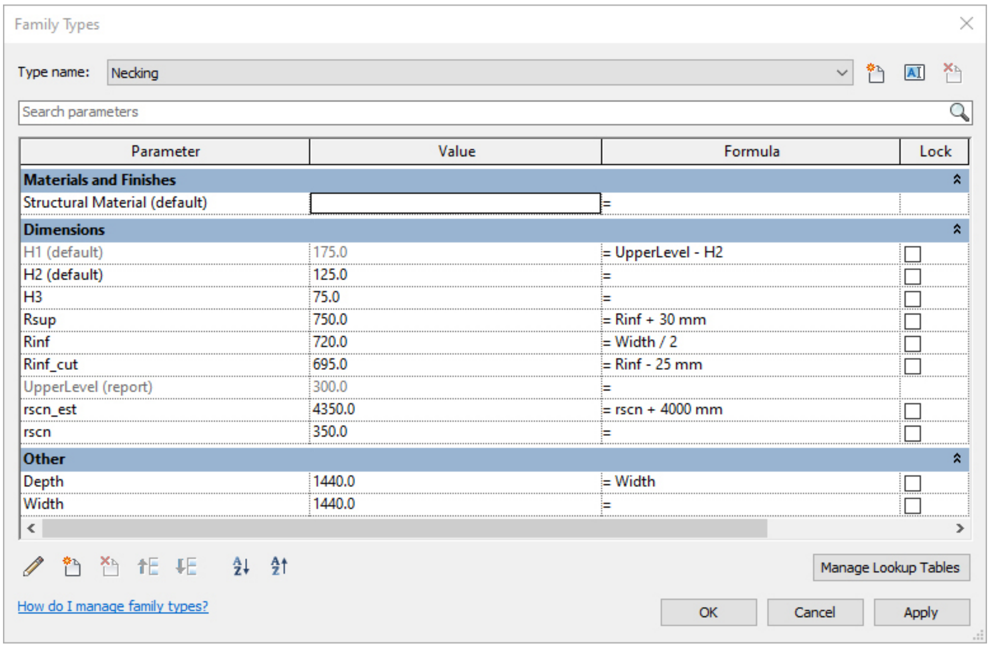


Figure 10.23 – *Necking* family parameters [AoE]

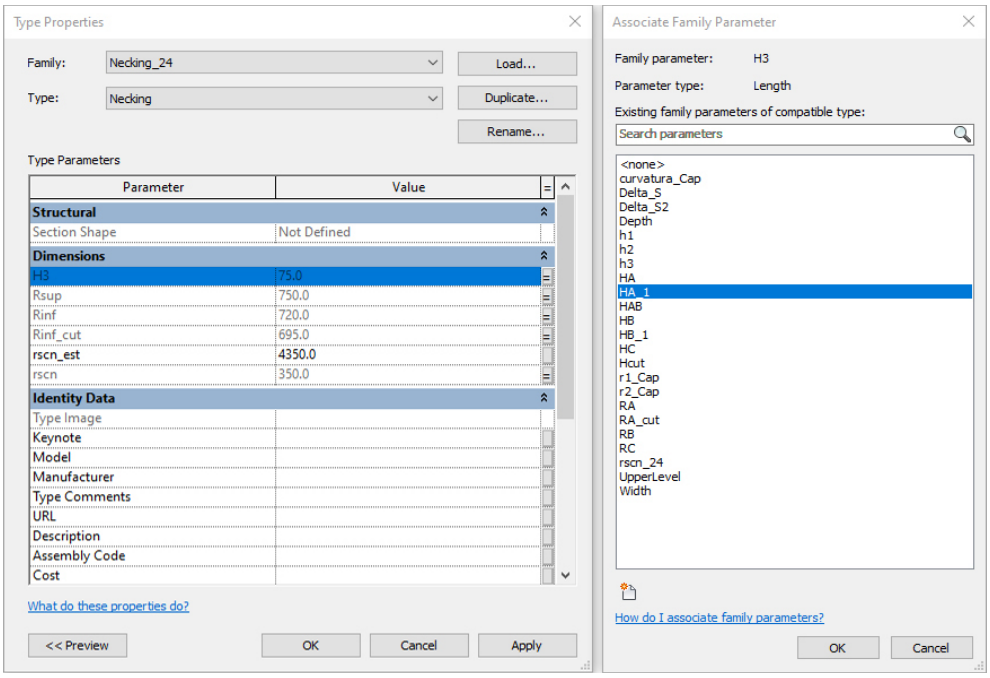


Figure 10.24 – Association between the nested *Necking* parameter *“H3”* and the specifically created *Capital* parameter *“HA_1”* [AoE]

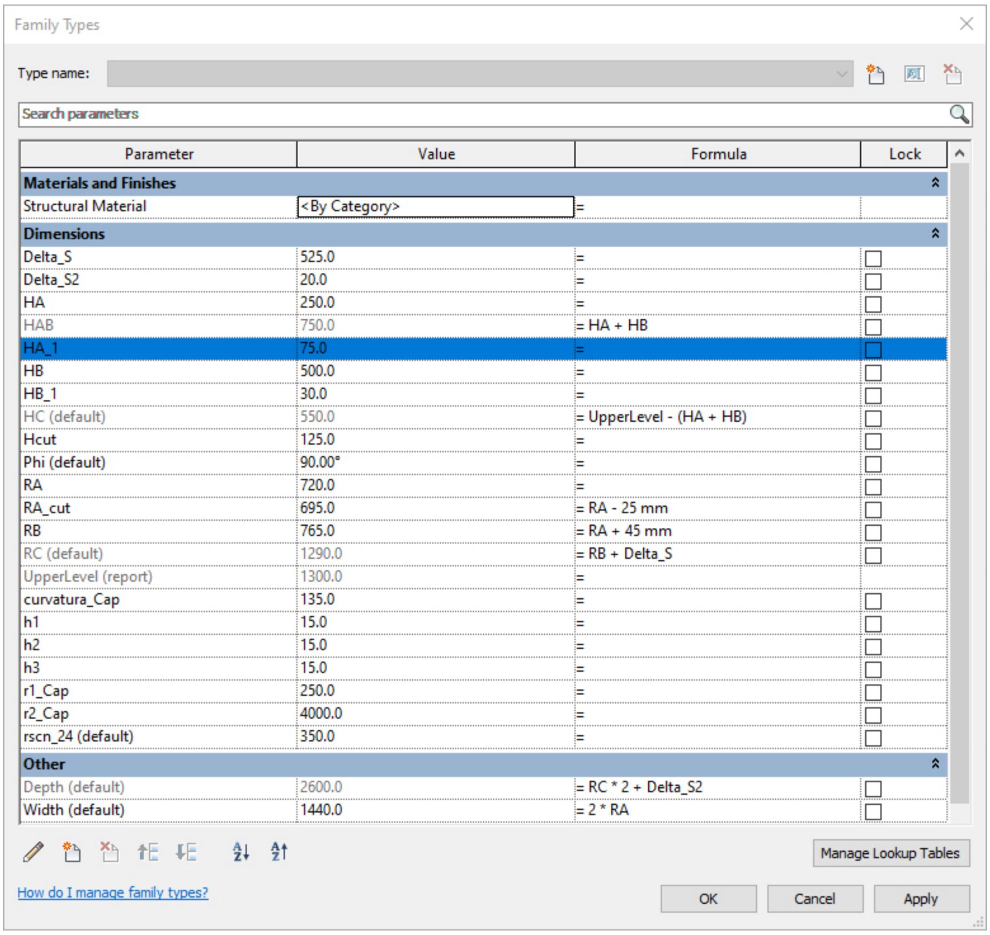


Figure 10.25 – *Doric Capital* parameters, with the *Necking* associated parameter “*HA_1*” highlighted [AoE]

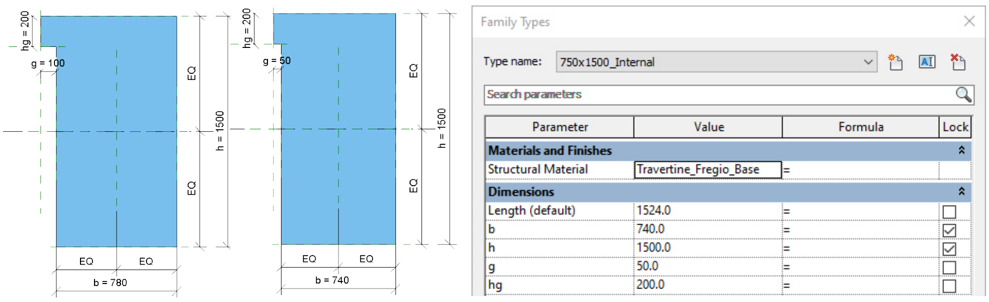


Figure 10.26 – *Architrave* family types: *External* (left) and *Internal* (middle) and *Internal type* parameters (right) [AoE]

10.3 Manual Scan-to-BIM modelling within the Revit environment

Once the point cloud has been correctly inserted and georeferenced [GEO] into the Revit environment, as illustrated at the beginning of this chapter, it was possible to start the manual Scan-to-BIM modelling process [STR].
First of all, the structure was broken down in planimetry and altimetry, respectively, setting up a *grid* to indicate the columns' positions (Figure 10.27) and thirteen *reference levels – (-3) Euthynteria, (-2) Crepidoma, (-1) Crepidoma, (0) Stilobate, (1) Pronao, (2) Cella, (3) Capitello Esterno, (4) Abaco Esterno, (5) Architrave Esterno, (6.1) Fregio, (6.2) Fregio, (7) Sotto Cornice, (8) Cornice, and (9) Sima* – to appropriately place the modelled components.
As far as the *unloadable families* are concerned, having been designed *ad hoc*, it was possible to adapt their instance parameters upon the point cloud to fit it. As the TLS point cloud is, by definition, much denser, it is suitable for the reconstruction of detailed geometric details, in particular bas-reliefs, projections, and generally speaking edges. However, in the case of the columns, which were built thousands of years ago and, due to gravity, assumed a nearly continuous, apparently seamless, configuration, it was necessary, during the modelling phase, to also rely on the photogrammetric orthoimages of the façades. Namely, in order to read the subdivision of the external columns into drums, the orthoimages (Figure 10.28) resulting from the 2017 UAS survey[48] were employed by inserting them – keeping their full size – into the Revit project in the corresponding view (Figure 10.29 and 10.30). On the other hand, when inserting the structural elements modelled as *floors* and *roofs*, the corresponding types were generated by duplicating and modifying the thickness of a monolayer (travertine) family (Figure 10.31).
It is worth noting that for the present application, only the structural elements were considered, leaving out the decorations, i.e., the frieze of the *tympana*, the *metopes*, and the *triglyphs*. Moreover, due to the not-so-clear reading of the *Naos* structure (from both the point clouds and the orthoimages) and keeping in mind that the *seismometers' network* was placed only on the roof above the external colonnade and on the ground, it was decided to model just the exterior of Temple of Neptune (Figure 10.32).

[48] The orthoimages (Figure 10.28) employed for the Scan-to-BIM modelling of the temple were edited by the surveyor who also carried out the 2017 UAS survey, i.e., Eng. M. Limongiello, PhD, pertaining to the *representation* group of the *Laboratorio Modelli – Surveying and Geo-Mapping for Environment and Cultural Heritage.*

Research carried out on the temple over the years has led to the conclusion that it was built using at least two different types of travertine, a harder grey one and a softer yellow one. The *grey travertine* was used to make the *Crepidoma*, the elements of the *Cornice* and the *Tiles*, while the *yellow travertine* was used to build the *Columns* and elements of the *Trabeation*. Most likely, within these two macro-categories, grey travertine coming from the more compact and, therefore, more resistant banks was used to realise the crepidoma and less resistant grey travertine was used for the roof elements; moreover, the blocks coming from the more resistant yellow travertine layers were used for the vertical elements, i.e., the columns, while the possibly less compact ones were used for the trabeation elements (Figure 10.33). It, therefore, felt appropriate to render this particular materic structuring by generating the aforementioned four types of travertine within the BIM environment, along with their descriptions, to which PBR maps (*Albedo*, *Roughness*, *Normal*, and *Ambient Occlusion* – Figure 10.34 and 10.35) were then associated for advanced visualisation[49] (Figure 10.36).

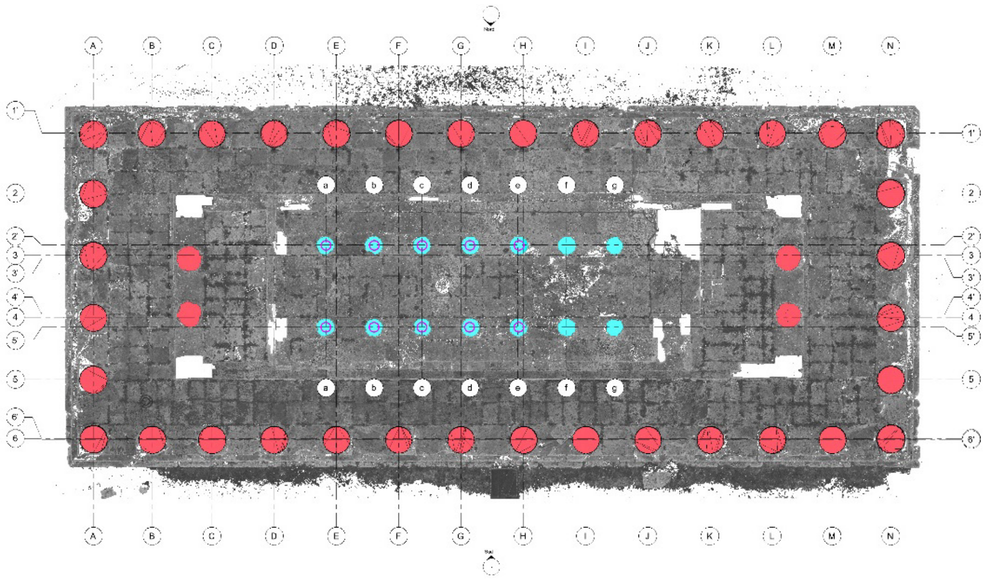


Figure 10.27 – Grid set up to easily identify the columns' positions [AoE]

[49] The tool used for the *real-time rendering* visualisation within the BIM environment is the Enscape plug-in in its 3.2 release.

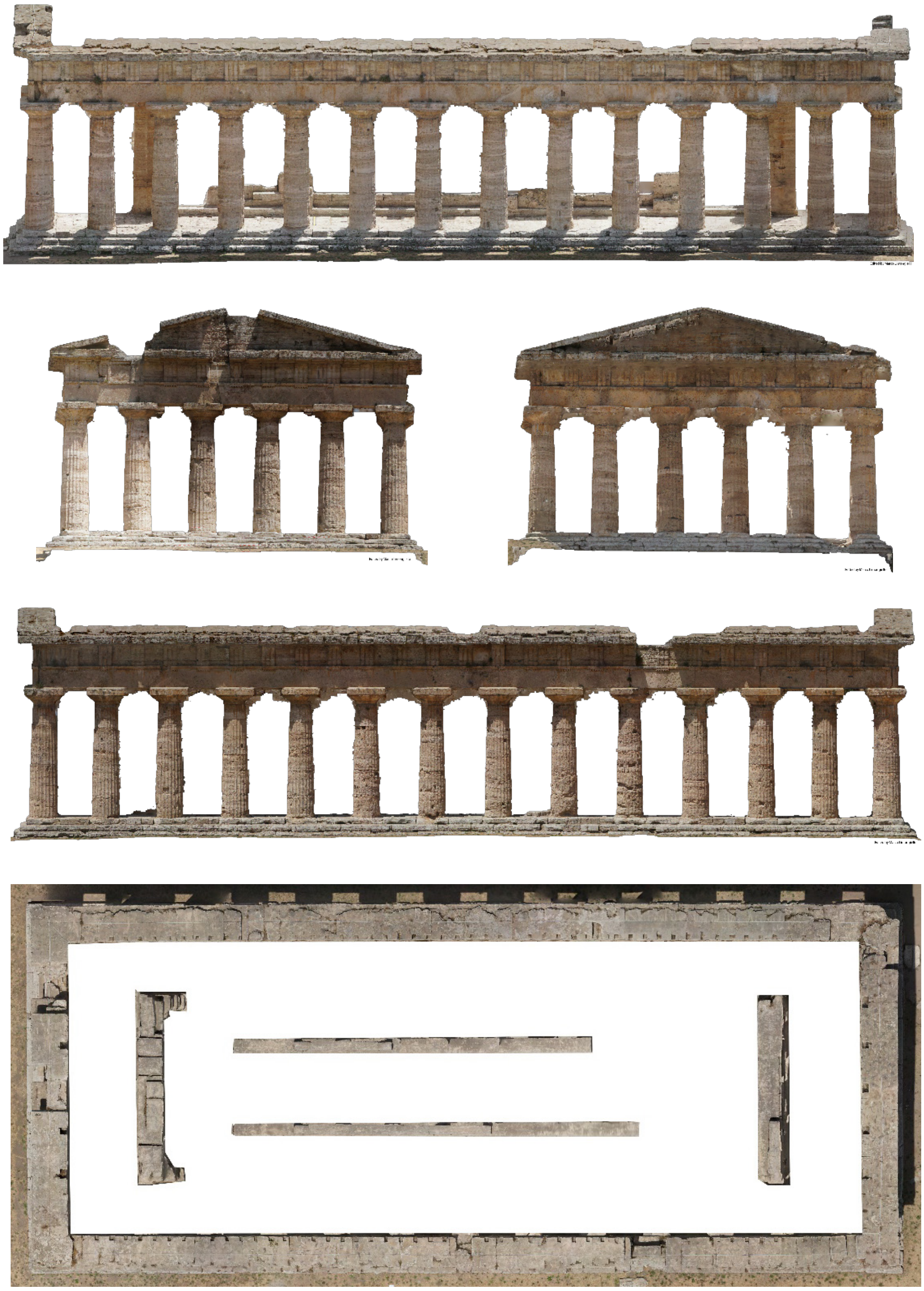


Figure 10.28 – Orthoimages edited by M. Limongiello: North view (upper), West view (upper right centre), East view (upper left centre), South (lower centre), and plan view of the Temple roofs (lower)

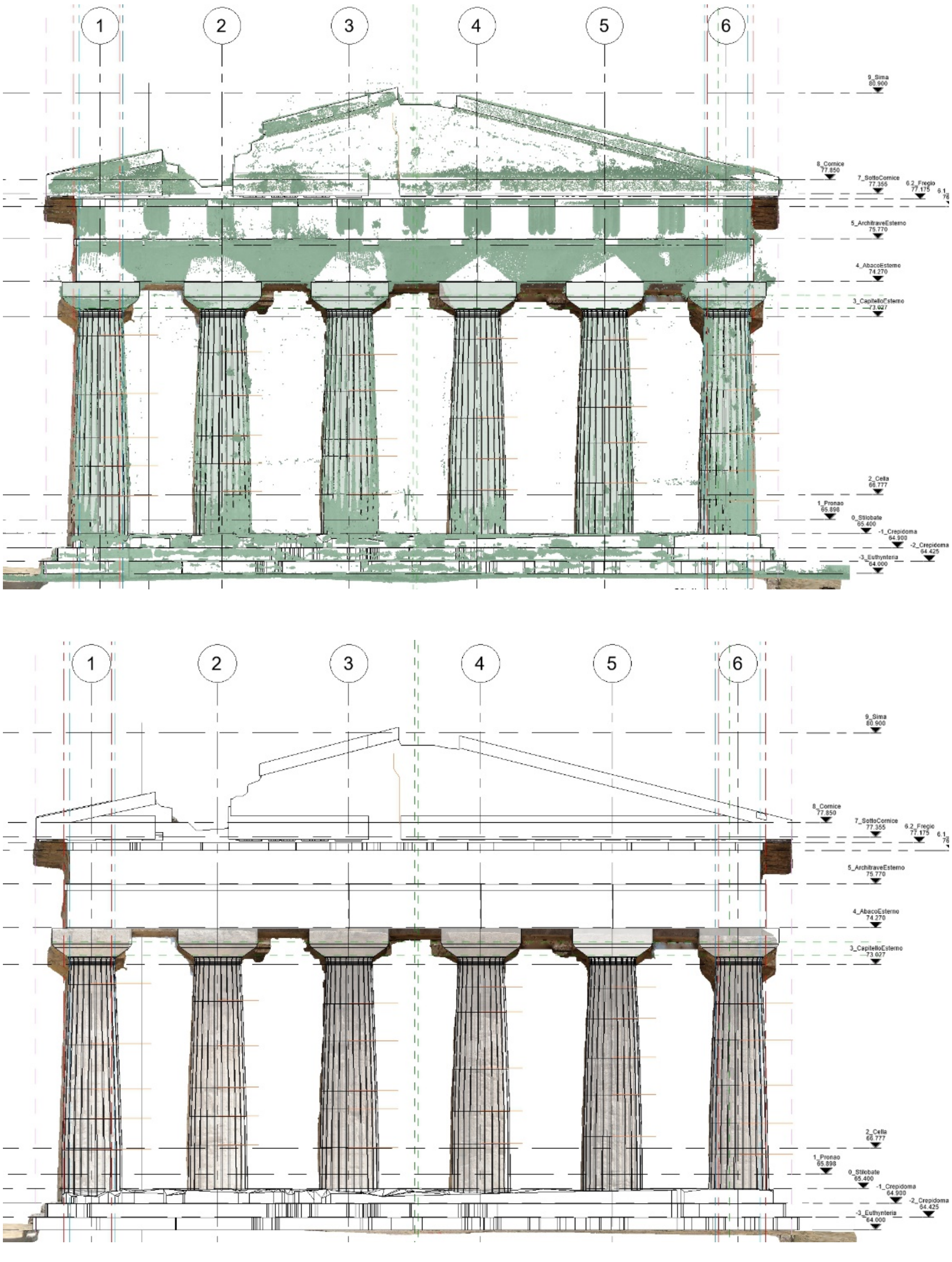


Figure 10.29 – Scan-to-BIM modelling: West view of the structural model overlapped over the point cloud (upper) and the corresponding orthoimage (lower) [AoE]

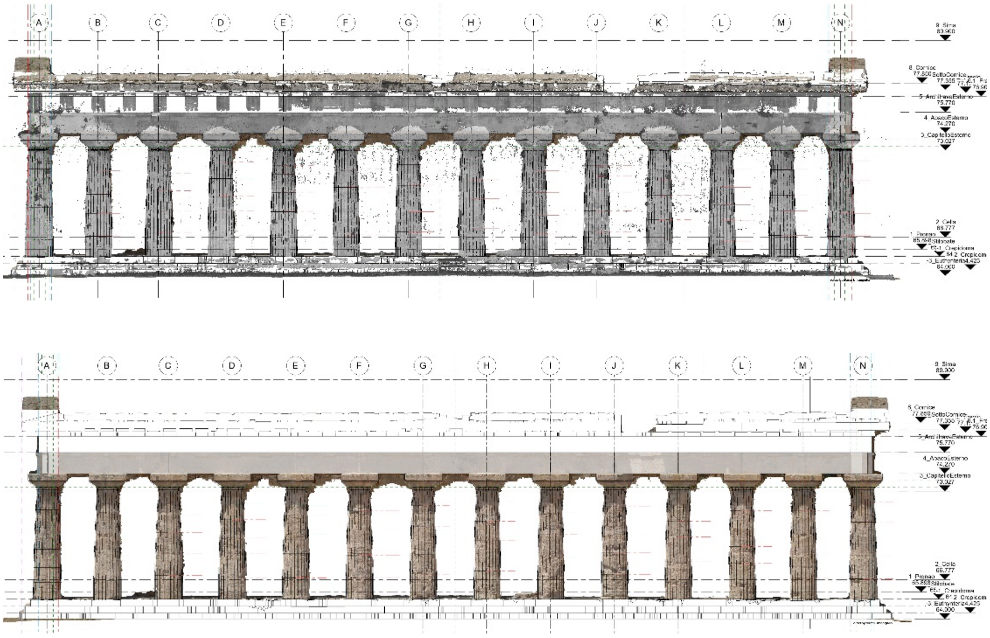


Figure 10.30 – Scan-to-BIM modelling: South view of the structural model overlapped over the point cloud (upper) and the corresponding orthoimage (lower) [AoE]

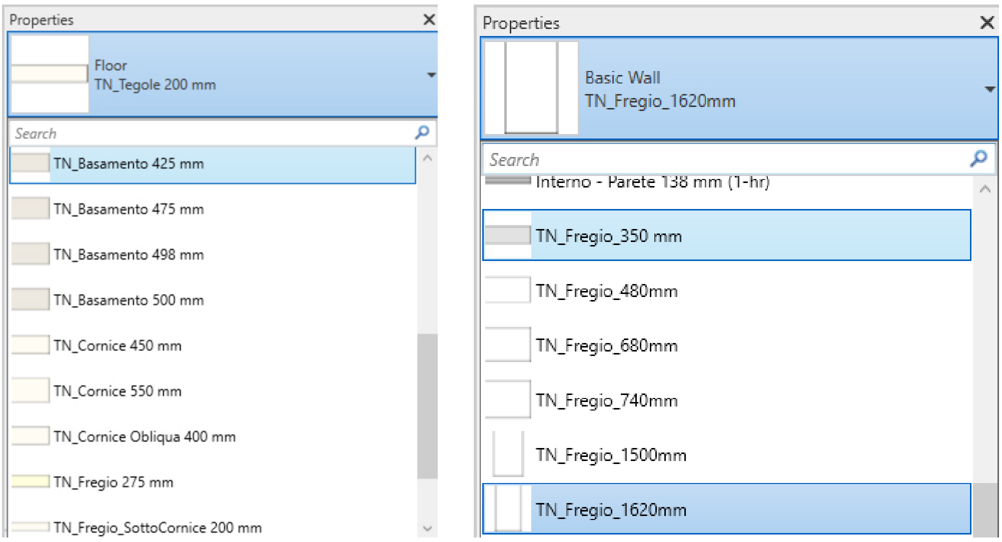


Figure 10.31 – System families of *Floors* (left) and *Walls* (right) generated to model the Temple of Neptune by duplicating a monolayer (Travertine) family and modifying the thickness per each of them [AoE]

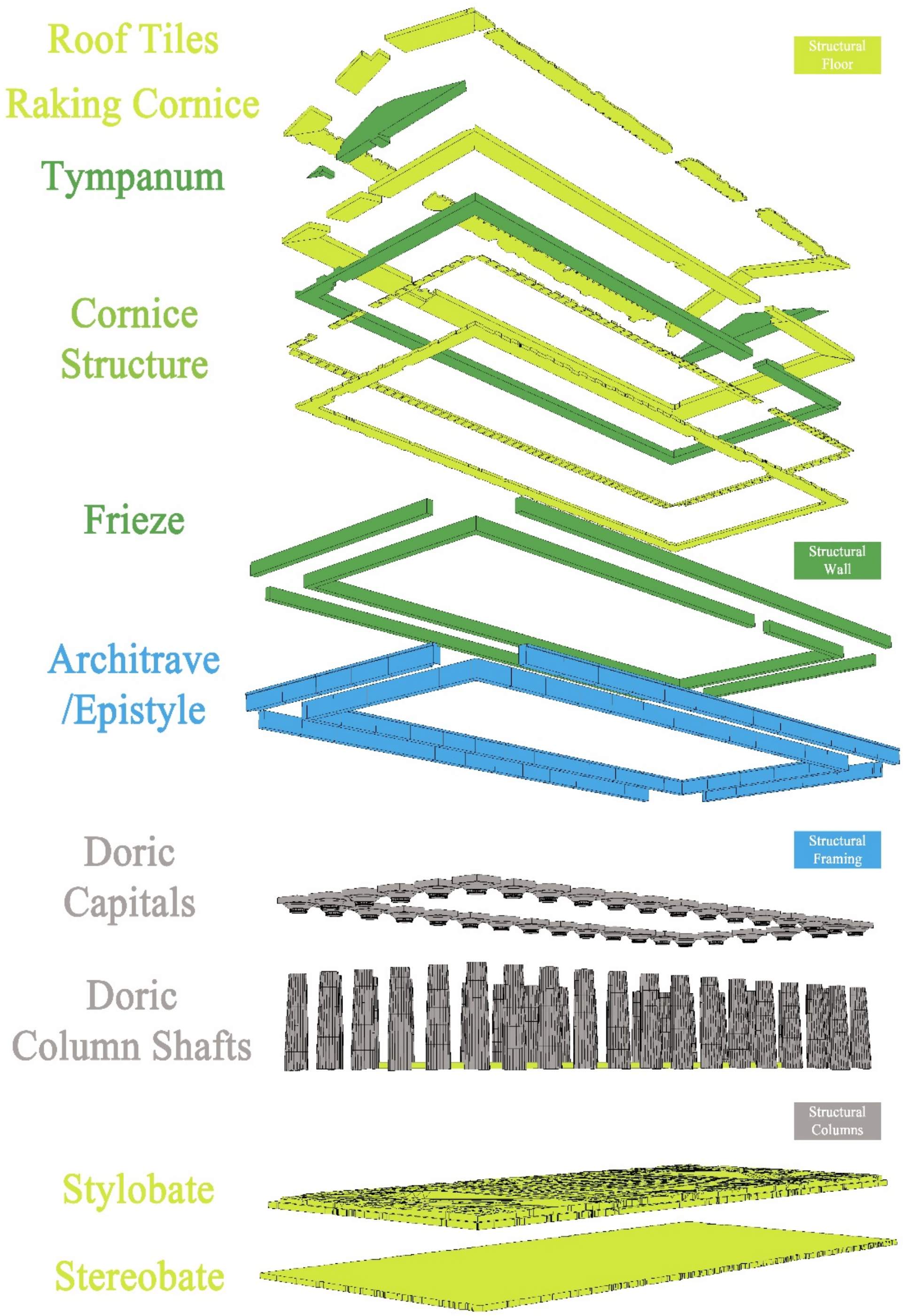


Figure 10.32 – Exploded axonometry to show the modelled BIM elements according to the Greek nomenclature and the assigned Revit categories [AoE]

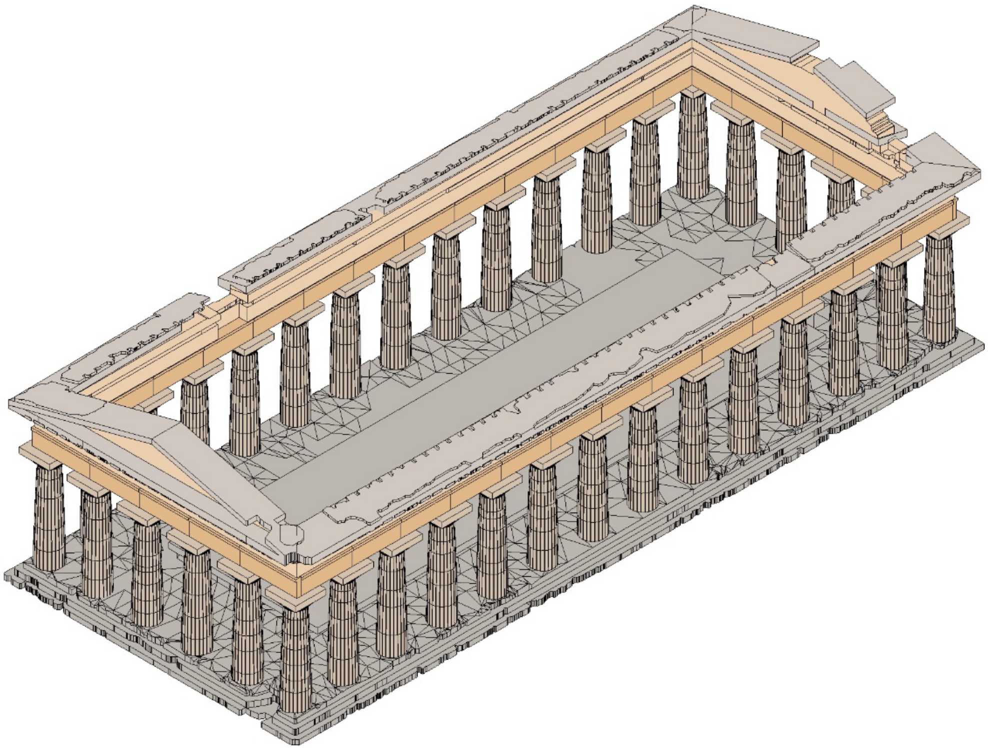


Figure 10.33 – Structural modelling [STR] of the Temple of Neptune showing the material properly assigned to the corresponding components [AoE]

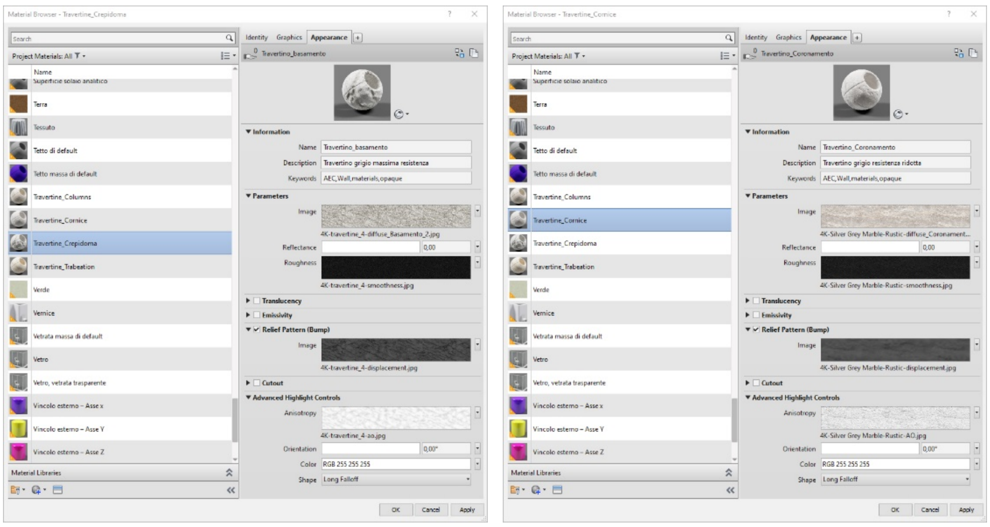


Figure 10.34 – The PBR harder *grey travertine* generated within the Revit *material browser* for the *Crepidoma* (left), the *Cornice* and the *Roof Tiles* (right) [AoE]

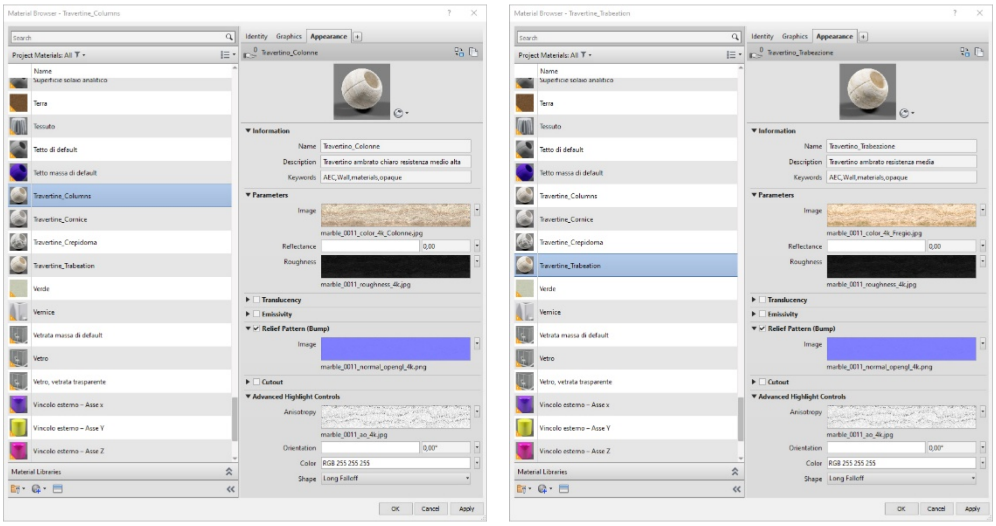


Figure 10.35 – The PBR softer *yellow travertine* generated within the Revit *material browser* for the *Columns* (left) and the *Trabeation* (right) [AoE]

Figure 10.36 – Rendered North-Eastern view of the Temple of Neptune generated with the real-time rendering plug-in Enscape for Revit [AoE]

11. Procedural workflows for Mesh-to-BIM applications

Although the long-term purpose of a BIM modelling is to standardise as many elements as possible, when the object to model is unique, as in the case of the urban context, which is typically different and distinctive from any asset, the aim should focus on standardising the process to reproduce it most authentically, for further in-depth study. Hence, the methodological applications proposed in this chapter involves two workflows developed to reproduce texturized photogrammetric meshes of the urban context, and some detailed areas of interest within a BIM environment, by parametrising the very components of the mesh model, its triangular faces. Particularly the first procedure can be further enhanced by means of *Physically Based Rendering* [PBR] materials, generating the advanced maps as a result of the photogrammetric process; while the second one may come in handy when the objective of the application is an accurate reproduction of selected areas for future qualitative and quantitative assessments. The aim is indeed to bridge the gap between the type of detail a survey can reach, precisely a photogrammetric one, when speaking about the colorimetric data, and what is possible to reproduce in a BIM environment when talking about distinctive if not unique elements such as the urban context or detailed relevant elements, such as frieze/decorations or damaged areas [3].

The two procedural workflows presented in the following – defined *Workflow A and B* for the sake of simplicity – are to all intents and purposes Mesh-to-BIM approaches. Therefore, for their effective implementation, some preliminary actions on the mesh surveyed model must be undertaken. Mesh simplification is a common practice for minimising model size by reducing the number of faces while preserving the shape, volume, and boundaries. Criteria for mesh decimation are generally user-defined, selecting the reduction method (working on the number of vertices, edges, or faces) and the reduction target, indeed, several commercial and open-source editing and modelling software include a mesh simplification module for handling this post-processing task efficiently [241]. Therefore, for an average notebook (Core i7 16GB of RAM, 2GB GPU) to be able to process the developed scripts and manage the results, it is advisable to keep the mesh faces count under 600'000 units, for the first method proposed, and under 20'000 units, for the second one, simplifying and splitting in more than one project the original photogrammetric mesh model (via Agisoft Metashape and ISTI-CNR MeshLab [3]).

11.1 Workflow A: Urban context meshes importing as a *unicum* into BIM

The first proposed workflow involves using a simple Dynamo VPL script (Figure 11.7 and 11.8) to *import* photogrammetric meshes (in OBJ format) of large areas of the urban context, chosen on a case-by-case basis given its distinctive uniqueness, in the BIM environment. Together with their related material, they are generated as *instances* falling under the categories *"Site"*. Once they have been *reprojected* in Revit, the mesh models of the general context can be easily textured through the *full-sized orthophotos* [241,242], imported in the *"Material Browser"* as colour maps (Figure 11.4 and 11.5). It is worth clarifying that, although the most common formats for orthoimages, such as TIFF and PNG, are equally adequate to be imported as textures into Revit's material browser, JPG is the one that leads to the best rendering results, due to the possibility of maintaining a transparent background and at the same time an optimal resolution/compression ratio [3].
As mentioned above, for the mesh model of the urban context to be imported to Revit, a transformation of the reference coordinate system must be performed to avoid approximation issues. It was carried out by operating for the 2017 UAS survey on the 11 initially measured GCPs and for the 2020 one on the 9 GCPs by subtracting a fixed quantity to the x, y and z coordinates (x = 500,514.0000 m, y = 4,474,384.0000 and z = 62.5000 m, the same used for the translation of the integrated point cloud, as explained at the beginning of chapter 10), resulting in the locally translated GCPs reported in Table 11.1.
Nevertheless, a simplification of the mesh models was also due, and it was accomplished via smoothing and decimation tools. This phase outputs consist of two context mesh models, respectively the temple sourroundings dating back to 2017 and the 2020 updated context. The resulting areas representing a mainly horizontal built environment were respectively made up of 199,999 and 575,000 faces. Both three-dimensional mesh models were then exported in an OBJ format to be later imported into Revit via the VPL script developed for workflow A (Figure 11.2 and 11.3). It was opted for assigning to the produced BIM instances the *"Site" category* – thus modelling them as *Topographies* – and additionally generating for every instance a *related material* under the same name. Finally, the *orthoimages* respectively with a 7.78 and a 7.41 mm/px resolution realised for each model were used at full-size to texturize them (Figure 11.4 and 11.5).

The results of the first workflow implementation were then two separate Revit projects: *“PaestumContext_2020_PBP.RVT”* and *“PaestumContext_2017_PBP.RVT”* as shown in Figure 11.6.

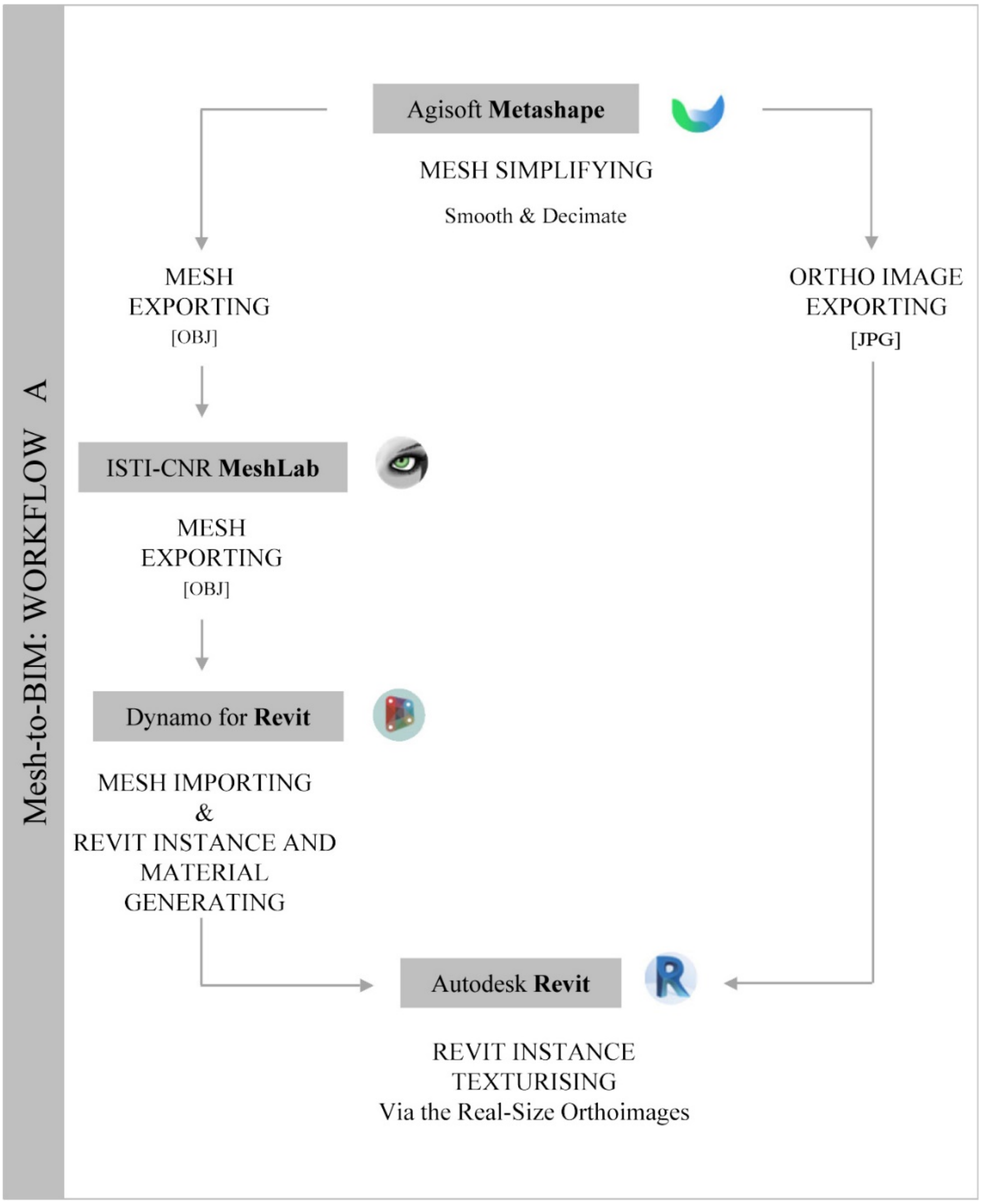


Figure 11.1 – Procedural workflow A explanatory diagram [AoE] [3]

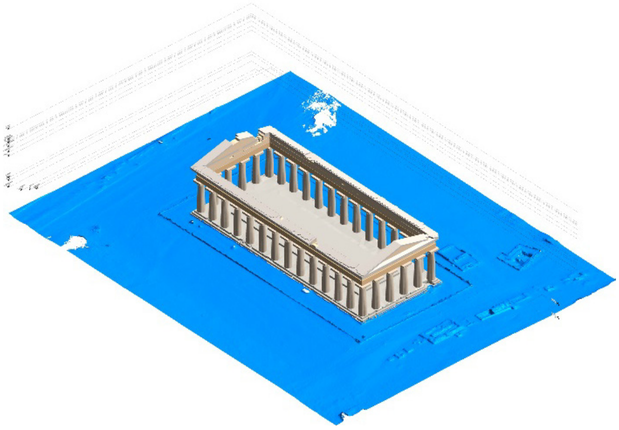


Figure 11.2 – *Revit "Site" instance* reproducing the 2017 UAS surveyed context [AoE]

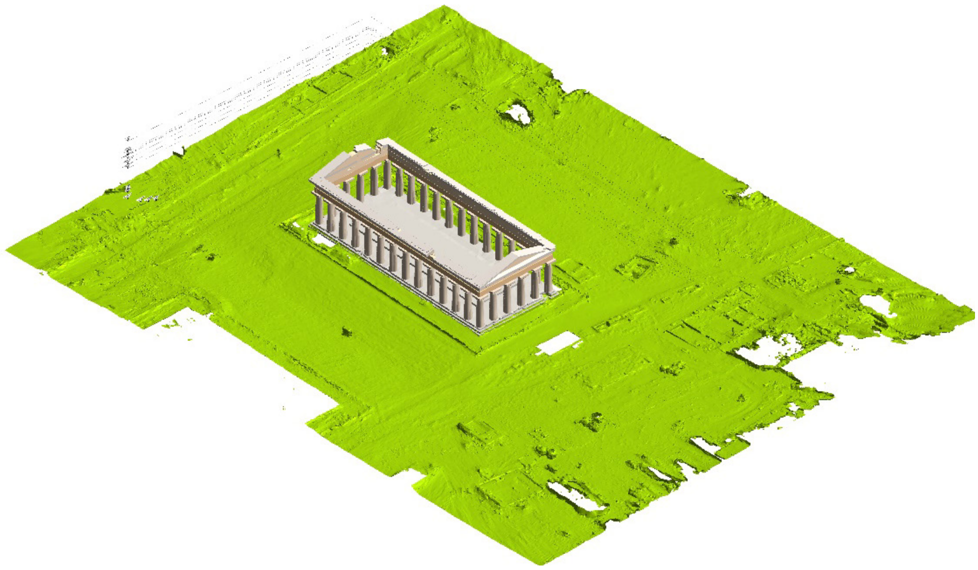


Figure 11.3 – *Revit "Site" instance* reproducing the 2020 UAS surveyed context [AoE]

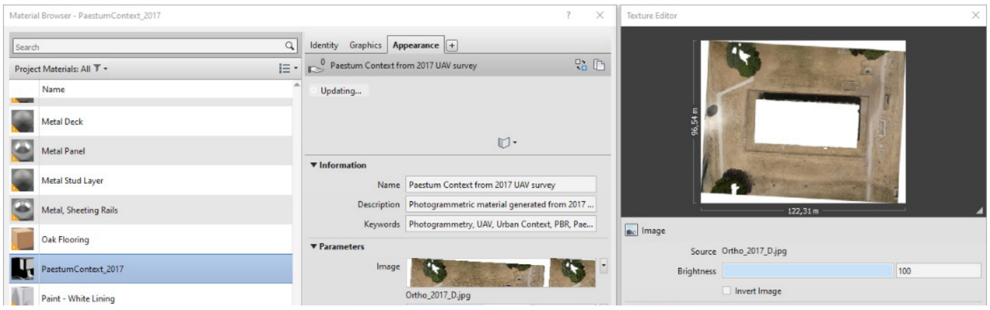


Figure 11.4 – Othoimage used as texture for the 2017 *Revit Instance* context [AoE]

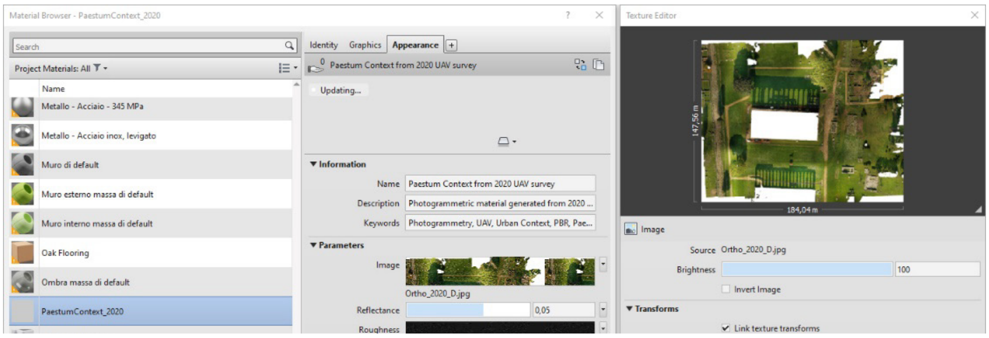
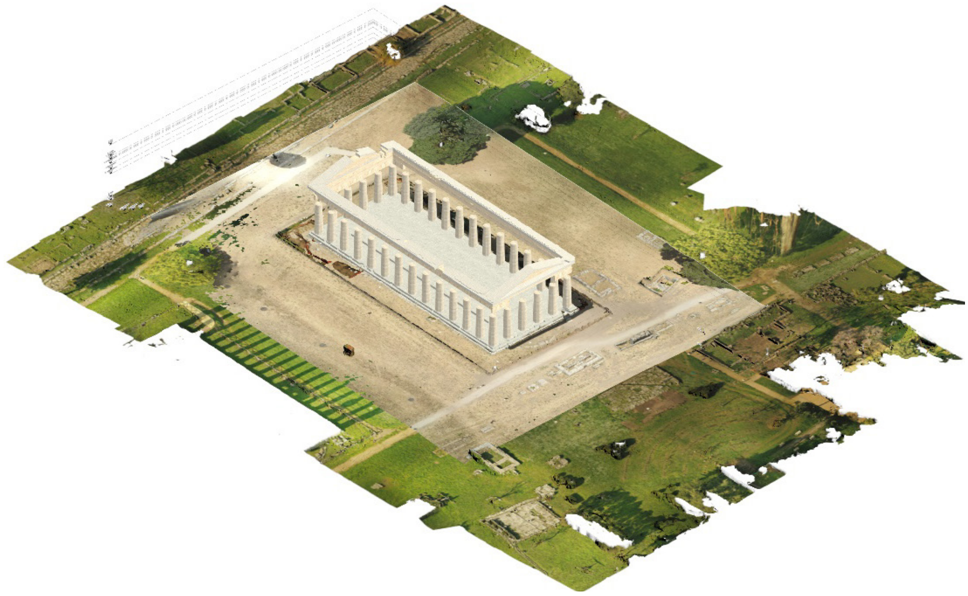


Figure 11.5 – Othoimage used as texture for the 2020 *Revit Instance* context [AoE]



Manage Links

Revit | IFC | CAD Formats | DWF Markups | Point Clouds | Topography | PDF | Images

Link Name	Status	Reference Type	Positions Not Saved	Saved Path	Path Type
TempioNettuno.rvt	Loaded	Overlay	☐	TempioNettuno_Material.rvt	Relative
Scavo_2_2021.rvt	Loaded	Overlay	☐	Scavo_2_2021.rvt	Relative
Scavo_1_2021.rvt	Loaded	Overlay	☐	Scavo_1_2021.rvt	Relative
PaestumContext_2020_PBP.rvt	Loaded	Overlay	☐	PaestumContext_2020_PBP.rvt	Relative
PaestumContext_2017_PBP.rvt	Loaded	Overlay	☐	PaestumContext_2017_PBP.rvt	Relative
Impianto_TN_2021.rvt	Loaded	Overlay	☐	Impianto_TN_2021.rvt	Relative
Artefatto 2021.rvt	Loaded	Overlay	☐	Artefatto 2021.rvt	Relative

Save Positions | Reload From... | Reload | Unload | Add... | Remove

OK | Cancel | Apply | Help

Figure 11.6 – Federated and overlapping textured *Revit projects* of 2017 and 2020 contexts [AoE]

Table 11.1 – The table shows the variation of x, y, and z coordinates in the translation from the Global Georeferenced System (EPSG: 32633 for the columns marked with *) to the Local One.

Survey	GCPs	x* [m]	x [m]	y* [m]	y [m]	z* [m]	z [m]
2017	01	500422,9110	-91,0890	4474361,3130	-22,6870	63,8580	1,3580
	02	500423,3990	-90,6010	4474350,0330	-33,9670	63,7950	1,2950
	03	500435,7770	-78,2230	4474349,0370	-34,9630	63,8710	1,3710
	04	500451,3720	-62,6280	4474350,6030	-33,3970	64,1370	1,6370
	05	500472,9010	-41,0990	4474347,9630	-36,0370	64,0190	1,5190
	06	500489,7350	-24,2650	4474349,1800	-34,8200	63,9570	1,4570
	07	500489,4470	-24,5530	4474359,6110	-24,3890	63,6670	1,1670
	08	500485,8860	-28,1140	4474378,6820	-5,3180	63,6650	1,1650
	09	500469,1230	-44,8770	4474379,1830	-4,8170	63,9420	1,4420
	10	500448,8700	-65,1300	4474381,0610	-2,9390	63,9950	1,4950
	11	500424,9520	-89,0480	4474381,8020	-2,1980	63,8830	1,3830
2020	01	500516,5620	2,5620	4474383,5800	-0,4200	62,5780	0,078
	02	500515,6500	1,6500	4474398,2050	14,2050	62,4350	-0,065
	03	500515,6850	1,6850	4474412,0150	28,0150	62,3070	-0,193
	04	500525,0180	11,0180	4474412,4690	28,4690	62,7540	0,254
	05	500480,7850	-33,2150	4474394,7890	10,7890	62,7490	0,249
	06	500438,5910	-75,4090	4474414,3750	30,3750	62,1770	-0,323
	07	500525,3040	11,3040	4474361,3400	-22,6600	63,0280	0,528
	08	500399,1720	-114,8280	4474394,2250	10,2250	62,0590	-0,441
	09	500482,6270	-31,3730	4474317,4670	-66,5330	63,1290	0,629

[Script 6] VPL Script for importing the mesh models by generating them as *Revit Instances*

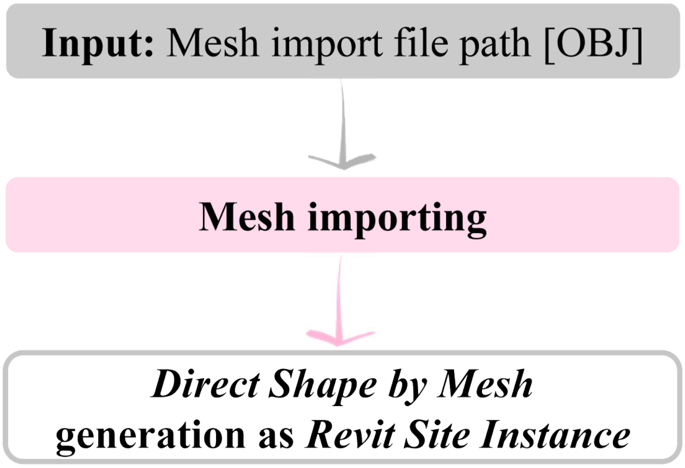


Figure 11.7 – Diagram breaking down the VPL script developed to import the mesh models by generating them as *Revit Instances* [AoE]

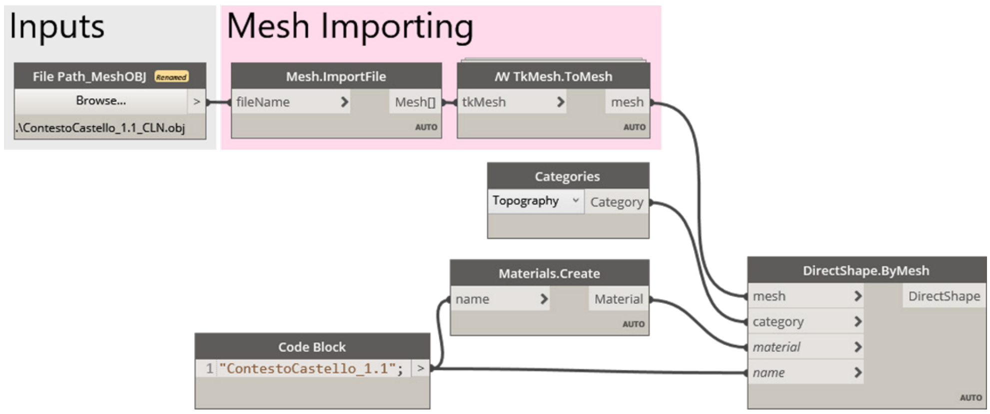


Figure 11.8 – Dynamo VPL script developed to to import the mesh models by generating them as *Revit Instances* [AoE]

11.2 Workflow A.1: Data enrichment via PBR photogrammetric material

In an attempt to combine parametric modelling and photorealistic visualisation within a BIM environment, it was decided to include the photogrammetric texture as stratified information, integrating the emerging technologies in terms of Virtual Reality plug-ins and Real-Time Rendering, capable of operating within a BIM workspace. In this way, the texture assumes a semantic character, providing information about the state of conservation of the Temple environment, at the same time, supporting a better definition of the geometric level of the model [LOG]. Specifically, the real-time rendering plug-in *Enscape for Revit* (in its 3.2 release) was used.
Starting from the UAS surveys, a further step was designed within the framework of the Workflow A application in order to obtain high-quality outputs suitable for the subsequent application, with the aim of enhancing the BIM-modelled objects via image-based elaborations. The proposed application hereto can therefore be additionally broken down into three subsequent steps summarised as follows (Figure 11.9).
The first phase, which takes place still within a photogrammetric environment (Agisoft Metashape – version 1.7.1) concerns the development of the first three maps of a Physically Based Rendering [PBR] material[50], i.e., the *Diffuse map*, commonly known as *Texture* or *Albedo*, the *Height map* and the *Normal map*, the latter two both fall under the sphere of the so-called *Bump mapping*, a range of image which graphically encodes the displacement function of each pixel along the normal to the material surface at the same point. The second stage focuses on the generation of a complete PBR material on the basis of the previous photogrammetric outputs; for these procedures, the open-source software Materialize (under the GNU GPL v3) was employed. The last stage finally takes place within the BIM environment, where the resultant photogrammetric PBR material is applied to the study object, employing the real-size scaled maps just produced.

[50] *Physically Based Rendering* [PBR] is a method of shading and rendering that provides a more accurate representation of how light interacts with surfaces. It is referred to as *Physically Based Rendering* [PBR] or *Physically Based Shading* [PBS]. Depending on what aspect of the pipeline is being discussed, PBS is usually specific to shading concepts, and PBR is specific to rendering and lighting. However, both terms describe the process of representing assets from a physically accurate standpoint [240].

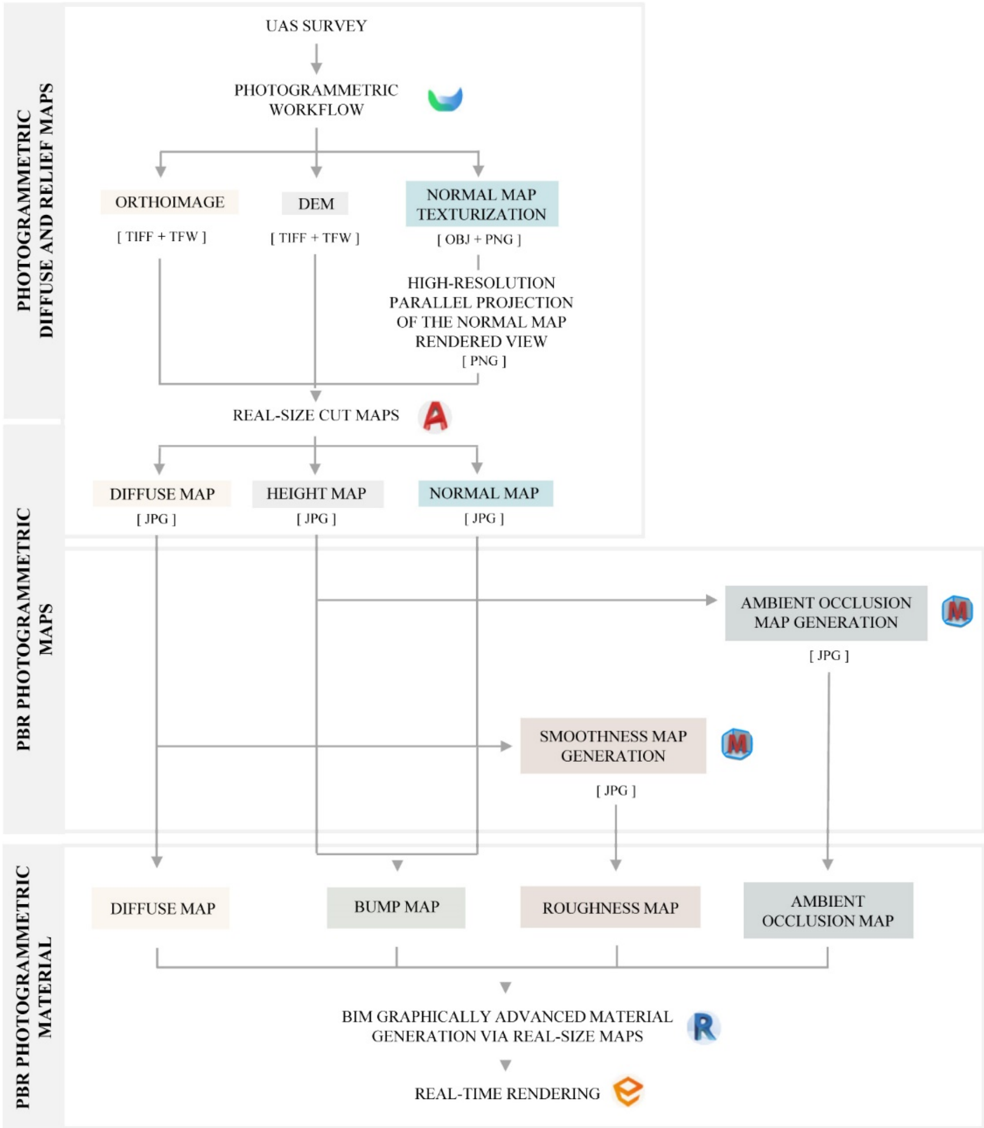


Figure 11.9 – Workflow A: additional procedural methodology for a Mesh-to-BIM to Real-Time Rendering approach [AoE]

Photogrammetric Diffuse and Relief Maps generation

As far as it concerns the maps resulting somewhat straightforwardly from the photogrammetric workflow, it can be safely assumed that an orthoimage of the surface under-study is in direct correspondence with the universally accepted concept of *Texture*, also known as *Albedo*; it's worth mentioning that within the

definition of the PBR material the classic texture takes the name of *Diffuse Map*. Knowing then the textbook definition of the *Digital Elevation Model*, being a raster image representing the elevation data usually of terrain via a graded colour scale, it is logical to link this kind of output to the *Height-type Bump mapping*, generally consisting of a grey-scaled image intended to simulate recess, marked in darker shades, and projections, corresponding to the lighter to white areas. Planar DEMs, parallel to the horizontal reference plane, are then to be produced and later colourised using a black-to-white palette other than the most common multicoloured one. The *Diffuse* and the *Height maps* produced within the photogrammetric environment can be exported directly as images in a TIFF format and imported, keeping their actual size in CAD thanks to the attached TFW file. On the other hand, the process of generating the *Normal map* is not as immediate as the previous ones.
Although the developers introduced the *Normal map* texturization feature in recent versions of *Agisoft Metashape*, this application is intended as a means to simulate a high-poly texture resolution for low-poly mesh so as to produce lighter models for online visualisation. In detail, the tool employs a high-poly mesh as source data for the texturization of a decimated mesh model of the very same surveyed object. Namely, for the *Metashape tool* to be suitable for the proposed methodology is necessary to decimate the high-quality mesh model enough to obtain a seemingly plane surface corresponding to the investigated façade and then proceed to texturize the latter keeping the former as a reference. It appears clear that, while the obtention of full-sized orthoimages and DEM, consists in straightforward exportation, it is not as easy to produce an orthorectified *Normal map*, being it just a texture. Hence, upon orienting the model according to a horizontal orthometric view, this view was rendered as a high-quality screenshot [PNG], to be later scaled over the real-size orthoimages in the Autodesk AutoCAD environment.

PBR Photogrammetric maps generation

For the second stage of the proposed workflow an open-source software, i.e., Materialize, can be used for the generation of the missing maps required for a full PBR photogrammetric material with a good graphic degree of approximation. Indeed, a *Revit material* can be additionally characterised by a *Roughness* and an *Ambient Occlusion map* beside the *Diffuse* and the *Bump* ones. The *Ambient Occlusion map*, being the one capable of realistically simulating the light refraction over the texturized surface, needs the *Height* and the *Normal* ones to be generated. On the other hand, the Materialize software allows to create a *Smoothness map* other than the required *Roughness* one; both these raster images are grayscale, with the former employing lighter shades for the smoother areas of the surface as opposed to darker shades for the rougher zones, on the contrary, the latter map uses an inverse greyscale for the identifications of the same kind of sections. In other terms, it is possible to just invert a *Smoothness map* and use it to simulate the roughness of the material. Of the five maps achievable so far, just four of them can be applied simultaneously within Autodesk Revit Material Browser, due to the *Relief* (Bump mapping) implementing either the *Height* (as a greyscale raster image) or the *Normal* one alternatively (as RGB raster image, whose pixel R, G, and B pixel values are interpreted so to simulate the displacement along an ideal vector perpendicular to the texturized surface and intersecting it in the same pixel); the most suitable map can be indifferently chosen, although its worthwhile remembering that both concur to the generation of the others, thus the necessity to obtain both of them from the photogrammetric process (Figure 11.10 and 11.14).

PBR Photogrammetric Material setting within a BIM environment

The third and final step of the proposed procedure concerns the actual implementation of the PBR photogrammetric material in the BIM software by assigning the additionally produced maps to the topographies' materials generated by running the Script 6 along with the *Revit Instances* bearing the same name.
Therefore, besides the orthoimages already produced for the 2017 (122.31x96.54 m dimensions – Figure 11.11) and the 2022 (184.04x147.56 m dimensions – Figure 11.15) Temple surroundings, the same-sized *Height*, *Normal*, *Smoothness* and *Ambient Occlusion maps* (Figure 11.12, 11.13, 11.16, and 11.17) in a JPG format were produced through the Materialize open-source tool to be subsequently implemented as additional maps, respectively for the *"PaestumContext_2017"* and the *"PaestumContext_2020"* materials via the *Revit Material browser* (Figure 11.18 and 11.19), in order to achieve an advanced visualisation, which is also metrically reliable in planimetry.
Indeed, the workflow A works quite good for larger urban areas that constitute the unique context of an architectonic asset, specifically whenever they are predominantly horizontal (Figure 11.20 and 11.21); on the contrary, this method does not work flawlessly in the case of particularly articulated areas deemed worthy of being accurately reproduced together with their colourimetric information within a BIM environment, for their distinctive value or so as to estimate their extension for further analysis (Figure 11.22 and 11.23); thus the need for implementing the workflow B presented next.

Figure 11.10 – *2017 Photogrammetric material*'s maps generation within Materialize [AoE]

Figure 11.11 – *2017 Orthoimage* of the Temple of Neptune immediate surroundings [AoE]

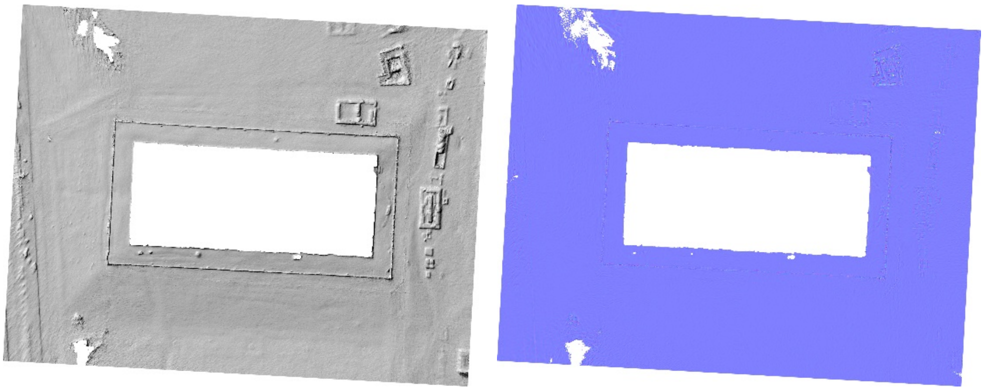


Figure 11.12 – *2017 Height* (left) and *Normal* (right) maps [AoE]

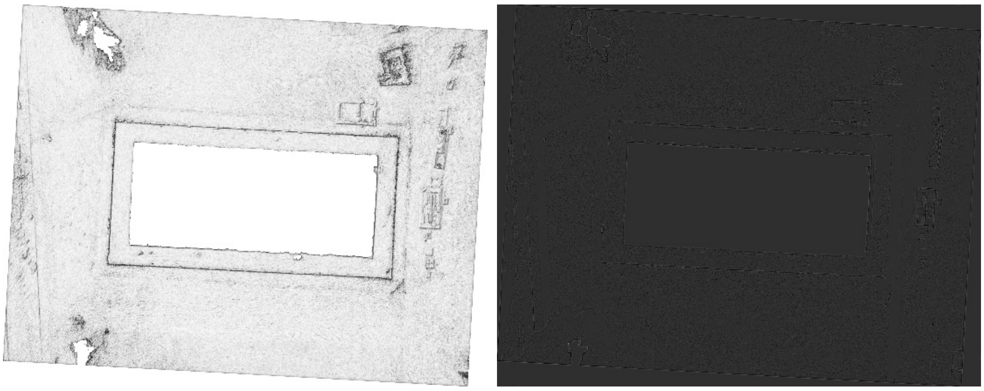


Figure 11.13 – *2017 Ambient Occlusion* (left) and *Smoothness* (right) maps [AoE]

Figure 11.14 – *2020 Photogrammetric material*’s maps generation within Materialize [AoE]

Figure 11.15 – *2020 Orthoimage* of the Temple of Neptune extended surroundings [AoE]

Figure 11.16 – *2020 Height* (left) and *Normal* (right) maps [AoE]

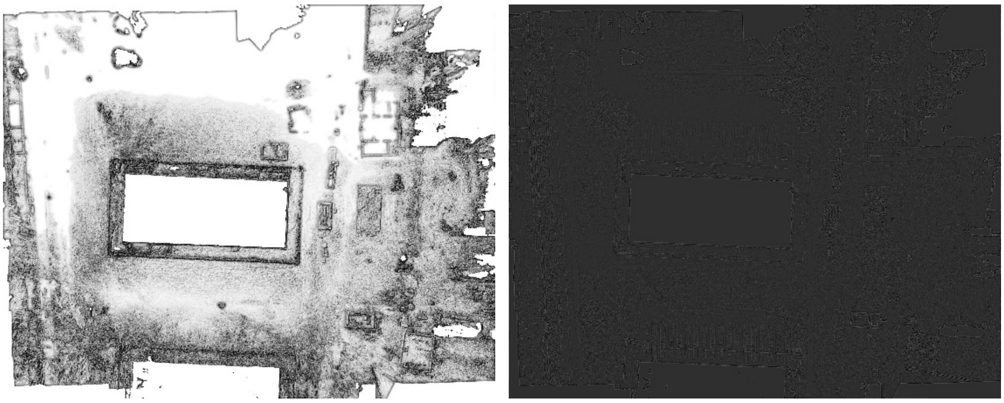


Figure 11.17 – ***2020 Ambient Occlusion*** **(left) and** ***Smoothness*** **(right) maps [AoE]**

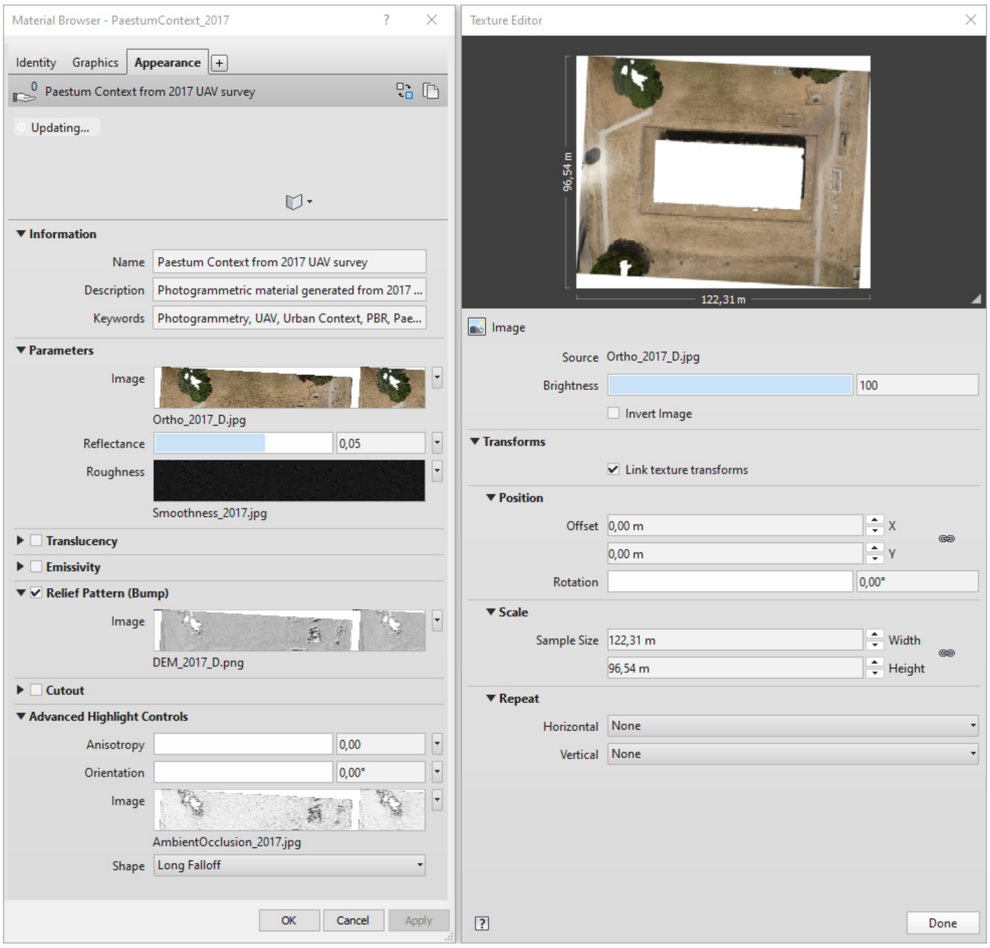


Figure 11.18 – ***2017 Photogrammetric material*** **implementation (*****Revit Material Browser*****) [AoE]**

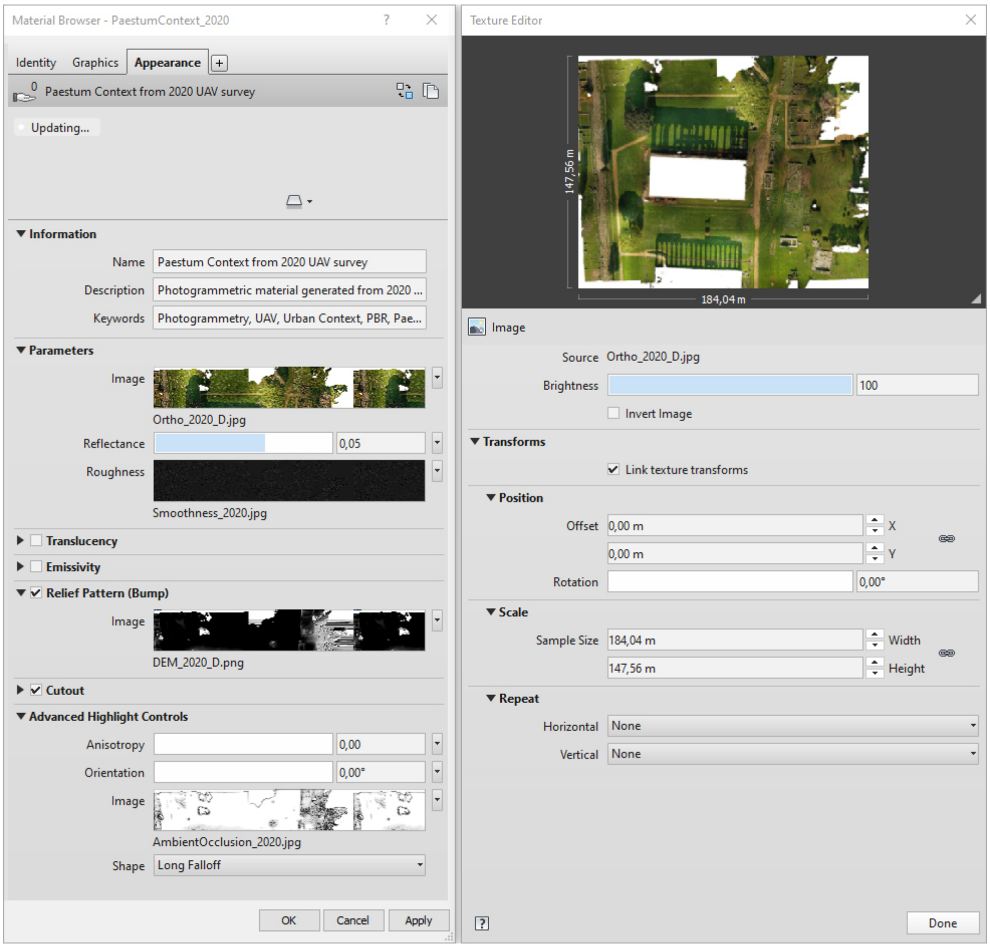


Figure 11.19 – *2020 Photogrammetric material* implementation (*Revit Material Browser*) [AoE]

Figure 11.20 – Rendered N-E view of the Temple of Neptune within its 2017 context [AoE]

Figure 11.21 – Rendered N-E view of the Temple of Neptune within its 2020 context [AoE]

Figure 11.22 – Rendered N-E view of the Temple of Neptune within its 2017 context: Zoom in on some articulated areas that represent a limitation for Workflow A implementation [AoE]

Figure 11.23 – Rendered N-E view of the Temple of Neptune within its 2020 context: Zoom in on some articulated areas that represent a limitation for Workflow A implementation [AoE]

11.3 Workflow B: Mesh model parametrisation into the BIM environment

Even though the second workflow (Figure 11.24) [3] also starts from photogrammetric meshes [PLY-ASCII encoding] appropriately simplified, as explained before, it focuses on selected detail areas with a much smaller extension to be exported with the relative texture [PNG]. The raster image representing the texture is first treated separately, reducing the colour scale from 256 to a range varying between 8 and 15 (the Adobe Photoshop *Indexed colours*[51] tool can be employed for the purpose), depending on the variegated nature of the image in question, so to reduce to the minimum number necessary the subsequent material generation. Through software capable of editing meshes, such as ISTI-CNR Meshlab, it is then possible to reassign the texture to the mesh, projecting the colours to its vertices and from the vertices to its faces[52]. On reexporting the resulting 3D model again in a PLY-ASCII format, their direct reading is allowed; namely, the very same files can be opened via a text pad or imported into the Microsoft Excel environment to have access to their geometric information. The numeric data derived in this way were then filtered to retrieve just the face information from it, which appears as in the following string:

$$3 \;\; I_1 \;\; I_2 \;\; I_3 \;\; 6 \;\; Tc_1 \;\; Tc_2 \;\; Tc_3 \;\; Tc_4 \;\; Tc_5 \;\; Tc_6 \;\; R \;\; G \;\; B \;\; a$$

Where, from left to right, the *"3"* value indicates the number of vertices of each face, the *"$I_\#$"* values stand for the index (the number that identifies a vertex) of each vertex that composes the face in question, the *"6"* value represents how may float-type texture coordinates are provided, followed by said coordinates, i.e., the *"$Tc_\#$"* values, and lastly we can find the numeric values of the colour assigned to

[51] When converting into *indexed colour*, the Photoshop tool builds a colour lookup table [CLUT], that appears as a reduced palette, which stores and indexes the colours in the image; if a colour in the original image does not appear in the table, the program chooses the closest one or simulates the colour using available colours. By limiting the panel of colours, indexed colour can reduce file size while maintaining visual quality, for example, for a web page [270].

[52] A polygonal mesh is at least composed of vertices, edges and faces. In the case of a triangular mesh, its faces have three vertices, located in space by their coordinates (x, y, z). To compose each triangle, it is therefore necessary to know the indices of its vertices, intended as the number that identifies the place of each vertex in the complete list. To learn more about polygonal meshes, visit: https://www.scratchapixel.com/lessons/3d-basic-rendering/introduction-polygon-mesh.

each face in the *"R"*, *"G"*, *"B"*, and *"a"* channel format. For the purposes of the proposed method, only the first and the last four digits will be considered.
Both the mesh in 3D format [PLY] and its data in numerical format [XLSX] are then used as input, together with an original family of triangles with adaptive vertices (*"Triangular Face.RFA"* – Figure 11.49, upper) for its discretised reproduction in the BIM environment through the second VPL script (Figure 11.25 and 11.26). Both the adaptive family component and the most complex script were explicitly developed for the proposed methodology.

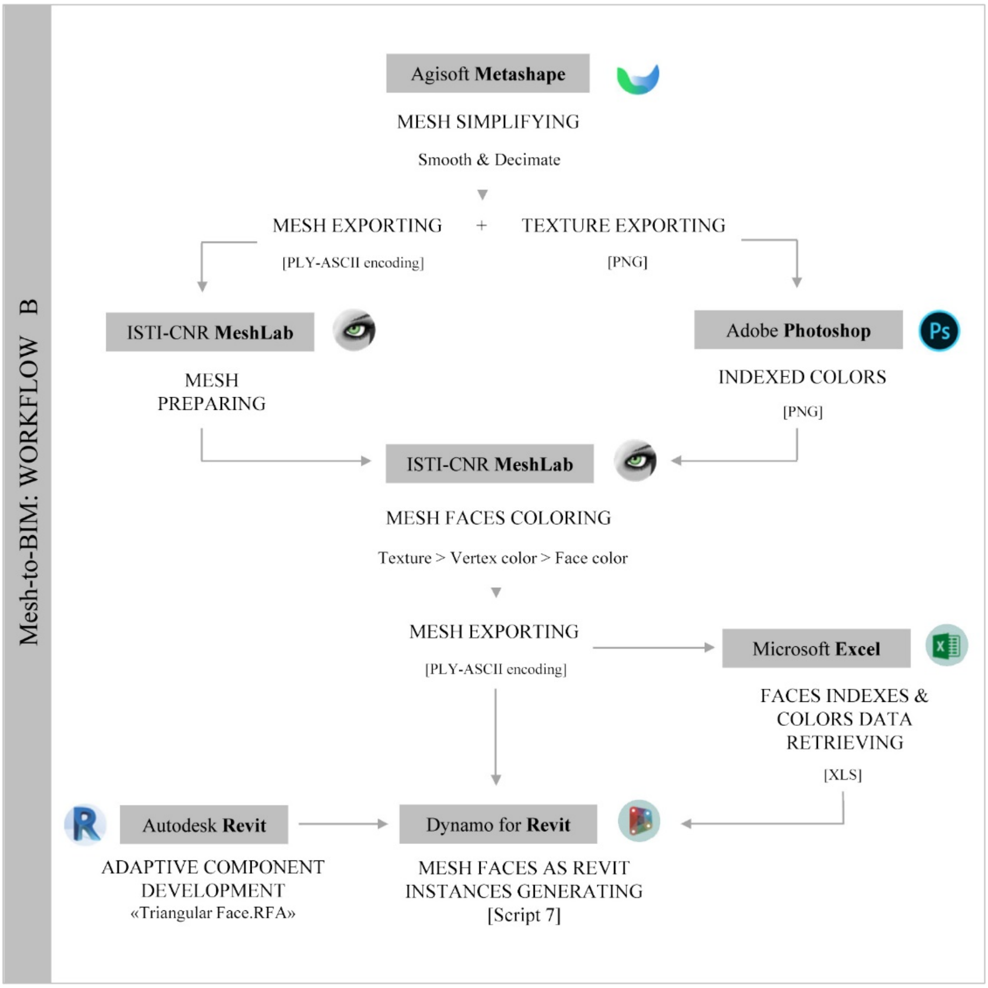


Figure 11.24 – Procedural workflow B explanatory diagram: the "*Mesh faces* as Revit *Instances* generation" step refers to the execution of the *ad-hoc* designed VPL script 7 [AoE] [3]

[Script 7] VPL script for the generation of the *Mesh Faces* as Revit *Instances* of the *"Triangular Face" Site* family

In a nutshell, the developed VPL script firstly retrieves the vertices coordinates from the same mesh in the PLY format and the related vertex indices and face colours from the spreadsheets. The photogrammetric colour information is then used to generate the minimum number of unique Revit materials corresponding to the *real colours* via the R, G, B, and alpha channel data. The proper colour material and the vertices of each mesh model face are then used as input data to set the *"Photogrammetric Color"* parameter and the *adaptive points* coordinates of the *"Triangular Face" family component* (Figure 11.49, upper) used to recreate a discretised version of the photogrammetric mesh in the BIM environment.

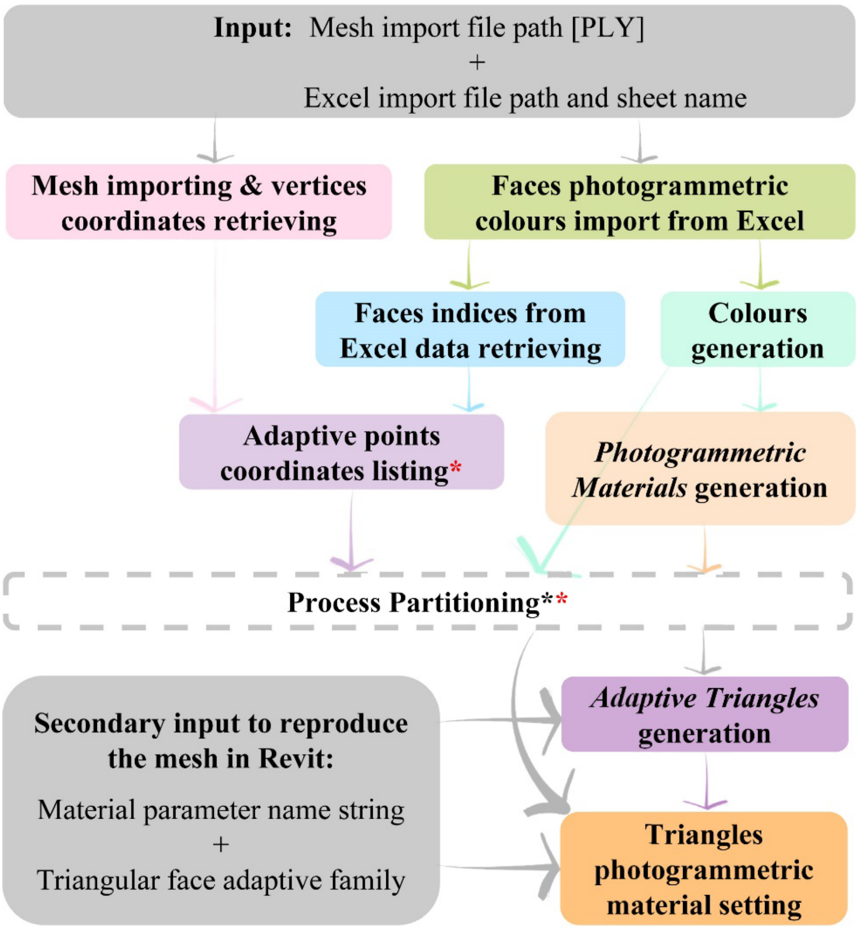


Figure 11.25 – Diagram breaking down the VPL script developed to generate the input *Mesh Faces* as Revit *Instances* of the *"Triangular Face" Site* family [AoE]

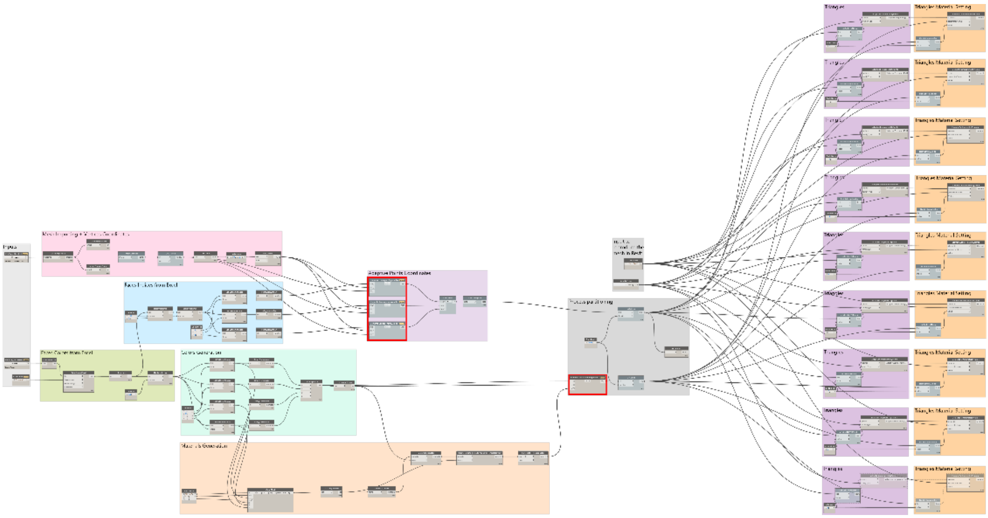


Figure 11.26 – Dynamo VPL script developed to generate the input *Mesh Faces* as Revit *Instances* of the *“Triangular Face” Site* family [AoE] [3]

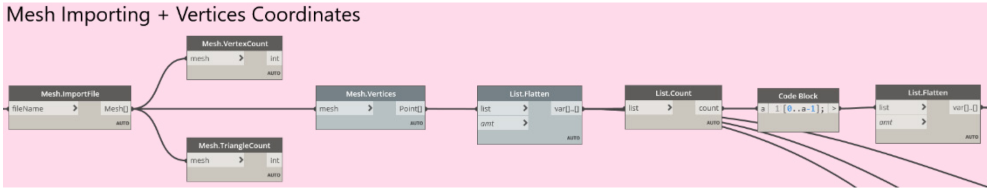


Figure 11.27 – Dynamo VPL script developed to generate the input *Mesh Faces* as Revit *Instances* of the *“Triangular Face” Site* family: Group of nodes dedicated to importing the mesh in PLY format and retrieving its vertices coordinates [AoE]

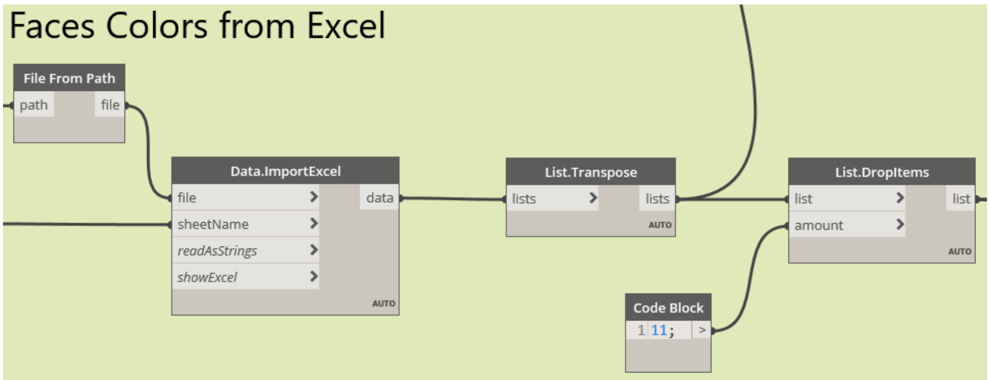


Figure 11.28 – Dynamo VPL script developed to generate the input *Mesh Faces* as Revit *Instances* of the *“Triangular Face” Site* family: Group of nodes dedicated to importing the colour assigned to each face from Excel [AoE]

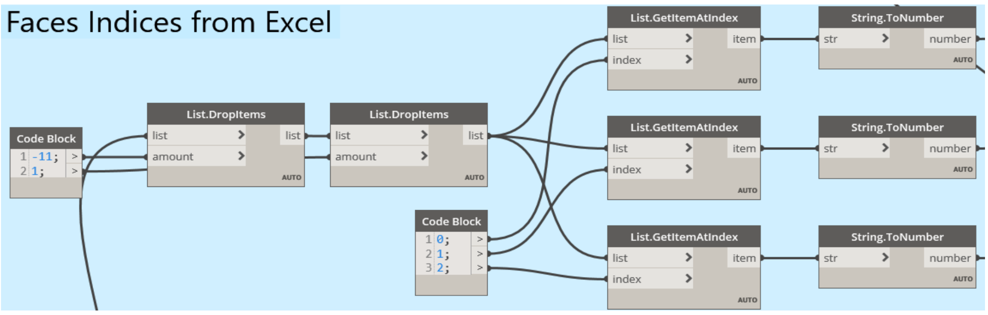


Figure 11.29 – Dynamo VPL script developed to generate the input *Mesh Faces* as Revit *Instances* of the *"Triangular Face" Site* family: Group of nodes dedicated to retrieving the mesh faces' indices from imported Excel data [AoE]

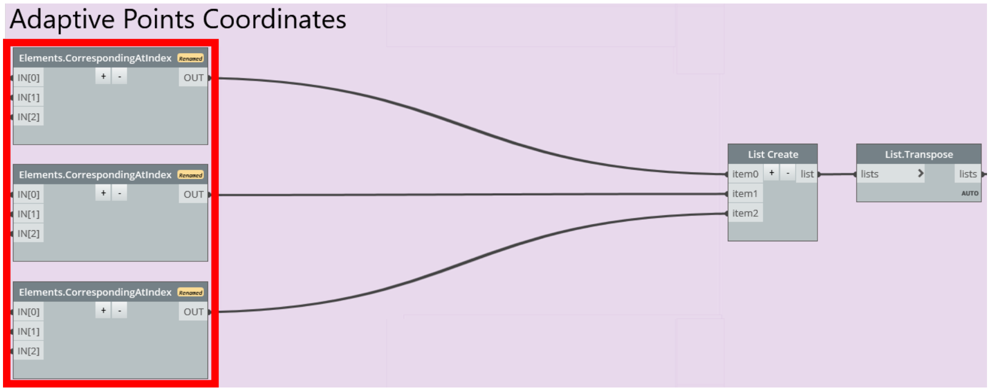


Figure 11.30 – Dynamo VPL script developed to generate the input *Mesh Faces* as Revit *Instances* of the *"Triangular Face" Site* family: Group of nodes dedicated to combining the coordinates for the *Adaptive triangles' vertices.* This group employs the custom node marked in red [AoE]

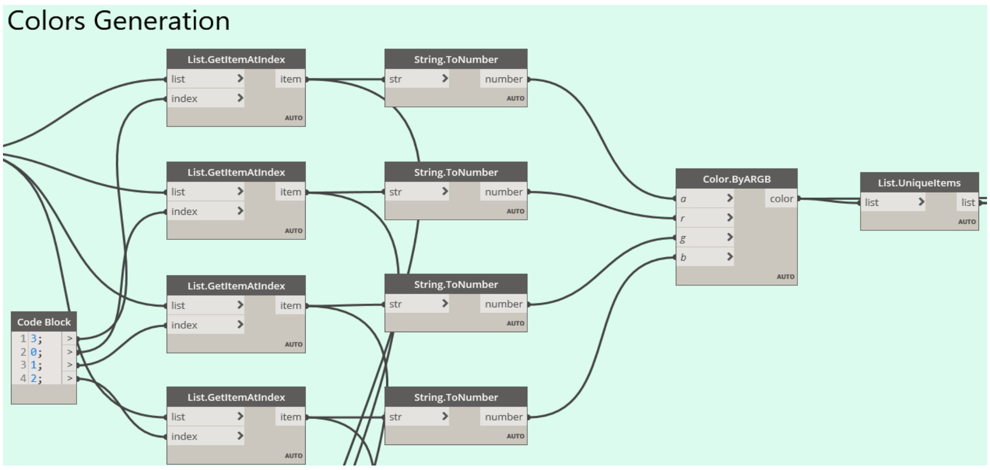


Figure 11.31 – Dynamo VPL script developed to generate the input *Mesh Faces* as Revit *Instances* of the *"Triangular Face" Site* family: Group of nodes dedicated to generating Revit colours from the photogrammetric ones [AoE]

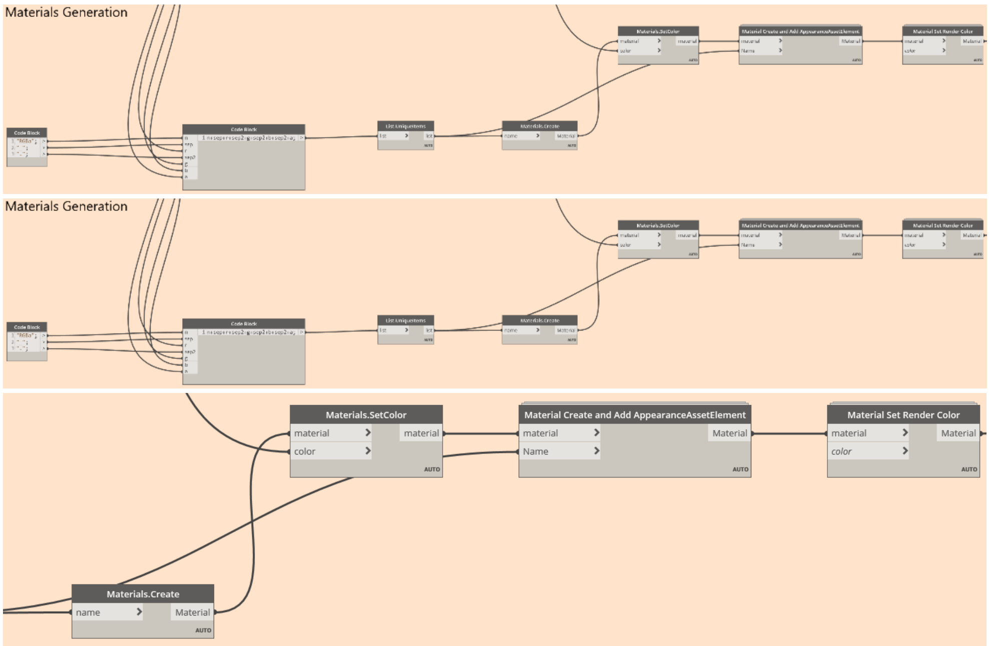


Figure 11.32 – Dynamo VPL script developed to generate the input *Mesh Faces* as Revit *Instances* of the *"Triangular Face" Site* family: Group of nodes dedicated to generating Revit material from the colours previously created [AoE]

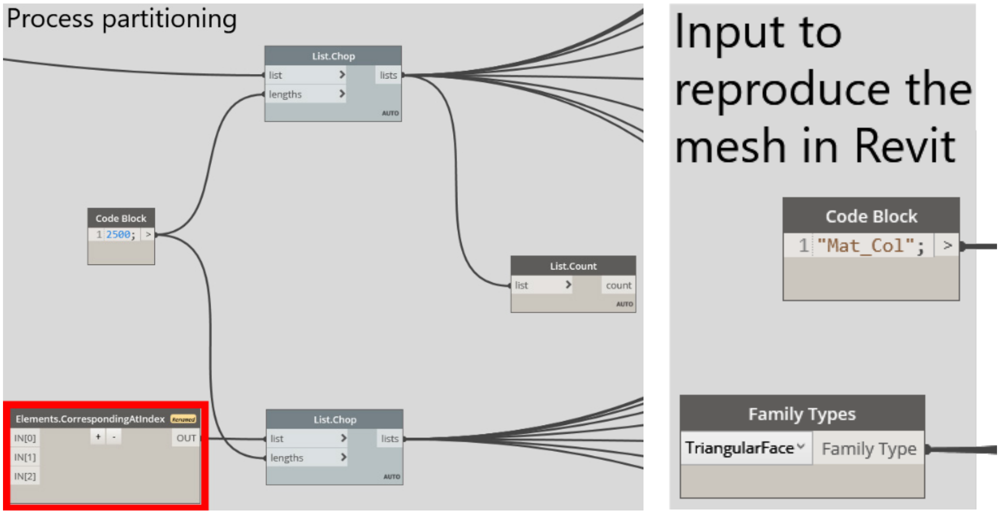


Figure 11.33 – Dynamo VPL script developed to generate the input *Mesh Faces* as Revit *Instances* of the *"Triangular Face" Site* family: Group of nodes dedicated to process partitioning*, which refers to the choice of partitioning the script by repeating the next two steps up to eight times in order to monitor the process and for the hardware to run it efficiently (left) and additional inputs for the last steps' execution (right). The process partitioning* group employs the custom node marked in red [AoE]

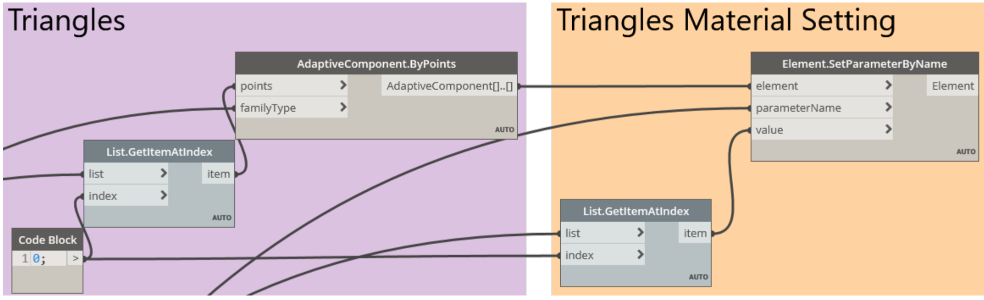


Figure 11.34 – Dynamo VPL script developed to generate the input *Mesh Faces* as Revit *Instances* of the *"Triangular Face" Site* family: Groups of nodes dedicated to generating the adaptive triangles' instances (left) and assigning to them the corresponding photogrammetric material previously created (right) [AoE]

Detailed mesh models discretising via Workflow B

Given the necessity of keeping the face count strictly under 20,000 units, for a manageable implementation of the second workflow, in terms of both the script execution and the results produced, the preparatory phase of the meshes proved to be even more relevant. A first *decimation* was performed still in the photogrammetric software on the selected areas – i.e., the areas excavated in 2020 near the temple's foundations (Figure 9.1 – areas A and D) and the eastern stone artefact (Figure 9.1 – area C).

The triangulated models were then exported, each in a PLY [ASCII encoding] format (Figure 11.35, 11.36 and 11.37) together with their *textures* [PNG] (Figure 11.38). The raster images that represented the textures were then also simplified, in Adobe Photoshop, by *indexing* their colour scale from 8 to a maximum of 15, depending on the variety of colours in the images (Figure 11.39). Once the mesh had been *decimated* again, and their edges and vertices thoroughly *cleaned* and *repaired*, employing suitable MeshLab filters, the respective textures were reapplied to project them to the vertices later and from the vertices to the faces – resulting in three texturised mesh models, listed as follows:

- *"Scavo_2_2021"* (Area A – 19,862 faces as shown in Figure 11.40)
- *"Scavo_1_2021"* (Area D – 19,381 faces as shown in Figure 11.41)
- *"Artefatto_2021"* (Area C – 17,928 faces as shown in Figure 11.42).

Once the meshes had been reexported in PLY-ASCII format, the numerical information that describes them was imported into Microsoft Excel to extract the faces-related information (Figure 11.43).

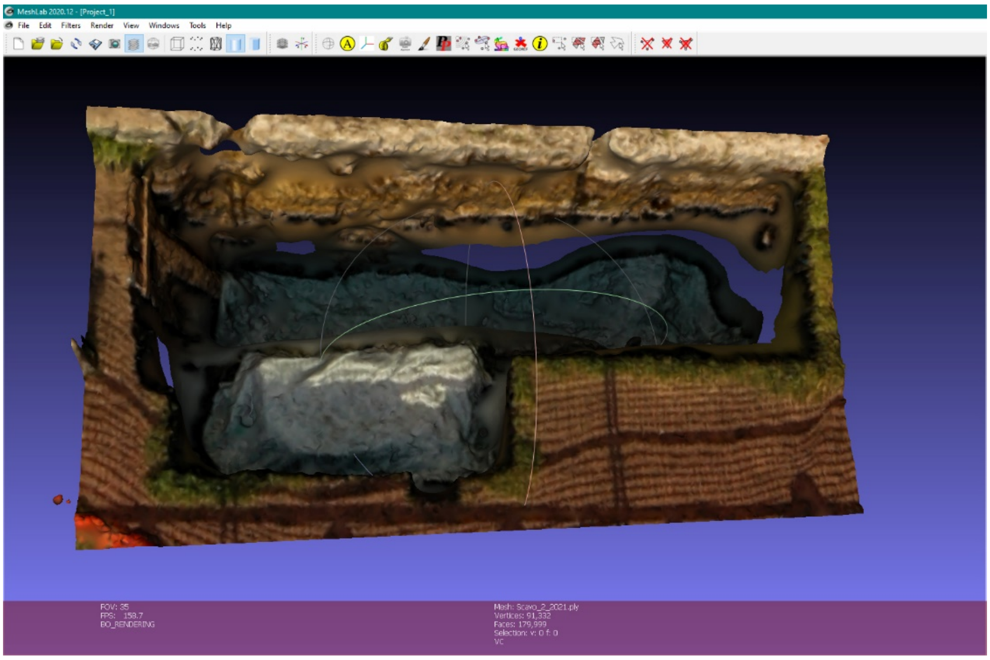


Figure 11.35 – “*Scavo_2.PLY*” (Area A) as exported from Agistoft Metashape after a first decimation of the high-quality mesh produced within the photogrammetric workflow [AoE]

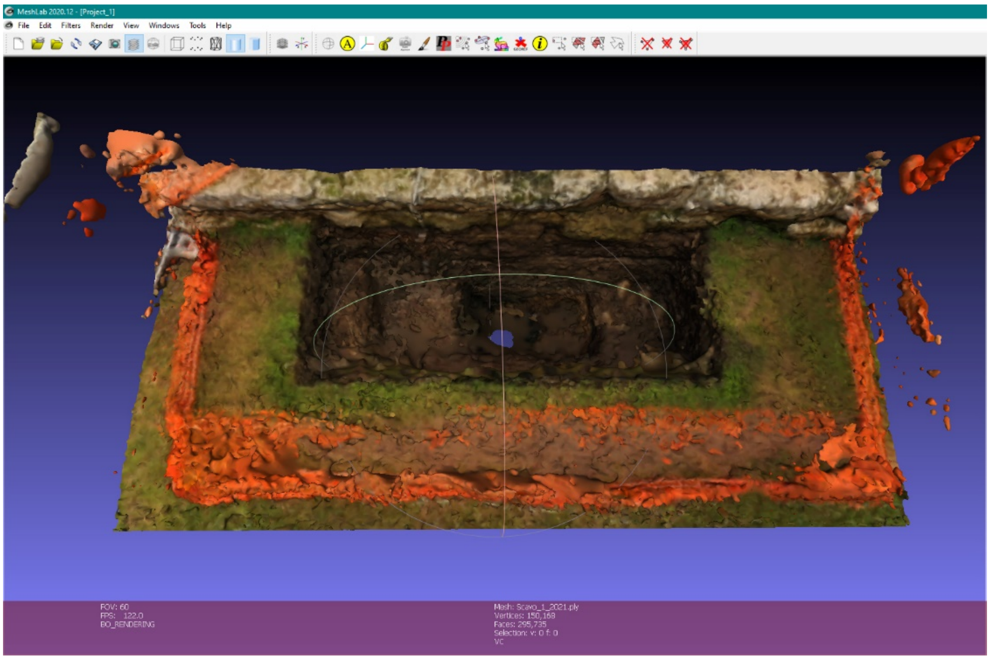


Figure 11.36 – “*Scavo_1.PLY*” (Area D) as exported from Agistoft Metashape after a first decimation of the high-quality mesh produced within the photogrammetric workflow [AoE]

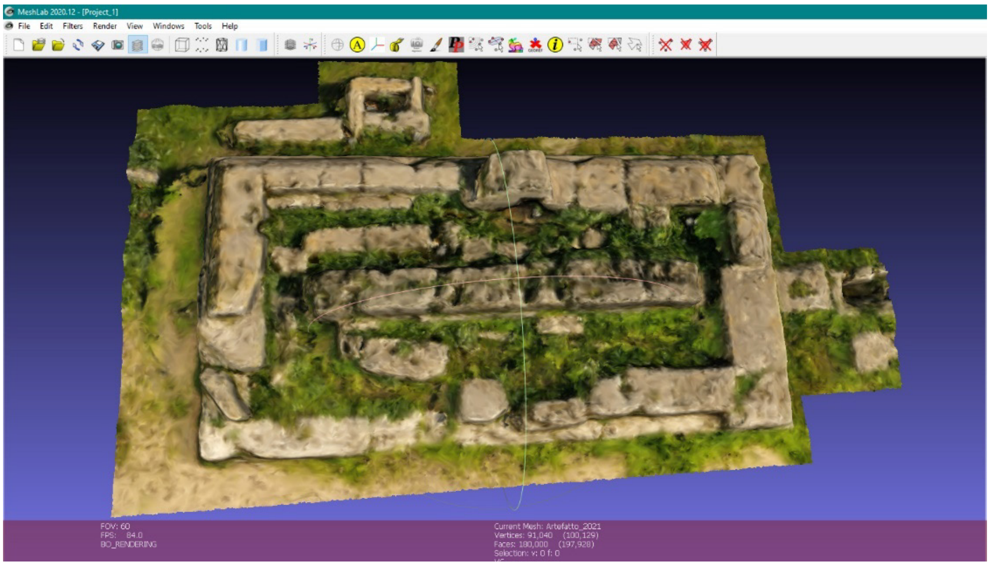


Figure 11.37 – *“Artefatto.PLY”* (Area C) as exported from Agistoft Metashape after a first decimation of the high-quality mesh produced within the photogrammetric workflow [AoE]

Figure 11.38 – Original textures in PNG format of the purged *“Scavo_2”*, *“Scavo_1”*, and *“Artefatto”* meshes before being indexed through Adobe Photoshop [AoE]

Figure 11.39 – Indexed textures (via Adobe Photoshop) in PNG format of the purged *“Scavo_2”*, *“Scavo_1”*, and *“Artefatto”* meshes [AoE]

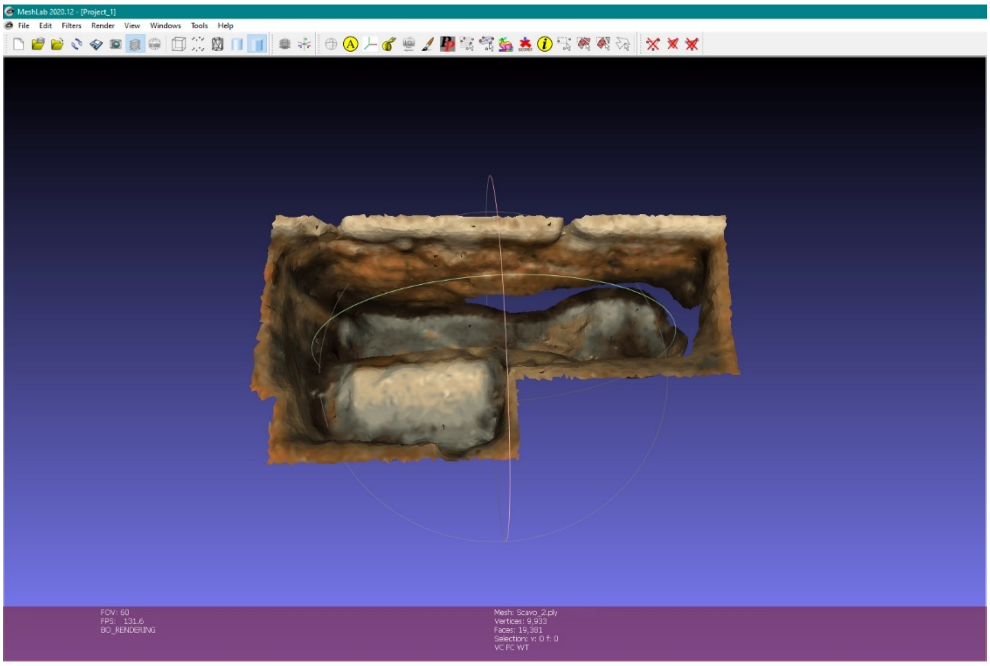


Figure 11.40 – *“Scavo_2.PLY”* (Area A) after being purged, repaired, and decimated again with the indexed texture reapplied as faces' colours [AoE]

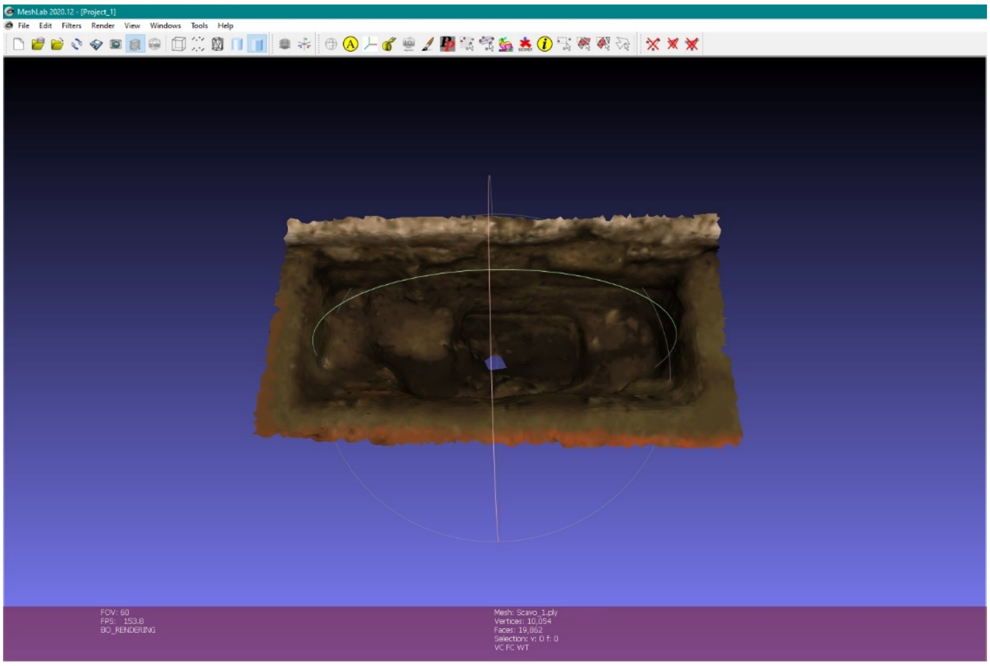


Figure 11.41 – *“Scavo_1.PLY”* (Area D) after being purged, repaired, and decimated again with the indexed texture reapplied as faces' colours [AoE]

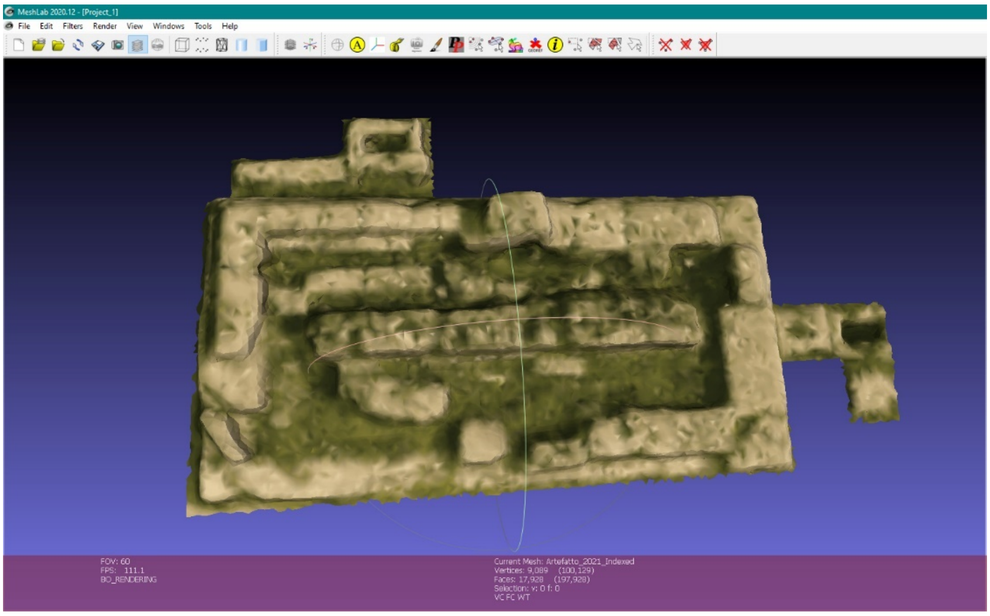
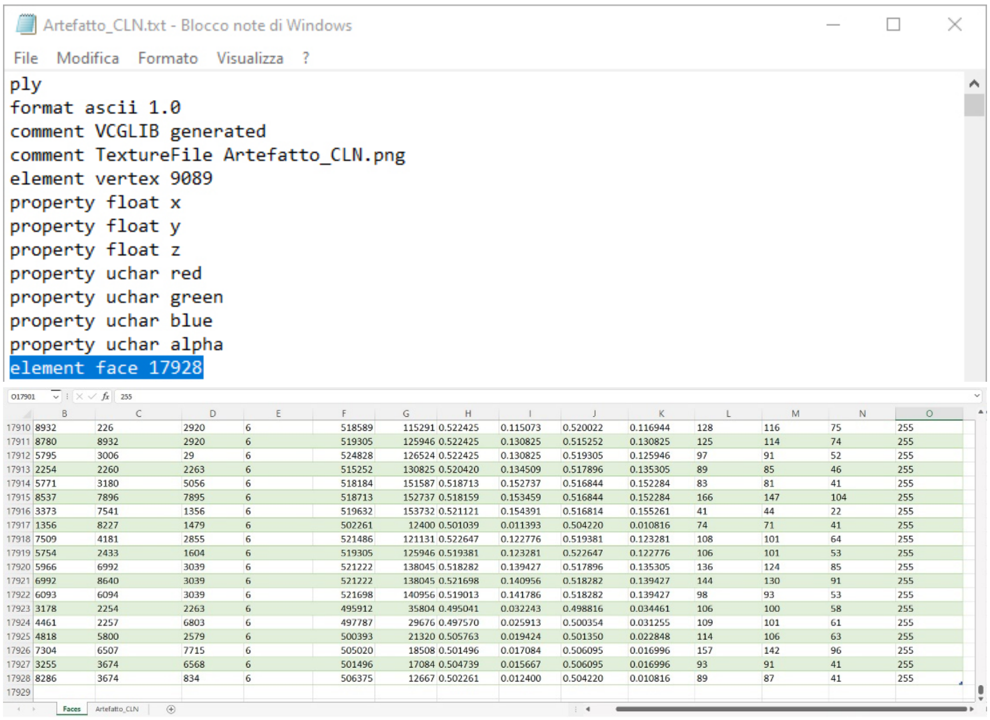


Figure 11.42 – *"Artefatto.PLY"* (Area C) after being purged, repaired, and decimated again with the indexed texture reapplied as faces' colours [AoE]




```
ply
format ascii 1.0
comment VCGLIB generated
comment TextureFile Artefatto_CLN.png
element vertex 9089
property float x
property float y
property float z
property uchar red
property uchar green
property uchar blue
property uchar alpha
element face 17928
```

	B	C	D	E	F	G	H	I	J	K	L	M	N	O
17910	8932	226	2920	6	518589	115291	0.522425	0.115073	0.520022	0.116944	128	116	75	255
17911	8780	8932	2920	6	519305	125946	0.522425	0.130825	0.515252	0.130825	125	114	74	255
17912	5795	3006	29	6	524828	126524	0.522425	0.130825	0.519305	0.125946	97	91	52	255
17913	2254	2260	2263	6	515252	130825	0.520420	0.134509	0.517896	0.135305	89	85	46	255
17914	5771	3180	5056	6	518184	151587	0.518713	0.152737	0.516844	0.152284	83	81	41	255
17915	8537	7896	7895	6	518713	152737	0.518159	0.153459	0.516844	0.152284	166	147	104	255
17916	3373	7541	1356	6	519632	153732	0.521121	0.154391	0.516814	0.155261	41	44	22	255
17917	1356	8227	1479	6	502261	12400	0.501039	0.011393	0.504220	0.010816	74	71	41	255
17918	7509	4181	2855	6	521486	121131	0.522647	0.122776	0.519381	0.123281	108	101	64	255
17919	5754	2433	1604	6	519305	125946	0.519381	0.123281	0.522647	0.122776	106	101	53	255
17920	5966	6992	3039	6	521222	138045	0.518282	0.139427	0.517896	0.135305	136	124	85	255
17921	6992	8640	3039	6	521222	138045	0.521698	0.140956	0.518282	0.139427	144	130	91	255
17922	6093	6094	3039	6	521698	140956	0.519013	0.141786	0.518282	0.139427	98	93	53	255
17923	3178	2254	2263	6	495912	35804	0.495041	0.032243	0.498816	0.034461	106	100	58	255
17924	4461	2257	6803	6	497787	29676	0.497570	0.025913	0.500354	0.031255	109	101	61	255
17925	4818	5800	2579	6	500393	21320	0.505763	0.019424	0.501350	0.022848	114	106	63	255
17926	7304	6507	7715	6	505020	18508	0.501496	0.017084	0.506095	0.016996	157	142	96	255
17927	3255	3674	6568	6	501496	17084	0.504739	0.015667	0.506095	0.016996	93	91	41	255
17928	8286	3674	834	6	506375	12667	0.502261	0.012400	0.504220	0.010816	89	87	41	255
17929														

Figure 11.43 – Example of the *"Artefatto"* mesh data (which readability was ensured by choosing the ASCII encoding format) imported into Excel to isolate the faces-related information [AoE]

Each of the three meshes was then reproduced in a single Revit project, using both the mesh in the PLY format and the related numeric data in XLSX as inputs for the VPL script (Figure 11.25); the former for determining and transforming the vertices into Dynamo points, the latter to retrieve the indices and the colours of the faces in order to generate triangles, belonging to the *"Triangular Face.RFA" family*, placed via their adaptive points, corresponding, in sequences of three, to the vertices of the meshes according to the order given by the indices.
After the generation of the triangular instances, the subsequent step was to assign the effective colours, as the newly realised Revit Materials, to the *"Photogrammetric Color" parameter*. Lastly, the adaptive triangles to be created were partitioned into 2,000-unit batches for the hardware to be able to process the script.
At the end of the second workflow application, four independent and correctly georeferenced – via the procedures explained in Chapter 10 – Revit projects, i.e., "*Scavo_1 _2021*.RVT", "*Scavo_2_2021*.RVT", and "*Artefatto_2021*.RVT" were produced too (Figures 11.44, 11.45, and 11.46).

Figure 11.44 – Federated Revit projects rendered overview representing the Temple of Neptune and its surroundings as of 2021 with the reprojected detailed areas marked in yellow [AoE]

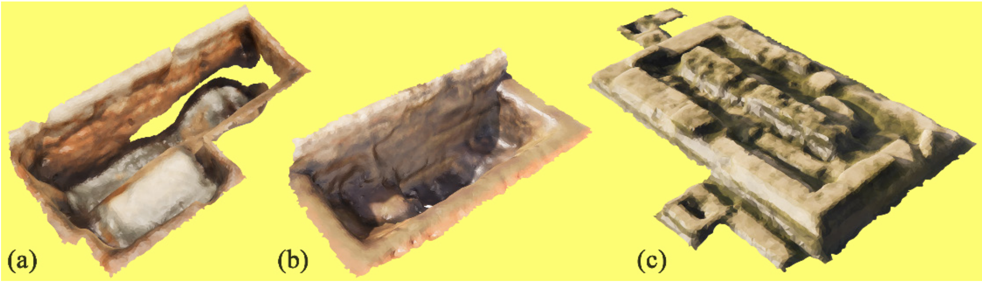


Figure 11.45 – Rendered views (via the real-time rendering plug-in Enscape for Revit) of the (a) *“Scavo_2_2021.RVT”*, (b) *“Scavo_1_2021. RVT”*, and (c) *“Artefatto_2021.RVT”*.

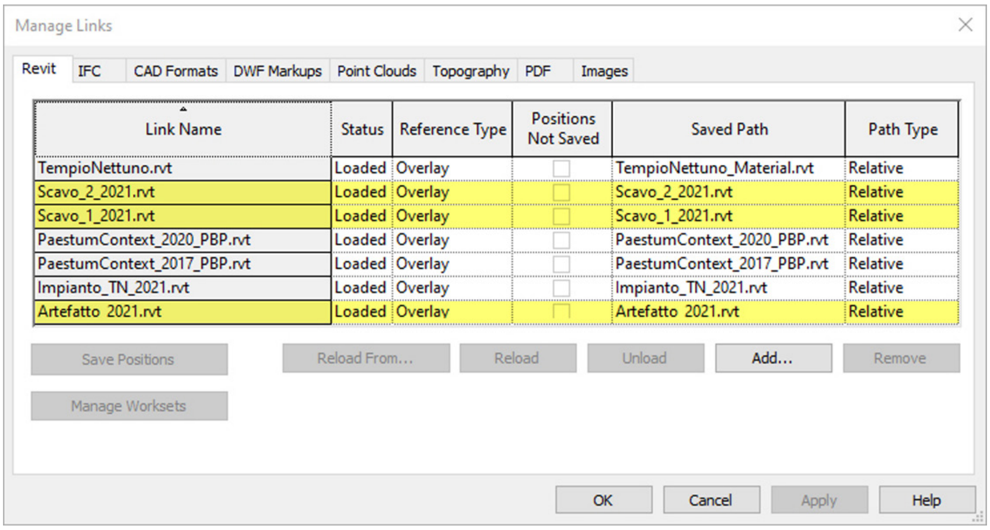


Figure 11.46 – Federated Revit projects overview of the reprojected detailed areas highlighted in yellow within the *Manage Links* dialogue box [AoE]

Figure 11.47 – Federated Revit projects rendered South-Western view representing the Temple of Neptune and its surroundings as of 2021 [AoE]

Figure 11.48 – Federated Revit projects rendered North-Eastern view representing the Temple of Neptune and its surroundings as of 2021 [AoE]

LOI enhancement for future assessments

It is worth mentioning that both workflow A and B keep an acceptable degree of approximation along the process, if we take into account the simplifications required by any modelling approach, indeed quantum physicist Niels Bohr would tell us that: *"When we measure something we are forcing an undetermined, undefined world to assume an experimental value; we are not measuring the world, we are creating it"*.
Additionally, in the case of flat surfaces both procedures would virtually produce the same geometrically accurate outputs. Anyway, small vertical imprecision may even be neglected when we are not interested in reaching the highest level of development for the selected areas. On the contrary, the consistent difference between the workflows lies in the discretisation of the imported mesh model by means of the *ad-hoc* developed *"Triangular Face.RFA"* element (Figure 11.49). This component is characterised by *Adaptive Vertices* – so as to be easily placed

just by picking three points in the space – and a set of *Shared Parameters*[53]: the *“Photogrammetric Material”*, the three sides, i.e., *“L1”*, *“L2”*, and *“L3”* – set as report parameters –, the *“Area”* – to be calculated via the *Heron’s formula* by running another simple VPL script (Script 8 explained via Figures 11.49, 11.50, 11.51, and 11.52) that uses *“L1”*, *“L2”*, and *“L3”* as inputs – and the *“Comment”* – set to be manually filled out – thus allowing their selection, filtering and scheduling in report sheets for possible future assessment (Figure 11.53).

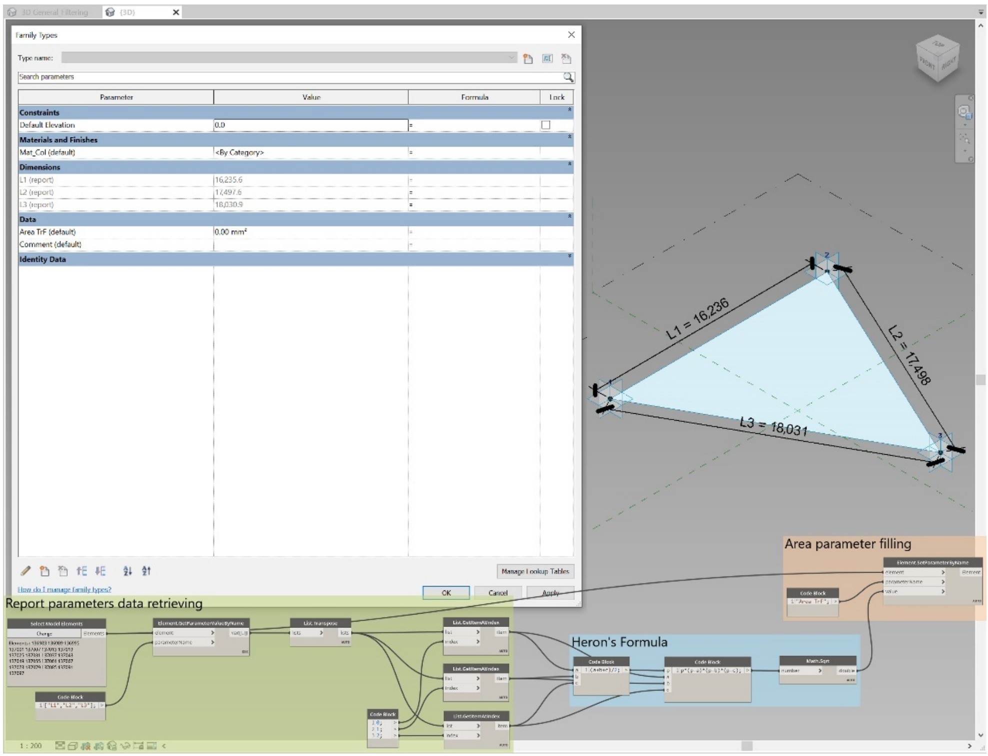


Figure 11.49 – Overview of the further implemented parameters for the *“Triangular Face.RFA”* adaptive component (upper) in order to calculate, e.g., the area of each triangular instance via the *Heron’s Formula* (implemented through script 8 – lower) [AoE] [3]

[53] Shared parameters are parameter definitions that can be used in multiple families or projects. Their definitions are stored in a file independent of any family file or Revit project; this allows one to access the file from different families or projects. The shared parameter is a definition of a container for information that can be used in multiple families or projects. To learn more about shared parameters, visit: https://knowledge.autodesk.com/support/revit/learn-explore/caas/CloudHelp/cloudhelp/2018/ENU/Revit-Model/files/GUID-E7D12B71-C50D-46D8-886B-8E0C2B285988-htm.html.

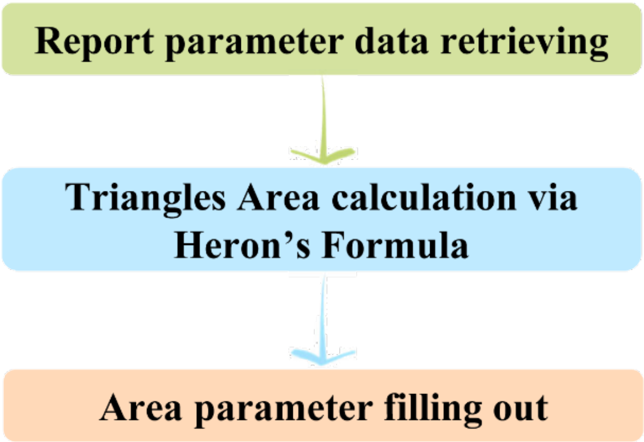


Figure 11.50 – Diagram breaking down the VPL script developed to run the *Heron's Formula* calculations for the *triangular faces' instances* [AoE]

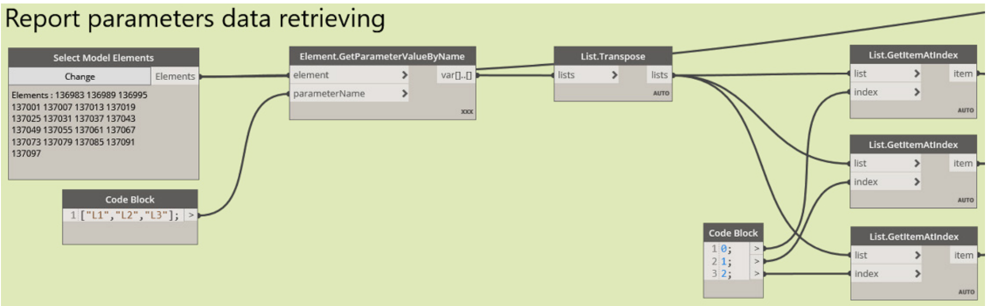


Figure 11.51 – Dynamo VPL script developed to run the *Heron's Formula* calculations for the *triangular faces' instances*: Group of nodes dedicated to retrieving the report parameters data, i.e., *"L1"*, *"L2"*, and *"L3"* [AoE]

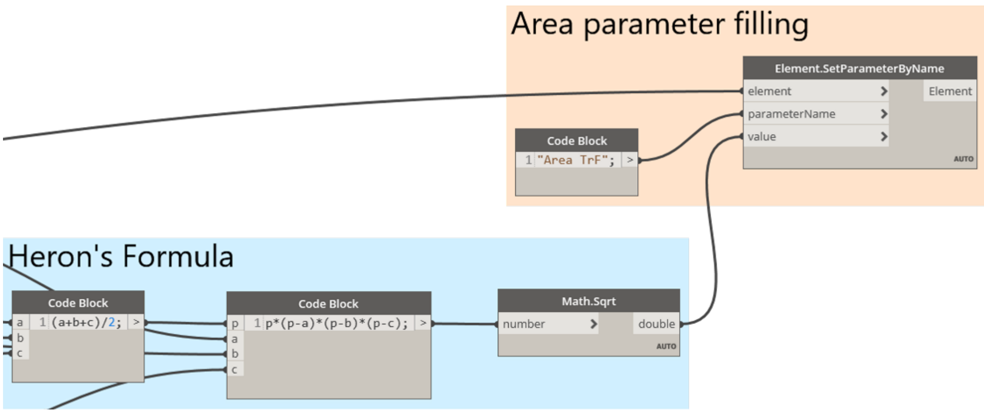
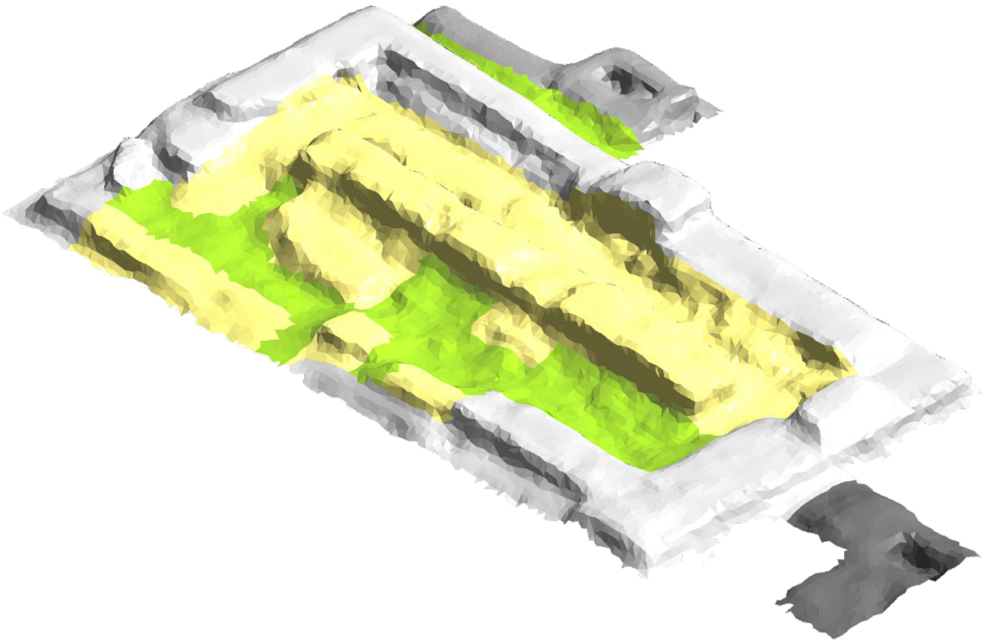


Figure 11.52 – Dynamo VPL script developed to run the *Heron's Formula* calculations for the *triangular faces' instances*: Groups of nodes dedicated to actually execute the *Heron's Formula* calculations and to filling the *triangular faces "Area"* parameter [AoE]



Triangular Face - Site Schedule

<Triangular Face - Site Schedule>						
A	B	C	D	E	F	G
Family	L1	L2	L3	Area TrF	Photogrammetric Color	Comment
TriangularFace	<varies>	<varies>	<varies>	33.556 m²	<varies>	External
TriangularFace	<varies>	<varies>	<varies>	3.814 m²	<varies>	External_East
TriangularFace	<varies>	<varies>	<varies>	3.826 m²	<varies>	External_South
TriangularFace	<varies>	<varies>	<varies>	11.313 m²	<varies>	Ground
TriangularFace	<varies>	<varies>	<varies>	28.200 m²	<varies>	Semi-Covered

Figure 11.53 – Example of the visual filtering (upper) and scheduling (lower) possibilities resulting from workflow B further implementations where the cumulative areas for each group of filtered triangles have been calculated (e.g., *"Artefatto_2021"* detailed Area) [AoE]

12. Seismometers network integration within the shared environment

The monitoring network consisting of seismometric sensors placed between the end of 2020 and the beginning of 2021 was also modelled using ad-hoc developed MEP families with a lower level of geometric detail – LOG 200 (purely volumetric). Subsequently, the information database related to the measurement instruments and real-time monitoring data available to date were linked to the MEP model via a VPL script (Script 10 – explained in detail from Figure 12.12 to Figure 12.28) customised onto this specific seismometer network. The full comprehension and utilisation of the seismometer signals are still under evaluation [252], as the network is still in the run-in phase, so the BIM interface had to be designed to be sufficiently flexible and upgradeable. To this end, the script was explicitly designed for possible future upgrades of the monitoring system by choosing Microsoft Excel as the source database and further automating the implementation of possible additionally required system descriptors defined as *shared parameters* (Script 9 – explained in detail from Figure 12.6 to Figure 12.11). Furthermore, the linked pictures useful to better understand the system have been made available online via an openly shared Google Drive folder.

12.1 Discretisation of the monitoring network and LOI enhancement

The seismometric monitoring network was modelled as a Revit MEP [*Mechanical, Electrical, and Plumbing engineering*] project, using the Temple's structural model as a baseline. First, for the establishment of a properly federated model [FSC], an empty RVT project was generated, named *"Impianto_TN_2021"*, which was attached to the overall shared environment using its internal PBP for reference; then, the shared coordinates were published back to the project and stored as its new internal origin. From then on, it was possible to interconnect each of the federated projects through the shared coordinates, thus avoiding any undetected interference. In particular, in order to model the monitoring network without any mistakes, the project containing the BIM model of the temple, i.e., *"TempioNettuno.RVT"*, was linked into the MEP project (Figure 12.1) so that the measurement points on the cornice and on the ground near the foundations could be precisely positioned.

As thoroughly explained in section 9.3, the monitoring network is essentially composed of DAQ [*Data Acquisition System*] installed in several of the *Measuring Points* and all connected to the *Totem-Leggio* cabinet, which transfers the data to the central acquisition and control unit located in the *Archaeological Park Museum* offices. Thus, four volumetric families were created for the purpose:

- a *"Data Acquisition System"* family: assigned to the *Data Devices Revit category* (Figure 12.2);
- a *"Measuring Point"* and an *"R.C. Manhole"* families: the first assigned to the *Data Devices Revit category* and the latter to the *Structural Foundations category*, respectively representing the measuring points placed upon the temple Cornice and those near the foundations (Figure 12.3 and 12.4);
- a *"Totem-Leggio"* family, also shaped as an inspectable manhole, but assigned to the *Data Devices Revit category* (Figure 12.5).

In the following pages, the functioning of the scripts developed for updating the monitoring network will be graphically explained, starting with a synthetic diagram followed by an overview of the VLP script organised into groups of nodes dedicated to the execution of a particular operation summarised by the title assigned to each group. In addition, to facilitate readability, zooms-in will be included for each group, and, where necessary, synthesised images of the input and/or output information will also be added, too.

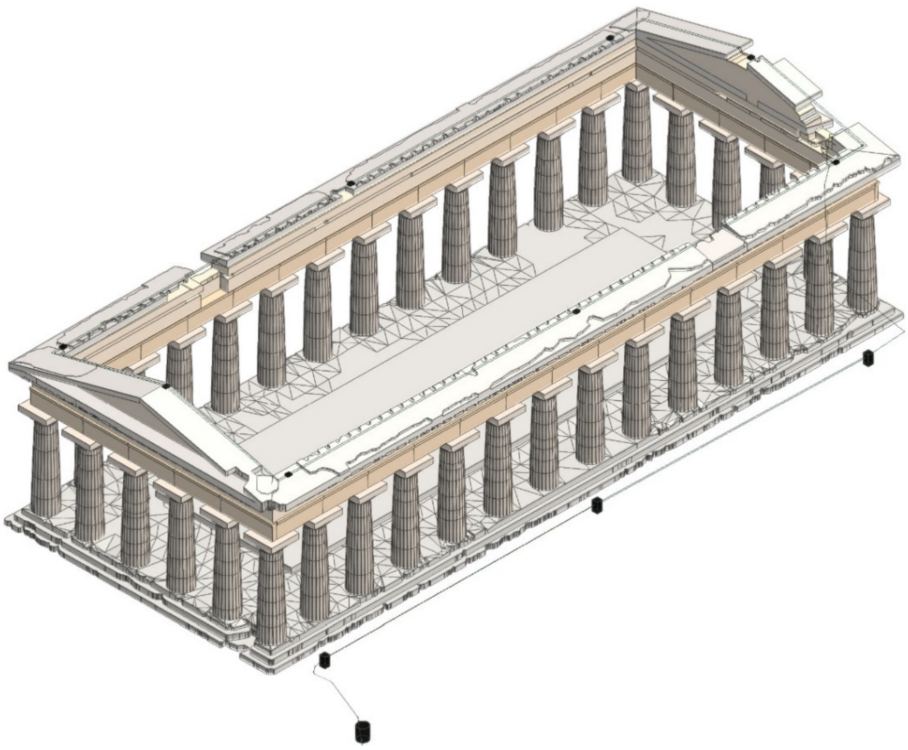


Figure 12.1 – Monitoring seismometers network overlayed upon the linked BIM model of the Temple of Neptune [AoE]

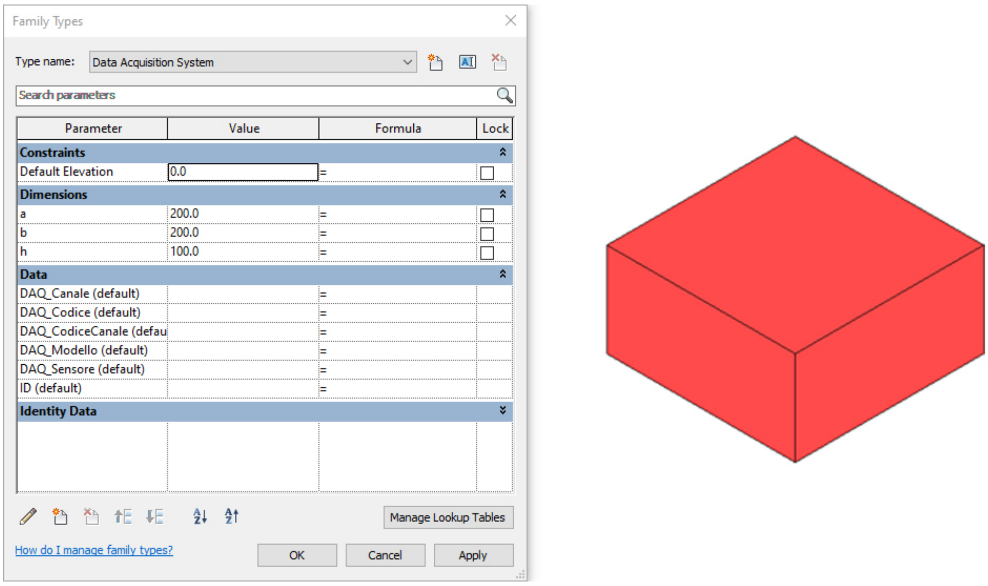


Figure 12.2 – Overview of the *"Data Acquisition System"* family (right) with its shared parameters (left) [AoE]

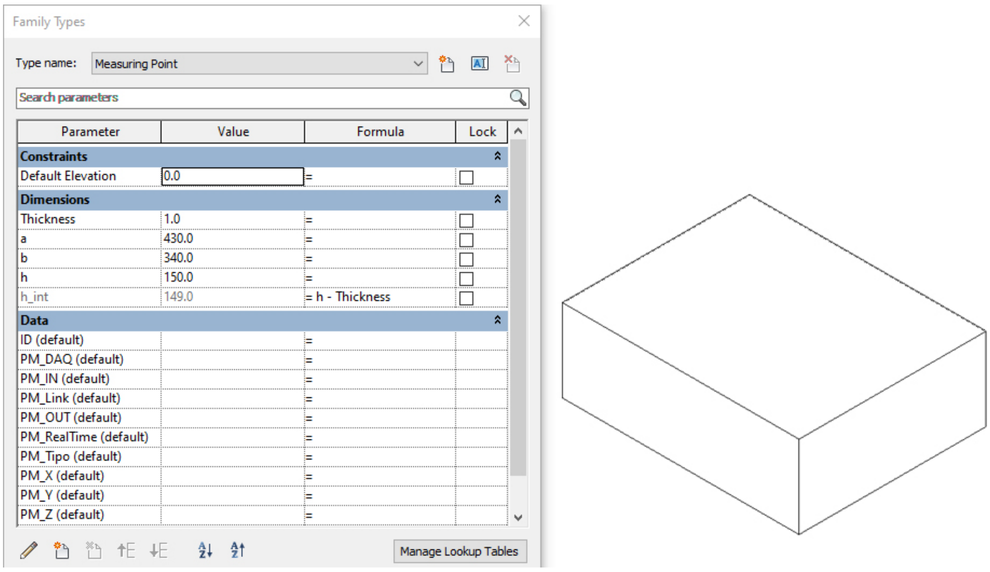


Figure 12.3 – Overview of the *"Measuring Point"* family (right) with its shared parameters (left) [AoE]

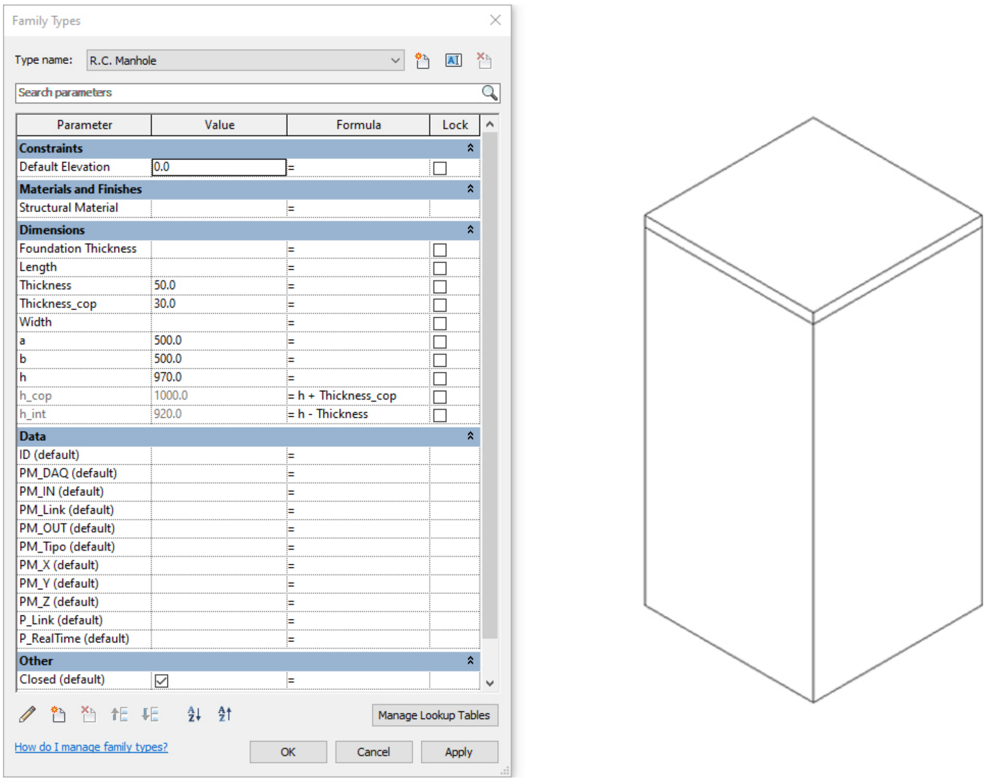


Figure 12.4 – Overview of the *"R.C. Manhole"* family (right) with its shared parameters (left) [AoE]

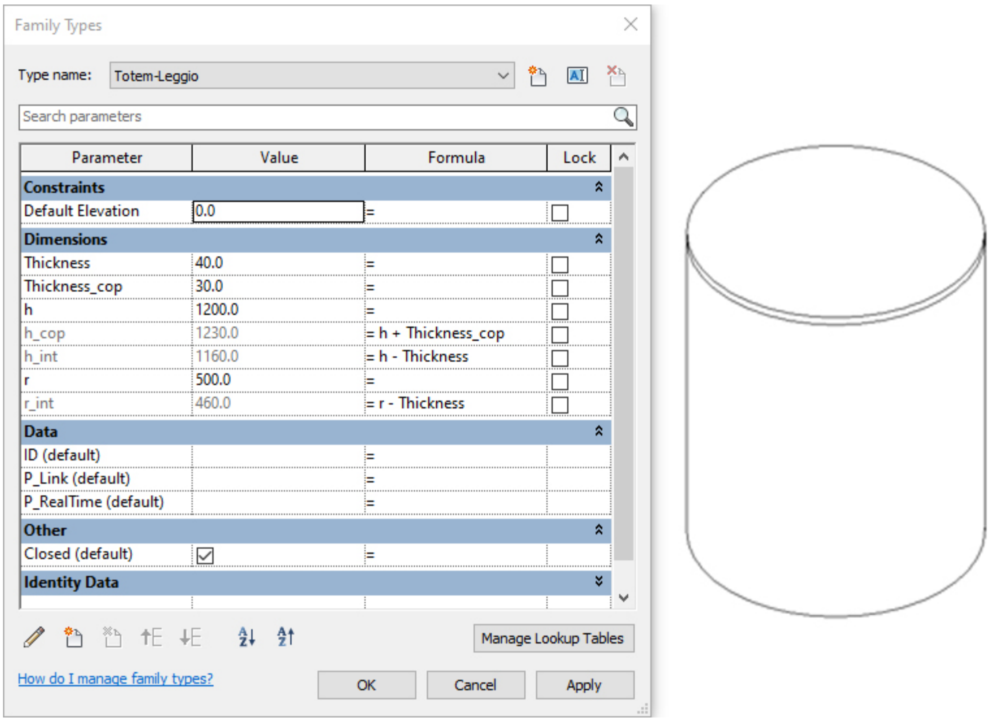


Figure 12.5 – Overview of the *"Totem-Leggio"* family (right) with its shared parameters (left) [AoE]

[Script 9] VPL script for automatic background implementing of additional *shared parameters* for the *sensors'* families

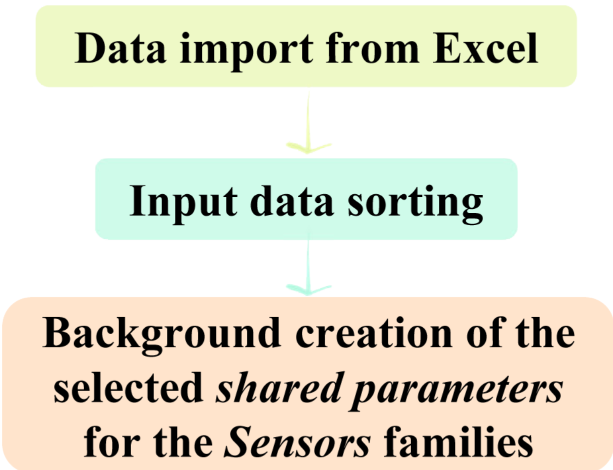


Figure 12.6 – Diagram breaking down the VPL script developed to automatically implement in background additional *shared parameters* within the *sensors'* families [AoE]

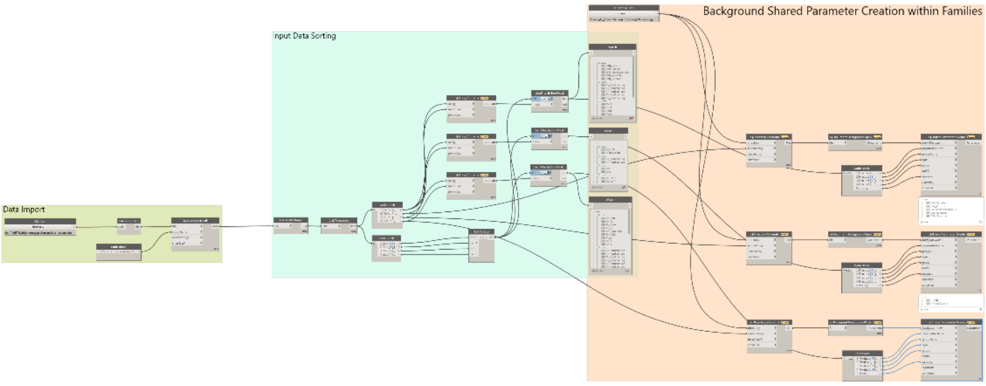


Figure 12.7 – Dynamo VPL script developed to automatically implement in background additional *shared parameters* within the *sensors'* families [AoE]

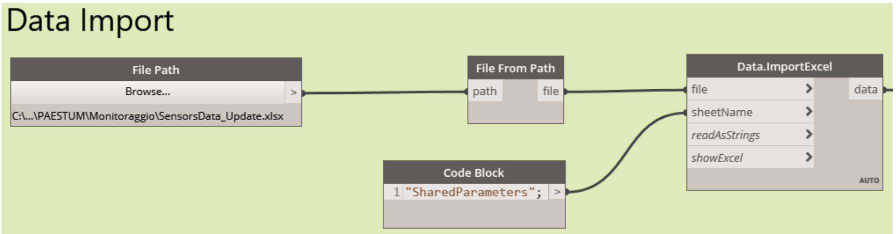


Figure 12.8 – Dynamo VPL script developed to automatically implement in background additional *shared parameters* within the *sensors'* families: Group of nodes dedicated to importing *sensors*' updated data from Excel [AoE]

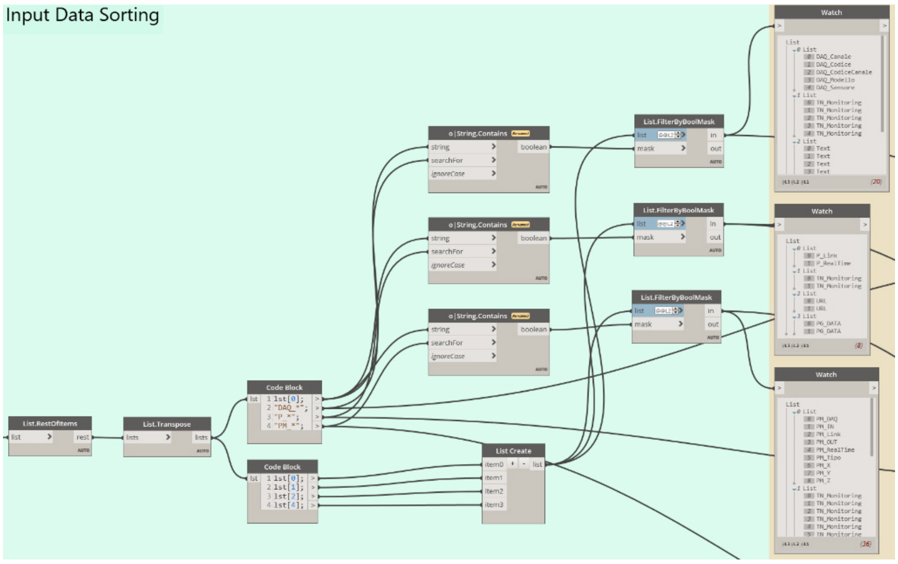


Figure 12.9 – Dynamo VPL script developed to automatically implement in background additional *shared parameters* within the *sensors'* families: Group of nodes dedicated to sorting data imported from Excel [AoE]

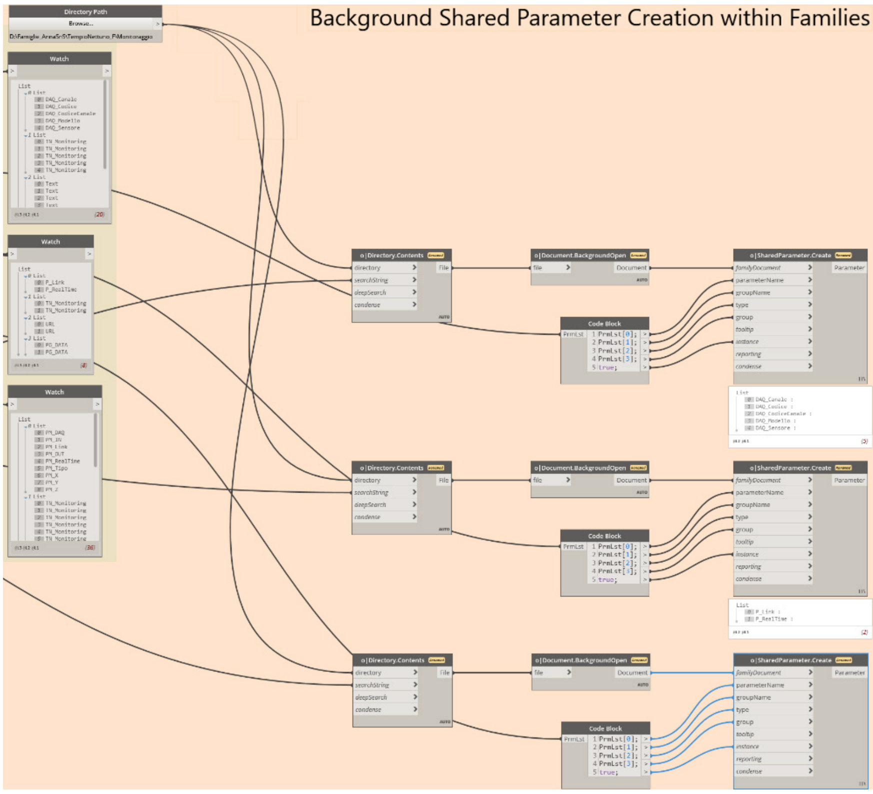


Figure 12.10 – Dynamo VPL script developed to automatically implement in background additional *shared parameters* within the *sensors'* families: Group of nodes dedicated to creating the additional *shared parameters* without manually opening and closing the Revit families [AoE]

SP_Name	SP_Group	ParameterType	ParameterGroup	RevitGroupName
DAQ_Canale	TN_Monitoring	Text	Data	PG_DATA
DAQ_Codice	TN_Monitoring	Text	Data	PG_DATA
DAQ_CodiceCanale	TN_Monitoring	Text	Data	PG_DATA
DAQ_Modello	TN_Monitoring	Text	Data	PG_DATA
DAQ_Sensore	TN_Monitoring	Text	Data	PG_DATA
P_Link	TN_Monitoring	URL	Data	PG_DATA
P_RealTime	TN_Monitoring	URL	Data	PG_DATA
PM_DAQ	TN_Monitoring	Text	Data	PG_DATA
PM_IN	TN_Monitoring	Text	Data	PG_DATA
PM_Link	TN_Monitoring	URL	Data	PG_DATA
PM_OUT	TN_Monitoring	Text	Data	PG_DATA
PM_RealTime	TN_Monitoring	URL	Data	PG_DATA
PM_Tipo	TN_Monitoring	Text	Data	PG_DATA
PM_X	TN_Monitoring	Text	Data	PG_DATA
PM_Y	TN_Monitoring	Text	Data	PG_DATA
PM_Z	TN_Monitoring	Text	Data	PG_DATA

Figure 12.11 – Input Excel data detailing the name [*"SP_Name"*], the group [*"SP_Group"*], the parameter type – e.g., textual, URL directory, number, etc. – [*"ParameterType"*], the Revit property's group [*"ParameterGroup"*], and the related Revit property's group nomenclature [*"RevitGroupName"*] of the additional *shared parameters* [AoE]

[Script 10] VPL script customised to update the seismometer network

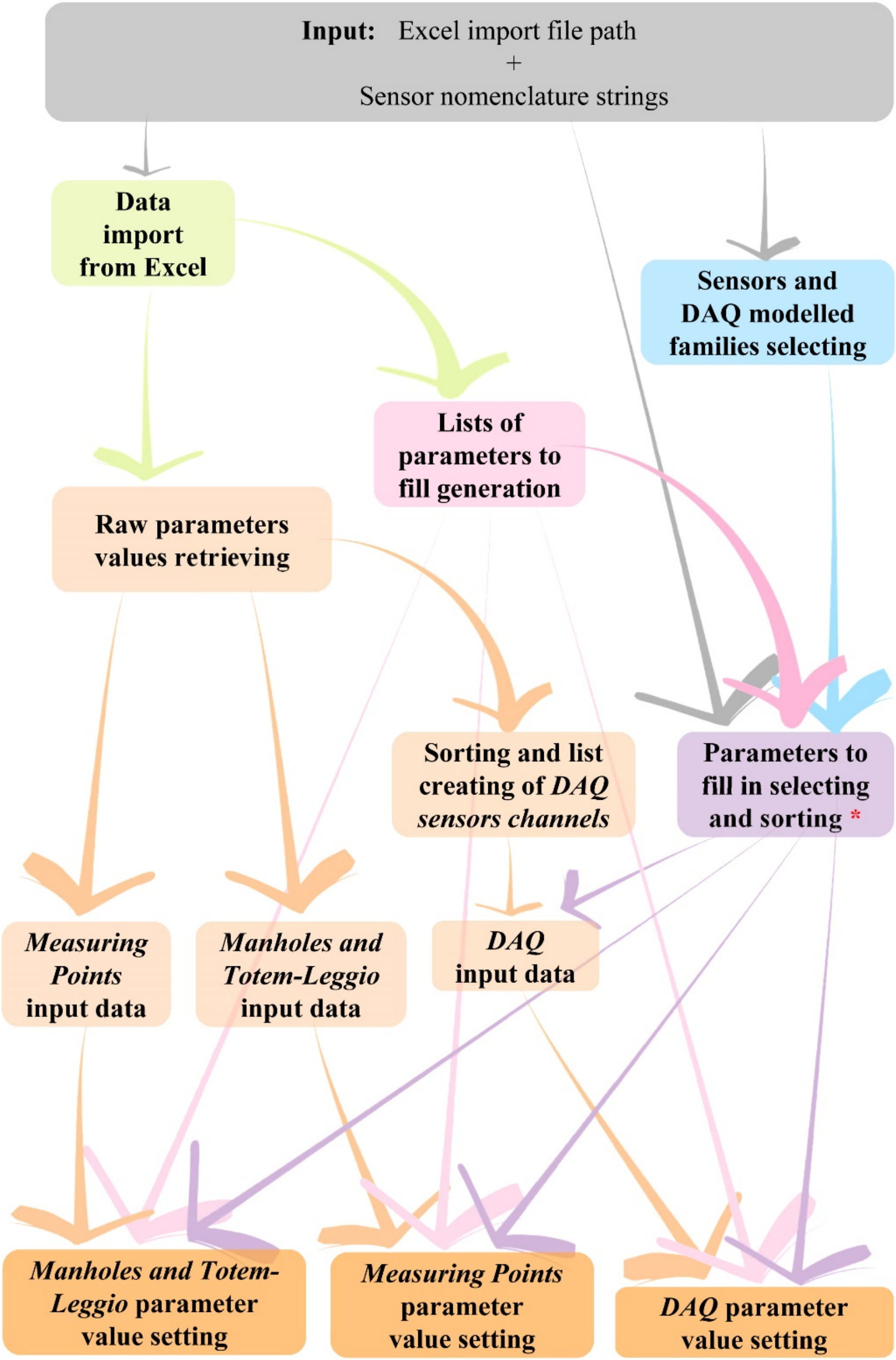


Figure 12.12 – Diagram breaking down the VPL script developed to keep the seismometer monitoring network updated [AoE]

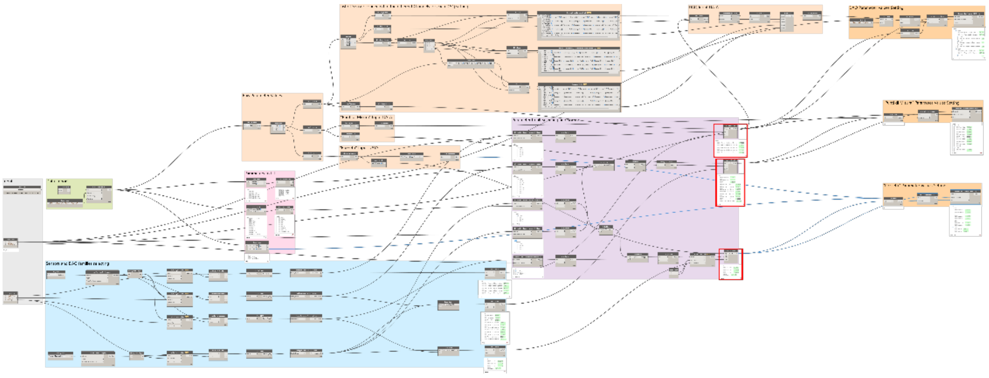


Figure 12.13 – Dynamo VPL script developed to keep the seismometer monitoring network updated [AoE]

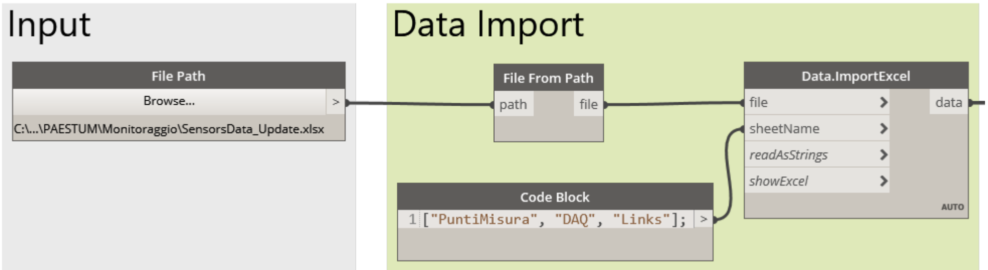
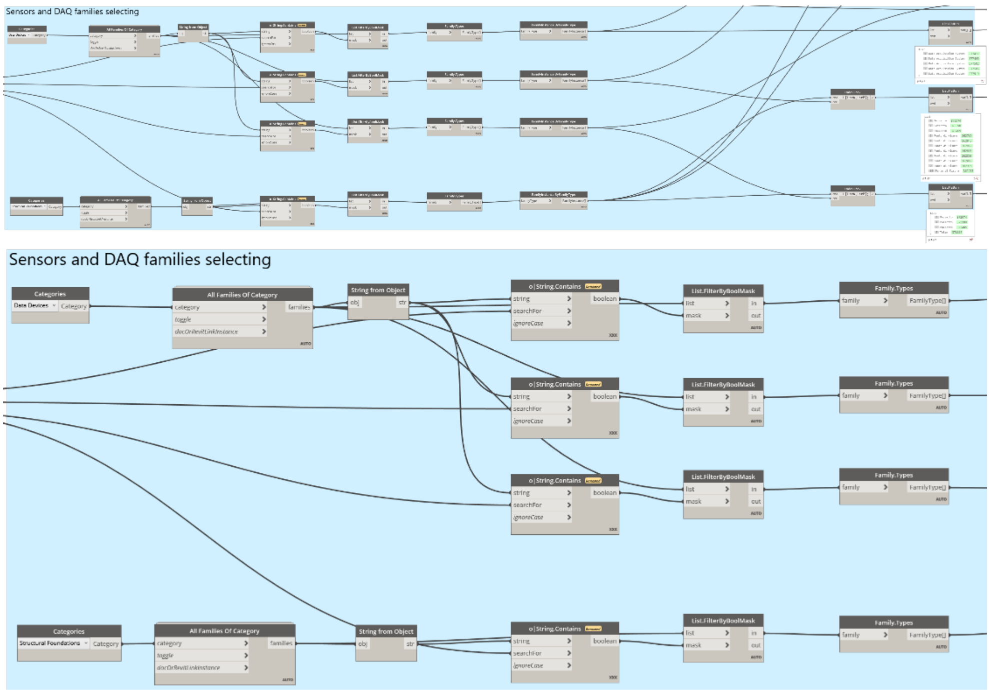


Figure 12.14 – Dynamo VPL script developed to keep the seismometer monitoring network updated: Groups of nodes dedicated to importing updated data from Excel [AoE]



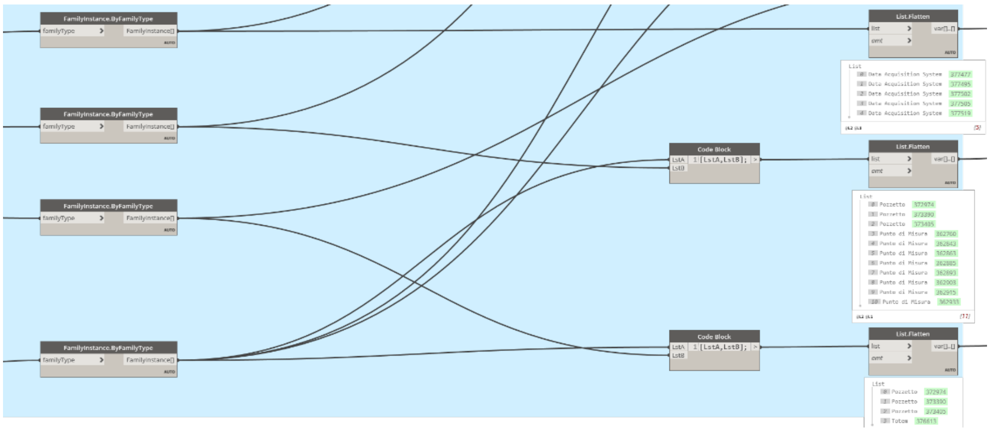


Figure 12.15 – Dynamo VPL script developed to keep the seismometer monitoring network updated: Groups of nodes dedicated to selecting modelled instances of the Sensors' and DAQ families [AoE]

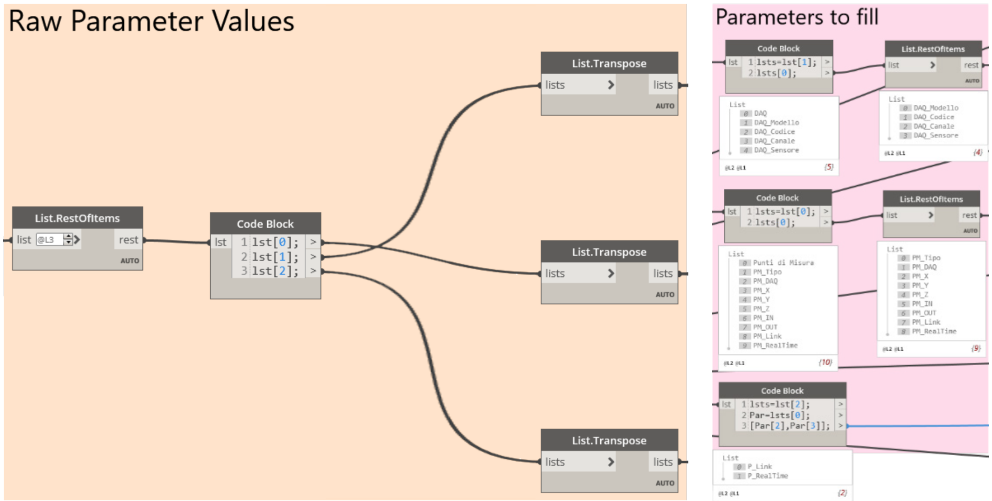
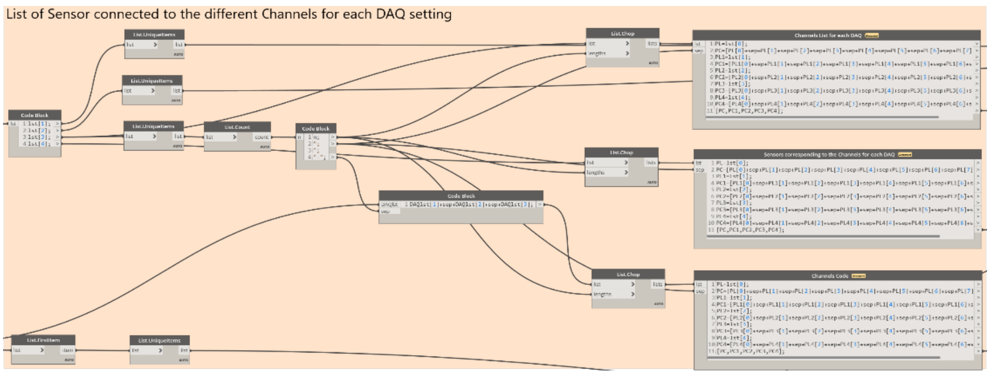


Figure 12.16 – Dynamo VPL script developed to keep the seismometer monitoring network updated: Groups of nodes dedicated to retrieving raw parameters' values (left) and generating the lists of parameters to fill out (right) [AoE]



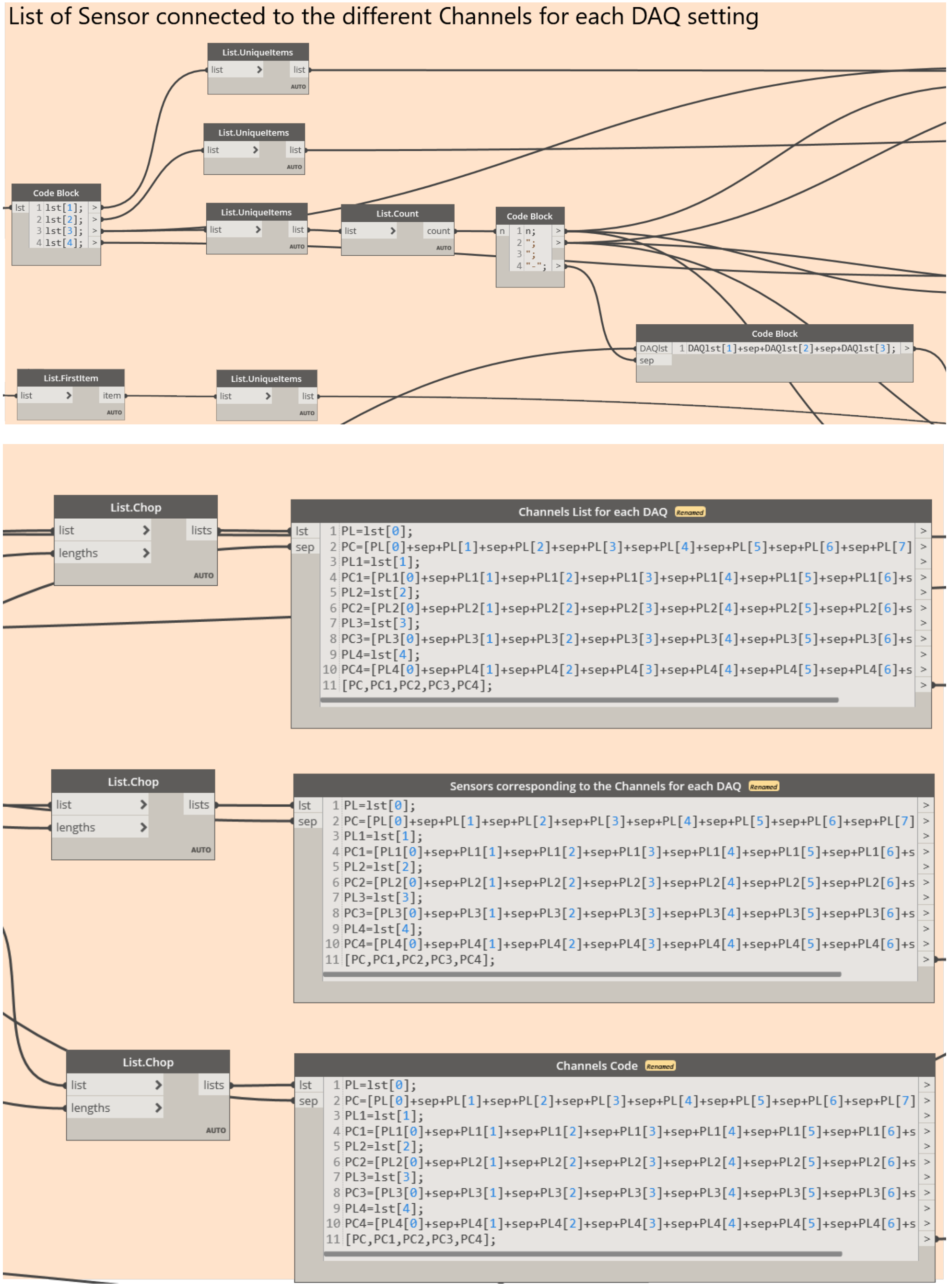


Figure 12.17 – Dynamo VPL script developed to keep the seismometer monitoring network updated: Group of nodes dedicated to sorting and creating the list of DAQ *sensors channels* [AoE]

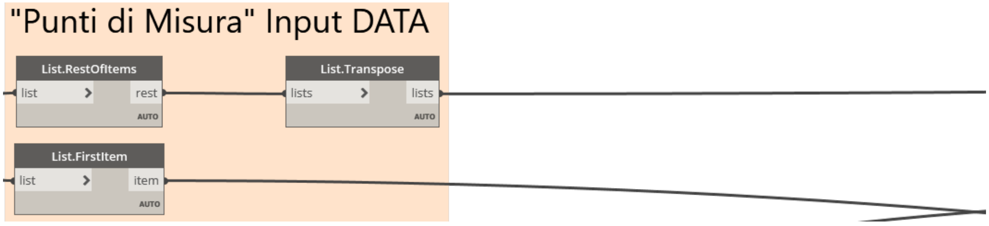


Figure 12.18 – Dynamo VPL script developed to keep the seismometer monitoring network updated: Group of nodes dedicated to sorting the *"Measuring Points"* input data to subsequently fill in the related parameter values [AoE]

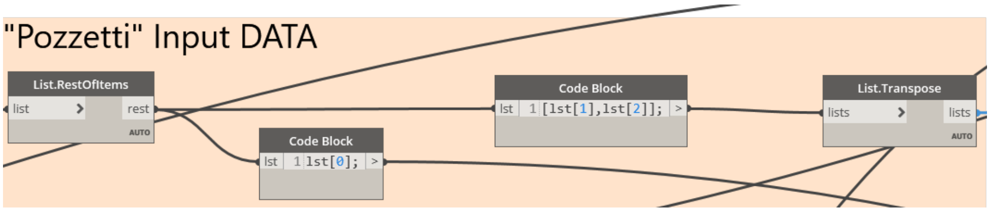


Figure 12.19 – Dynamo VPL script developed to keep the seismometer monitoring network updated: Group of nodes dedicated to sorting the *"R.C. Manholes"* input data to subsequently fill in the related parameter values [AoE]

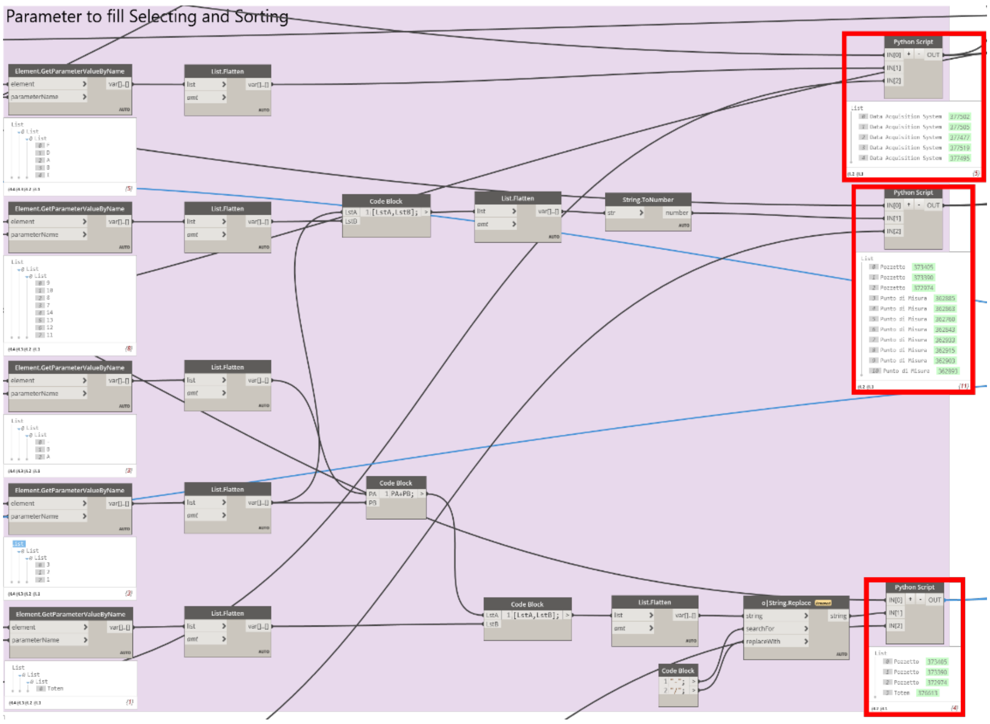
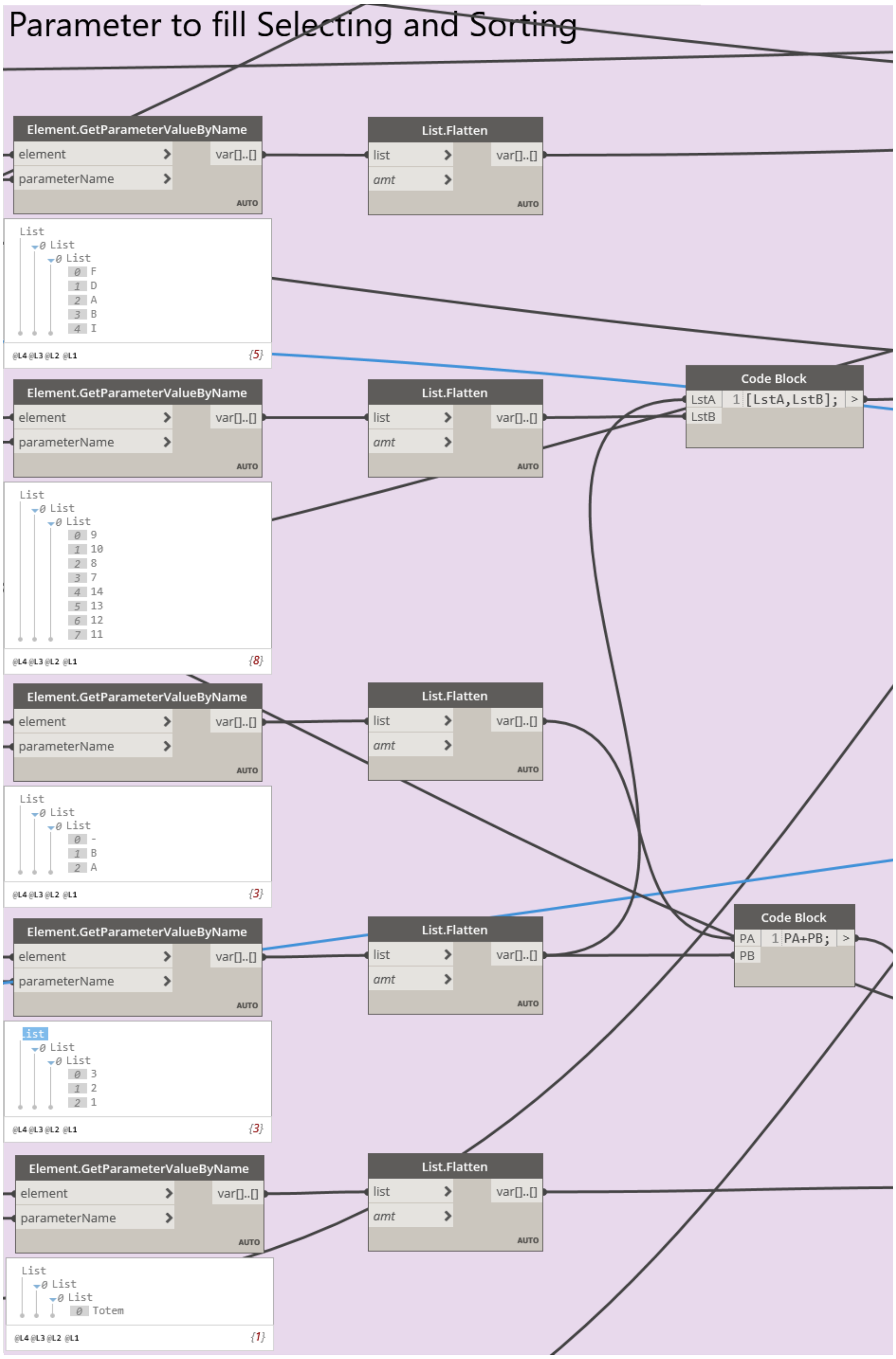


Figure 12.20 – Dynamo VPL script developed to keep the seismometer monitoring network updated: Group of nodes dedicated to retrieving and sorting the selected modelled instances' parameters to fill out with the imported data. This group of nodes employs the custom node marked in red [AoE]


Parameter to fill Selecting and Sorting
Element.GetParameterValueByName
element
parameterName
var[]..[]
List.Flatten
list
amt
List
0 List
0 List
0 F
1 D
2 A
3 B
4 I
{5}
0 9
1 10
2 8
3 7
4 14
5 13
6 12
7 11
{8}
0 -
1 B
2 A
{3}
0 3
1 2
2 1
0 Totem
{1}
Code Block
LstA
LstB
1 [LstA,LstB];
PA
PB
1 PA+PB;

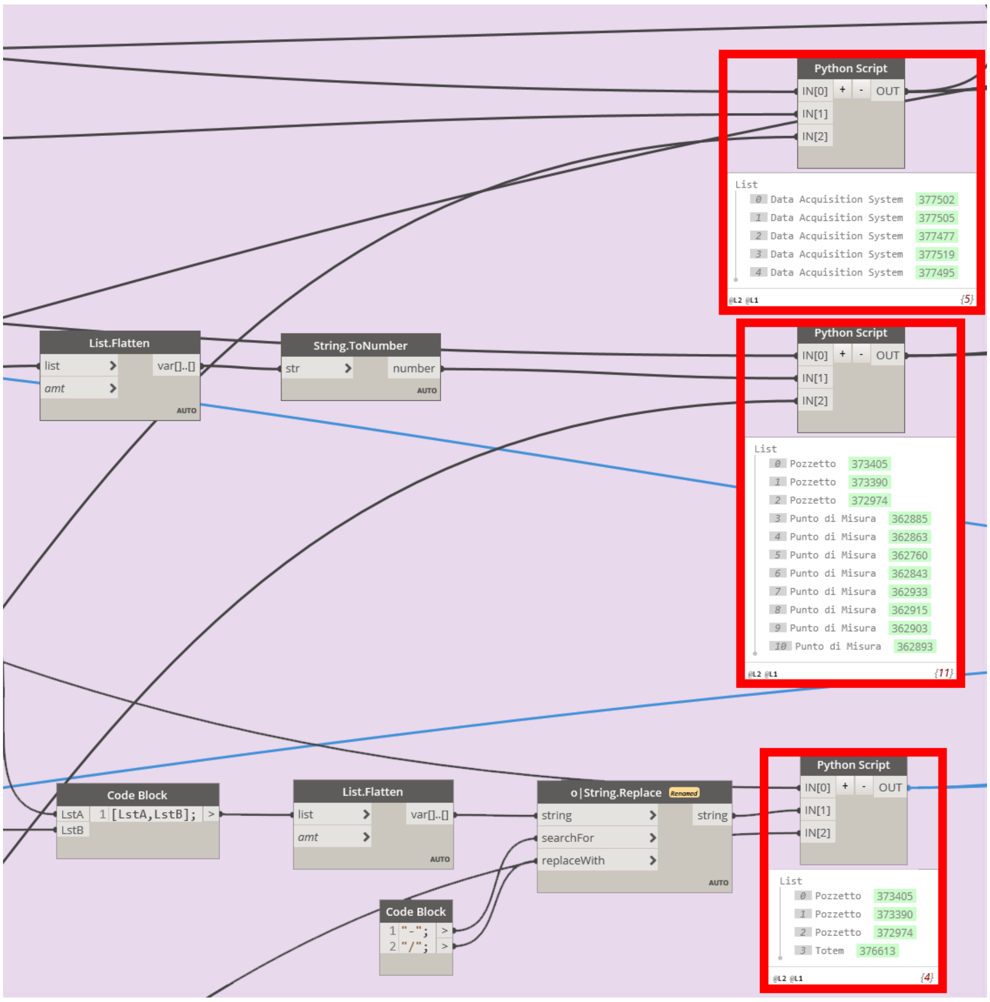


Figure 12.21 – Dynamo VPL script developed to keep the seismometer monitoring network updated: Zoom in on the group of nodes dedicated to retrieving and sorting the selected modelled instances' parameters to fill out with the imported data. This group of nodes employs the custom node marked in red [AoE]

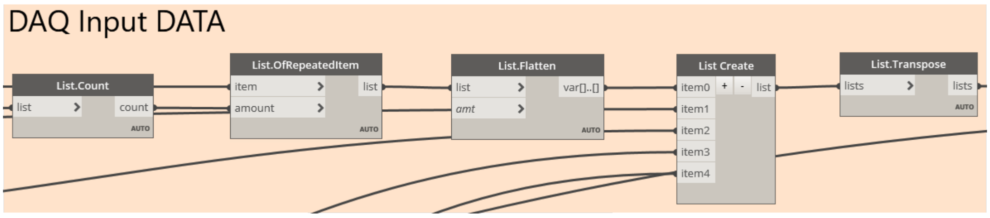


Figure 12.22 – Dynamo VPL script developed to keep the seismometer monitoring network updated: Group of nodes dedicated to sorting the *"Data Acquisition Systems"* input data to subsequently fill in the related parameter values [AoE]

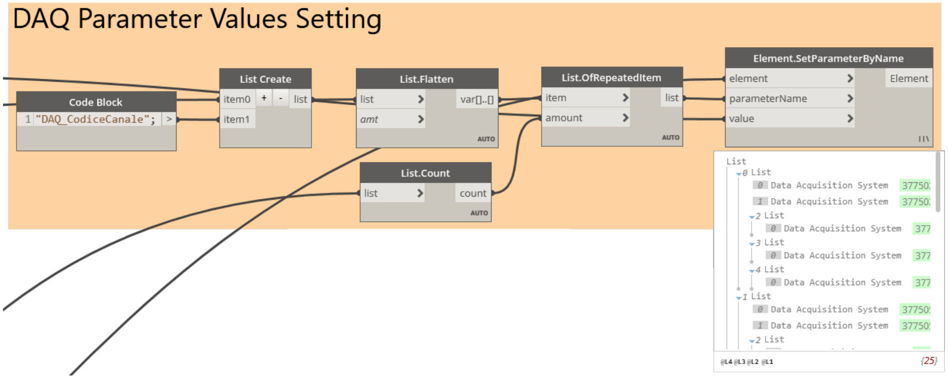


Figure 12.23 – Dynamo VPL script developed to keep the seismometer monitoring network updated: Group of nodes dedicated to assigning the imported and sorted data to the modelled *instances* belonging to the "*Data Acquisition Systems*" familiy[AoE]

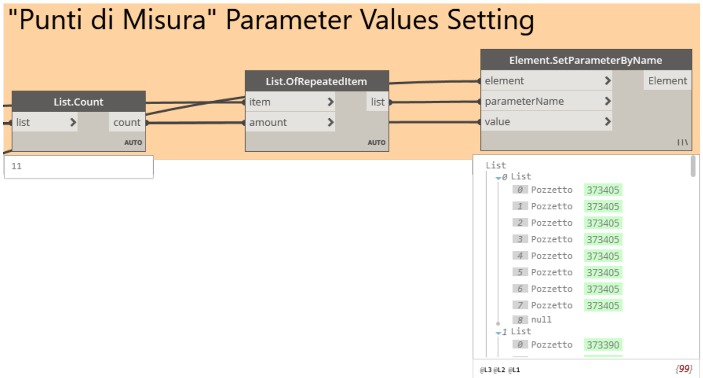


Figure 12.24 – Dynamo VPL script developed to keep the seismometer monitoring network updated: Group of nodes dedicated to assigning the imported and sorted data to the modelled *instances* belonging to the "*Measuring Points*" family [AoE]

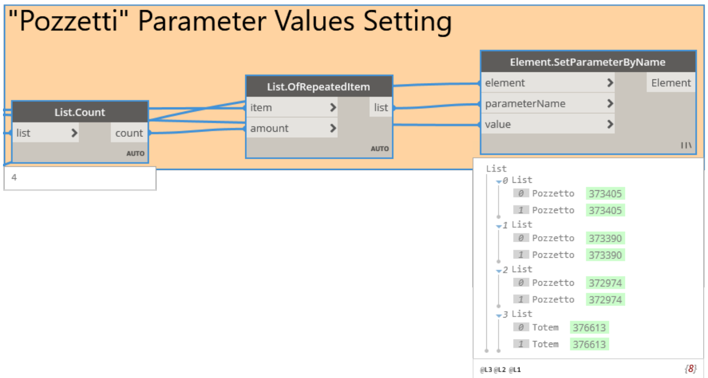


Figure 12.25 – Dynamo VPL script developed to keep the seismometer monitoring network updated: Group of nodes dedicated to assigning the imported and sorted data to the modelled *instances* belonging to the "*R.C. Manholes*" family [AoE]

DAQ	DAQ_Modello	DAQ_Codice	DAQ_Canale	DAQ_Sensore
A	FD11603	1DF80C2	Bank1/ai0	3V
A	FD11603	1DF80C2	Bank1/ai1	17H
A	FD11603	1DF80C2	Bank1/ai2	18H
A	FD11603	1DF80C2	Bank1/ai3	nc
A	FD11603	1DF80C2	Bank2/ai0	nc
A	FD11603	1DF80C2	Bank2/ai1	nc
A	FD11603	1DF80C2	Bank2/ai2	nc
A	FD11603	1DF80C2	Bank2/ai3	nc
B	FD11603	1DF80C4	Bank1/ai0	19H
B	FD11603	1DF80C4	Bank1/ai1	20H
B	FD11603	1DF80C4	Bank1/ai2	22H
B	FD11603	1DF80C4	Bank1/ai3	4V
B	FD11603	1DF80C4	Bank2/ai0	21H
B	FD11603	1DF80C4	Bank2/ai1	nc
B	FD11603	1DF80C4	Bank2/ai2	nc
B	FD11603	1DF80C4	Bank2/ai3	nc
F	FD11603	1DF80C3	Bank1/ai0	5H
F	FD11603	1DF80C3	Bank1/ai1	6H
F	FD11603	1DF80C3	Bank1/ai2	9H
F	FD11603	1DF80C3	Bank1/ai3	10H
F	FD11603	1DF80C3	Bank2/ai0	7H
F	FD11603	1DF80C3	Bank2/ai1	8H
F	FD11603	1DF80C3	Bank2/ai2	nc
F	FD11603	1DF80C3	Bank2/ai3	nc
I	FD11603	1DF80C5	Bank1/ai0	15H
I	FD11603	1DF80C5	Bank1/ai1	16H
I	FD11603	1DF80C5	Bank1/ai2	13H
I	FD11603	1DF80C5	Bank1/ai3	14H
I	FD11603	1DF80C5	Bank2/ai0	11H
I	FD11603	1DF80C5	Bank2/ai1	12H
I	FD11603	1DF80C5	Bank2/ai2	nc
I	FD11603	1DF80C5	Bank2/ai3	nc
D	FD11603	1DF80A8	Bank1/ai0	1H
D	FD11603	1DF80A8	Bank1/ai1	2H
D	FD11603	1DF80A8	Bank1/ai2	1V
D	FD11603	1DF80A8	Bank1/ai3	3H
D	FD11603	1DF80A8	Bank2/ai0	4H
D	FD11603	1DF80A8	Bank2/ai1	2V
D	FD11603	1DF80A8	Bank2/ai1	nc
D	FD11603	1DF80A8	Bank2/ai1	nc

Figure 12.26 – Input Excel data concerning the *"Data Acquisition Systems"* instances [AoE]

Punti di Misura	PM_Tipo	PM_DAQ	PM_X	PM_Y	PM_Z	PM_IN	PM_OUT	PM_Link	PM_RealTime
1	3D	A	17H	18H	3V	B	Totem-leggio	https://drive.google.com	https://www.museopaestu
2	3D	B	19H	20H	4V	F	A	https://drive.google.com	https://www.museopaestu
3	2D	-	21H	22H	-	-	B	https://drive.google.com	https://www.museopaestu
7	3D	D	1H	2H	1V	I	F	https://drive.google.com	https://www.museopaestu
8	3D	-	3H	4H	2V	-	D	https://drive.google.com	https://www.museopaestu
9	2D	F	5H	6H	-	D	B	https://drive.google.com	https://www.museopaestu
10	2D	-	7H	8H	-	-	F	https://drive.google.com	https://www.museopaestu
11	2D	-	9H	10H	-	-	F	https://drive.google.com	https://www.museopaestu
12	2D	-	11H	12H	-	-	I	https://drive.google.com	https://www.museopaestu
13	2D	I	13H	14H	-	-	D	https://drive.google.com	https://www.museopaestu
14	2D	-	15H	16H	-	-	I	https://drive.google.com	https://www.museopaestu

Punti di Misura	PM_Tipo	PM_DAQ	PM_X	PM_Y	PM_Z
1	3D	A	17H	18H	3V
2	3D	B	19H	20H	4V
3	2D	-	21H	22H	-
7	3D	D	1H	2H	1V
8	3D	-	3H	4H	2V
9	2D	F	5H	6H	-
10	2D	-	7H	8H	-
11	2D	-	9H	10H	-
12	2D	-	11H	12H	-
13	2D	I	13H	14H	-
14	2D	-	15H	16H	-

PM_IN	PM_OUT	PM_Link	PM_RealTime
B	Totem-leggio	https://drive.google.com	https://www.museopaestu
F	A	https://drive.google.com	https://www.museopaestu
-	B	https://drive.google.com	https://www.museopaestu
I	F	https://drive.google.com	https://www.museopaestu
-	D	https://drive.google.com	https://www.museopaestu
D	B	https://drive.google.com	https://www.museopaestu
-	F	https://drive.google.com	https://www.museopaestu
-	F	https://drive.google.com	https://www.museopaestu
-	I	https://drive.google.com	https://www.museopaestu
-	D	https://drive.google.com	https://www.museopaestu
-	I	https://drive.google.com	https://www.museopaestu

Figure 12.27 – Input Excel data concerning the *"Measuring Points"* instances [AoE]

Famiglia	Tipo	P_Link	P_RealTime
Pozzetto	A1	https://drive.google.com/file/	https://www.museopaestum.be
Pozzetto	B2	https://drive.google.com/file/	https://www.museopaestum.be
Pozzetto	/3	https://drive.google.com/file/	https://www.museopaestum.be
Pozzetto	Totem	https://drive.google.com/file/	https://www.museopaestum.be

Figure 12.28 – Input Excel data concerning the *"R.C. Manholes"* instances [AoE]

Figure 12.29 – Federated Revit projects rendered plan view representing the Temple of Neptune, its surroundings, and the monitoring seismometers network as of 2021 [AoE]

Figure 12.30 – Federated Revit projects rendered North-Eastern view representing the Temple of Neptune, its surroundings, and the monitoring seismometers network as of 2021 [AoE]

12.2 Open BIM models exportation for data exchange and assessment

As already illustrated in section 7.2, the implementation of federated models [FSC] through shared coordinates also allows an easy export to IFC of such models while preserving their spatial location [GEO] (Figures 12.31, 12.33, 12.34, and 12.36). This type of federated models, enriched in terms of the level of information, are therefore well suited for the sharing of knowledge between stakeholders with different degrees of know-how and experience in the field of BIM modelling (Figures 12.33, 12.35, 12.37, and 12.39). In particular, they are already optimised for the validation phase, the so-called Clash Detection, thus fulfilling one of the paradigms of BIM in the easy detection of possible interferences between the several interacting systems and their rapid resolution, thus minimising the possibility of committing errors in the construction phase, for new buildings, or in the design and realisation of maintenance works on the built heritage.
Furthermore, the enhanced parametric meshes generated as separate *triangular faces*, each with its own photogrammetric material, as illustrated in section 11.3, also possess the advantage of retaining the colour of the corresponding material even when exported to IFC, a format that commonly disregards textural representation (Figure 12.38 and 12.39).

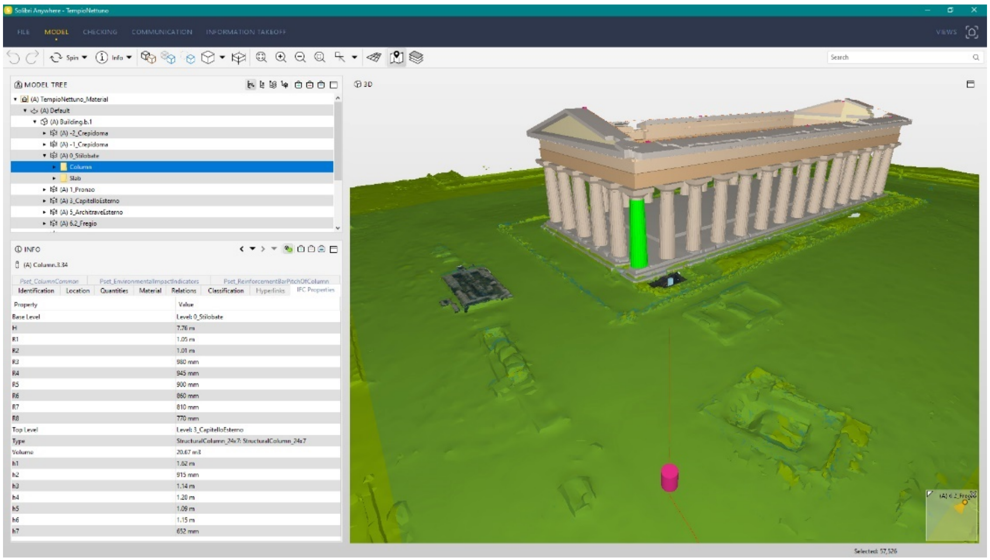


Figure 12.31 – Federated models exported to IFC and visualised via Nemetschek Solibri Anywhere: Example of the customised properties added to a *Structural Column instance* [AoE]

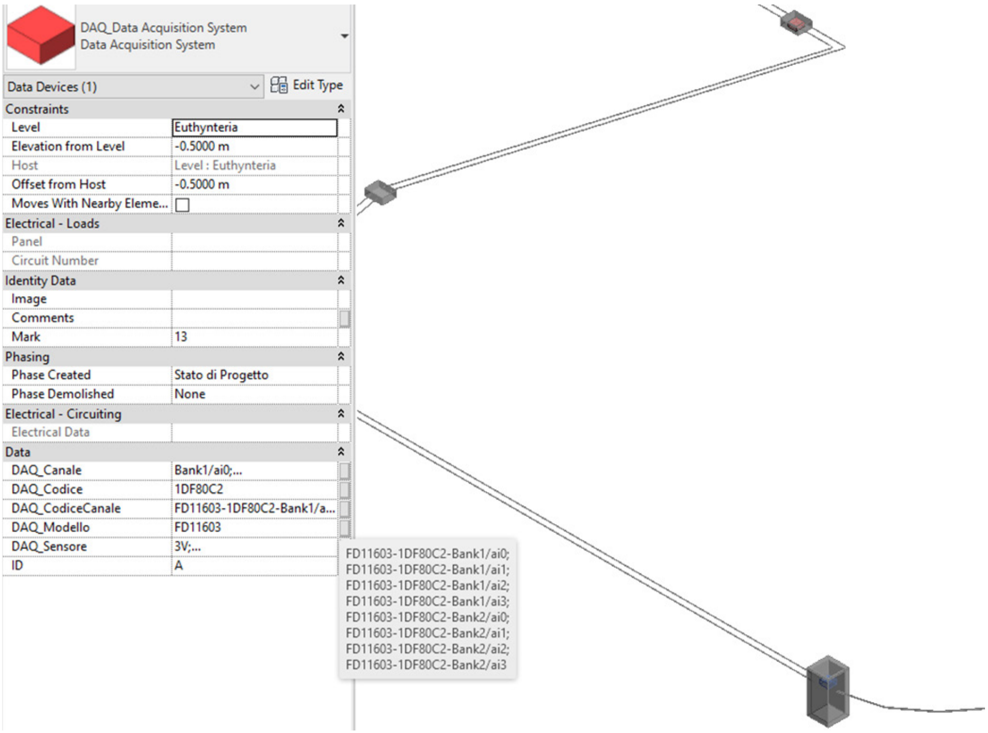


Figure 12.32 – Example of the properties added as shared parameters to a modelled *"Data Acquisition System" instance* within the native Revit Environment [AoE]

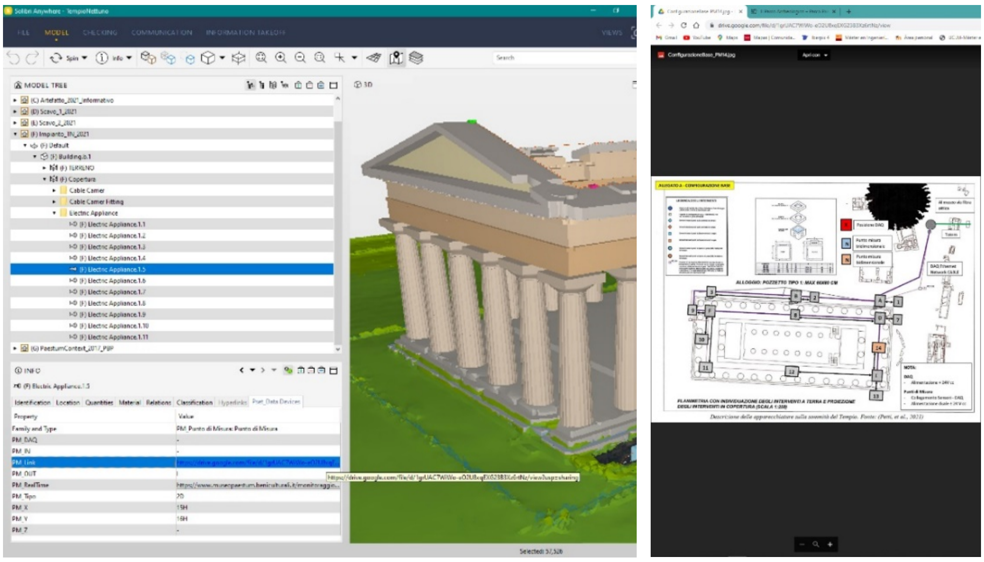


Figure 12.33 – Federated models exported to IFC and visualised via Nemetschek Solibri Anywhere: Example of the customised properties added to a *"Measuring Point" instance* (left) and the plan view indicating its location (right) linked via the *"PM_Link"* parameter [AoE]

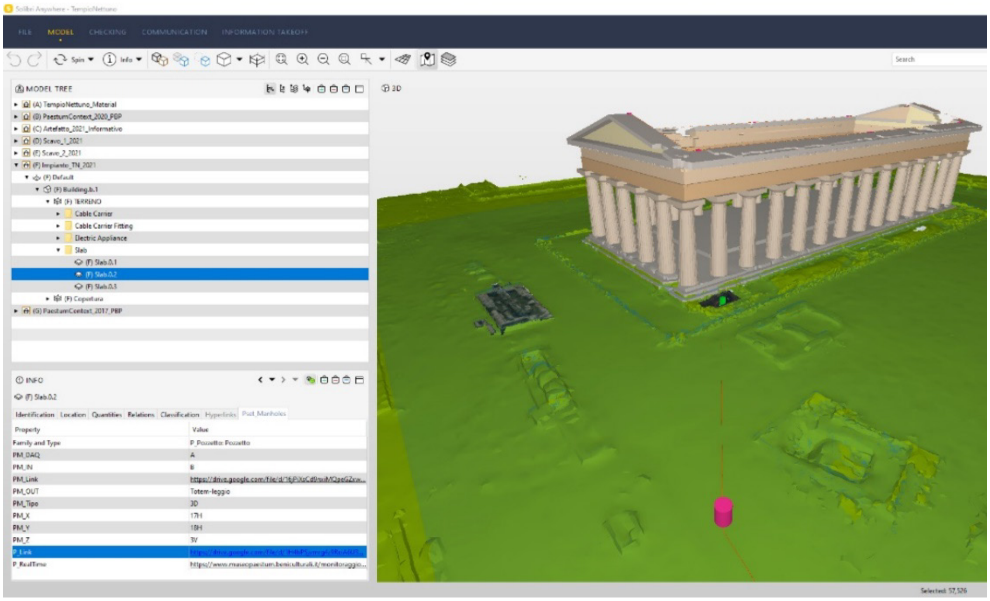


Figure 12.34 – Federated models exported to IFC and visualised via Nemetschek Solibri Anywhere: Example of the customised properties added to a *"R.C. Manhole" instance* [AoE]

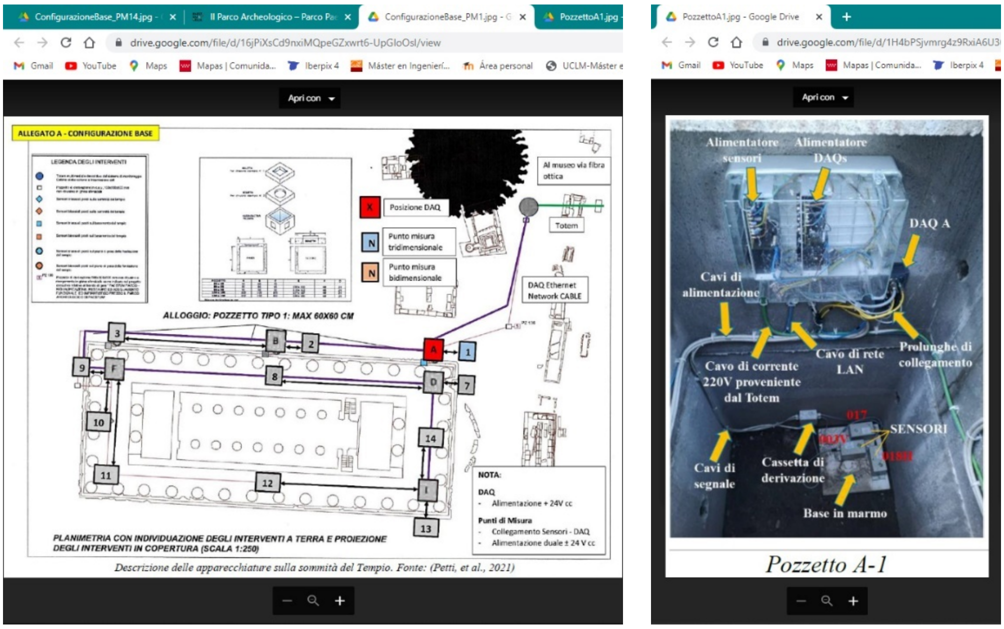


Figure 12.35 – Federated models exported to IFC and visualised via Nemetschek Solibri Anywhere: Example of the linked plan view indicating its location and a detailed image breaking down the *"R.C. Manhole" instance* selected in Figure 12.34 [AoE]

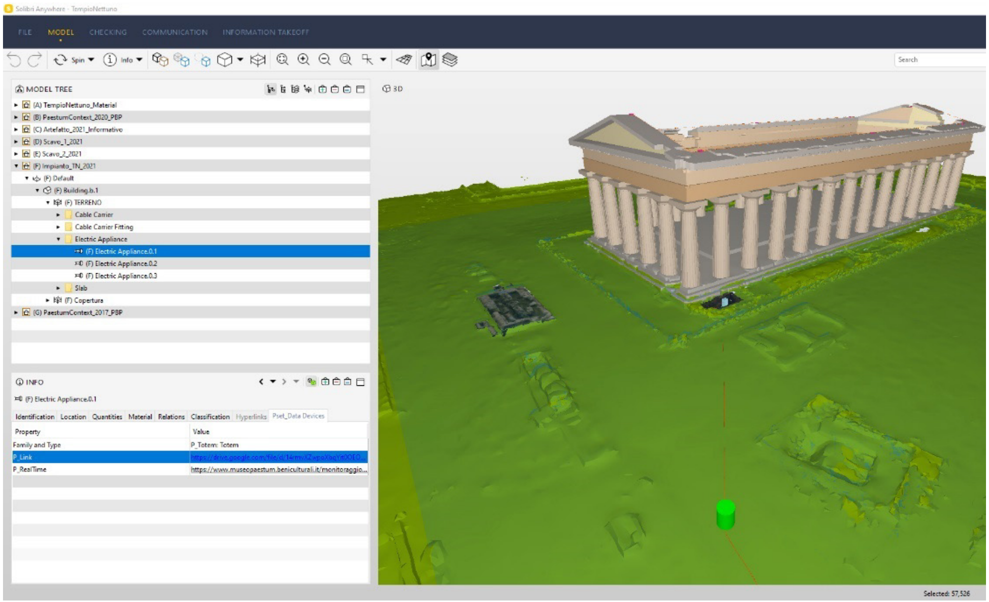


Figure 12.36 – Federated models exported to IFC and visualised via Nemetschek Solibri Anywhere: Example of the customised properties added to the *"Totem-Leggio" instance* [AoE]

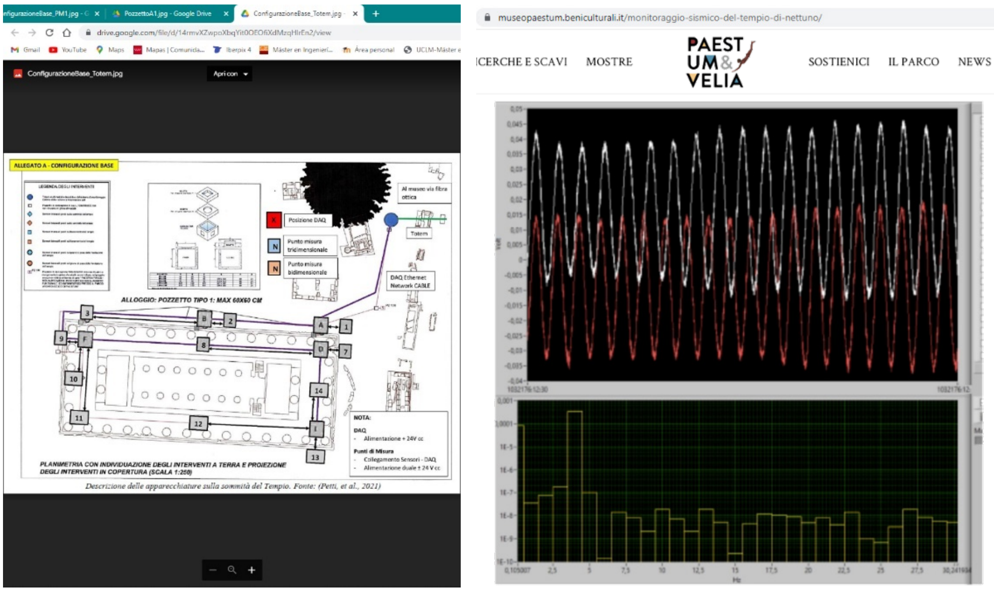


Figure 12.37 – Federated models exported to IFC and visualised via Nemetschek Solibri Anywhere: Example of the linked plan view indicating the location of the *"Totem-Leggio" instance* (also selected in Figure 12.36) and a screenshot of the real-time data coming from the on-site monitoring system accessible via the *"P_RealTime"* parameter [AoE]

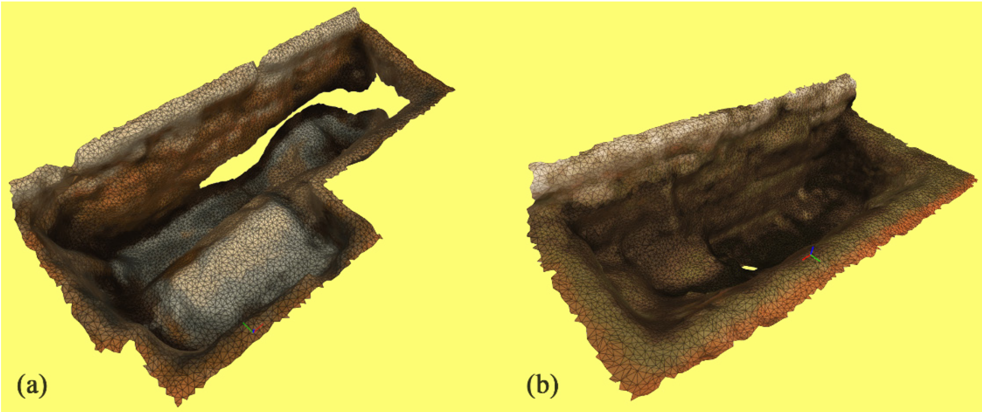


Figure 12.38 – (a) *"Scavo_2.IFC"* and (b) *"Scavo_1.IFC"* visualisation via BIM Vision [AoE]

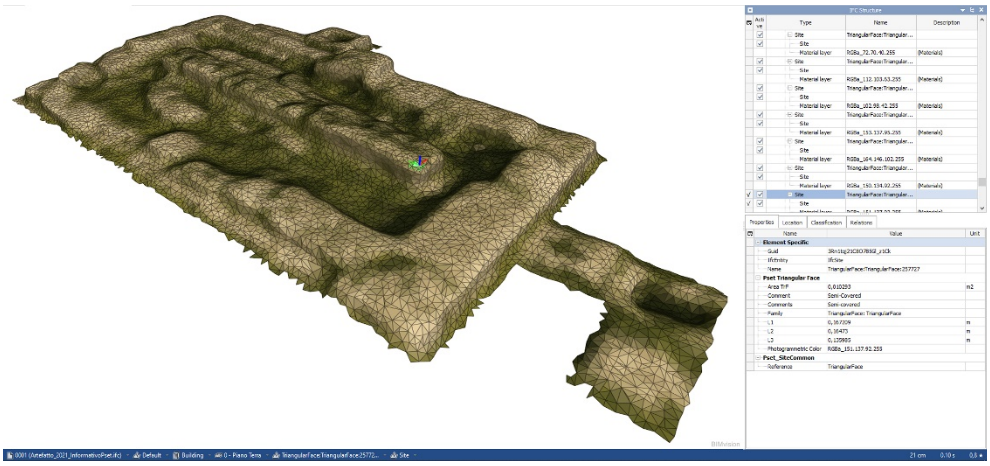


Figure 12.39 – *"Artefatto.IFC"* visualisation via BIM Vision: Example of the customized properties added as shared parameters to a selected "Triangular Face" instance [AoE]

Accurate modelling of the structural elements, starting from three-dimensional survey data, has therefore made it possible to introduce a further stage in the use of this type of data, implementing an a-posteriori comparison between the remodelled object and the survey three-dimensional point cloud.
It is actually rather straightforward to transform a georeferenced IFC type of model – which is already a BREP[54] [*Boundary Representation*] representation – into a

[54] In solid modelling, the so-called Boundary representation, also often abbreviated as B-REP, is a way of representing surfaces. BREP is a vector graphics format that represents only the edges of the solid, like wires stretched between vertices, and then dresses these surfaces with textures to represent the final shape. BREP has also become a neutral computer drawing format that aids the exchange of data between different CAD applications.

continuous triangulated model, in OBJ or PLY format, using software such as FME Workbench (in its 2021.2.0.1 release – Figure 12.40). From this data, a comparison was then made in the Cloud Compare environment (in its 2.12 alpha release) between the continuous model and the discrete one represented by the point cloud. Most of the deviations detected are in the range of 5 five centimetres (Figure 12.41), going as far as 10 centimetres in certain areas affected by misalignment in the physical asset (Figure 12.42 and 12.43), except for deliberately non-modelled elements, i.e., decorations, metopes and triglyphs, in addition to the Naos of the Temple (Figure 12.44). First of all, the deviations detected represent a quality assessment datum, concerning the correctness of the modelling carried out and, at a later stage, constitute the benchmark – at time zero [t_0] – for future verifications carried out by always comparing the same continuous model with updated survey data, while simply taking care to always use the same topographical reference system.

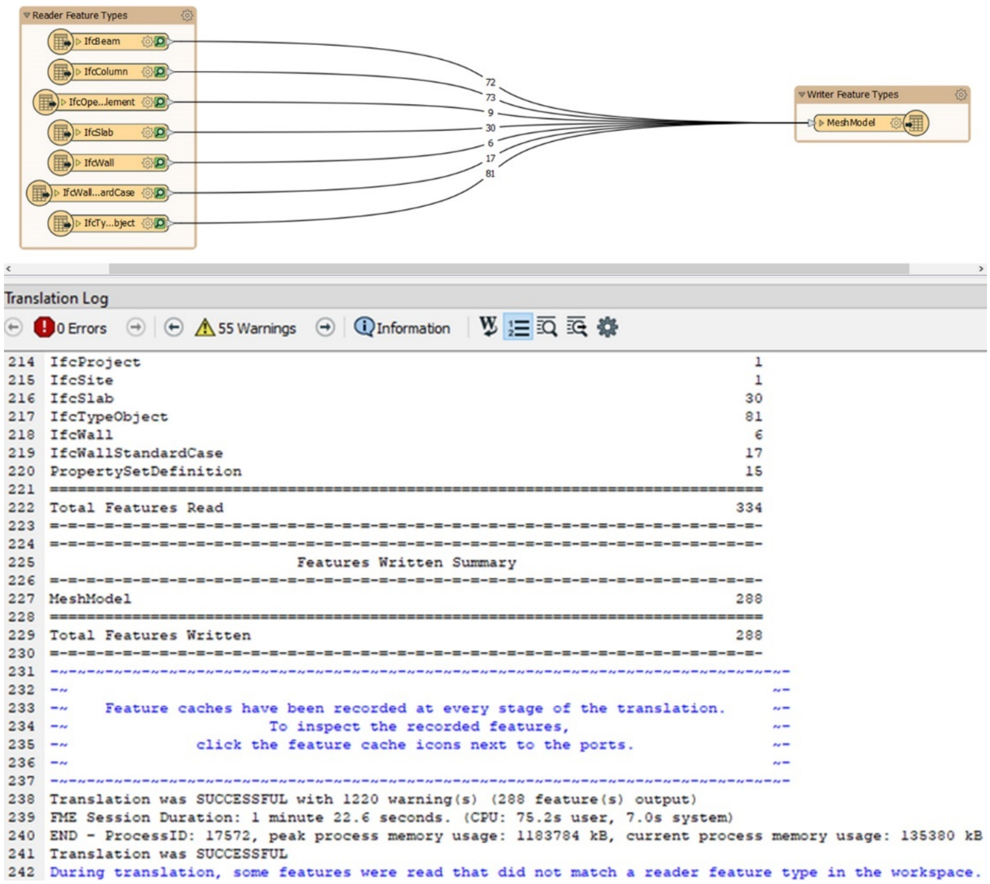


Figure 12.40 – Example of the conversion process from IFC to OBJ via FME Workbench [AoE]

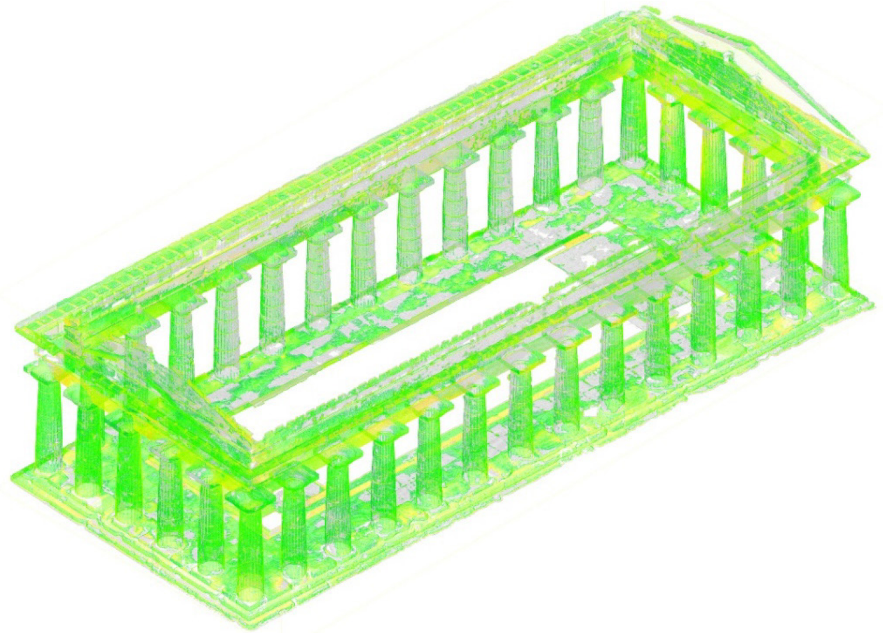


Figure 12.41 – Comparison between the continuous model of the Temple [OBJ] and the integrated point cloud performed via Cloud Compare, showing in green-yellow shades the absolute distances inferior to 5 cm between the points and the mesh [AoE]

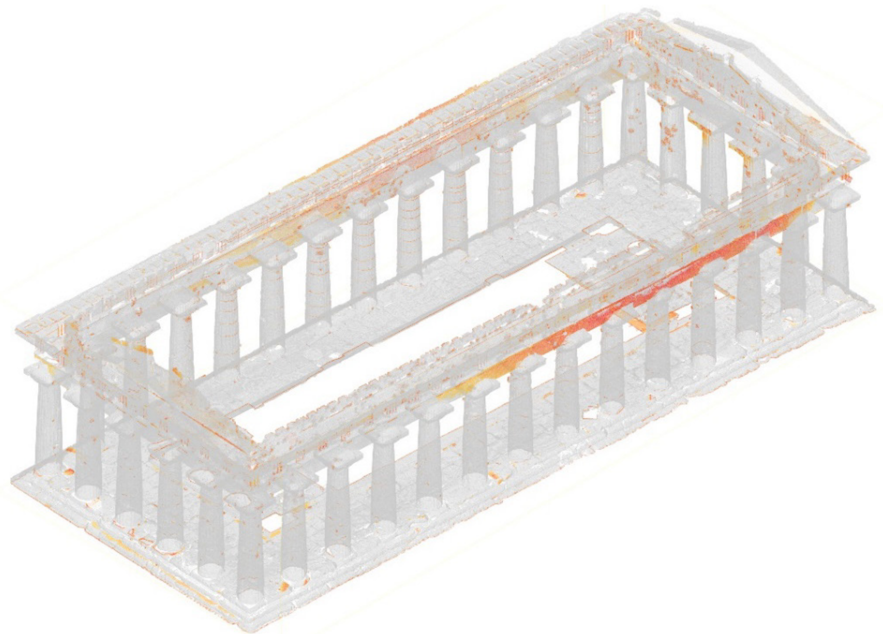


Figure 12.42 – Comparison between the continuous model of the Temple [OBJ] and the integrated point cloud performed via Cloud Compare, showing in orange-red shades the positive distances ranging from 5 to 10 cm between the points and the mesh [AoE]

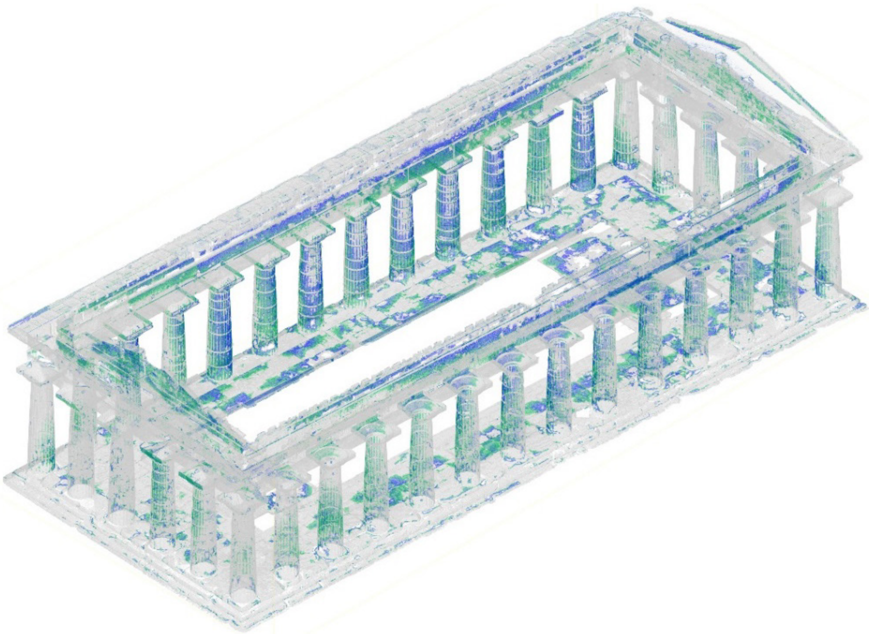


Figure 12.43 – Comparison between the continuous model of the Temple [OBJ] and the integrated point cloud performed via Cloud Compare, showing in dark green-blue shades the negative distances ranging from 5 to 10 cm between the points and the mesh [AoE]

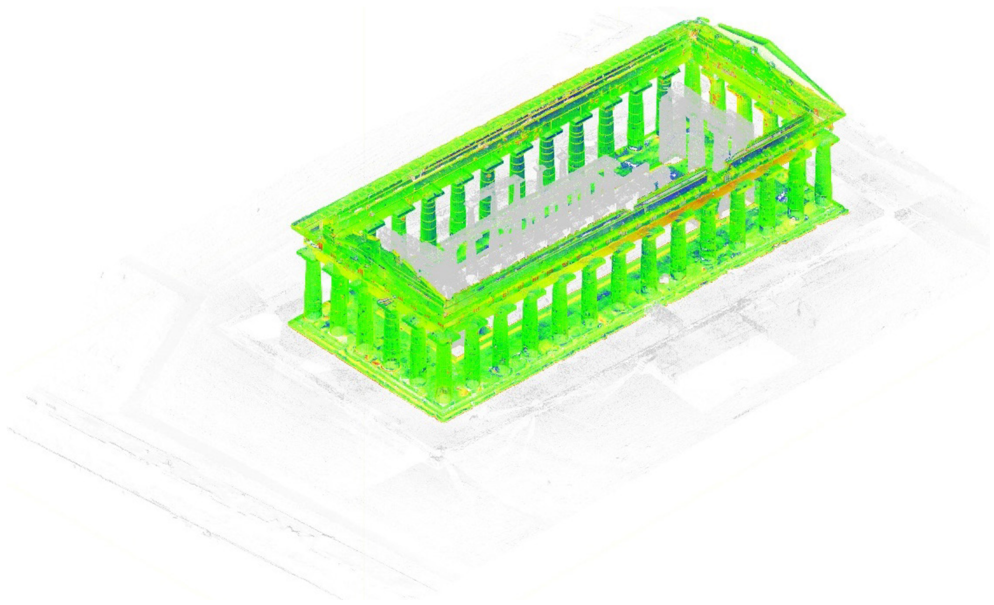


Figure 12.44 – Comparison between the continuous model of the Temple [OBJ] and the integrated point cloud performed via Cloud Compare, showing absolute distances inferior to 10 cm between the points and the mesh in blue to red shades; non-modelled elements have been greyed out [AoE]

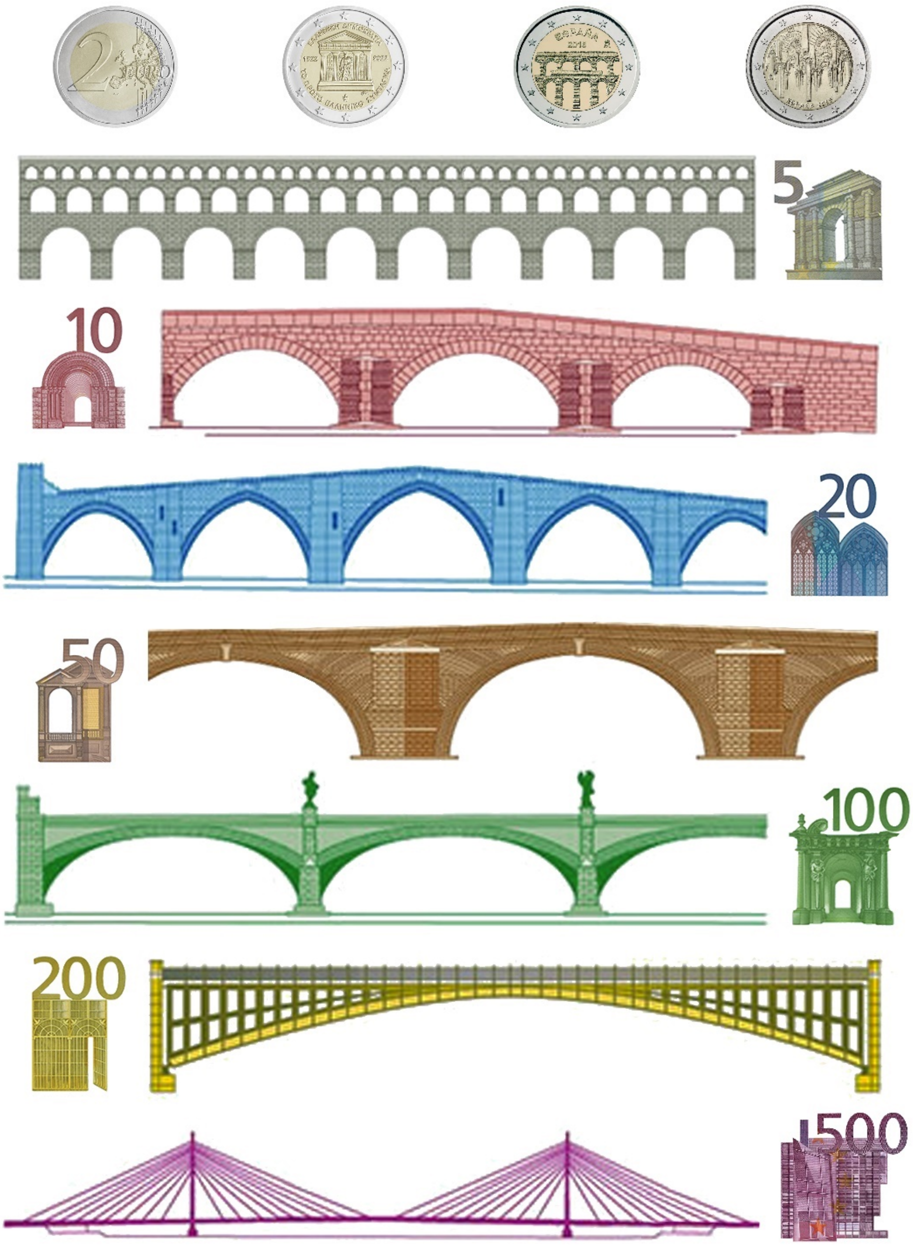


Figure 13.1 – The value of structural monitoring. Throughout history, trilithons and arches have represented the essential components of any structure. Here is a graphic summary of some real monuments and ideal bridges captured respectively on the European coins and banknotes. The back of each banknote features a bridge from one of the seven periods in Europe's architectural history, which is a metaphor for the close cooperation and communication between the people of Europe and between Europe and the rest of the world. The images are based on the typical architectural style of each period – i.e., Classical, Romanesque, Gothic, Renaissance, Baroque & Rococo, Iron & Glass, and Modern architecture – rather than on specific structures.

Conclusions

This thesis work is considered to have achieved the objective of defining a good operational practice for the realisation of what, adopting a terminology typical of BIM methodology, is defined as a Common Data Environment. The application of the proposed methodology for the standardisation of the Scan-to-BIM approach to information modelling is thus practically configured as an algorithm aimed at simplifying the entire usual process, both to facilitate newcomers and to support more experienced modellers.

The CDE is configured in the present discussion as a true ECO-system, not coincidentally adopting the chosen graphics. The Enriched COperative System concept is intended to emphasise how an effective management plan cannot and should not be a closed system frozen in time. Its success or failure is in fact, exclusively linked to the commitment of future managers in keeping it in a good state of efficiency. Collaboration between different specialists is, therefore, a fundamental moment in the perspective of continuous updating and enrichment. Fruitful cooperation with other fields of knowledge appears to be indispensable at the present time for the all-around management of the built heritage.

The use of the general algorithm is therefore enriched by good procedural practices, without claiming to want or be able to exhaust the set of possible implementation systems regarding the plethora of possible input data. Given the burgeoning technological development witnessed by this generation, the optimum in setting up a monitoring ECO-System is to make it open, flexible and easy to update. Indeed, the exponential trend of technological evolution has shown that, in today's context, yesterday's limitations are today's challenges and tomorrow's history. History should not be forgotten but rather catalogued and neatly archived through digital repositories from which it can be retrieved, if necessary, in the form of an *infographic image* (an example of infographics metaphorically evoking the importance of structural health monitoring is presented in Figure 13.1).

This electronic model – fully defined apart from traditional representations – therefore constitutes a new artificial reality, not graphic but digital, as opposed to objective reality: another reality, capable of providing all information, starting with graphic descriptions, aimed at understanding objective reality. Digital images, as visible representations of conceptual and abstract models, constitute themselves a new *hybrid language*. The word virtual can be used here because, on reflection, the infographic image is always *virtual*. The adjective must be understood as something that is latent, but above all as what possesses *potential*; that is – according to the Aristotelian category – what is *fundamentally potential*. In fact, all digital images – even those processed with pure delineation software – are virtual because they are *hidden* in the computer's memory and are only created at the moment they are called up [255].

The first case study proposed concerning the knowledge updating and digitisation of the Olivieri Viaduct (Salerno), is part of the more general framework oriented towards the preservation of Italy's infrastructural heritage, which, as widely discussed, has a rather complex past behind it, often falling into total oblivion. The proposed application has a strong experimental character, both with regard to the proposed modelling and information update procedure and because it aims to act as a reference point for the effective implementation of the recommendations contained in the ***Guidelines for Risk Classification and Management, Safety Assessment and Monitoring of Existing Bridges*** issued in 2020 [4].
The greatest challenge concerned the simplification and optimisation of the procedure for the effective use of BIM-type models in the processes of cataloguing and inspecting existing bridges, viaducts, and overpasses so that it would be a valid support tool rather than a barrier for the C.U.G.R.I. [*Inter-University Consortium for the Forecast and Prevention of Major Risks*] technicians who are not experts in the field of three-dimensional information modelling. In fact, C.U.G.R.I.'s collaborators include not only professors and researchers from the two consortium universities but also Bachelor's and Master's degree students.
On the other hand, the direct confrontation with experts specialised in design and structural monitoring made it possible to fill some technical gaps while also receiving valuable feedback in real time. Beginning with the first rudimentary scripts for the population of composite parameters, the resulting procedural methodology – proposed for the digitisation of road structures scattered throughout Italy – succeeds in responding well to the demands dictated by the regulations in force. In fact, manual intervention is reduced to a minimum when connecting the information database for cataloguing the components of the structure under study with the online platform for bridge management [BMS], currently being developed by C.U.G.R.I.'s IT technicians. Equally automated is the procedure developed for the re-import into an editable BIM environment of the data resulting from the inspections carried out in situ.

Likewise characterised by a high degree of experimentation are the applications developed for the modelling and implementation of sensor-based data developed for the second case study, the Temple of Neptune at Paestum. The objective, in this case, was to propose procedures, once again open and updatable, for importing data from the three-dimensional survey or from real-time measurements into the BIM environment, minimising the essential discretisation steps in the modelling phase and retaining as much information as possible, thus ensuring traceability of the data throughout the process. The procedures developed, far from being exhaustive, are therefore proposed as a framework for the possible integration of Machine Learning and Artificial Intelligence techniques within the prepared monitoring ECO-Systems. These procedures may concern, for example, increasingly detailed segmentation of the source data (the point cloud) to optimise the modelling phase or implement *Pattern Recognition* algorithms, which generally use photographic data, and consequently, data collected using drones, to recognise deteriorated areas. This type of documentation, which goes in the direction of *as-built* modelling, is proposed as a valid support tool for management and maintenance purposes as well as an effective means of updating the actual state of knowledge about the built environment. The results achieved proves how the proposed study provides an efficient semi-automated approach to extract geometric information from a complex topography acquired with laser scanning and photogrammetry data to perform a correct contextualisation based on the extracted information within a BIM *as-built* model.

The possibility of building an actual bridge between the surveyed database and the BIM models, where the data can be enriched as required, moves in the direction of concretely employing the informative models as support tools for maintenance and refurbishment projects. Hence, the implementation of mesh and material models derived directly from the photogrammetric survey in the BIM environment allows a reliable measurement of the object surveyed and reproduced as an *instance* with a good degree of approximation. Depending on the required level of detail, it is then possible to obtain both a contextualisation precise enough and a morphologically and colourimetrically accurate reproduction of selected areas of detail, for those elements of the built environment with a unique formal and cultural value, thus worthy of informative parametric modelling within a wider monitoring system.

On the other hand, in case more detailed modelling of selected areas along with their realistic colourimetric data is required they could be reproduced into the BIM environment no longer as a *unicum*, but rather as discretised elements storing *shared parameters* on which to perform any sort of filtering and assessment. The parameters assigned to the parametric triangles – reproducing the triangular faces of the photogrammetric mesh – are updatable and

increasable on a case-by-case basis. By customising them, e.g., by filling in the *"Comment"* parameter, it would be possible to select, visually filter and group the *triangular faces* to also calculate their cumulative area [3].
Evidently, this kind of application could significantly improve damage monitoring processes by precisely placing within a georeferenced digital ecosystem any detected problematic area of interest, identified either manually or with the help of *Pattern Recognition* algorithms, going into the direction of a fully automated procedure. If it exists, the surveyed and modelled damage area will then be stored in the BIM repository, available for any query and ready to set alerts.
Accurate structural modelling has also made it possible to demonstrate, for the case study of the Temple of Neptune, the usefulness of correctly georeferenced federated models created from three-dimensional survey data by experimenting with comparison procedures between continuous models derived from BIM and discrete models represented by point clouds. Considering a certain tolerance associated with the discretisation carried out during the remodelling phase, any future deviation greater in absolute value than that detected at time zero [t_0] between the continuous reference model and discrete models derived from updated surveys, georeferenced in the same topographical reference system, will therefore constitute an immediate warning signal of possible displacements taking place in the structure.
The management of existing heritage cannot be dissociated from a thorough investigation of the state of preservation of materials and a detailed 3D reconstruction. The morphological and colourimetric reconstruction of complex structures, elements and specific damaged areas in the BIM environment is essential for the development of databases to store data and facilitate the planning of refurbishments and, in general, any intervention activity on the asset under study [51].

Future developments will certainly try to combine TLS and close-range photogrammetry data for indoor applications. This type of integrated data, which is certainly indispensable for the realisation of the BIM model with a manual approach, also represents an interesting challenge if used as the source for the proposed procedural workflows, implementing triangulated mesh models derived from both the laser and the entire integrated dataset. On the other hand, should the integration of sensor-based data become a common practice for monitoring procedures, this praxis will certainly optimise conservation assessments, accurately highlighting changes in the geometry and texture of the asset, by merely comparing updated survey data with the modelled asset at regular intervals.
Although most philosophers and time management experts recommend focusing on the present and planning for the future, Seneca rather reminds us

to focus on the past: *“Life is very short and anxious for those who forget the past, neglect the present and fear the future”*. Ultimately, Seneca argues that reflecting on the events and lessons of one’s past will not only prevent one from making time-wasting mistakes in the future but will also provide clarity on how to live a better life.

Looking to the future without forgetting the past, asking questions, and being open to debate are the keys to scientific research and continuous personal growth. As the astronomer Margherita Hack also recalled: *“The fun of scientific research is also to constantly seek new frontiers to overcome, to build more powerful means of investigation, more complex theories, to always try to make progress while knowing that we will probably grow closer and closer to understanding reality, without ever arriving at a complete understanding of it”*.

Conclusioni

Con il presente lavoro di tesi si ritiene di aver raggiunto l'obiettivo prepostosi di definire una buona pratica operativa per la realizzazione di quello che, adottando una terminologia tipica della metodologia BIM, viene definito *Ambiente condiviso di dati*. L'applicazione della metodologia proposta per la standardizzazione dell'approccio Scan-to-BIM alla modellazione informativa si configura quindi, nella pratica, come un algoritmo orientato allo snellimento dell'intero usuale processo, sia per facilitare i nuovi avventori, sia per supportare i modellatori più esperti.
L'ACDat si configura nella presente trattazione come un vero e proprio ECO-sistema, adottando non casualmente la grafica scelta. Il concetto di Enriched COperative System è teso a rimarcare in che modo un piano di gestione efficace non possa e non debba essere un sistema chiuso e congelato nel tempo. Il suo successo o fallimento è infatti legato esclusivamente all'impegno profuso dai futuri gestori nel mantenerlo in buono stato di efficienza. La collaborazione tra diversi specialisti è dunque momento fondamentale nell'ottica di un aggiornamento e arricchimento continuo. Una proficua cooperazione con gli altri settori della conoscenza appare imprescindibile all'attualità per una gestione a tutto tondo del patrimonio costruito.
L'impiego dell'algoritmo generale si arricchisce quindi di buone prassi procedurali, senza pretendere di voler o poter esaurire l'insieme dei possibili sistemi di implementazione riguardanti la pletora di possibili dati in ingresso. Dato il fiorente sviluppo tecnologico di cui è testimone questa generazione, l'optimum nella predisposizione di un ECO-Sistema di monitoraggio consiste nel renderlo aperto, flessibile e di facile aggiornamento. L'esponenziale andamento dell'evoluzione tecnologica ha infatti dimostrato che, nel contesto attuale, i limiti di ieri si configurano come le sfide di oggi e la storia di domani. Storia che non va dimenticata, ma piuttosto catalogata e ordinatamente archiviata attraverso repository digitali dai quali potrà essere richiamata all'occorrenza sotto forma di *immagine infografica* (un esempio di infografica che evoca metaforicamente l'importanza del monitoraggio della salute strutturale è presentato in Figura 13.1).
Tale modello elettronico – compiutamente definito a prescindere dalle rappresentazioni tradizionali – costituisce pertanto una nuova realtà artificiale, non grafica bensì digitale, rispetto a quella oggettiva: una realtà altra, in grado di fornire tutte le informazioni, a cominciare dalle descrizioni grafiche, finalizzata alla comprensione della realtà oggettiva. Le immagini digitali, in

quanto rappresentazioni visibili di modelli concettuali e astratti, si costituiscono come un nuovo *linguaggio ibrido*. A tal proposito è possibile utilizzare la parola *virtuale* perché, a ben riflettere, l'immagine infografica è sempre virtuale. L'aggettivo deve essere inteso come ciò che è latente, ma soprattutto come ciò che *possiede una potenzialità*; ossia – secondo la categoria aristotelica – come ciò che è *fondamentalmente potenziale*. In effetti, tutte le immagini digitali – anche quelle elaborate con i software di pura delineazione – sono virtuali, perché sono *nascoste* nella memoria del computer e vengono create solo al momento in cui le si richiama [255].

Il primo caso studio proposto, riguardante l'aggiornamento della conoscenza e la digitalizzazione del Viadotto Olivieri (Salerno), si colloca nel quadro più generale, orientato alla salvaguardia del patrimonio infrastrutturale italiano, che, come ampiamente discusso, ha un passato piuttosto complesso alle spalle, cadendo spesso nel più totale oblio. L'applicazione proposta ha un carattere fortemente sperimentale, tanto per quanto riguarda la procedura di modellazione e aggiornamento informativo proposta, quanto perché vorrebbe configurarsi come punto di riferimento per l'effettiva implementazione delle raccomandazioni contenute nelle ***Linee Guida per la Classificazione e Gestione del Rischio, la Valutazione della Sicurezza ed il Monitoraggio dei Ponti Esistenti*** emanate nel 2020 [4].
La sfida più grande ha riguardato la fase di semplificazione e ottimizzazione della procedura per l'effettivo impiego dei modelli di tipo BIM nei processi di catalogazione e ispezione dei ponti, viadotti e cavalcavia esistenti, in modo che costituisse un valido strumento di supporto piuttosto che una barriera per i tecnici del C.U.G.R.I. [*Consorzio inter-Universitario per la previsione e prevenzione dei Grandi Rischi*], non esperti nel settore della modellazione tridimensionale di tipo informativo. Tra i collaboratori del CUGRI si annoverano infatti, oltre a professori e ricercatori delle due università consorziate, anche laureandi triennali e magistrali. D'altro canto, il confronto diretto con esperti specializzati nella progettazione e il monitoraggio strutturale ha permesso di colmare alcune lacune tecniche, ricevendo inoltre un prezioso feedback in tempo reale. A partire dai primi rudimentali script per la popolazione di parametri composti, la risultante metodologia procedurale - proposta per la digitalizzazione delle opere d'arte stradali disseminate sul territorio nazionale italiano - riesce a rispondere bene alle richiese imposte dalla normativa vigente. Viene infatti ridotto al minimo l'intervento manuale in fase di collegamento del database informativo di catalogazione delle componenti della struttura oggetto di studio con la piattaforma online per la gestione di ponti [*Bridge Management System* – BMS], correntemente in fase di sviluppo da parte dei tecnici informatici del C.U.G.R.I.

Ugualmente automatizzata è la procedura sviluppata per la reimportazione in ambiente BIM editabile dei dati risultati dalle ispezioni effettuate in Situ.
Altrettanto caratterizzate da un elevato grado di sperimentazione sono le applicazioni sviluppate per la modellazione e l'implementazione di dati provenienti da sensori sviluppate per il secondo caso studio, il tempio di Nettuno a Paestum. L'obiettivo in questo caso era proporre procedure, ancora una volta aperte e aggiornabili, per l'importazione in ambiente BIM di dati provenienti dal rilievo tridimensionale o da misurazioni in tempo reale, riducendo al minimo i passaggi di discretizzazione fondamentali in fase di modellazione e conservando il maggior numero possibile di informazioni, assicurando così una tracciabilità del dato lungo tutto il processo. Le procedure sviluppate, ben lungi dall'essere esaustive, si propongono dunque come quadro di riferimento per l'eventuale integrazione di tecniche di Machine Learning e Intelligenza artificiale all'interno degli ECO-Sistemi di monitoraggio predisposti. Tali procedure possono riguardare ad esempio una *segmentazione* sempre più dettagliata del dato sorgente (la nuvola di punti) per ottimizzare la fase di modellazione o implementare algoritmi di *Pattern Recognition*, che generalmente adoperano dati fotografici, e di conseguenza dati rilevati attraverso l'impiego di droni, per il riconoscimento di aree deteriorate.
Questo tipo di documentazione, orientata nella direzione di una modellazione di tipo *as-built* [*Come Costruito*], intende configurarsi come un valido strumento di supporto ai fini della gestione e della manutenzione, oltre che come un efficace mezzo di aggiornamento dello stato attuale delle conoscenze sul costruito. I risultati ottenuti dimostrano come lo studio proposto fornisca un efficiente approccio semi-automatico per estrarre informazioni geometriche da una topografia complessa, acquisita con dati da scansione laser e fotogrammetrici, al fine di realizzare una corretta contestualizzazione all'interno di un modello BIM di tipo *as-built.*
La metodologia proposta intende costruire un vero e proprio ponte tra i database dei rilievi e i modelli BIM, in cui i dati possano essere arricchiti secondo le necessità, così da impiegare concretamente i modelli informativi come strumenti di supporto per progetti di manutenzione e ristrutturazione. Pertanto, l'implementazione di modelli mesh e di materiali derivati direttamente dal rilievo fotogrammetrico in ambiente BIM consente una misurazione con buon grado di approssimazione dell'oggetto rilevato e riprodotto come *istanza* in maniera affidabile. A seconda del livello di dettaglio richiesto, è possibile ottenere sia una contestualizzazione sufficientemente precisa dal punto di vista metrico, che una riproduzione morfologicamente e colorimetricamente accurata di aree di dettaglio selezionate, per quegli elementi dell'ambiente costruito con un valore formale e culturale unico, quindi meritevoli di una modellazione parametrica informativa all'interno di un sistema di monitoraggio più ampio.

D'altra parte, nel caso in cui sia richiesta una modellazione più dettagliata di aree selezionate unitamente ai relativi dati colorimetrici realistici, queste potranno essere riprodotte in ambiente BIM non più come un *unicum*, quanto piuttosto come elementi discretizzati in grado di archiviare parametri condivisi attraverso cui effettuare eventuali selezioni e verifiche. I parametri assegnati ai triangoli parametrici – che riproducono le maglie triangolari della mesh fotogrammetrica – sono aggiornabili e incrementabili all'occorrenza; personalizzando ad esempio il parametro *"Commento"*, sarebbe possibile selezionare le *facce triangolari*, filtrarle visivamente e raggrupparle calcolandone anche l'area cumulativa [3].
Appare evidente che questo tipo di applicazioni migliorerebbe significativamente anche i processi di monitoraggio dei dissesti, collocando con precisione all'interno di un ecosistema digitale opportunamente georeferenziato ogni area di interesse individuata manualmente o con l'ausilio di algoritmi di *Pattern Recognition*, andando quindi in direzione di una procedura completamente automatizzata. L'eventuale zona danneggiata rilevata e rimodellata potrà quindi essere archiviata nel *repository* BIM, disponibile per qualsiasi interrogazione e pronta per la generazione di eventuali segnalazioni d'allarme.
Una modellazione strutturale accurata ha inoltre permesso di dimostrare, per il caso studio del Tempio di Nettuno, l'utilità dei modelli federati correttamente georeferenziati, realizzati a partire dai dati del rilievo tridimensionale, sperimentando procedure di confronto tra modelli continui derivati da quelli di tipo BIM e i modelli discreti, rappresentati dalle nuvole di punti. Considerando una certa tolleranza associata alla discretizzazione effettuata in fase di rimodellazione, qualunque scostamento futuro, superiore in valore assoluto a quello rilevato al tempo zero [t_0] tra il modello continuo di riferimento e modelli discreti provenienti da rilievi aggiornati, georeferenziati nello stesso sistema di riferimento topografico, costituirà dunque un segnale di allerta immediato di possibili spostamenti in atto nella struttura.
La gestione del patrimonio esistente non può oggi prescindere da un'indagine approfondita dello stato di conservazione dei materiali e da una dettagliata ricostruzione 3D. La ricostruzione morfologica e colorimetrica di strutture complesse, di elementi e di specifiche aree danneggiate in ambiente BIM è essenziale per lo sviluppo di databases che consentano di archiviare i dati e di facilitare la pianificazione di ristrutturazioni e, in generale, di qualsiasi attività di intervento sul bene oggetto di studio [51].

Sviluppi futuri saranno sicuramente orientati a combinare i dati TLS con quelli della fotogrammetria a distanza ravvicinata per le applicazioni di tipo indoor. Questo tipo di dati integrati, che appaiono indispensabili per la realizzazione del modello BIM con

approccio di tipo manuale, rappresenta anche una sfida interessante per l'implementazione dei workflow procedurali proposti, implementando modelli mesh derivati sia dal laser che dall'intero set di dati integrati. D'altra parte, quando l'integrazione di dati basati su sensori diventerà una pratica comune per le procedure di monitoraggio, questa prassi permetterà sicuramente di ottimizzare sicuramente le analisi effettuate sullo stato conservazione, evidenziando con precisione i cambiamenti nella geometria e nella texture del manufatto, semplicemente confrontando i dati di rilievo aggiornati con l'oggetto modellato a intervalli regolari.
Sebbene la maggior parte dei filosofi e studiosi esperti nella gestione del tempo raccomandi di concentrarsi sul presente e di pianificare il futuro, Seneca ci ricorda piuttosto di concentrarci sul passato: *"La vita è molto breve e ansiosa per chi dimentica il passato, trascura il presente e teme il futuro"*. In definitiva, Seneca sostiene che riflettere sugli eventi e sulle lezioni del proprio passato non solo impedirà di commettere errori che comportino perdite di tempo in futuro, ma fornirà anche chiarezza su come vivere una vita migliore.
Guardare al futuro senza dimenticare il passato, porsi domande, aprirsi al dibattito, queste le chiavi della ricerca scientifica e della continua crescita personale. Come ricordava anche l'astronoma Margherita Hack: *"Il divertimento della ricerca scientifica è anche trovare sempre altre frontiere da superare, costruire mezzi più potenti d'indagine, teorie più complesse, cercare sempre di progredire pur sapendo che probabilmente ci si avvicinerà sempre di più a comprendere la realtà, senza arrivare mai a capirla completamente."*

Conclusiones

La presente tesis tiene como objetivo plantear una buena práctica operativa para la realización de lo que, adoptando la terminología propia de la metodología BIM, se define como *Common Data Environment*. La aplicación de la metodología propuesta para la normalización del método Scan-to-BIM de modelado de la información, se configura en la práctica como un algoritmo orientado a facilitar tanto a los principiantes como a modeladores con más experiencia a agilizar el proceso.
El CDE se configura en la presente discusión como un verdadero *ECO-Sistema*, adoptando la gráfica elegida no por casualidad. El concepto de *Sistema Cooperativo Enriquecido* pretende destacar precisamente cómo un plan de gestión eficaz no puede ni debe ser un sistema cerrado y paralizado en el tiempo. De hecho, su éxito o fracaso está vinculado exclusivamente al compromiso de los futuros gestores para mantenerlo en un buen estado de eficiencia. La colaboración entre los distintos especialistas es, por tanto, un momento fundamental en la óptica de la actualización y el enriquecimiento continuo. De hecho, una cooperación fructífera con otros campos del conocimiento es esencial en la actualidad para una gestión integral del patrimonio construido.
El planteamiento algorítmico general se enriquece así con las buenas prácticas procedimentales, sin pretender agotar el conjunto de posibles sistemas de implementación respecto a la gran cantidad de datos de entrada posibles. Dado el creciente desarrollo tecnológico de nuestra generación, lo óptimo para establecer un *ECO-Sistema* de vigilancia es que sea abierto, flexible y de fácil actualización. De hecho, la tendencia exponencial de la evolución tecnológica nos ha demostrado que, en el contexto actual, las limitaciones de ayer son los retos de hoy y la historia de mañana. Una historia que no debe ser olvidada, sino catalogada y prolijamente archivada a través de repositorios digitales desde los cuales se puede recuperar la información, si es necesario, en forma de infografía (en la Figura 13.1 se presenta un ejemplo de infografía que evoca metafóricamente la importancia del monitoreo de la salud estructural).
Este modelo electrónico – definido independientemente de las representaciones tradicionales – constituye una nueva realidad artificial, no gráfica sino digital, capaz de proporcionar toda la información a partir de descripciones gráficas, para comprender la realidad objetiva. Las imágenes digitales, como representaciones visibles de modelos conceptuales y abstractos, se constituyen en un nuevo lenguaje híbrido. La palabra virtual bien puede emplearse en este sentido porque, al reflexionar, la imagen infográfica es siempre virtual: entendiendo el adjetivo como

lo que está latente, pero sobre todo como lo que posee potencialidad; es decir, según la categoría aristotélica, como lo que es fundamentalmente potencial. De hecho, todas las imágenes digitales – incluso aquellas procesadas con software de delineación puro – son virtuales porque están ocultas en la memoria del ordenador y sólo se crean en el momento en que se llaman [255].

El primer caso de estudio propuesto, relativo a la actualización de las informaciones y la digitalización del Viaducto Olivieri (Salerno), se inscribe, por tanto, en el marco más general orientado a la conservación del patrimonio infraestructural italiano, que, como se ha comentado ampliamente, tiene un pasado complejo a sus espaldas, cayendo a menudo en el olvido total. La aplicación propuesta tiene un carácter fuertemente experimental, tanto por el procedimiento de modelización y actualización de la información que la infrascrita propone, como por el hecho de proponerse a modo de referencia para la aplicación concreta de las recomendaciones contenidas en las ***Líneas Guías para la clasificación y gestión de riesgos, la evaluación de la seguridad y la supervisión de los puentes existentes*** publicadas en 2020 [4].
El mayor reto era, por tanto, la simplificación y optimización del procedimiento para el uso efectivo de los modelos tipo BIM en la catalogación e inspección de los puentes, viaductos y pasos elevados existentes, de forma que fuera una herramienta de apoyo y no una barrera para los técnicos del C.U.G.R.I. [*Consorzio inter-Universitario per la previsione e prevenzione dei Grandi Rischi*], que no son expertos en el campo del modelado de información tridimensional. De hecho, entre los colaboradores del CUGRI no sólo hay profesores e investigadores de las dos universidades del consorcio, sino también estudiantes de grado y máster. La interacción directa con expertos especializados en el proyecto y el monitoreo estructural permitió a la autora llenar algunas lagunas técnicas y recibir una valiosa retroalimentación en tiempo real. Partiendo de los primeros scripts rudimentarios para la población de parámetros compuestos, la metodología de procedimiento que se propone para la digitalización de las obras de la red vial nacional Italiana consigue responder a las exigencias impuestas por la normativa vigente. Es así que, la intervención manual se reduce al mínimo al vincular la base de datos de información relativa a la catalogación de los componentes de la estructura bajo estudio con la plataforma online para la gestión de puentes [*Bridge Management System* – BMS], actualmente en desarrollo por los técnicos informáticos del C.U.G.R.I. Al mismo tiempo, igualmente automatizado es el procedimiento desarrollado para la reimportación en un entorno BIM editable de los datos resultantes a partir de las inspecciones realizadas in situ.

Caracterizadas por un elevado grado de experimentación, las aplicaciones desarrolladas para la modelización y para los datos de los sensores utilizados en el segundo caso de estudio, el Templo de Neptuno en Paestum, tienen como objetivo, proponer nuevos procedimientos abiertos y actualizables, con la finalidad de importar los datos del levantamiento tridimensional o de las mediciones en tiempo real en el entorno BIM. Minimizando los pasos de discretización esenciales en la fase de modelado y conservando la mayor cantidad de información posible, garantizando al mismo tiempo la trazabilidad de los datos a lo largo del proceso. Los procedimientos, lejos de ser exhaustivos, se proponen como marco de referencia para la posible integración de técnicas de Machine Learning e Inteligencia Artificial dentro de los ECO-Sistemas de monitorización ya configurados. Estos procedimientos pueden referirse, por ejemplo, a una segmentación más detallada de los datos de origen (nube de puntos) optimizando la fase de modelado o la aplicación de algoritmos de reconocimiento de patrones, generalmente utilizando datos fotográficos recopilados mediante drones, para reconocer las zonas deterioradas.
Este tipo de documentación, que va en la dirección de una modelización *as-built,* se propone como una herramienta válida de apoyo a la gestión y al mantenimiento, así como un medio eficaz para actualizar el estado actual del conocimiento sobre el entorno construido. Los resultados obtenidos, demuestran cómo el estudio propuesto brinda un enfoque semiautomático eficiente para extraer información geométrica de una topografía compleja, adquirida de datos de escaneo láser y fotogrametría con el fin de realizar la correcta contextualización de un modelo BIM *as-built*.
La metodología propuesta permite construir un verdadero puente entre la *base* de datos de levantamiento y los modelos BIM, donde los datos pueden enriquecerse según sea necesario, de modo que los modelos de información puedan utilizarse concretamente como herramientas de apoyo para los proyectos de mantenimiento y renovación. La implementación de modelos *mesh* y materiales derivados directamente del levantamiento fotogramétrico en el entorno BIM permite la medición con un buen grado de aproximación del objeto registrado y reproducido como *ejemplar* de forma fiable. Dependiendo del nivel de detalle requerido, es posible obtener tanto una contextualización suficientemente precisa como una reproducción morfológica y colorimétricamente exacta de las áreas de detalle seleccionadas, para aquellos elementos del entorno construido con un valor formal y cultural único, que merecen por tanto una modelización paramétrica informativa dentro de un sistema de seguimiento más amplio.
En el caso de que se requiera un modelado más detallado de las zonas seleccionadas junto con sus datos colorimétricos realistas, éstos ya no se

reproducirán en el entorno BIM como un *unicum*, sino como elementos discretizados que almacenan parámetros compartidos a través de los cuales realizar las selecciones y verificaciones. Los parámetros asignados a los triángulos paramétricos – que reproducen cada malla triangular de la *mesh* fotogramétrica – son actualizables e incrementables según sea necesario; personalizando el parámetro *"Comentario"*, por ejemplo, sería posible seleccionar, filtrar visualmente y agrupar las *mallas triangulares* calculando también su área acumulada [3].
Es evidente que este tipo de aplicación mejoraría significativamente los procesos de monitorización de las alteraciones, situando con precisión dentro de un ecosistema digital georreferenciado cada área de interés identificada manualmente o con la ayuda de algoritmos de Reconocimiento de Patrones, avanzando así en la dirección de un procedimiento completamente automatizado. Cualquier área dañada relevada y remodelada quedará entonces archivada en el repositorio BIM, disponible para cualquier consulta y lista para la generación de posibles alertas.
Un modelado estructural riguroso también permitió demostrar, en el marco del caso de estudio del Templo de Neptuno, la utilidad de los modelos federados correctamente georreferenciados y creados a partir de datos topográficos tridimensionales, experimentando procedimientos de comparación entre modelos continuos derivados de BIM y modelos discretos representados por nubes de puntos. De hecho, teniendo en cuenta una cierta tolerancia asociada a la discretización realizada durante la fase de remodelación, cualquier desviación futura, mayor en valor absoluto que la que se haya detectado en el momento cero [t0] entre el modelo de referencia continuo y los modelos discretos derivados de los levantamientos actualizados, georreferenciados en el mismo sistema de referencia topográfico, constituirá, por tanto, una señal de alerta inmediata de posibles desplazamientos que se estén produciendo en la estructura.
La gestión del patrimonio existente no puede prescindir de una investigación exhaustiva del estado de conservación de los materiales y de una reconstrucción detallada en 3D. La reconstrucción morfológica y colorimétrica de estructuras complejas, elementos y zonas específicas dañadas en un entorno BIM es esencial para el desarrollo de bases de datos que faciliten la planificación de las renovaciones y, en general, de cualquier actividad de intervención sobre el bien en estudio [51].

Los desarrollos futuros se orientarán sin duda hacia la combinación de datos de TLS con datos de fotogrametría de corto alcance para aplicaciones en interiores. Este tipo de datos integrados, ciertamente indispensables para la realización del modelo BIM con un enfoque manual, también representa un reto interesante para la implementación de los flujos de trabajo procedimentales propuestos, implementando modelos *mesh* derivados tanto del láser como del conjunto de datos integrados. Por otra parte, en el momento en que la integración de los datos procedentes de los sensores se convierta en una práctica habitual para los procedimientos de seguimiento, esta praxis permitirá sin duda de optimizar los análisis realizados sobre el estado de conservación, destacando con precisión los cambios en la geometría y la textura del artefacto, con sólo comparar en intervalos regulares los datos topográficos actualizados con el objeto modelado.

Aunque la mayoría de los filósofos y estudiosos especializados en la gestión del tiempo recomiendan centrarse en el presente y planificar el futuro, Séneca nos recuerda más bien que debemos centrarnos en el pasado: *"La vida es muy corta y angustiosa para los que olvidan el pasado, descuidan el presente y temen el futuro"*. En última instancia, Séneca sostiene que reflexionar sobre los acontecimientos y las lecciones del pasado no sólo evitará que se cometan errores que impliquen una pérdida de tiempo en el futuro, sino que también proporcionará claridad sobre cómo vivir una vida mejor.

Mirar al futuro sin olvidar el pasado, plantearse preguntas, estar abierto al debate: estas son las claves de la investigación científica y del crecimiento personal continuo. Como nos recordaba también la astrónoma Margherita Hack: *"Lo divertido de la investigación científica es encontrar siempre nuevas fronteras que superar, construir medios de investigación más potentes, teorías más complejas, intentar siempre avanzar sabiendo que probablemente te acercarás cada vez más a la comprensión de la realidad, sin llegar nunca a entenderla del todo"*.

Acknowledgements

"No man is an island, entire of itself; every man is a piece of the continent, a part of the main."

[John Donne – ***No man is an island***]

My first thanks go to the academic tutors who shaped my path, i.e., Professor Barbara Messina, Professor Salvatore Barba and Professor José Antonio Lozano Galant.
Due thanks go to Professor Luigi Petti, Eng. Constanza Maria De Gaetano, Eng. Michela Landi, and all the C.U.G.R.I. technicians with whom I collaborated in developing the experimental research on both case studies presented.
Thanks to Professor Sandro Parrinello for his guidance.
Thanks to Alessandro Di Benedetto and Marco Limongiello, without whose survey works and insights, it would have been impossible to develop the proposed Scan-to-BIM and Mesh-to-BIM applications.
Thanks to Lucas Gujski for his patience in listening to my IT queries and helping me to implement my ideas.
Thanks to old and new friends, in particular Victoria Ferraris, Carla Ferreyra, Sara Morena, Lorena Centarti, Maria Belén Trivi, Caterina Gabriella Guida, Francesca Picchio, Silvia La Placa, Raffaella De Marco, Anna Dell'Amico, Elisabetta Doria, Francesca Galasso, Hangjun Fu, Giulia Porcheddu, Chiara Rivellino, Annabella Paciello, and Rosa Anna Auletta whose positivity, help, or a simple kind word felt crucial in completing this journey.
Thanks to all the members of the *Laboratorio Modelli – Surveying and Geo-Mapping for Environment and Cultural Heritage* – who took part in my adventure over the years and those who joined in by welcoming me at the *DAda Lab – Drawing Architecture Documentaction Laboratory*.

References

[1] Laubscher, J., Ferreyra, C., & Sanseverino, A. (2019). SSIMM. Italy – South Africa joint Research Project. La proposta architettonica. *Il Simposio UID Di Internazionalizzazione Della Ricerca*, 312–315.

[2] Sanseverino, A., Ferraris, V., Barbato, D., & Messina, B. (2021). Un approccio collaborativo di tipo BIM per colmare distanze fisiche, sociali e culturali. In A. Arena, M. Arena, D. Mediati, & P. Raffa (Eds.), *42th INTERNATIONAL CONFERENCE OF REPRESENTATION DISCIPLINES TEACHERS. CONGRESS OF UNIONE ITALIANA PER IL DISEGNO. PROCEEDINGS 2020. Connecting. Drawing for weaving relationship. Languages Distances Technologies* (pp. 1814–1831). FrancoAngeli srl. https://doi.org/10.3280/oa-693.102

[3] Sanseverino, A., Messina, B., Limongiello, M., & Guida, C. G. (2022). An HBIM Methodology for the Accurate and Georeferenced Reconstruction of Urban Contexts Surveyed by UAV: The Case of the Castle of Charles V. *Remote Sensing*, *14*(15), 3688. https://doi.org/10.3390/rs14153688

[4] Linee Guida per la Classificazione e Gestione del Rischio, la Valutazione della Sicurezza ed il Monitoraggio dei Ponti Esistenti, (2020).

[5] Zinno, R., & Artese, S. (2021). Innovative methods and materials in structural health monitoring of civil infrastructures. *Applied Sciences (Switzerland)*, *11*(3), 1–5. https://doi.org/10.3390/app11031140

[6] Song, G., Wang, C., & Wang, B. (2017). *Structural Health Monitoring (SHM) of Civil Structures*. https://doi.org/10.3390/app7080789

[7] Chen, H.-P., & Ni, Y.-Q. (2018). *Structural health monitoring of large civil engineering structures*.

[8] Farrar, C. R., & Worden, K. (2007). An introduction to structural health monitoring. *Philosophical Transaction of the Royal Society A*, *365*, 303–315. https://doi.org/10.1098/rsta.2006.1928

[9] Balageas, D. (2006). Introduction to Structural Health Monitoring. In D. Balageas, C.-P. Fritzen, & A. Guemes (Eds.), *Structural Health Monitoring* (pp. 13–43).

[10] Gattulli, V., Lepidi, M., & Potenza, F. (2016). Dynamic testing and health monitoring of historic and modern civil structures in Italy. *Structural Monitoring and Maintenance*, *3*(1), 71–90. https://doi.org/10.12989/smm.2016.3.1.071

[11] Achuthan, K., Hay, N., Aliyari, M., & Ayele, Y. Z. (2021). A Digital Information Model Framework for UAS-Enabled Bridge Inspection. *Energies*, *14*(19). https://doi.org/10.3390/en14196017

[12] Sacks, R., Eastman, C. M., Lee, G., & Teicholz, P. (2018). *BIM Handbook: A guide to building information modeling for owners, managers, designers, engineers, and contractors* (Thrid). John Wiley & Sons, Inc.

[13] Kreider, R. G., & Messner, J. I. (2013, September). *The Uses of BIM: Classifying and Selecting BIM Use*. The Pennsylvania State University. http://bim.psu.edu

[14] Sacchi, L. (2016). Il punto sul B.I.M./ On B.I.M. *DisegnareCON*, *9*(16), 1.1-1.8.

[15] Parrinello, S., & Dell'Amico, A. (2021). From Survey to Parametric Models: HBIM Systems for Enrichment of Cultural Heritage Management. In C. Bolognesi & D. Villa (Eds.), *From Building Information Modelling to Mixed Reality* (pp. 89–107). Springer International Publishing. https://doi.org/https://doi.org/10.1007/978-3-030-49278-6_6

[16] lo Turco, M. (2011). Il Building Information Modeling tra ricerca, didattica e professione/ Building Information Modeling between research, teaching and professional. *DisegnareCON*, *4*(7), 42–51.

[17] Bellido-Montesinos, P., Lozano-Galant, F., Castilla, F. J., & Lozano-Galant, J. A. (2019). Experiences learned from an international BIM contest: Software use and information workflow analysis to be published in: Journal of

Building Engineering. *Journal of Building Engineering*, *21*, 149–157. https://doi.org/10.1016/j.jobe.2018.10.012

[18] DM 560/2017 Modalità e i tempi di progressiva introduzione dei metodi e degli strumenti elettronici di modellazione per l'edilizia e le infrastrutture (Decreto BIM), (2017).

[19] Pavan, A. (2020). *SMARTBUILDING Italia roadshow 2020: la progettazione BIM come premessa all'efficienza energetica*. Polytechnic University of Milan.

[20] UNI/PdR 74:2019 Sistema di Gestione BIM – Requisiti, (2019).

[21] ACCA SOFTWARE. (2020). *GUIDA AL BIM 2. La rivoluzione digitale dell'edilizia* (First). ACCA software S.p.A. www.acca.it

[22] Sacks, R., Eastman, C. M., Lee, G., & Teicholz, P. (2018). *BIM Handbook: A guide to building information modeling for owners, managers, designers, engineers, and contractors* (Thrid). John Wiley & Sons, Inc.

[23] Grieves, M. W. (2005). Product lifecycle management: the new paradigm for enterprises. In *International Journal of Product Development* (Vol. 2, Issues 1–2). Inderscience Publishers. https://doi.org/10.1504/IJPD.2005.006669

[24] Kaewunruen, S., Sresakoolchai, J., Ma, W., & Phil-Ebosie, O. (2021). Digital twin aided vulnerability assessment and risk-based maintenance planning of bridge infrastructures exposed to extreme conditions. *Sustainability (Switzerland)*, *13*(4), 1–19. https://doi.org/10.3390/su13042051

[25] Jiang, F., Ma, L., Broyd, T., & Chen, K. (2021). Digital twin and its implementations in the civil engineering sector. *Automation in Construction*, *130*. https://doi.org/10.1016/j.autcon.2021.103838

[26] Stylianidis, E. (2020). *Photogrammetric Survey for the Recording and Documentation of Historic Buildings* (G. Solari, S.-H. Chen, M. di Prisco, & I. Vayas, Eds.; 1st ed.). Springer Cham. https://doi.org/https://doi.org/10.1007/978-3-030-47310-5

[27] Brumana, R., Della Torre, S., Oreni, D., Previtali, M., Cantini, L., Barazzetti, L., Franchi, A., & Banfi, F. (2017). HBIM challenge among the

paradigm of complexity, tools and preservation: The basilica di Collemaggio 8 years after the earthquake (L'Aquila). *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*, *42*(2W5), 97–104. https://doi.org/10.5194/isprs-archives-XLII-2-W5-97-2017

[28] Rocha, G., Mateus, L., Fernández, J., & Ferreira, V. (2020). A Scan-to-BIM methodology applied to heritage buildings. *Heritage*, *3*(1), 47–65. https://doi.org/10.3390/heritage3010004

[29] Badenko, V., Fedotov, A., Zotov, D., Lytkin, S., Volgin, D., Garg, R. D., & Min, L. (2019). Scan-to-BIM methodology adapted for different application. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*, *42*(5/W2), 1–7. https://doi.org/10.5194/isprs-archives-XLII-5-W2-1-2019

[30] Teruggi, S., Grilli, E., Fassi, F., & Remondino, F. (2021). 3D surveying, semantic enrichment and virtual access of large Cultural Heritage. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *8*(M-1–2021), 155–162. https://doi.org/10.5194/isprs-annals-VIII-M-1-2021-155-2021

[31] Grilli, E., & Remondino, F. (2019). Classification of 3D digital heritage. *Remote Sensing*, *11*(7). https://doi.org/10.3390/RS11070847

[32] Lato, M., Kemeny, J., Harrap, R. M., & Bevan, G. (2013). Rock bench: Establishing a common repository and standards for assessing rockmass characteristics using LiDAR and photogrammetry. *Computers & Geosciences*, *50*, 106–114. https://doi.org/10.1016/j.cageo.2012.06.014

[33] Che Ku Abdullah, C. K. A. F., Baharuddin, N. Z. S., Ariff, M. F. M., Majid, Z., Lau, C. L., Yusoff, A. R., Idris, K. M., & Aspuri, A. (2017). Integration of Point Clouds Dataset from Different Sensors. *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *42W3*, 9–15. https://doi.org/10.5194/isprs-archives-XLII-2-W3-9-2017

[34] Romero-Jarén, R., & Arranz, J. J. (2021). Automatic segmentation and classification of BIM elements from point clouds. *Automation in Construction*, *124*, 103576. https://doi.org/10.1016/j.autcon.2021.103576

[35] De Geyter, S., Vermandere, J., de Winter, H., Bassier, M., & Vergauwen, M. (2022). Point Cloud Validation: On the Impact of Laser Scanning Technologies on the Semantic Segmentation for BIM Modeling and Evaluation. *Remote Sensing*, *14*(3), 582. https://doi.org/10.3390/rs14030582

[36] Hübner, P., Clintworth, K., Liu, Q., Weinmann, M., & Wursthorn, S. (2020). Evaluation of HoloLens Tracking and Depth Sensing for Indoor Mapping Applications. *Sensors*, *20*(4), 1021. https://doi.org/10.3390/s20041021

[37] BIM Forum. (2019). *Level of Development (LOD) Specification Part I & Commentary. For Building Information Models*. www.bimforum.org/lod

[38] UNI 11337-4:2017 Edilizia e opere di ingegneria civile - Gestione digitale dei processi informativi delle costruzioni - Parte 4: Evoluzione e sviluppo informativo di modelli, elaborati e oggetti, (2017).

[39] Sun, C., Zhou, Y., & Han, Y. (2022). Automatic generation of architecture facade for historical urban renovation using generative adversarial network. *Building and Environment*, *212*, 108781. https://doi.org/10.1016/j.buildenv.2022.108781

[40] Sun, Z., Xie, J., Zhang, Y., & Cao, Y. (2019). As-built BIM for a fifteenth-century Chinese brick structure at various LoDs. *ISPRS International Journal of Geo-Information*, *8*(12). https://doi.org/10.3390/ijgi8120577

[41] Yang, X., Lu, Y. C., Murtiyoso, A., Koehl, M., & Grussenmeyer, P. (2019). HBIM modeling from the surface mesh and its extended capability of knowledge representation. *ISPRS International Journal of Geo-Information*, *8*(7). https://doi.org/10.3390/IJGI8070301

[42] Sun, Z., Xie, J., Zhang, Y., & Cao, Y. (2019). Geo-Information As-Built BIM for a Fifteenth-Century Chinese Brick Structure at Various LoDs. *ISPRS International Journal of Geo-Information*, *8*(12). https://doi.org/10.3390/ijgi8120577

[43] Ferreyra, C., Sanseverino, A., & di Filippo, A. (2021). Image-Based elaborations to improve the HBIM Level of Development. *Dn. Building Information Modeling, Data & Semantics*, *8*, 109–120.

[44] Barazzetti, L., Banfi, F., Brumana, R., & Previtali, M. (2015). Creation of parametric BIM Objects from Point Clouds using NURBS. *The Photogrammetric Record*, *30*(152), 339–362. https://doi.org/10.1111/phor.12122

[45] Tommasi, C., Achille, C., & Fassi, F. (2016). From point cloud to BIM: A modelling challenge in the cultural heritage field. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*, *41*, 429–436. https://doi.org/10.5194/isprsarchives-XLI-B5-429-2016

[46] Jia, S., Liao, Y., Xiao, Y., Zhang, B., Meng, X., & Qin, K. (2022). Methods of Conserving and Managing Cultural Heritage in Classical Chinese Royal Gardens Based on 3D Digitalization. *Sustainability (Switzerland)*, *14*(7), 4108. https://doi.org/10.3390/su14074108

[47] Rashdi, R., Martínez-Sánchez, J., Arias, P., & Qiu, Z. (2022). Scanning Technologies to Building Information Modelling: A Review. *Infrastructures*, *7*(4), 49. https://doi.org/10.3390/infrastructures7040049

[48] Barazzetti, L., Banfi, F., Brumana, R., Previtali, M., & Roncoroni, F. (2016). BIM from laser scans… not just for buildings: NURBS-based parametric modeling of a medieval bridge. *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences*, *III–5*, 51–56. https://doi.org/10.5194/isprsannals-iii-5-51-2016

[49] Acosta, E., Spettu, F., & Fiorillo, F. (2022). A procedure to import a complex geometry model of a Heritage building into BIM for advanced architectural representations. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XLVI-2/W1-2022*, 9–16. https://doi.org/10.5194/isprs-archives-XLVI-2-W1-2022-9-2022

[50] Parrinello, S., Picchio, F., & De Marco, R. (2018). Urban modeling experiences for the representation of the historical city in Holy Land. *Disegnare Con*, *11*(21), 5.1-5.22.

[51] Barrile, V., Bernardo, E., & Bilotta, G. (2022). An Experimental HBIM Processing: Innovative Tool for 3D Model Reconstruction of Morpho-Typological Phases for the Cultural Heritage. *Remote Sensing*, *14*(5), 1288. https://doi.org/10.3390/rs14051288

[52] Costin, A., Adibfar, A., Hu, H., & Chen, S. S. (2018). Building Information Modeling (BIM) for transportation infrastructure - Literature review, applications, challenges, and recommendations. *Automation in Construction*, *94*, 257–281. https://doi.org/10.1016/j.autcon.2018.07.001

[53] Borrmann, A., Muhic, S., Hyvärinen, J., Chipman, T., Jaud, S., Castaing, C., Dumoulin, C., Liebich, T., & Mol, L. (2019). The IFC-Bridge project – Extending the IFC standard to enable high-quality exchange of bridge information models. *Proceedings of the 2019 European Conference on Computing in Construction*, *1*, 377–386. https://doi.org/10.35490/ec3.2019.193

[54] ISO 16739:2013 Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries, (2013).

[55] La Russa, F. M. (2021). AI for AEC: Open Data and VPL Approach for Urban Seismic Vulnerability. In *Representation Challenges. Augmented Reality and Artificial Intelligence in Cultural Heritage and Innovative Design Domain*. FrancoAngeli srl. https://doi.org/10.3280/oa-686.61

[56] Collao, J., Lozano-Galant, F., Lozano-Galant, J. A., & Turmo, J. (2021). BIM visual programming tools applications in infrastructure projects: A state-of-the-art review. *Applied Sciences (Switzerland)*, *11*(18). https://doi.org/10.3390/app11188343

[57] Pavan, A. (2019). *Digitalizzazione del settore delle costruzioni: UNI11337:2009-2018*. Polytechnic University of Milan.

[58] ISO 16739-1:2018 Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries – Part 1: Dasa schema, (2018).

[59] Artus, M., & Koch, C. (2020). State of the art in damage information modeling for RC bridges - A literature review. *Advanced Engineering Informatics*, *46*. https://doi.org/10.1016/j.aei.2020.101171

[60] Rapetti, N. (2019). Strumenti e metodi per la progettazione InfraBIM. In A. Osello, A. Fonsati, N. Rapetti, & F. Semeraro (Eds.), *InfraBIM. Il BIM per le infrastrutture* (pp. 45–63). Gangemi Editore spa.

[61] Osello, A., Rapetti, N., & Semeraro, F. (2017). BIM Methodology Approach to Infrastructure Design: Case Study of Paniga Tunnel. *IOP Conference*

Series: Materials Science and Engineering, *245*. https://doi.org/10.1088/1757-899X/245/6/062052

[62] Collao, J., Ma, H., Lozano-Galant, J. A., & Turmo, J. (2021). Traffic Road Emission Estimation through Visual Programming Algorithms and Building Information Models: A Case Study. *IEEE Access*, *9*, 150846–150864. https://doi.org/10.1109/ACCESS.2021.3123565

[63] Grimaldi, M., Giordano, C., Graziuso, G., Barba, S., & Fasolino, I. (2022). A GIS-BIM Approach for the Evaluation of Urban Transformations. A Methodological Proposal. *WSEAS TRANSACTIONS ON ENVIRONMENT AND DEVELOPMENT*, *18*, 247–254. https://doi.org/10.37394/232015.2022.18.26

[64] Noardo, F., Ohori, K., Biljecki, F., Krijnen, T., Ellul, C., Harrie, L., & Stoter, J. (2019). GeoBIM benchmark 2019: design and initial results. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XLII-2/W13*. https://doi.org/10.5194/isprs-archives-XLII-2-W13-1339-2019

[65] Osello, A. (2019). Approccio metodologico all'InfraBIM. In A. Osello, A. Fonsati, N. Rapetti, & F. Semeraro (Eds.), *InfraBIM. Il BIM per le infrastrutture* (pp. 15–23). Gangemi Editore spa.

[66] Giusti, F. (2018, August 20). Quando nel 1967 crollò il Ponte di Ariccia e i giornali titolavano: "In Italia nessuno controlla i ponti." *Ilmamilio.It*. https://www.ilmamilio.it/c/news/9370-quando-crollo-il-viadotto-di-ariccia-e-i-giornali-titolavano-in-italia-nessuno-controlla-i-ponti.html

[67] De Matteis, G., Bencivenga, P., & Zizi, M. (2019, September). Rischio strutturale di ponti esistenti: considerazioni preliminari sullo scenario in provincia di Caserta. *XVIII Convegno ANIDIS. L'ingegneria Sismica in Italia*. https://www.researchgate.net/publication/335927927

[68] Alessandrini, S. (2020, December 22). Il crollo del ponte Morandi a Genova. *Ingenio Informazione Tecnica e Progettuale*. https://www.ingenio-web.it/20966-il-crollo-del-ponte-morandi-a-genova

[69] Salvatore, W. (2019, February 14). *Valutazione del rischio strutturale dei ponti nelle reti infrastrutturali*. ENEA Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile.

[70] Frosina, P. (2020, December 21). Ponte Morandi, la perizia: "I controlli e la manutenzione avrebbero impedito il crollo. Dal 1993 nessun intervento sul pilone caduto." *Il Fatto Quotidiano*. https://www.ilfattoquotidiano.it/2020/12/21/ponte-morandi-la-perizia-del-gip-i-controlli-e-la-manutenzione-avrebbero-impedito-il-crollo/6044625/

[71] Salvatore, W. (2020, May 20). *Linee guida per la classificazione e gestione del rischio, la valutazione della sicurezza ed il monitoraggio dei ponti esistenti - Parte 1: Classificazione e gestione del Rischio*. Consiglio Nazionale degli Ingegneri.

[72] Braga, F., Buratti, G., Cosentino, A., Dall'Asta, A., de Matteis, G., Gigliotti, R., Mezzina, M., Morelli, F., Ristori, C., & Salvatore, W. (2019, September). Multi-level approach for the assessment of bridge and viaducts within road networks. *XVIII Convegno ANIDIS. L'Ingegneria Sismica in Italia*.

[73] Piano Operativo Fondo Sviluppo e Coesione Infrastrutture 2014 – 2020 (Legge n. 190 del 23 dicembre 2014, c. 703 - Delibera CIPE n. 25 del 10/08/2016), (2019).

[74] Pierluigi, B. (2019, November 28). Dossier UPI: Monitoraggio Ponti. *Unione Province d'Italia*.

[75] Pierluigi, B. (2018, October 5). Monitoraggio ponti: Upi "Censite 5.931 opere: servono 3 miliardi per intervenire su sicurezza." *Unione Province d'Italia*. https://www.provinceditalia.it/monitoraggio-ponti-upi-censite-5-931-opere-servono-3-miliardi-per-intervenire-su-sicurezza/

[76] Gabanelli, M., & Pasqualetto, A. (2019, February 3). Viadotti: 1.425 sono senza un proprietario e nessuno fa la manutenzione. Ecco la mappa. *Corriere Della Sera. Dataroom*. https://www.corriere.it/dataroom-milena-gabanelli/viadotti-1425-sono-senza-proprietario-nessuno-fa-la-manutenzione-ponti-crolli-ecco-mappa/ae3102d2-263f-11e9-9b5e-1a58eb1d569a-va.shtml

[77] Gabanelli, M., & Gabanelli, M. (2020, January 19). Ponti a rischio: ancora 3.500 quelli senza controlli e manutenzione in Italia. *Corriere Della Sera. Dataroom*. https://www.corriere.it/dataroom-milena-gabanelli/ponti-viadotti-pericolosi-anas-3500-ponti-fuori-controllo-763-senza-proprieta/b79e6a4c-3ac7-11ea-9d89-0cf44350b722-va.shtml

[78] Petrangeli, M. P. (1996). *Progettazione e costruzione di ponti. Con cenni di patologia e diagnostica delle opere esistenti* (4th ed.). CEA.

[79] Buratti, G., Cosentino, A., Morelli, F., Salvatore, W., & Bencivenga, P. (2019, September). Consideration on Italian code evolution of traffic loads in design of road bridges. *XVIII Convegno ANIDIS. L'Ingegneria Sismica in Italia*.

[80] Ministerio de Fomento. (2010). *Guía de inspecciones básicas de obras de paso. Red de carreteras del estado*. D.G. de carreteras. Centro de publicaciones, Ministerio de Fomento.

[81] Fariña, V. M. (2015, November). Sistema Integral de Gerencia y Mantenimiento de Puentes en Argentina. *XX Congreso Internacional Del CLAD Sobre La Reforma Del Estado y de La Administración Pública*.

[82] DM 430/2019 Archivio Informatico Nazionale delle Opere Pubbliche (AINOP), Pub. L. No. 430 (2019).

[83] Circolare del Ministero dei Lavori Pubblici 19 Luglio 1967 n° 6736/61/A1 – Controllo delle condizioni di stabilità delle opere d'arte stradali, (1967).

[84] Circolare del Ministero dei Lavori Pubblici 25 febbraio 1991 n. 34233 (pres. cons. sup. serv. tecnico centrale) – legge 2 febbraio 1974, n. 64 - art. 1 decreto ministeriale 4 maggio 1990 – Istruzioni relative alla normativa tecnica dei ponti stradali, (1991).

[85] DM 17/01/2018 Aggiornamento delle "Norme Tecniche per le costruzioni," (2018).

[86] Circolare del Ministero dei Lavori Pubblici 21 Gennaio 2019 n° 7 C.S.LL.PP. - Istruzioni per l'applicazione dell'«Aggiornamento delle "Norme tecniche per le costruzioni"» di cui al decreto ministeriale 17 gennaio 2018, (2019).

[87] DM 14/01/2008 Norme Tecniche per le Costruzioni - NTC 2008, (2008).

[88] DM 578/2020 Adozione delle linee guida per la gestione del rischio dei ponti esistenti e per la definizione di requisiti ed indicazioni relativi al sistema di monitoraggio dinamico, (2020).

[89] DL 109/2018 Disposizioni urgenti per la città di Genova, la sicurezza della rete nazionale delle infrastrutture e dei trasporti, gli eventi sismici del

2016 e 2017, il lavoro e le altre emergenze. (18G00137), Gazzetta Ufficiale della Repubblica Italiana (2018).

[90] Guerriero, M. (2019, November 21). Opere pubbliche: in vigore il decreto attuativo per l'istituzione di AINOP e IOP. *BibLus-Net*. https://biblus.acca.it/arriva-aniop-archivio-nazionale-informatico-opere-pubbliche/#:~:text=AINOP%20(Archivio%20informatico%20nazionale%20delle%20opere%20pubbliche)%2C%20cos'%C3%A8&text=L'archivio%20sar%C3%A0%20suddiviso%20nelle,ponti%20viadotti%20e%20cavalcavia%20ferroviari

[91] Retico, C., Lia, S., & Paolucci, M. (2020). *AINOP: Archivio Informatico Nazionale delle Opere Pubbliche. Modalità di accesso e alimentazione della banca dati*.

[92] Salvatore, W., & Cosentino, A. (2020). *Linee guida per la classificazione e gestione del rischio, la valutazione della sicurezza ed il monitoraggio dei ponti esistenti – Parte 1: Classificazione e gestione del rischio dei ponti esistenti - Aspetti operativi e dettaglio della metodologia: Esempi di applicazione*.

[93] Linee Guida per la Classificazione e Gestione del Rischio, la Valutazione della Sicurezza ed il Monitoraggio dei Ponti Esistenti - Allegato A: Schede di censimento ponti di Livello 0, (2020).

[94] Linee Guida per la Classificazione e Gestione del Rischio, la Valutazione della Sicurezza ed il Monitoraggio dei Ponti Esistenti - Allegato B: Schede di Valutazione dei Difetti, (2020).

[95] Linee Guida per la Classificazione e Gestione del Rischio, la Valutazione della Sicurezza ed il Monitoraggio dei Ponti Esistenti - Allegato C: Schede difettologiche, (2020).

[96] De Gaetano, C. M. (2020). *Analisi di procedure innovative per la sorveglianza delle opere d'arte*. University of Salerno.

[97] Linee Guida per la Classificazione e Gestione del Rischio, la Valutazione della Sicurezza ed il Monitoraggio dei Ponti Esistenti - Allegato B: Schede descrittive di ispezione ponti di Livello 1, (2020).

[98] Linee Guida per la Classificazione e Gestione del Rischio, la Valutazione della Sicurezza ed il Monitoraggio dei Ponti Esistenti - Allegato B:

Schede descrittive di ispezione ponti di Livello 1 - Fenomeni di frana e fenomeni idraulici, (2020).

[99] ASPI Autostrade per l'Italia. (2020). *Manuale della Sorveglianza. Opere d'Arte Maggiori. Ambito: Ispezioni Visive (Bozza)*.

[100] SPEA Engineering S.p.A., & ASPI Autostrade per l'Italia. (2015). *Manuale della Sorveglianza. Manutenzione Programmata Delle Opere D'Arte Stradali*.

[101] Nguyen, D.-C., Nguyen, T.-Q., Jin, R., Jeon, C.-H., & Shim, C.-S. (2022). BIM-based mixed-reality application for bridge inspection and maintenance. *Construction Innovation - England*, *22*(3), 487–503. https://doi.org/10.1108/CI-04-2021-0069

[102] Xu, S., Wang, J., Wang, X., Wu, P., Shou, W., & Liu, C. (2022). A Parameter-Driven Method for Modeling Bridge Defects through IFC. *Journal of Computing in Civil Engineering*, *36*(4). https://doi.org/10.1061/(ASCE)CP.1943-5487.0001026

[103] Nie, L., Hou, G., Li, W., & Li, P. (2022). Research on automatic visualization technology of bridge disease information based on BIM. In G. Tan & F. Cen (Eds.), *International Conference on Intelligent Traffic Systems and Smart City (ITSSC 2021)* (Vol. 12165). Proceedings of SPIE. https://doi.org/10.1117/12.2627935

[104] Saback, V., Popescu, C., Blanksvard, T., & Taljsten, B. (2022). Asset Management of Existing Concrete Bridges Using Digital Twins and BIM: a State-of-the-Art Literature Review. *Nordic Concrete Research*, *66*(1), 91–111. https://doi.org/10.2478/ncr-2021-0020

[105] Akanbi, T., & Zhang, J. (2022). Framework for Developing IFC-Based 3D Documentation from 2D Bridge Drawings. *Journal of Computing in Civil Engineering*, *36*(1). https://doi.org/10.1061/(ASCE)CP.1943-5487.0000986

[106] Dayan, V., Chileshe, N., & Hassanli, R. (2022). A Scoping Review of Information-Modeling Development in Bridge Management Systems. *Journal of Construction Engineering and Management*, *148*(9). https://doi.org/10.1061/(ASCE)CO.1943-7862.0002340

[107] Li, X. F., Xiao, Y. Y., Guo, H. N., & Zhang, J. S. (2022). A BIM Based Approach for Structural Health Monitoring of Bridges. *KSCE Journal of Civil Engineering*, *26*(1), 155–165. https://doi.org/10.1007/s12205-021-2040-3

[108] Riedlinger, U., Oppermann, L., Klein, F., Hill, M., Bahlau, S., Lambracht, C., Nieborowski, S., & Holst, R. (2022). Mixed Reality Support for Bridge Inspectors. *IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, 704–705. https://doi.org/10.1109/VRW55335.2022.00203

[109] Adibfar, A., & Costin, A. M. (2022). Creation of a Mock-up Bridge Digital Twin by Fusing Intelligent Transportation Systems (ITS) Data into Bridge Information Model (BrIM). *Journal of Construction Engineering and Management*, *148*(9). https://doi.org/10.1061/(ASCE)CO.1943-7862.0002332

[110] Wang, Y.-G., He, X.-J., He, J., & Fan, C. (2022). Virtual trial assembly of steel structure based on BIM platform. *Automation in Construction*, *141*. https://doi.org/10.1016/j.autcon.2022.104395

[111] Bono, A., D'Alfonso, L., Fedele, G., Filice, A., & Natalizio, E. (2022). Path Planning and Control of a UAV Fleet in Bridge Management Systems. *Remote Sensing*, *14*(8). https://doi.org/10.3390/rs14081858

[112] Taraben, J., Helmrich, M., & Morgenthal, G. (2022). Integration and linking of inspection data in digital bridge models. *Bautechnik*, *99*(2), 134–142. https://doi.org/10.1002/bate.202100091

[113] Artus, M., Alabassy, M. S. H., & Koch, C. (2022). A BIM Based Framework for Damage Segmentation, Modeling, and Visualization Using IFC. *Applied Sciences (Switzerland)*, *12*(6). https://doi.org/10.3390/app12062772

[114] Naraniecki, H., Hartung, R., Marx, S., & Klemt-Albert, K. (2022). Condition state prediction of engineering structures based on digital twins and inspection data. *Bautechnik*, *99*(3), 173–181. https://doi.org/10.1002/bate.202100100

[115] Previtali, M., Brumana, R., & Banfi, F. (2022). Existing infrastructure cost effective informative modelling with multisource sensed data: TLS, MMS and photogrammetry. *Applied Geomatics*, *14*(SUPPL 1), 21–40. https://doi.org/10.1007/s12518-020-00326-3

[116] Chai, Y. T., & Wang, T.-K. (2022). Evaluation and decision-making framework for concrete surface quality based on computer vision and ontology. *Engineering Construction and Architectural Management*, *7*. https://doi.org/10.1108/ECAM-01-2022-0064

[117] Bouzas, O., Cabaleiro, M., Conde, B., Cruz, Y., & Riveiro, B. (2022). Structural health control of historical steel structures using HBIM. *Automation in Construction*, *140*. https://doi.org/10.1016/j.autcon.2022.104308

[118] El-Mahrouk, O., Baumgartner, S., Pfleger, M.-P., & Vill, M. (2022). The Implementation Potentials of BIM in Bridge Maintenance Workflows. *IABSE Symposium Prague, 2022: Challenges for Existing and Oncoming Structures - Report (IABSE 2022)*, 1851–1858.

[119] Liu, L., Hagedorn, P., & König, M. (2022). BIM-Based Organization of Inspection Data Using Semantic Web Technology for Infrastructure Asset Management. In C. Pellegrino, F. Faleschini, M. A. Zanini, J. C. Matos, J. R. Casas, & A. Strauss (Eds.), *1st Conference of the European Association on Quality Control of Bridges and Structures (EUROSTRUCT 2021). Lecture Notes in Civil Engineering 200: Vol. 200 LNCE* (pp. 1117–1126). https://doi.org/10.1007/978-3-030-91877-4_127

[120] El-Mahrouk, O., Baumgartner, S., Pfleger, M.-P., & Vill, M. (2022). Combined LOD-Definition for Bridge Maintenance and 3D City Maps. *IABSE Symposium Prague, 2022: Challenges for Existing and Oncoming Structures - Report (IABSE 2022)*, 1859–1866.

[121] Hajdin, R., & Samec, V. (2022). BIM and BMS: Current Status and Challenges. *IABSE Symposium Prague, 2022: Challenges for Existing and Oncoming Structures - Report (IABSE 2022)*, 710–715.

[122] Riedlinger, U., Klein, F., Hill, M., Lambracht, C., Nieborowski, S., Holst, R., Bahlau, S., & Oppermann, L. (2022). Evaluation of Mixed Reality Support for Bridge Inspectors Using BIM Data Digital Prototype for a Manual Task with a Long-Lasting Tradition. *I-Com*, *21*(2), 253–267. https://doi.org/10.1515/icom-2022-0019

[123] Mafipour, M. S., Vilgertshofer, S., & Borrmann, A. (2022). Creating digital twins of existing bridges through AI-based methods. *IABSE Symposium Prague, 2022: Challenges for Existing and Oncoming Structures - Report (IABSE 2022)*, 727–734.

[124] Polania, D. R., Tondolo, F., Osello, A., Fonsati, A., De Gaetani, C., Trincianti, C., & Gazulli, D. (2022). Digitalization Processes and Bridge Information Modeling for Existing Bridges. In C. Pellegrino, F. Faleschini, M. A. Zanini, J. C. Matos, J. R. Casas, & A. Strauss (Eds.), *1st Conference of the European Association on Quality Control of Bridges and Structures (EUROSTRUCT 2021). Lecture Notes in Civil Engineering 200: Vol. 200 LNCE* (pp. 944–953). https://doi.org/10.1007/978-3-030-91877-4_108

[125] Pellegrino, C., Faleschini, F., Zanini, M. A., Matos, J. C., Casas, J. R., & Strauss, A. (2022). 1st Conference of the European Association on Quality Control of Bridges and Structures, EUROSTRUCT 2021. *1st Conference of the European Association on Quality Control of Bridges and Structures (EUROSTRUCT 2021). Lecture Notes in Civil Engineering 200*, *200 LNCE*.

[126] Akhnoukh, A., Kaloush, K., Elabyad, M., Halleman, B., Erian, N., Enmon II, S., & Henry, C. (2022). 18th International Road Federation World Meeting and Exhibition, 2021. In *Sustainable Civil Infrastructures*.

[127] Wojcik, B., & Zarski, M. (2021). The measurements of surface defect area with an RGB-D camera for a BIM-backed bridge inspection. *Bulletin of the Polish Academy of Sciences: Technical Sciences*, *69*(3). https://doi.org/10.24425/bpasts.2021.137123

[128] Kaewunruen, S., Sresakoolchai, J., Ma, W., & Phil-Ebosie, O. (2021). Digital Twin Aided Vulnerability Assessment and Risk-Based Maintenance Planning of Bridge Infrastructures Exposed to Extreme Conditions. *Sustainability*, *13*(4). https://doi.org/10.3390/su13042051

[129] Won, Cho Mun, Hyuk, L. J., Moo, R. Y., Jeongjun, P., & Yoon, H. (2021). Image-Based Automatic Bridge Component Classification Using Deep Learning. *KSCE Journal of Civil and Environmental Engineering Research*, *41*(6), 751–760. https://doi.org/10.12652/Ksce.2021.41.6.0751

[130] Marra, A., Trizio, I., Fabbrocino, G., & Savini, F. (2021). Digital models for e-conservation: the HBrIM of a bridge along the Aterno river. *SCIentific RESearch and Information Technology (SCIRES-It)*, *11*(2), 83–96. https://doi.org/10.2423/i22394303v11n2p83

[131] Hong, Y., Park, S., Kim, H., & Kim, H. (2021). Synthetic data generation using building information models. *Automation in Construction*, *130*. https://doi.org/10.1016/j.autcon.2021.103871

[132] Hou, G., Li, L., Xu, Z., Chen, Q., Liu, Y., & Qiu, B. (2021). A BIM-Based Visual Warning Management System for Structural Health Monitoring Integrated with LSTM Network. *KSCE Journal of Civil Engineering*, *25*(8), 2779–2793. https://doi.org/10.1007/s12205-021-0565-0

[133] Pereira, A., Cabaleiro, M., Conde, B., & Sanchez-Rodriguez, A. (2021). Automatic Identification and Geometrical Modeling of Steel Rivets of Historical Structures from Lidar Data. *Remote Sensing*, *13*(11). https://doi.org/10.3390/rs13112108

[134] Hamdan, A.-H., Taraben, J., Helmrich, M., Mansperger, T., Morgenthal, G., & Scherer, R. J. (2021). A semantic modeling approach for the automated detection and interpretation of structural damage. *Automation in Construction*, *128*. https://doi.org/10.1016/j.autcon.2021.103739

[135] Tanaka, F., Nakajima, Y., Egusa, E., & Onosato, M. (2021). Data modeling based on a 3D BIM standard and viewer system for the bridge inspections. *Bridge Maintenance, Safety, Management, Life-Cycle Sustainability and Innovations - Proceedings of the 10th International Conference on Bridge Maintenance, Safety and Management (IABMAS 2020)*, 2984–2991. https://doi.org/10.1201/9780429279119-406

[136] Liu, X., Pan, Y., & Zhao, X. (2021). Research on key technology of operation and maintenance management of long span railway steel bridge based on BIM. *IABSE Conference, Seoul 2020: Risk Intelligence of Infrastructures - Report*, 222–229.

[137] Wakabayashi, Y., Yasuda, K., Tsujii, H., Konno, K., & Hirahara, Y. (2021). Labor productivity improvement of concrete bridge through utilizing BIM and ICT. *2021 Fib Symposium of Concrete Structures: New Trends for Eco-Efficiency and Performance*, *2021-June*, 1914–1921.

[138] Riedlinger, U., Klein, F., Hill, M., Neumann, S., Holst, R., Oppermann, L., & Bahlau, S. (2021). Digital Support for Bridge Inspectors through Mixed Reality BIM Data Visualizations. *Computing in Civil Engineering 2021 - Selected Papers from the ASCE International Conference on Computing in Civil Engineering 2021*, 1359–1366. https://doi.org/10.1061/9780784483893.166

[139] Li, Z. H., & Dong, M. (2021). Application of bridge maintenance and management system with BIM technology. *Bridge Maintenance, Safety, Management, Life-Cycle Sustainability and Innovations - Proceedings of the 10th International Conference on Bridge Maintenance, Safety and Management (IABMAS 2020)*, 1917–1922. https://doi.org/10.1201/9780429279119-260

[140] Linneberg, P. (2021). From condition to performance assessment of bridges - The challenge. *Bridge Maintenance, Safety, Management, Life-Cycle Sustainability and Innovations - Proceedings of the 10th International Conference on Bridge Maintenance, Safety and Management, IABMAS 2020*, 3201–3208. https://doi.org/10.1201/9780429279119-434

[141] Jeon, H., Yu, Y., Ko, B., Kim, S., & Koo, B. (2021). Augmented reality-based safety inspection framework for safety management in railway bridge and tunnel projects. *Journal of the Korean Society for Railway*, *24*(7), 590–607. https://doi.org/10.7782/JKSR.2021.24.7.590

[142] Zhu, R., Shi, X. F., & Li, X. X. (2021). Application of bridge construction monitoring management system based on Internet. *Bridge Maintenance, Safety, Management, Life-Cycle Sustainability and Innovations - Proceedings of the 10th International Conference on Bridge Maintenance, Safety and Management, IABMAS 2020*, 782–788. https://doi.org/10.1201/9780429279119-103

[143] Olsson, F., & Pétursson, H. (2021). Data-driven asset management by the swedish transport administration. *Bridge Maintenance, Safety, Management, Life-Cycle Sustainability and Innovations - Proceedings of the 10th International Conference on Bridge Maintenance, Safety and Management, IABMAS 2020*, 3209–3214. https://doi.org/10.1201/9780429279119-435

[144] Schacht, G., Wenner, M., & Marx, S. (2021). The digital bridge twin | Der digitale brückenzwilling. *AVN Allgemeine Vermessungs-Nachrichten*, *128*(5), 256–263.

[145] Leitner, B., & Luskova, M. (2021). Unmanned Aerial Vehicles as a Tool for Monitoring and Protection of Physical Infrastructure Systems. *Transport Means - Proceedings of the International Conference*, *2021-Octob*, 290–296.

[146] Zhang, X., Shi, Z., Liu, J., Han, K., Yan, W., Zhang, X., & Li, Q. (2020). Exploring the Application of BIM Technology in Bridge Inspection. *IEEE 5th International Conference on Intelligent Transportation Engineering (IEEE ICITE 2020)*, 446–450. https://doi.org/10.1109/ICITE50838.2020.9231350

[147] Erdene, K., Kwon, T. H., & Lee, S.-H. (2020). Integration of Extended IFC-BIM and Ontology for Information Management of Bridge Inspection. *Journal of the Computational Structural Engineering Institute of Korea*, *33*(6), 411–417. https://doi.org/10.7734/COSEIK.2020.33.6.411

[148] Isailovic, D., Stojanovic, V., Trapp, M., Richter, R., Hajdin, R., & Doellner, J. (2020). Bridge damage: Detection, IFC-based semantic enrichment and visualization. *Automation in Construction*, *112*. https://doi.org/10.1016/j.autcon.2020.103088

[149] Zhang, K., Wang, C., & Liu, X. (2020). Research on Construction of Highway Bridge Quality Engineering Based on BIM Technology. *4th International Workshop on Renewable Energy and Development (IWRED 2020). IOP Conference Series: Earth and Environmental Science*, *510*(5). https://doi.org/10.1088/1755-1315/510/5/052092

[150] Wojcik, B., & Zarski, M. (2020). Assessment of State-of-the-Art Methods for Bridge Inspection: case study. *Archives of Civil Engineering*, *66*(4), 343–362. https://doi.org/10.24425/ace.2020.135225

[151] Hartung, R., Naraniecki, H., Klemt-Albert, K., & Marx, S. (2020). Concept for BIM-based maintenance of engineering structures with monitoring systems. *Bautechnik*, *97*(12), 826–835. https://doi.org/10.1002/bate.202000095

[152] Grabe, M., Ullerich, C., Wenner, M., & Herbrand, M. (2020). SmartBridge Hamburg - prototypische Pilotierung eines digitalen Zwillings. *Bautechnik*, *97*(2), 118–125. https://doi.org/10.1002/bate.201900108

[153] Nettis, A., Saponaro, M., & Nanna, M. (2020). RPAS-Based Framework for Simplified Seismic Risk Assessment of Italian RC-Bridges. *Buildings*, *10*(9). https://doi.org/10.3390/buildings10090150

[154] Kang, T.-W. (2020). Identifying Considerations for Developing SLAM-based Mobile Scan Backpack System for Rapid Building Scanning. *Journal of Korea Academia-Industrial Cooperation Society*, *21*(3), 312–320. https://doi.org/10.5762/KAIS.2020.21.3.312

[155] Ma, G., & Du, Q. (2020). Optimization on the intellectual monitoring system for structures based on acoustic emission and data mining. *Measurement*, *163*. https://doi.org/10.1016/j.measurement.2020.107937

[156] Wang, Q. (2020). Construction Method of Cable-Stayed Bridge Based on BIM Platform. In *Advances in Intelligent Systems and Computing: Vol. 1146 AISC*. https://doi.org/10.1007/978-3-030-43306-2_51

[157] Dang, N. S., & Shim, C. S. (2020). BIM-based innovative bridge maintenance system using augmented reality technology. In *Lecture Notes in Civil Engineering* (Vol. 54). https://doi.org/10.1007/978-981-15-0802-8_195

[158] Zheng, Y., & Xu, C. (2020). Application of BIM in Bridge Engineering and Its Risk Analysis. *IOP Conference Series: Earth and Environmental Science*, *526*(1). https://doi.org/10.1088/1755-1315/526/1/012223

[159] Al-Adhamia, M., Roobleb, S., Wuc, S., Osuna-Yevenesb, C., Ruby-Lewisb, V., Greatrixb, M., Cartagenaa, Y., & Talebi, S. (2020). An automated approach to digitise railway bridges. *Proceedings of the 37th International Symposium on Automation and Robotics in Construction, ISARC 2020: From Demonstration to Practical Use - To New Stage of Construction Robot*, 962–968.

[160] Sofia, H., Anas, E., & Faiz, O. (2020). Mobile mapping, machine learning and digital twin for road infrastructure monitoring and maintenance: Case study of Mohammed VI bridge in Morocco. *Proceedings - 2020 IEEE International Conference of Moroccan Geomatics, MORGEO 2020*. https://doi.org/10.1109/Morgeo49228.2020.9121882

[161] Gou, H., Yang, B., Hua, H., Xie, R., Liu, C., Liu, Y., & Pu, Q. (2020). State-of-the-art review of bridge informatization and intelligent bridge in 2019 | 桥梁信息化及智能桥梁2019年度研究进展. *Tumu Yu Huanjing Gongcheng Xuebao/Journal of Civil and Environmental Engineering*, *42*(5), 14–27. https://doi.org/10.11835/j.issn.2096-6717.2020.103

[162] Artus, M., & Koch, C. (2020). Modeling geometry and semantics of physical damages using IFC. *EG-ICE 2020 Workshop on Intelligent Computing in Engineering, Proceedings*, 144–153.

[163] Xie, Y., Wang, W., Zhao, J., & Li, H. (2020). Study and Application of Key Technologies in Intelligent Construction of Railway Continuous Beam Bridge | 铁路连续梁桥智能施工关键技术研究与应用. *Journal of Railway Engineering Society*, *37*(11).

[164] Singh, P., & Sadhu, A. (2020). System Identification-Enhanced Visualization Tool for Infrastructure Monitoring and Maintenance. *Frontiers in Built Environment*, *6*. https://doi.org/10.3389/fbuil.2020.00076

[165] Wan, C., Zhou, Z., Li, S., Ding, Y., Xu, Z., Yang, Z., Xia, Y., & Yin, F. (2019). Development of a bridge management system based on the building information modeling technology. *Sustainability (Switzerland)*, *11*(17). https://doi.org/10.3390/su11174583

[166] Joo, B. N., Kang, Y. J., seok, H. whi, woong, K. young, & Han, S. (2019). A Study on Integrated Information System for BIM Application of Bridge Maintenance. *Journal of The Korean Society of Hazard Mitigation*, *19*(2), 25–34. https://doi.org/10.9798/KOSHAM.2019.19.2.25

[167] Liu, B., Cai, T., Xiao, S., Fu, H., & Chu, W. (2019). Research on application of BIM technology in municipal road construction. *International Conference on Advances in Civil Engineering, Energy Resources and Environment Engineering (ACCESE 2019). IOP Conference Series: Earth and Environmental Science*, *330*(2), 022078. https://doi.org/10.1088/1755-1315/330/2/022078

[168] Boddupalli, C., Sadhu, A., Azar, E. R., & Pattyson, S. (2019). Improved visualization of infrastructure monitoring data using building information modeling. *Structure and Infrastructure Engineering* , *15*(9), 1247–1263. https://doi.org/10.1080/15732479.2019.1602150

[169] Yamamoto, T., Konuma, K., Yaguchi, T., Furuta, H., Tsuruta, H., & Ueda, N. (2019). Investigation of the lifetime extension of bridges, using three-dimensional CIM data. *Life-Cycle Analysis and Assessment in Civil Engineering: Towards an Integrated Vision - Proceedings of the 6th International Symposium on Life-Cycle Civil Engineering (IALCCE 2018)*, 2543–2548.

[170] Betkowski, P. (2019). Selected Bearing Problems of Old Railway Bridges Located on Mining Areas in Poland. *3rd World Multidisciplinary Civil Engineering, Architecture, Urban Planning Symposium (WMCAUS 2018)*, *471*(5). https://doi.org/10.1088/1757-899X/471/5/052068

[171] Perry, B. J., Guo, Y., Atadero, R., & van de Lindt, J. W. (2019). Unmanned aerial vehicle (UAV) enabled building information modeling for bridge inspection. *9th International Conference on Structural Health Monitoring of Intelligent*

Infrastructure: Transferring Research into Practice, SHMII 2019 - Conference Proceedings, *1*, 503–508.

[172] Isailović, D., Petronijević, M., & Hajdin, R. (2019). The future of BIM and Bridge Management Systems. *IABSE Symposium, Guimaraes 2019: Towards a Resilient Built Environment Risk and Asset Management - Report*, 1673–1680.

[173] Mo, T., Wu, F., Zhang, Y., & Wang, M. (2019). Application of BIM Technology in Zhuhai Port Project of Hong Kong-Zhuhai-Macao Bridge. *ICCREM 2019: Innovative Construction Project Management and Construction Industrialization - Proceedings of the International Conference on Construction and Real Estate Management 2019*, 185–191. https://doi.org/10.1061/9780784482308.021

[174] Zhang, G., Zhao, W., & Zhang, H. (2019). Design and Development of Digital Operation and Maintenance System for Hutong Yangtze River Bridge | 沪通长江大桥数字化运维系统的设计研发. *Tiedao Xuebao/Journal of the China Railway Society*, *41*(5), 16–26. https://doi.org/10.3969/j.issn.1001-8360.2019.05.003

[175] Mabrich, A., & Hatami, A. (2019). Application of 3D bridge information modeling in the life-cycle of bridges. *20th Congress of IABSE, New York City 2019: The Evolving Metropolis - Report*, 1549–1552.

[176] Popescu, C., Täljsten, B., Blanksvärd, T., Sas, G., Jimenez, A., Crabtree Gärdin, D., Elfgren, L., & Carolin, A. (2019). Optical methods and wireless sensors for monitoring of bridges. *IABSE Symposium, Guimaraes 2019: Towards a Resilient Built Environment Risk and Asset Management - Report*, 1191–1198.

[177] Royes, M. M., Gil, L. G., Caldentey, A. P., Vila, J. G., Lasso, A. C., & Navascues, Ó. M. (2019). Intelligent, sustainable and integrated system of management of structures. *IABSE Symposium, Guimaraes 2019: Towards a Resilient Built Environment Risk and Asset Management - Report*, 948–954.

[178] Dang, N. S., & Shim, C. S. (2018). BIM authoring for an image-based bridge maintenance system of existing cable-supported bridges. *IOP Conference Series: Earth and Environmental Science*, *143*(1). https://doi.org/10.1088/1755-1315/143/1/012032

[179] Qin, Y. D., & Xiao, R. E. (2018). Research on Bridge Management System Based on BIM Technology. *9th International Conference on Bridge Maintenance, Safety and Management (IBAMAS 2018)*, 226–230.

[180] Wang, Q., Sohn, H., & Cheng, J. C. P. (2018). Automatic As-Built BIM Creation of Precast Concrete Bridge Deck Panels Using Laser Scan Data. *Journal of Computing in Civil Engineering*, *32*(3). https://doi.org/10.1061/(ASCE)CP.1943-5487.0000754

[181] Hallennann, N., Taraben, J., & Morgenthal, G. (2018). BIM related workflow for an image-based deformation monitoring of bridges. In N. Powers, D. M. Frangopol, R. Al-Mahaidi, & C. Caprani (Eds.), *Maintenance, Safety, Risk, Management and Life-Cycle Performance of Bridges: Proceedings of the 9th International Conference on Bridge Maintenance, Safety and Management (IABMAS 2018)*.

[182] Huthwohl, P., Brilakis, I., Borrmann, A., & Sacks, R. (2018). Integrating RC Bridge Defect Information into BIM Models. *Journal of Computing in Civil Engineering*, *32*(3). https://doi.org/10.1061/(ASCE)CP.1943-5487.0000744

[183] Singh, H. (2018). Repair and Retrofitting of Bridges - Present and Future. *9th International Conference on Bridge Maintenance, Safety and Management (IBAMAS 2018)*, 1208–1215.

[184] Alaghbandrad, A., & Hammad, A. (2018). Developing Information Model for Multi-Purpose Utility Tunnel Lifecycle Management. *Construction Research Congress 2018: Infrastructure and Facility Management*, 393–402. https://doi.org/10.1061/9780784481295.040

[185] Zhang, Z., Hamledari, H., Billington, S., & Fischer, M. (2018). 4D beyond construction: Spatio-temporal and life-cyclic modeling and visualization of Infrastructure data. *Journal of Information Technology in Construction*, *23*, 285–304.

[186] Sacks, R., Kedar, A., Borrmann, A., Ma, L., Brilakis, I., Hüthwohl, P., Daum, S., Kattel, U., Yosef, R., Liebich, T., Barutcu, B. E., & Muhic, S. (2018). SeeBridge as next generation bridge inspection: Overview, Information Delivery Manual and Model View Definition. *Automation in Construction*, *90*, 134–145. https://doi.org/10.1016/j.autcon.2018.02.033

[187] Gottfredsen, F. R., & Pedersen, H. (2018). Creation of “live data” for existing infrastructure. *Maintenance, Safety, Risk, Management and Life-Cycle Performance of Bridges - Proceedings of the 9th International Conference on Bridge Maintenance, Safety and Management, IABMAS 2018*, 179–186.

[188] Jeong, S., Hou, R., Lynch, J. P., Sohn, H., & Law, K. H. (2017). An information modeling framework for bridge monitoring. *Advances in Engineering Software*, *114*, 11–31. https://doi.org/10.1016/j.advengsoft.2017.05.009

[189] Aziz, Z., Riaz, Z., & Arslan, M. (2017). Leveraging BIM and Big Data to deliver well maintained highways. *Facilities*, *35*(13–14), 818–832. https://doi.org/10.1108/F-02-2016-0021

[190] Hendy, C., Brock, C., & Nicholls, T. (2017). Management of the M4 Elevated Section substructures. *Proceedings of the Institution of Civil Engineers-Bridge Engineering*, *170*(3), 159–167. https://doi.org/10.1680/jbren.16.00006

[191] Kim, T. H., & Kim, S. J. (2017). A study on BIM application for the efficient maintenance management of bridge structures. *Information (Japan)*, *20*(5), 3691–3698.

[192] Jiang, X., Zhao, X., & Hu, S. (2017). A PHM system for bridge monitoring on high speed railway. *Proceedings - 2017 International Conference on Sensing, Diagnostics, Prognostics, and Control, SDPC 2017*, *2017-Decem*, 371–376. https://doi.org/10.1109/SDPC.2017.77

[193] Che-Ani, A. I., Harris, M., Mohd-Nor, M. F. I., Razak, M. Z. A., & Hussain, A. H. (2017). A review of Building Information Modelling (BIM)-based building condition assessment concept. *Malaysian Construction Research Journal*, *20*(3), 85–101.

[194] McGuire, B., Atadero, R., Clevenger, C., & Ozbek, M. (2016). Bridge Information Modeling for Inspection and Evaluation. *Journal of Bridge Engineering*, *21*(4). https://doi.org/10.1061/(ASCE)BE.1943-5592.0000850

[195] Chan, B., Guan, H., Hou, L., Jo, J., Blumenstein, M., & Wang, J. (2016). Defining a conceptual framework for the integration of modelling and advanced imaging for improving the reliability and efficiency of bridge assessments. *Journal of Civil Structural Health Monitoring*, *6*(4), 703–714. https://doi.org/10.1007/s13349-016-0191-6

[196] Wang, H., Zheng, R., & Xiong, F. (2016). Application of BIM-based 5D construction technique to Chenglang Bridge. *Proceedings of the 2016 5th International Conference on Sustainable Energy and Environment Engineering (ICSEEE 2016)*, 31–38. https://doi.org/10.2991/icseee-16.2016.6

[197] Brilakis, I. (2016). Virtualizing infrastructure. In S. Christodoulou & R. Scherer (Eds.), *eWork and eBusiness in Architecture, Engineering and Construction - Proceedings of the 11th European Conference on Product and Process Modelling (ECPPM 2016)*.

[198] Huston, D., Burns, D., & Razinger, J. (2016). Structural health monitoring and maintenance aided by building information modelling and repair information tools. In A. Galiano-Garrigos & C. A. Brebbia (Eds.), *The Sustainable City XI - Proceedings of the 11th International Conference on Urban Regeneration and Sustainability (SC 2016)* (Vol. 1, pp. 897–907). WIT Press. https://doi.org/10.2495/sc160731

[199] Sedek, M., & Serwa, A. (2016). Development of new system for detection of bridges construction defects using terrestrial laser remote sensing technology. *Egyptian Journal of Remote Sensing and Space Sciences*, *19*(2), 273–283. https://doi.org/10.1016/j.ejrs.2015.12.005

[200] Chagas, D. M., & Silva Filho, L. C. P. (2016). Improvement opportunity to bridge inspections in Brazil. *Maintenance, Monitoring, Safety, Risk and Resilience of Bridges and Bridge Networks - Proceedings of the 8th International Conference on Bridge Maintenance, Safety and Management, IABMAS 2016*, 2258–2263.

[201] Partovi, M., Schreppers, G. J., de Boer, A., & Galgoul, N. S. (2016). Design checks and nonlinear response of a full 3D model of a box girder bridge. *Maintenance, Monitoring, Safety, Risk and Resilience of Bridges and Bridge Networks - Proceedings of the 8th International Conference on Bridge Maintenance, Safety and Management, IABMAS 2016*, 1546–1550.

[202] Hyeonseung, K., LeenSeokKang, 문소영, & 윤수영. (2015). Improved Method for Increasing Maintenance Efficiency of Construction Structure Using Augmented Reality by Marker-Less Method. *Journal of the Korean Society of Civil Engineers*, *35*(4), 961–968. https://doi.org/10.12652/Ksce.2015.35.4.0961

[203] Wang, Q., Cheng, J. C. P., & Sohn, H. (2015). Automated quality inspection of precast concrete elements with irregular shapes using terrestrial laser

scanner and BIM technology. *32nd International Symposium on Automation and Robotics in Construction and Mining: Connected to the Future, Proceedings*. https://doi.org/10.22260/isarc2015/0035

[204] Kasireddy, V., & Akinci, B. (2015). Challenges in generation of as-is bridge information model: A case study. *32nd International Symposium on Automation and Robotics in Construction and Mining: Connected to the Future, Proceedings*. https://doi.org/10.22260/isarc2015/0037

[205] Dunn, R., & Harwood, K. (2015). Bridge Asset Management in Hertfordshire - Now and in the future. *IET Conference Publications*, *2015*(CP669). https://doi.org/10.1049/cp.2015.1722

[206] Fruguglietti, E., Pasqualato, G., & Spallarossa, E. (2014). Bridge management system implementation for Italian highways: From Pontis® towards SIOS (Sistema Ispettivo Opere Sineco) and new generation systems. *Bridge Maintenance, Safety, Management and Life Extension - Proceedings of the 7th International Conference of Bridge Maintenance, Safety and Management, IABMAS 2014*, 2087–2091. https://doi.org/10.1201/b17063-321

[207] 2014 International Conference on Materials Science and Computational Engineering, ICMSCE 2014. (2014). In *Advanced Materials Research* (Vols. 926–930).

[208] Lindenberg, R. E., & McGormley, J. C. (2013). Visualizing bridge inspection with 2D software. *Computing in Civil Engineering - Proceedings of the 2013 ASCE International Workshop on Computing in Civil Engineering*, 857–864.

[209] Kim, M. K., Sohn, H., Wu, D., Cheng, J. C. P., & Chang, C. C. (2013). Formulation of a framework for quality assessment of precast concrete based on 3D laser scanning. *ISARC 2013 - 30th International Symposium on Automation and Robotics in Construction and Mining, Held in Conjunction with the 23rd World Mining Congress*, 1464–1472. https://doi.org/10.22260/isarc2013/0166

[210] Previtali, M., Barazzetti, L., Brumana, R., & Roncoroni, F. (2013). Thermographic analysis from UAV platforms for energy efficiency retrofit applications. *Journal of Mobile Multimedia*, *9*(1–2), 66–82.

[211] Dibernardo, S. (2012). Integrated modeling systems for bridge asset management - Case study. *Structures Congress 2012 - Proceedings of the 2012 Structures Congress*, 483–493. https://doi.org/10.1061/9780784412367.043

[212] 2012 Proceedings of the 29th International Symposium of Automation and Robotics in Construction, ISARC 2012. (2012). *2012 Proceedings of the 29th International Symposium of Automation and Robotics in Construction, ISARC 2012*.

[213] Wan, C., Zhou, Z., Li, S., Ding, Y., Xu, Z., Yang, Z., Xia, Y., & Yin, F. (2019). Development of a Bridge Management System Based on the Building Information Modeling Technology. *Sustainability*, *11*(17). https://doi.org/10.3390/su11174583

[214] Fruguglietti, E., Pasqualato, G., & Spallarossa, E. (2012). Bridge Management System implementation in ltaly: Pontis® and other BMS application in Italy. In F. Biondini & D. M. Frangopol (Eds.), *Bridge maintenance, safety, management, resilience and sustainability: proceedings of the sixth International Conference on Bridge Maintenance, Safety and Management, Stresa, Lake Maggiore, Italy, 8-12 July 2012* (pp. 3052–3057). CRC Press.

[215] Ormando, C., Raeisi, F., Clemente, P., & Mufti, A. (2022). The SHM as Higher Level Inspection in the Evaluation of Structures. In C. Pellegrino, F. Faleschini, M. A. Zanini, J. C. Matos, J. R. Casas, & A. Strauss (Eds.), *1st Conference of the European Association on Quality Control of Bridges and Structures (EUROSTRUCT 2021). Lecture Notes in Civil Engineering 200: Vol. 200 LNCE* (pp. 452–461). https://doi.org/10.1007/978-3-030-91877-4_52

[216] De Matteis, G., Bencivenga, P., & Zizi, M. (2022). Structural Risk Assessment of Existing Road Bridges According to Italian Guidelines Based on a Territorial Case Study. In C. Pellegrino, F. Faleschini, M. A. Zanini, J. C. Matos, J. R. Casas, & A. Strauss (Eds.), *1st Conference of the European Association on Quality Control of Bridges and Structures (EUROSTRUCT 2021). Lecture Notes in Civil Engineering 200: Vol. 200 LNCE* (pp. 527–534). https://doi.org/10.1007/978-3-030-91877-4_60

[217] Trizio, I., Marra, A., Savini, F., & Fabbrocino, G. (2021). Survey methodologies and 3D modelling for conservation of historical masonry bridges. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume VIII-M-1-2021. 28th CIPA Symposium "Great Learning & Digital Emotion,"* 163–170. https://doi.org/10.5194/isprs-annals-VIII-M-1-2021-163-2021

[218] ANAS Gruppo FS Italiane. (2018). *Direzione Progettazione e Realizzazione Lavori. Capitolato speciale BIM.*

[219] *Google Earth Pro*. (n.d.). Retrieved January 21, 2022, from https://earth.google.com/web/@0,0,0a,22251752.77375655d,35y,0h,0t,0r

[220] *La Città. Quotidiano di Salerno e Provincia*. (n.d.). Retrieved January 21, 2022, from https://www.lacittadisalerno.it/

[221] Barba, S., Fiani, M., Di Benedetto, A., Limongiello, M., & Sanseverino, A. (in press). Rilievi della rete di infrastrutture con tecniche di rilevamento attivo e passivo. In CUR (Comitato Universitario Regionale - Regione Campania) (Ed.), *Progetto CUR_CIS2020 - Metodologie per la valutazione puntuale del rischio idrogeologico in aree fortemente antropizzate e strumenti per le strategie di sviluppo regionale: Applicazione al caso studio del "Corridoio Infrastrutturale Strategico" (CIS) di livello regionale: Tratto autostradale Salerno-Cava de' Tirreni - A3 Napoli - Salerno e delle altre infrastrutture viarie a valle della stessa. Regione Campania: Vol. in press*.

[222] Fiani, M. (2021). Metodologie di rilievo e modellazione topografica. In Giunta Regionale della Campania, *Progetto: CUR_CIS2020 "Metodologie per la valutazione puntuale del rischio idrogeologico in aree fortemente antropizzate e strumenti per le strategie di sviluppo regionale". Applicazione al caso studio "Corridoio Infrastrutturale Strategico" (CIS)*.

[223] Laat, R., & van Berlo, L. (2011). Integration of BIM and GIS: The development of the CityGML GeoBIM extension. In *Advances in 3D Geo-information Sciences* (pp. 211–225). https://doi.org/10.1007/978-3-642-12670-3_13

[224] Truong-Hong, L., & Laefer, D. (2014). Application of Terrestrial Laser Scanner in Bridge Inspection: Review and an Opportunity. *IABSE Symposium Report*, *102*. https://doi.org/10.2749/222137814814070190

[225] Di Benedetto, A., Barba, S., Fiani, M., Limongiello, M., & Sanseverino, A. (2021). BIM and GIS integration for infrastructure analysis. *EGU General Assembly*. https://doi.org/10.5194/egusphere-egu21-8293

[226] Del Grosso, A. (2020). *Linee Guida per la Classificazione e Gestione del Rischio, la Valutazione della Sicurezza e il Monitoraggio dei Ponti esistenti. PARTE III: Sistema di Sorveglianza e Monitoraggio*.

[227] Autodesk. (2018). *Manuale dello standard IFC per Revit. Istruzioni dettagliate per l'utilizzo dei file IFC* (Vol. 2).

[228] *BuildingSMART International*. (n.d.). Retrieved January 21, 2022, from https://www.buildingsmart.org/

[229] Colomina, I., & Molina, P. (2014). Unmanned aerial systems for photogrammetry and remote sensing: A review. *ISPRS Journal of Photogrammetry and Remote Sensing*, *92*, 79–97. https://doi.org/10.1016/j.isprsjprs.2014.02.013

[230] Silverberg, L. M., & Bieber, C. (2014). Central Command Architecture for High-Order Autonomous Unmanned Aerial Systems. *Intelligent Information Management*, *06*(04), 183–195. https://doi.org/10.4236/iim.2014.64019

[231] Eppelbaum, L., & Mishne, A. (2011). Unmanned Airborne Magnetic and VLF Investigations: Effective Geophysical Methodology for the Near Future. *Positioning*, *02*(03), 112–133. https://doi.org/10.4236/pos.2011.23012

[232] Hadjimitsis, D. G., Agapiou, A., Themistocleous, K., Alexakis, D. D., & Sarris, A. (2012). Remote Sensing Applications in Archaeological Research. In *Remote Sensing - Applications*. InTech. https://doi.org/10.5772/37668

[233] Barba, S., Barbarella, M., Di Benedetto, A., Fiani, M., & Limongiello, M. (2019). Comparison of UAVs performance for a Roman Anphitheatre Survey: the case of Avella (Italy). *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XLII-2/W11*, 179–186. https://doi.org/10.5194/isprs-archives-XLII-2-W11-179-2019

[234] Federman, A., Santana Quintero, M., Kretz, S., Gregg, J., Lengies, M., Ouimet, C., & Laliberte, J. (2017). UAV photogrammetric workflows: a best practice guideline. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XLII-2/W5*, 237–244. https://doi.org/10.5194/isprs-archives-XLII-2-W5-237-2017

[235] Remondino, F., Barazzetti, L., Nex, F., Scaioni, M., & Sarazzi, D. (2012). UAV photogrammetry for mapping and 3D modeling - current status and future perspectives. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XXXVIII-1/C22*, 25–31. https://doi.org/10.5194/isprsarchives-XXXVIII-1-C22-25-2011

[236] Adamopoulos, E., & Rinaudo, F. (2020). UAS-Based Archaeological Remote Sensing: Review, Meta-Analysis and State-of-the-Art. *Drones*, *4*(3), 46. https://doi.org/10.3390/drones4030046

[237] Brumana, R., Oreni, D., van Hecke, L., Barazzetti, L., Previtali, M., Roncoroni, F., & Valente, R. (2013). Combined geometric and thermal analysis from UAV platforms for Archaeological Heritage Documentation. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *II-5/W1*, 49–54. https://doi.org/10.5194/isprsannals-II-5-W1-49-2013

[238] Nikolakopoulos, K. G., Soura, K., Koukouvelas, I. K., & Argyropoulos, N. G. (2017). UAV vs classical aerial photogrammetry for archaeological studies. *Journal of Archaeological Science: Reports*, *14*, 758–773. https://doi.org/10.1016/j.jasrep.2016.09.004

[239] Barazzetti, L., Brumana, R., Oreni, D., Previtali, M., & Roncoroni, F. (2014). True-orthophoto generation from UAV images: Implementation of a combined photogrammetric and computer vision approach. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *II–5*, 57–63. https://doi.org/10.5194/isprsannals-II-5-57-2014

[240] Mc Dermott, W. (2018). *The PBR Guide 2018 version* (C. Damez, N. Wirrmann, A. Bagard, P. Gresty, & C. Vance, Eds.; Third edition). Allegorithmic SAS.

[241] Farella, E. M., Morelli, L., Rigon, S., Grilli, E., & Remondino, F. (2022). Analysing Key Steps of the Photogrammetric Pipeline for Museum Artefacts 3D Digitisation. *Sustainability*, *14*(9), 5740. https://doi.org/10.3390/su14095740

[242] Fassi, F., Fregonese, L., Adami, A., & Rechichi, F. (2017). BIM system for the conservation and preservation of the mosaics of san Marco in Venice. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*, *42*(2W5), 229–236. https://doi.org/10.5194/isprs-archives-XLII-2-W5-229-2017

[243] Fiorillo, F., Jiménez Fernández-Palacios, B., Remondino, F., & Barba, S. (2013). 3D Surveying and modelling of the Archaeological Area of Paestum, Italy. *Virtual Archaelogy Review*, *4*(8). http://157.88.193.21/~lfa-davap

[244] Gujski, L. M., di Filippo, A., & Limongiello, M. (2022). Machine learning clustering for point clouds optimisation via feature analysis in Cultural Heritage. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*, *46*(2/W1-2022), 245–251. https://doi.org/10.5194/isprs-archives-XLVI-2-W1-2022-245-2022

[245] Petti, L., Barone, F., Greco, D., Mammone, A., Armenante, M., Iannone, E., & Lodato, A. (2021). *Sistema di monitoraggio del Tempio di Nettuno. Report Scientifico.*

[246] Barone, F., & Giordano, G. (2018). The UNISA folded pendulum: A very versatile class of low frequency high sensitive sensors. *Measurement: Journal of the International Measurement Confederation*, *118*, 339–347. https://doi.org/10.1016/j.measurement.2017.09.001

[247] Regione Campania. Comune di Capaccio Paestum. (2022). *Il tempio di Nettuno*. Retrieved January 28, 2022, from https://www.comune.capaccio.sa.it/territorio/sito-archeologico/il-tempio-di-nettuno/

[248] L'area Archeologica di Paestum. (n.d.). *Il Tempio di Nettuno o Poseidone (metà del V sec a.C.)*. Retrieved January 28, 2022, from https://www.paestumsites.it/paestum/il-tempio-di-nettuno-o-poseidone

[249] Parrinello, S. (2018). Figure 31. In S. Parrinello & A. Dell'Amico (Eds.), *Atlante pittoresco di una settimana in viaggio nel Sud Italia. Racconti pittografici del DAda-LAB, Drawing Architecture DocumentAction* (Vol. 1, pp. 54–55). PUP - Pavia University Press.

[250] Picchio, F. (2018). Figure 29. In S. Parrinello & A. Dell'Amico (Eds.), *Atlante pittoresco di una settimana in viaggio nel Sud Italia. Racconti pittografici del DAda-LAB, Drawing Architecture DocumentAction* (Vol. 1, pp. 52–53). PUP - Pavia University Press.

[251] Barba, S., Barbarella, M., Di Benedetto, A., Fiani, M., Gujski, L., & Limongiello, M. (2019). Accuracy Assessment of 3D Photogrammetric Models from an Unmanned Aerial Vehicle. *Drones*, *3*(79). https://doi.org/10.3390/drones3040079

[252] Lamberti, A. (2021). *Metodologie e procedure innovative per il monitoraggio dei monumenti*. University of Salerno.

[253] Parco Archeologico di Paestum e Velia. (2022). *Attività di monitoraggio in corso*. Retrieved January 27, 2022, from https://museopaestum.cultura.gov.it/monitoraggio-sismico-del-tempio-di-nettuno/

[254] Grilli, E., Menna, F., & Remondino, F. (2017). A review of point clouds segmentation and classification algorithms. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*, *42*(2W3), 339–344. https://doi.org/10.5194/isprs-archives-XLII-2-W3-339-2017

[255] Cardone, V. (2015). *Modelli grafici dell'architettura e del territorio* (S. Barba, Ed.; 3rd ed.). Maggioli editore.

[256] Charef, R., Alaka, H., & Emmitt, S. (2018). Beyond the third dimension of BIM: A systematic review of literature and assessment of professional views. *Journal of Building Engineering*, *19*, 242–257. https://doi.org/10.1016/j.jobe.2018.04.028

[257] *The dimensions of BIM – 3D, 4D, 5D, 6D, 7D, 8D, 9D, 10D BIM explained*. (2018, April 17). Biblus. https://biblus.accasoftware.com/en/bim-dimensions/

[258] Directive 2014/24/EU of the European Parliament and of the Council on public procurement and repealing Directive 2004/18/EC, Official Journal of the European Union (2014).

[259] D.Lgs. 50/2016 Attuazione delle direttive 2014/23/UE, 2014/24/UE e 2014/25/UE sull'aggiudicazione dei contratti di concessione, sugli appalti pubblici e sulle procedure d'appalto degli enti erogatori nei settori dell'acqua, dell'energia, dei trasporti e dei servizi postali, nonché per il riordino della disciplina vigente in materia di contratti pubblici relativi a lavori, servizi e forniture, Gazzetta Ufficiale (2016).

[260] UNI 11337:2018 Edilizia e opere di ingegneria civile - Gestione digitale dei processi informativi delle costruzioni, (2018).

[261] ISO 19650-1:2018 Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM) – Information management using building information modelling – Part 1: Concepts and principles, (2018).

[262] USIBD U.S. Institute of Building Documentation. (2016). *USIBD Level of Accuracy (LOA) Specification Guide. Document C120 - Version 2.0-2016*.

[263] Sarkar, S. (2016). Ecology. In E. N. Zalta (Ed.), *The Standard Encyclopedia of Philosophy* (Winter 2016). Metaphysics Research Lab, Stanford University. https://plato.stanford.edu/archives/win2016/entries/ecology/

[264] Taylor, P. (2015). Ecological Philosophy. In *Oxford Bibliographies*. https://doi.org/10.1093/OBO/9780199830060-0133

[265] ISO 19650-2:2018 Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM) – Information management using building information modelling – Part 2: Delivery phase of the assets, (2018).

[266] EN 17412-1:2020 Building Information Modelling - Level of Information Need - Part 1: Concepts and principles, (2020).

[267] CFR – Tile 23: Highways – Chapter I: Federal Highway Administration, Department of Transportation -Subchapter G: Engineering and Traffic Operations – Part 650: Bridges, Structures, and Hydraulics – Subpart C: National Bridge Inspection Standards [NBIS], Pub. L. No. 650.301-650.317 (2022). https://www.ecfr.gov/current/title-23/chapter-I/subchapter-G/part-650?toc=1

[268] Project Management Institute. (2004). *A Guide to the Project Management Body of Knowledge: PMBOK® guide - Third Edition. An American National Standards Institute ANSI/PMI 99-001-2000* (3rd ed.). Project Management Institute, Inc.

[269] Parco Archeologico di Paestum e Velia. (2021). *Paestum: on line il monitoraggio sismico del Tempio di Nettuno dagli scavi sul tempio emerge la storia della sua costruzione*. https://drive.google.com/drive/u/0/folders/1U65dRztS9aicBLf2JLRQIyqOUkCUR2zN

[270] Adobe ®. (2022, January 12). *Using image modes and color tables*. Photoshop Elements User Guide.

Figure index[55]

Figure 1.1 – Timeframe for the progressive introduction of BIM according to DM 560/2017 [19]........45

Figure 1.2 – Schema of the voluntary international regulation concerning information management and Industry Foundation Classes adoption [19]........47

Figure 1.3 – Issued Parts of the UNI 11337 (as of 2018) [21]........47

Figure 1.4 – Level of development schema (upper) and example of LOD applied to Structures (middle) and Infrastructure (lower) [19]........51

Figure 1.5 – Graphic representation of a Digital Twin [AoE]........53

Figure 2.1 – Common Data Environment [CDE] schema according to the United Kingdom Regulation that implemented the ISO 19650 [19]........60

Figure 2.2 – In the Scan-to-BIM process, an accurate integrated survey (3DS - grey) represents the first fundamental phase, followed by the Georeferencing (GEO - green), the Federate modelling and Shared Coordinates setting up (FSC - orange), the Structural modelling (STR - cyan), and the Level of Information enhancement (LOI - magenta) stages that constitute the core of the BIM modelling methodology, culminating if necessary in the exportation to OpenBIM formats (IFC - grey) for information exchange [AoE]........66

Figure 2.3 – Graphical representation of the LOD according to the UNI 11337-4:2017 [57]........70

Figure 2.4 – Graphical representation of the LOIN definition to be introduced by the updated version of the UNI 11337-4:2017 [57]........71

Figure 2.5 – IFC 2x3 Model View Definition [MVD] as required by the ISO 16739 [19]..72

Figure 2.6 – IFC 4 Model View Definition [MVD] as required by the ISO 16739 [19]......73

Figure 3.1 – Archive photo from *L'Unità* of the Ariccia Bridge after the collapse (Left). Front page of the newspaper *La Stampa* dated Friday 20th January 1967 (Right) [66].......78

Figure 3.2 – Bridge failures occurred in Italy in the last seven years (2013-2020) [71]......78

Figure 3.3 – Collapsed section of the Morandi Bridge [68]........78

Figure 3.4 – 5,931 road structures requiring intervention (aggregated by region) [75].......81

[55] When the source of a figure is indicated as [AoE] it stands for *Author's own Elaboration*. When the source of a figure is indicated as [MbA] additionally to the original reference, it stands for *Modified by the Author*.

Figure 3.5 – 1,918 road structures requiring urgent action - priority 1 (aggregated by region) [75] 82

Figure 3.6 – 14,089 road structures requiring monitoring (aggregated by region) [75] 83

Figure 3.7 – 2,994 bridges of uncertain ownership according to the 2017 ANAS road census. In 2018, at the end of the survey: 983 bridges were found to be owned by Anas, 586 by other operators, and 1,425 by unidentified owners. As of 2017, Anas's road network was 27,000 km long, of which 20,000 km were state roads, 1,300 km of motorways, and 5,700 km of bypasses, coplanars and roads yet to be classified [76]..84

Figure 3.8 – Mandatory annual inspections to be carried out on at-risk bridges dated 2019: inspected (grey) and yet to be inspected (red). Of the bridges at risk, only 818 out of a total of 4,045 "main bridges" – i.e., those with a span greater than 30 m – and 601 out of a total of 946 "other bridges" were inspected. [77]..85

Figure 3.9 – The age of Italian bridges as of 2019: 24% of Italian bridges are more than 58 years old, having been built before 1961; 28% of those built between 1961 and 1980 are between 58 and 39 years old; 33% are between 38 and 19 years old, having been built between 1981 and 2000; while only 15% are less than 18 years old, having been built after 2000 [76] 87

Figure 3.10 – Bending stresses for single-supported beams obtained from the parametric study conducted by Buratti et al. [79] 89

Figure 3.11 – Results of the parametric study conducted by Buratti et al. [79] 89

Figure 4.1 – Example of the IOP: public structures identification code [90] – [MbA]......112

Figure 4.2 – Schematisation of the AINOP filing system [91]..113

Figure 4.3 – AINOP *feeding* modality [91] [MbA]...114

Figure 4.4 – Pyramidal data organisation of the AINOP database [91] [MbA] 114

Figure 4.5 – Asset file form [91]...115

Figure 4.6 – Basic register data form [91]..115

Figure 4.7 – Specific register data form [91] 115

Figure 4.8 – Extended register data form [91] 116

Figure 4.9 – Inspection levels proposed by the LG20 [92] 117

Figure 4.10 – Basic survey tools used for visual inspections [92] 121

Figure 4.11 – The Olivieri viaduct registered defects affecting girders and beams [96]....121

Figure 4.12 – Example of rough geometric sketches indicating the main dimensions [92] 122

Figure 4.13 – Example of the Bridge defect evaluation template (for concrete abutments) corresponding to Level 1 that can be found in Annex B of the LG20 [94] 123

Figure 4.14 – The five colour-coded Attention Classes identified by the LG20 [92] 126

Figure 4.15 – The four types of risk: structural and foundation, seismic, landslide, and hydraulic [92] 126

Figure 4.16 – The three main factors: Hazard, Vulnerability, and Exposure [92] 126

Figure 4.17 – Primary and secondary parameters combination to determine the Attention classes [CdAs] [92] 126

Figure 4.18 – Determination of the overall Attention Class [CdA] [92]............................127

Figure 4.19 – Relationship between demand induced by the traffic loads provided by the standards of the time and the demand obtained using those of the current standards [71].128

Figure 4.20 – Multilevel approach and analysis level dependencies [4] 129

Figure 4.21 – Defect assessment form (Level 1) for concrete abutments [94]...................133

Figure 4.22 – Defect assessment form (Level 1) for concrete piers [94] 133

Figure 4.23 – Defect assessment form (Level 1) for concrete arches [94].........................134

Figure 4.24 – Logic diagram for attributing ratings to the defects according to the 2015 handbook [100] 138

Figure 4.25 – Diagram graphically summarising the distribution of publications worldwide [AoE]..158

Figure 4.26 – Types of global structures [99] 164

Figure 4.27 – Types of partial structures [99] 165

Figure 4.28 – Breakdown of the asset [99]...165

Figure 4.29 – Schematisation of the different assets associated with their respective localization [99] 165

Figure 4.30 – Outline of the STONE Code 169

Figure 4.31 – Localisation system [99] 170

Figure 4.32 – Reference system for the localisation elements [99]....................................171

Figure 4.33 – Example of span and structure numbering – Side view [99] 172

Figure 4.34 – Example of span and structure numbering – Plan view [99] 172

Figure 4.35 – Components of the Foundations [99]...172

Figure 4.36 – Components of the Abutments [99]...173

Figure 4.37 – Components of the Piers [99]...173

Figure 4.38 – Components of the Bearings [99] 173

Figure 4.39 – Components of the Arches [99] 174

Figure 4.40 – Components of the Decks [99]....174

Figure 4.41 – Components of the Joints [99] 175

Figure 4.42 – Components of the Seismic Equipment [99] 175

Figure 4.43 – Latticework decks: plan view (up) and perspective view (down) [99] 176

Figure 4.44 – Caisson decks: plan view (up) and perspective view (down) [99]....177

Figure 4.45 – Cellular arches: plan view (up) and perspective view (down) [99]....178

Figure 4.46 – Truss arches: plan view (up) and perspective view (down) [99]....179

Figure 4.47 – Hollow components localisation system – pier shafts [99]....180

Figure 4.48 – Hollow components localisation system – caissons, elevation elements, beams, bearings, main structure [99]....181

Figure 5.1 – Olivieri Viaduct overview from Google Earth [219]....184

Figure 5.2 – View of the Olivieri Viaduct [220] 185

Figure 5.3 – Archival original drawings of the Olivieri Viaduct project: Elevation view [MbA] 185

Figure 5.4 – Archival original drawings of the Olivieri Viaduct project: Floor plan view of the Bridge deck [MbA] 186

Figure 5.5 – Archival original drawings of the Olivieri Viaduct project: Details of the Floor plan view of the Bridge deck [MbA] 186

Figure 5.6 – Archival original drawings of the Olivieri Viaduct project: Elevation view of the arched substructure [MbA] 186

Figure 5.7 – Archival original drawings of the Olivieri Viaduct project: Details and Floor plan view of the arched substructure [MbA]....187

Figure 5.8 – Archival original drawings of the Olivieri Viaduct project: Construction Details of the bridge deck [MbA] 187

Figure 5.9 – Layout of the 10 surveying stations (left) and views of the aligned and georeferenced point cloud depicting the viaduct and the valley beneath (right) [222]....189

Figure 5.10 – Overview of the integrated GeoBIM model, including the infrastructure, the valley, and part of the urbanised context [AoE]....190

Figure 5.11 – Point cloud segmentation within the Autodesk ReCap Pro environment [225] 191

Figure 5.12 – Revit dialog box to manage the sub-projects linked within a superordinate one [AoE]......192

Figure 5.13 – *Ad hoc* parametric family of the bridge deck [AoE]......192

Figure 5.14 – *Ad hoc* parametric family of the bridge piers [AoE]......193

Figure 5.15 – Exploded axonometric view of the structural BrIM model [AoE]......193

Figure 5.16 – Diagram breaking down the VPL script developed to model the safety barriers [AoE]......194

Figure 5.17 – Dynamo VPL script developed to model the safety barriers with the Dynamo environment [AoE]......194

Figure 5.18 – Dynamo VPL script developed to model the safety barriers: Group of nodes dedicated to breaking down the modelled polycurves following the bridge alignment [AoE]......195

Figure 5.19 – Dynamo VPL script developed to model the safety barriers: Group of nodes dedicated to generating the barriers' structural columns instances [AoE]......195

Figure 5.20 – Dynamo VPL script developed to model the safety barriers: Groups of nodes dedicated to rotating the barriers' structural columns instances for orienting according to the bridge alignment [AoE]......196

Figure 5.21 – Dynamo VPL script developed to model the safety barriers: Group of nodes dedicated to generating the barriers' upper beams instances [AoE]......196

Figure 5.22 – Dynamo VPL script developed to model the safety barriers: Group of nodes dedicated to generating the barriers' lower beams instances [AoE]......196

Figure 5.23 – Plan view of the overall environmental system [AoE]......197

Figure 5.24 – Section views of the overall environmental system [AoE]......198

Figure 6.1 – Structure of the multi-level interconnected identification system envisaged by the LG20 [4]......201

Figure 6.2 – Structural BrIM model of the Olivieri Viaduct broken down into components, with the third *Structural Section* [*Parte d'Opera*] highlighted [AoE]......203

Figure 6.3 – Exploded axonometric view of the structural BrIM model *components* comprising the third *Structural Section* [AoE]......204

Figure 6.4 – TXT file storing the shared parameters set up for the proposed application [AoE]......206

Figure 6.5 – Example of the shared parameter assigned as *project instance parameters* (*Properties* dialog box to the left) and as *project type parameters* (*Type properties* dialog box to the right) to a Joist of the Arched substructure [AoE]......206

Figure 6.6 – Plan view of the viaduct divided into 18 sections [Developed by the C.U.G.R.I. engineers] 207

Figure 6.7 – X-Bridge section's diagram at different heights [Developed by the C.U.G.R.I. engineers] 207

Figure 6.8 – Numbering system used for the Olivieri Viaduct [Developed by the C.U.G.R.I. engineers] 209

Figure 6.9 – Recap of some of the ASPI identifiers assigned to the third Structural Section's Components [AoE]..209

Figure 6.10 – Methodological procedure for the digitisation of the A3 infrastructure heritage: Exporting stage [AoE]..211

Figure 6.11 – Methodological procedure for the digitisation of the A3 infrastructure heritage: Importing stage [AoE]..212

Figure 7.1 – Custom VPL node Elements.CorrspondingAtIndex and its Python source code [AoE]..217

Figure 7.2 – Diagram breaking down the VPL script developed to automatically assign the shared parameters "Typology" [Tipologia], "Form" [Scheda] and "GlobalStructureCode" [CodiceOperaGlobale] to all the modelled elements [AoE]..218

Figure 7.3 – Dynamo VPL script developed to automatically assign the shared parameters "Typology" [Tipologia], "Form" [Scheda] and "GlobalStructureCode" [CodiceOperaGlobale] to all the modelled elements [AoE]..218

Figure 7.4 – Dynamo VPL script developed to automatically assign the shared parameters "Typology" [Tipologia], "Form" [Scheda] and "GlobalStructureCode" [CodiceOperaGlobale] to all the modelled elements: Group of nodes dedicated to generating the shared parameters within the Revit environment by first adding them to the TXT storing file and then assigning them to the modelled elements [AoE] 219

Figure 7.5 – Diagram breaking down the VPL script developed to automatically populate the *"Form"* [*Scheda*] according to the Annex B of the LG20, once the *Typology* parameter has been additionally filled out by the supervisor [AoE] 220

Figure 7.6 – Dynamo VPL script developed to automatically populate the *"Form"* [*Scheda*] according to the Annex B of the LG20, once the *Typology* parameter has been additionally filled out by the supervisor [AoE]..220

Figure 7.7 – Dynamo VPL script developed to automatically populate the *"Form"* [*Scheda*] according to the Annex B of the LG20, once the *Typology* parameter has been additionally filled out by the supervisor: Group of nodes dedicated to retrieving the classification parameters values [AoE] 221

Figure 7.8 – Dynamo VPL script developed to automatically populate the *"Form"* [*Scheda*] according to the Annex B of the LG20, once the *Typology* parameter has been additionally

filled out by the supervisor: Group of nodes dedicated to importing the Excel spreadsheet tables as lists that uniquely assign the inspection form's number to the modelled elements [AoE]....222

Figure 7.9 – Dynamo VPL script developed to automatically populate the *"Form"* [*Scheda*] according to the Annex B of the LG20, once the *Typology* parameter has been additionally filled out by the supervisor: Group of nodes dedicated to assigning the "Form" parameter values to each modelled element. This group employs the custom node marked in red [AoE]....223

Figure 7.10 – Input Excel data further detailing, in this case, the typology to determine the appropriate inspection form according to the structural behaviour of the arch elements [AoE]....224

Figure 7.11 – Diagram breaking down the VPL script developed to automatically populate the composed parameters: *"Form Link"* [*Link Scheda*], *"ID_ASPI"*, *"GlobalStructureCode"* [*CodiceOperaGlobale*] [AoE] 225

Figure 7.12 – Dynamo VPL script developed to automatically populate the composed parameters: *"Form Link"* [*Link Scheda*], *"ID_ASPI"*, *"GlobalStructureCode"* [*CodiceOperaGlobale*] [AoE]....226

Figure 7.13 – Dynamo VPL script developed to automatically populate the composed parameters: *"Form Link"* [*Link Scheda*], *"ID_ASPI"*, *"GlobalStructureCode"* [*CodiceOperaGlobale*]: Group of nodes dedicated to sorting the selected model elements [AoE]....226

Figure 7.14 – Dynamo VPL script developed to automatically populate the composed parameters: *"Form Link"* [*Link Scheda*], *"ID_ASPI"*, *"GlobalStructureCode"* [*CodiceOperaGlobale*]: Group of nodes dedicated to creating the list of parameters [AoE] 227

Figure 7.15 – Dynamo VPL script developed to automatically populate the composed parameters: *"Form Link"* [*Link Scheda*], *"ID_ASPI"*, *"GlobalStructureCode"* [*CodiceOperaGlobale*]: Group of nodes dedicated to assigning the parameter values to the selected elements [AoE]....228

Figure 7.16 – IFC BrIM model of the Olivieri Viaduct with the 00.AR.001.SP.006.CAO component pointed out and screenshot of the C.U.G.R.I. BMS web page corresponding to the URL associated to the [AoE] 229

Figure 7.17 – Diagram breaking down the VPL script developed to plot *Components*' register data [AoE]....230

Figure 7.18 – Dynamo VPL script developed to plot *Components*' register data [AoE] ...230

Figure 7.19 – Dynamo VPL script developed to plot *Components*' register data: Group of nodes dedicated to inputting data [AoE] 231

Figure 7.20 – Dynamo VPL script developed to plot *Components*' register data: Group of nodes dedicated to sorting selected model elements [AoE] 232

Figure 7.21 – Dynamo VPL script developed to plot *Components*' register data: Extract of the group of nodes dedicated to creating the lists of parameters values to export [AoE]...232

Figure 7.22 – Dynamo VPL script developed to plot *Components*' register data: Group of nodes dedicated to exporting to Excel the lists previously created [AoE] 233

Figure 7.23 – Extract of the Excel data plotted [AoE] 233

Figure 7.24 – Tree structure and possible enumerations of the IfcSlabType [228]............237

Figure 7.25 – Tree structure and possible enumerations of the IfcColumnType [228]......237

Figure 7.26 – Tree structure and possible enumerations of the IfcBeamType [228]..........238

Figure 7.27 – Tree structure and possible enumerations of the IfcWallType [228]...........239

Figure 7.28 – IFC model of the Olivieri Viaduct. As previously mentioned, the *Project Name* parameter (in cyan) has been filled out with the Infrastructure ID – *"03.03.0327.0.0"* according to the *STONE CODING* system – while the *Site Name* (in yellow) has been temporally filled in – *"Inserire Geolocalizzazione"* – waiting for the most suitable geolocalisation data format to be decided [AoE] 240

Figure 7.29 – Defects affecting the beams and joists of the Olivieri Viaduct [96] 242

Figure 7.30 – Defects affecting the arch slab and joists of the Olivieri Viaduct [96] 242

Figure 7.31 – Extract of two filled-in defect forms of the Olivieri Viaduct [96]...............243

Figure 7.32 – Mapping of the Olivieri Viaduct based on the Dr parameter. It is easy to see that all the elements of the viaduct possess a Low, at most Medium-Low, level of defectiveness [AoE] 244

Figure 7.33 – Diagram breaking down the VPL script developed to automatically import *relative defectiveness* [Dr] data and visualise the results in the BIM environment [AoE].245

Figure 7.34 – Dynamo VPL script developed to automatically import *relative defectiveness* [Dr] data and visualise the results in the BIM environment [AoE]...................................246

Figure 7.35 – Dynamo VPL script developed to automatically import *relative defectiveness* [Dr] data and visualise the results in the BIM environment: Group of nodes dedicated to generating the shared parameter [*Dr_InspectionYear*] [AoE]...246

Figure 7.36 – Dynamo VPL script developed to automatically import *relative defectiveness* [Dr] data and visualise the results in the BIM environment: Group of nodes dedicated to filtering *Structural Sections* and *Components* data from the Excel spreadsheet [AoE] 246

Figure 7.37 – Dynamo VPL script developed to automatically import *relative defectiveness* [Dr] data and visualise the results in the BIM environment: Group of nodes dedicated to retrieving the Excel sheets to import Dr values from [AoE]...247

Figure 7.38 – Dynamo VPL script developed to automatically import *relative defectiveness* [Dr] data and visualise the results in the BIM environment: Group of nodes dedicated to importing Dr values corresponding to each *Component* [AoE] 247

Figure 7.39 – Dynamo VPL script developed to automatically import *relative defectiveness* [Dr] data and visualise the results in the BIM environment: Group of nodes dedicated to filtering BIM modelled *Components* according to their *Structural Section* and their numbering [AoE] 247

Figure 7.40 – Dynamo VPL script developed to automatically import *relative defectiveness* [Dr] data and visualise the results in the BIM environment: Group of nodes dedicated to sorting and filtering the selected BIM elements according to the *Component* full IDs [AoE] 248

Figure 7.41 – Dynamo VPL script developed to automatically import *relative defectiveness* [Dr] data and visualise the results in the BIM environment: Group of nodes dedicated to generating the list of repeated items used to order the selected elements [AoE] 248

Figure 7.42 – Dynamo VPL script developed to automatically import *relative defectiveness* [Dr] data and visualise the results in the BIM environment: Group of nodes dedicated to generating the list of model elements to which assign the Dr values [AoE] 249

Figure 7.43 – Dynamo VPL script developed to automatically import *relative defectiveness* [Dr] data and visualise the results in the BIM environment: Group of nodes dedicated to sorting and assigning the Dr values to the BIM modelled elemental components. This group employs the custom node marked in red [AoE] 250

Figure 7.44 – Dynamo VPL script developed to automatically import *relative defectiveness* [Dr] data and visualise the results in the BIM environment: Group of nodes dedicated to setting up the colour filter for a selected view based on the Dr *attention classes'* ranges [AoE]..250

Figure 8.1 – Example of a PBR generic brick wall: (a) *Diffuse map*; (b) *Height map*; (c) *Normal map*; (d) *Roughness map*; (e) *Ambient Occlusion map*; (f) Physically realistic visualisation within the *Materialize* standalone open tool [AoE] 257

Figure 9.1 – North-oriented plan view showing the six additional sampling points identified during the placement of the dynamic monitoring system on the Temple of Neptune [245] 259

Figure 9.2 – Plan of the Paestum Archaeological zone [243] 261

Figure 9.3 – *"Raindrops fall while we walk among the Paestum ruins, where a temple stands out, white, pure and perfect, from the soft masses of the Mediterranean scrub. Column drums in the foreground gain strength from that same purity and, resting on the ground, transform the clearing into an open-air museum"*. Quote and drawing by Sandro Parrinello [249] 263

Figure 9.4 – *“Sitting on the ground, leaning with our backs against a column, we endeavour to describe the double order of columns that characterise the Naos of the Temple of Neptune. The grandiose majesty of the architectural elements overpowers any attempt to balance the space in the drawing sheet, the task is arduous, it requires “distorting” the point of view slightly, it requires dedication and all the time necessary to render that action of transposing thoughts, a language of signs. A moment of pure pleasure. Paestum, interior of the Temple of Neptune”.* Quote and drawing by Francesca Picchio [250] 263

Figure 9.5 – TLS acquisition via the *Leica Geosystem HDS 7000 laser scanner*, to the left [243], and a perspective view of the resulting point cloud, where each scan is highlighted in a different colour, to the right [AoE]..265

Figure 9.6 – Plan view of the TLS point cloud, where each scan is highlighted in a different colour and the acquisitions’ location are identified by black circles [AoE] 266

Figure 9.7 – Integrated point cloud divided into three new sampled scan locations: the inner Temple in yellow, the external colonnade in green and the surroundings in purple [AoE]266

Figure 9.8 – Overview of the 2017 UAS survey within the Agisoft Metashape environment [AoE]..268

Figure 9.9 – Overview of the 2020 UAS survey within the Agisoft Metashape environment [AoE]..269

Figure 9.10 – Overview of the schematised monitoring network [245] 273

Figure 9.11 – Plan view showing the designation of the 11 measuring points, the DAQ modules and their connections [245]..275

Figure 9.12 – Installed seismometers and identification of the signal acquisition DAQ module [252] 276

Figure 10.1 – Differences highlighted in yellow, between the same mesh imported as Revit instance. It was generated in the first case (upper, in pink), keeping the geographical coordinates, while in the second case (lower, in blue) using a local reference system [AoE] 278

Figure 10.2 – Detail of the same mesh generated as Revit instance, the first time keeping the georeferenced coordinates (upper, in pink) and the second time employing a local coordinate system (lower, in blue) [AoE] 279

Figure 10.3 – First experimental segmentation of the laser point cloud of the Temple of Naptune, carried out by Fiorillo et al. in 2011 [243]..280

Figure 10.4 – Temple of Neptune: classification levels, metrics, and point cloud resolutions at each level (upper) and Multi-Resolution access to the first level of classification (lower), performed and reported by Teruggi et al. in 2021 [30] 281

Figure 10.5 – 3D (upper) and plan (lower) views of the integrated point cloud manually segmented into twelve regions listed to the left [AoE] 282

Figure 10.6 – Study sketches: the Doric Temple of Neptune components [AoE].............284

Figure 10.7 – Study sketches: the Temple of Neptune *Doric Columns* disposition [AoE] 285

Figure 10.8 – Study sketches: *Doric Drum* (left) and *Drum* generator profile (right) with 24 flutings [AoE]..285

Figure 10.9 – Study sketches: *Drum* generator profiles with 20 (left) and 16 (right) flutings [AoE]...286

Figure 10.10 – Study sketches: *Echinus* (left) and *Necking* (Right) geometric generation [AoE]...286

Figure 10.11 – Study sketches: Temple of Neptune *Trabeation* and *Roof* structure with first *Revit categories* assignation [AoE] 286

Figure 10.12 – Scheme explaining the Temple of Neptune discretisation into its elemental components and *Revit categories* assignation [AoE] 287

Figure 10.13 – Scheme explaining the breaking down of the *Doric Shafts* and their *Capitals* when modelling the *Nested Families* [AoE] 288

Figure 10.14 – Example of a *Doric Column* composed of eight *Drums* with 24 flutings (left) and decomposition of its *Capital* into subcomponents [AoE]..................................289

Figure 10.15 – *Structural Shafts* composed respectively of eight, seven, six, five, and four *Drums* with 24 flutings [AoE] 290

Figure 10.16 – *Structural Shafts* composed respectively of five, four, and *Drums* with 20 flutings [AoE]..290

Figure 10.17 – *Structural Shafts* composed respectively of four, three, and two *Drums* with 16 flutings [AoE]..290

Figure 10.18 – Example of the parameters of the *Structural Shaft* family composed of eight *Drums* with 24 flutings [AoE]..291

Figure 10.19 – The three types of *Doric Drums* (upper) created and their generator profiles (lower), respectively with 24, 20, and 16 flutings [AoE] 292

Figure 10.20 – *Doric Drum* family parameters [AoE] 292

Figure 10.21 – The three types of *Capitals* generated, respectively with 24, 20, and 16 flutings [AoE]...293

Figure 10.22 – *Echinus* family parameters [AoE]...293

Figure 10.23 – *Necking* family parameters [AoE]...294

Figure 10.24 – Association between the nested *Necking* parameter *"H3"* and the specifically created *Capital* parameter *"HA_1"* [AoE] 294

Figure 10.25 – *Doric Capital* parameters, with the *Necking* associated parameter "*HA_1*" highlighted [AoE] 295

Figure 10.26 – *Architrave* family types: *External* (left) and *Internal* (middle) and *Internal type* parameters (right) [AoE]..295

Figure 10.27 – Grid set up to easily identify the columns' positions [AoE] 297

Figure 10.28 – Orthoimages edited by M. Limongiello: North view (upper), West view (upper right centre), East view (upper left centre), South (lower centre), and plan view of the Temple roofs (lower)..298

Figure 10.29 – Scan-to-BIM modelling: West view of the structural model overlapped over the point cloud (upper) and the corresponding orthoimage (lower) [AoE] 299

Figure 10.30 – Scan-to-BIM modelling: South view of the structural model overlapped over the point cloud (upper) and the corresponding orthoimage (lower) [AoE] 300

Figure 10.31 – System families of *Floors* (left) and *Walls* (right) generated to model the Temple of Neptune by duplicating a monolayer (Travertine) family and modifying the thickness per each of them [AoE] 300

Figure 10.32 – Exploded axonometry to show the modelled BIM elements according to the Greek nomenclature and the assigned Revit categories [AoE] 301

Figure 10.33 – Structural modelling [STR] of the Temple of Neptune showing the material properly assigned to the corresponding components [AoE]..302

Figure 10.34 – The PBR harder *grey travertine* generated within the Revit *material browser* for the *Crepidoma* (left), the *Cornice* and the *Roof Tiles* (right) [AoE]...............302

Figure 10.35 – The PBR softer *yellow travertine* generated within the Revit *material browser* for the *Columns* (left) and the *Trabeation* (right) [AoE].....................................303

Figure 10.36 – Rendered North-Eastern view of the Temple of Neptune generated with the real-time rendering plug-in Enscape for Revit [AoE] 303

Figure 11.1 – Procedural workflow A explanatory diagram [AoE] [3].............................307

Figure 11.2 – *Revit "Site" instance* reproducing the 2017 UAS surveyed context [AoE].308

Figure 11.3 – *Revit "Site" instance* reproducing the 2020 UAS surveyed context [AoE].308

Figure 11.4 – Othoimage used as texture for the 2017 *Revit Instance* context [AoE]........308

Figure 11.5 – Othoimage used as texture for the 2020 *Revit Instance* context [AoE]........309

Figure 11.6 – Federated and overlapping textured *Revit projects* of 2017 and 2020 contexts [AoE]...309

Figure 11.7 – Diagram breaking down the VPL script developed to import the mesh models by generating them as *Revit Instances* [AoE]..311

Figure 11.8 – Dynamo VPL script developed to to import the mesh models by generating them as *Revit Instances* [AoE] 311

Figure 11.9 – Workflow A: additional procedural methodology for a Mesh-to-BIM to Real-Time Rendering approach [AoE] 313

Figure 11.10 – *2017 Photogrammetric material*'s maps generation within Materialize [AoE]..316

Figure 11.11 – *2017 Orthoimage* of the Temple of Neptune immediate surroundings [AoE] 316

Figure 11.12 – *2017 Height* (left) and *Normal* (right) maps [AoE] 317

Figure 11.13 – *2017 Ambient Occlusion* (left) and *Smoothness* (right) maps [AoE] 317

Figure 11.14 – *2020 Photogrammetric material*'s maps generation within Materialize [AoE]..317

Figure 11.15 – *2020 Orthoimage* of the Temple of Neptune extended surroundings [AoE] 318

Figure 11.16 – *2020 Height* (left) and *Normal* (right) maps [AoE] 318

Figure 11.17 – *2020 Ambient Occlusion* (left) and *Smoothness* (right) maps [AoE] 319

Figure 11.18 – *2017 Photogrammetric material* implementation (*Revit Material Browser*) [AoE]..319

Figure 11.19 – *2020 Photogrammetric material* implementation (*Revit Material Browser*) [AoE]..320

Figure 11.20 – Rendered N-E view of the Temple of Neptune within its 2017 context [AoE] 320

Figure 11.21 – Rendered N-E view of the Temple of Neptune within its 2020 context [AoE] 321

Figure 11.22 – Rendered N-E view of the Temple of Neptune within its 2017 context: Zoom in on some articulated areas that represent a limitation for Workflow A implementation [AoE]..321

Figure 11.23 – Rendered N-E view of the Temple of Neptune within its 2020 context: Zoom in on some articulated areas that represent a limitation for Workflow A implementation [AoE]..322

Figure 11.24 – Procedural workflow B explanatory diagram: the "*Mesh faces* as Revit *Instances* generation" step refers to the execution of the *ad-hoc* designed VPL script 7 [AoE] [3]...324

Figure 11.25 – Diagram breaking down the VPL script developed to generate the input *Mesh Faces* as Revit *Instances* of the *"Triangular Face" Site* family [AoE]....................325

Figure 11.26 – Dynamo VPL script developed to generate the input *Mesh Faces* as Revit *Instances* of the *"Triangular Face" Site* family [AoE] [3]...326

Figure 11.27 – Dynamo VPL script developed to generate the input *Mesh Faces* as Revit *Instances* of the *"Triangular Face" Site* family: Group of nodes dedicated to importing the mesh in PLY format and retrieving its vertices coordinates [AoE]...................................326

Figure 11.28 – Dynamo VPL script developed to generate the input *Mesh Faces* as Revit *Instances* of the *"Triangular Face" Site* family: Group of nodes dedicated to importing the colour assigned to each face from Excel [AoE] 326

Figure 11.29 – Dynamo VPL script developed to generate the input *Mesh Faces* as Revit *Instances* of the *"Triangular Face" Site* family: Group of nodes dedicated to retrieving the mesh faces' indices from imported Excel data [AoE]...327

Figure 11.30 – Dynamo VPL script developed to generate the input *Mesh Faces* as Revit *Instances* of the *"Triangular Face" Site* family: Group of nodes dedicated to combining the coordinates for the *Adaptive triangles' vertices.* This group employs the custom node marked in red [AoE]...327

Figure 11.31 – Dynamo VPL script developed to generate the input *Mesh Faces* as Revit *Instances* of the *"Triangular Face" Site* family: Group of nodes dedicated to generating Revit colours from the photogrammetric ones [AoE] 327

Figure 11.32 – Dynamo VPL script developed to generate the input *Mesh Faces* as Revit *Instances* of the *"Triangular Face" Site* family: Group of nodes dedicated to generating Revit material from the colours previously created [AoE]..328

Figure 11.33 – Dynamo VPL script developed to generate the input *Mesh Faces* as Revit *Instances* of the *"Triangular Face" Site* family: Group of nodes dedicated to process partitioning*, which refers to the choice of partitioning the script by repeating the next two steps up to eight times in order to monitor the process and for the hardware to run it efficiently (left) and additional inputs for the last steps' execution (right). The process partitioning* group employs the custom node marked in red [AoE] 328

Figure 11.34 – Dynamo VPL script developed to generate the input *Mesh Faces* as Revit *Instances* of the *"Triangular Face" Site* family: Groups of nodes dedicated to generating the adaptive triangles' instances (left) and assigning to them the corresponding photogrammetric material previously created (right) [AoE] 329

Figure 11.35 – *"Scavo_2.PLY"* (Area A) as exported from Agistoft Metashape after a first decimation of the high-quality mesh produced within the photogrammetric workflow [AoE] 330

Figure 11.36 – *“Scavo_1.PLY”* (Area D) as exported from Agistoft Metashape after a first decimation of the high-quality mesh produced within the photogrammetric workflow [AoE] 330

Figure 11.37 – *“Artefatto.PLY”* (Area C) as exported from Agistoft Metashape after a first decimation of the high-quality mesh produced within the photogrammetric workflow [AoE] 331

Figure 11.38 – Original textures in PNG format of the purged *“Scavo_2”*, *“Scavo_1”*, and *“Artefatto”* meshes before being indexed through Adobe Photoshop [AoE] 331

Figure 11.39 – Indexed textures (via Adobe Photoshop) in PNG format of the purged *“Scavo_2”*, *“Scavo_1”*, and *“Artefatto”* meshes [AoE] 331

Figure 11.40 – *“Scavo_2.PLY”* (Area A) after being purged, repaired, and decimated again with the indexed texture reapplied as faces' colours [AoE]..........332

Figure 11.41 – *“Scavo_1.PLY”* (Area D) after being purged, repaired, and decimated again with the indexed texture reapplied as faces' colours [AoE]..........332

Figure 11.42 – *“Artefatto.PLY”* (Area C) after being purged, repaired, and decimated again with the indexed texture reapplied as faces' colours [AoE]..........333

Figure 11.43 – Example of the *“Artefatto”* mesh data (which readability was ensured by choosing the ASCII encoding format) imported into Excel to isolate the faces-related information [AoE]..........333

Figure 11.44 – Federated Revit projects rendered overview representing the Temple of Neptune and its surroundings as of 2021 with the reprojected detailed areas marked in yellow [AoE]..........334

Figure 11.45 – Rendered views (via the real-time rendering plug-in Enscape for Revit) of the (a) *“Scavo_2_2021.RVT”*, (b) *“Scavo_1_2021. RVT”*, and (c) *“Artefatto_2021.RVT”.* 335

Figure 11.46 – Federated Revit projects overview of the reprojected detailed areas highlighted in yellow within the *Manage Links* dialogue box [AoE] 335

Figure 11.47 – Federated Revit projects rendered South-Western view representing the Temple of Neptune and its surroundings as of 2021 [AoE] 335

Figure 11.48 – Federated Revit projects rendered North-Eastern view representing the Temple of Neptune and its surroundings as of 2021 [AoE] 336

Figure 11.49 – Overview of the further implemented parameters for the *“Triangular Face.RFA”* adaptive component (upper) in order to calculate, e.g., the area of each triangular instance via the *Heron’s Formula* (implemented through script 8 – lower) [AoE] [3]..........337

Figure 11.50 – Diagram breaking down the VPL script developed to run the *Heron's Formula* calculations for the *triangular faces' instances* [AoE]......................................338

Figure 11.51 – Dynamo VPL script developed to run the *Heron's Formula* calculations for the *triangular faces' instances*: Group of nodes dedicated to retrieving the report parameters data, i.e., *"L1"*, *"L2"*, and *"L3"* [AoE] 338

Figure 11.52 – Dynamo VPL script developed to run the *Heron's Formula* calculations for the *triangular faces' instances*: Groups of nodes dedicated to actually execute the *Heron's Formula* calculations and to filling the *triangular faces "Area"* parameter [AoE] 338

Figure 11.53 – Example of the visual filtering (upper) and scheduling (lower) possibilities resulting from workflow B further implementations where the cumulative areas for each group of filtered triangles have been calculated (e.g., *"Artefatto_2021"* detailed Area) [AoE]..339

Figure 12.1 – Monitoring seismometers network overlayed upon the linked BIM model of the Temple of Neptune [AoE] 343

Figure 12.2 – Overview of the *"Data Acquisition System"* family (right) with its shared parameters (left) [AoE] 343

Figure 12.3 – Overview of the *"Measuring Point"* family (right) with its shared parameters (left) [AoE]..344

Figure 12.4 – Overview of the *"R.C. Manhole"* family (right) with its shared parameters (left) [AoE 344

Figure 12.5 – Overview of the *"Totem-Leggio"* family (right) with its shared parameters (left) [AoE]..345

Figure 12.6 – Diagram breaking down the VPL script developed to automatically implement in background additional *shared parameters* within the *sensors'* families [AoE] 345

Figure 12.7 – Dynamo VPL script developed to automatically implement in background additional *shared parameters* within the *sensors'* families [AoE] 346

Figure 12.8 – Dynamo VPL script developed to automatically implement in background additional *shared parameters* within the *sensors'* families: Group of nodes dedicated to importing *sensors*' updated data from Excel [AoE]..346

Figure 12.9 – Dynamo VPL script developed to automatically implement in background additional *shared parameters* within the *sensors'* families: Group of nodes dedicated to sorting data imported from Excel [AoE] 346

Figure 12.10 – Dynamo VPL script developed to automatically implement in background additional *shared parameters* within the *sensors'* families: Group of nodes dedicated to creating the additional *shared parameters* without manually opening and closing the Revit families [AoE]...347

Figure 12.11 – Input Excel data detailing the name [*"SP_Name"*], the group [*"SP_Group"*], the parameter type – e.g., textual, URL directory, number, etc. – [*"ParameterType"*], the Revit property's group [*"ParameterGroup"*], and the related Revit property's group nomenclature [*"RevitGroupName"*] of the additional *shared parameters* [AoE]....347

Figure 12.12 – Diagram breaking down the VPL script developed to keep the seismometer monitoring network updated [AoE] 348

Figure 12.13 – Dynamo VPL script developed to keep the seismometer monitoring network updated [AoE]....349

Figure 12.14 – Dynamo VPL script developed to keep the seismometer monitoring network updated: Groups of nodes dedicated to importing updated data from Excel [AoE]....349

Figure 12.15 – Dynamo VPL script developed to keep the seismometer monitoring network updated: Groups of nodes dedicated to selecting modelled instances of the Sensors' and DAQ families [AoE] 350

Figure 12.16 – Dynamo VPL script developed to keep the seismometer monitoring network updated: Groups of nodes dedicated to retrieving raw parameters' values (left) and generating the lists of parameters to fill out (right) [AoE] 350

Figure 12.17 – Dynamo VPL script developed to keep the seismometer monitoring network updated: Group of nodes dedicated to sorting and creating the list of DAQ *sensors channels* [AoE] 351

Figure 12.18 – Dynamo VPL script developed to keep the seismometer monitoring network updated: Group of nodes dedicated to sorting the *"Measuring Points"* input data to subsequently fill in the related parameter values [AoE]....352

Figure 12.19 – Dynamo VPL script developed to keep the seismometer monitoring network updated: Group of nodes dedicated to sorting the *"R.C. Manholes"* input data to subsequently fill in the related parameter values [AoE]....352

Figure 12.20 – Dynamo VPL script developed to keep the seismometer monitoring network updated: Group of nodes dedicated to retrieving and sorting the selected modelled instances' parameters to fill out with the imported data. This group of nodes employs the custom node marked in red [AoE] 352

Figure 12.21 – Dynamo VPL script developed to keep the seismometer monitoring network updated: Zoom in on the group of nodes dedicated to retrieving and sorting the selected modelled instances' parameters to fill out with the imported data. This group of nodes employs the custom node marked in red [AoE] 354

Figure 12.22 – Dynamo VPL script developed to keep the seismometer monitoring network updated: Group of nodes dedicated to sorting the *"Data Acquisition Systems"* input data to subsequently fill in the related parameter values [AoE]....354

Figure 12.23 – Dynamo VPL script developed to keep the seismometer monitoring network updated: Group of nodes dedicated to assigning the imported and sorted data to the modelled *instances* belonging to the "*Data Acquisition Systems"* familiy[AoE] 355

Figure 12.24 – Dynamo VPL script developed to keep the seismometer monitoring network updated: Group of nodes dedicated to assigning the imported and sorted data to the modelled *instances* belonging to the "*Measuring Points"* family [AoE]..........................355

Figure 12.25 – Dynamo VPL script developed to keep the seismometer monitoring network updated: Group of nodes dedicated to assigning the imported and sorted data to the modelled *instances* belonging to the "*R.C. Manholes"* family [AoE] 355

Figure 12.26 – Input Excel data concerning the *"Data Acquisition Systems"* instances [AoE]..356

Figure 12.27 – Input Excel data concerning the *"Measuring Points"* instances [AoE].....357

Figure 12.28 – Input Excel data concerning the *"R.C. Manholes"* instances [AoE] 357

Figure 12.29 – Federated Revit projects rendered plan view representing the Temple of Neptune, its surroundings, and the monitoring seismometers network as of 2021 [AoE].....358

Figure 12.30 – Federated Revit projects rendered North-Eastern view representing the Temple of Neptune, its surroundings, and the monitoring seismometers network as of 2021 [AoE]..358

Figure 12.31 – Federated models exported to IFC and visualised via Nemetschek Solibri Anywhere: Example of the customised properties added to a *Structural Column instance* [AoE]..359

Figure 12.32 – Example of the properties added as shared parameters to a modelled *"Data Acquisition System" instance* within the native Revit Environment [AoE] 360

Figure 12.33 – Federated models exported to IFC and visualised via Nemetschek Solibri Anywhere: Example of the customised properties added to a *"Measuring Point" instance* (left) and the plan view indicating its location (right) linked via the *"PM_Link"* parameter [AoE]..360

Figure 12.34 – Federated models exported to IFC and visualised via Nemetschek Solibri Anywhere: Example of the customised properties added to a *"R.C. Manhole" instance* [AoE]..361

Figure 12.35 – Federated models exported to IFC and visualised via Nemetschek Solibri Anywhere: Example of the linked plan view indicating its location and a detailed image breaking down the *"R.C. Manhole" instance* selected in Figure 12.34 [AoE] 361

Figure 12.36 – Federated models exported to IFC and visualised via Nemetschek Solibri Anywhere: Example of the customised properties added to the *"Totem-Leggio" instance* [AoE]..362

Figure 12.37 – Federated models exported to IFC and visualised via Nemetschek Solibri Anywhere: Example of the linked plan view indicating the location of the *"Totem-Leggio" instance* (also selected in Figure 12.36) and a screenshot of the real-time data coming from the on-site monitoring system accessible via the *"P_RealTime"* parameter [AoE]...........362

Figure 12.38 – (a) *"Scavo_2.IFC"* and (b) *"Scavo_1.IFC"* visualisation via BIM Vision [AoE]..363

Figure 12.39 – *"Artefatto.IFC"* visualisation via BIM Vision: Example of the customized properties added as shared parameters to a selected "Triangular Face" instance [AoE]....363

Figure 12.40 – Example of the conversion process from IFC to OBJ via FME Workbench [AoE]..364

Figure 12.41 – Comparison between the continuous model of the Temple [OBJ] and the integrated point cloud performed via Cloud Compare, showing in green-yellow shades the absolute distances inferior to 5 cm between the points and the mesh [AoE] 365

Figure 12.42 – Comparison between the continuous model of the Temple [OBJ] and the integrated point cloud performed via Cloud Compare, showing in orange-red shades the positive distances ranging from 5 to 10 cm between the points and the mesh [AoE] 365

Figure 12.43 – Comparison between the continuous model of the Temple [OBJ] and the integrated point cloud performed via Cloud Compare, showing in dark green-blue shades the negative distances ranging from 5 to 10 cm between the points and the mesh [AoE] .366

Figure 12.44 – Comparison between the continuous model of the Temple [OBJ] and the integrated point cloud performed via Cloud Compare, showing absolute distances inferior to 10 cm between the points and the mesh in blue to red shades; non-modelled elements have been greyed out [AoE] 366

Figure 13.1 – The value of structural monitoring. Throughout history, trilithons and arches have represented the essential components of any structure. Here is a graphic summary of some real monuments and ideal bridges captured respectively on the European coins and banknotes. The back of each banknote features a bridge from one of the seven periods in Europe's architectural history, which is a metaphor for the close cooperation and communication between the people of Europe and between Europe and the rest of the world. The images are based on the typical architectural style of each period – i.e., Classical, Romanesque, Gothic, Renaissance, Baroque & Rococo, Iron & Glass, and Modern architecture – rather than on specific structures. 368

Table index

Table 4.1 – List of defects reported on the Defect forms with their numbering; the code is assigned on the basis of the structural typology (concrete, steel and wooden bearing and non-bearing structures, foundations, and joints) of the bridge component affected by the degradation phenomenon [96] 120

Table 4.2 – List of defects reported on the Defect forms with their numbering; the code is assigned on the basis of the structural typology (masonry and auxiliary elements) of the bridge component affected by the degradation phenomenon [96] 121

Table 4.3 – Minimum interval of routine inspections according to the LG20 [4] 132

Table 4.4 – The papers are listed, from the most recent to the oldest publication year, according to the relevance criteria established by the Web of Science [Wos] and Scopus databases within the same year. The first column contains the *reference number* [REF], followed by the *title of the article*, the *type of publication* – J = *Journal Article*, C = *Conference Proceedings*, B = *Book Chapter* –, the purpose of the contribution, and its year. The *open access* papers (30) are highlighted in yellow, while the *review* ones (11) are in blue; whether a review contribution also has open access (4) will be marked in green. The indexed abstracts introducing the conference proceedings volumes are considered reviews. 139

Table 4.5 – Breakdown of the structural sections – foundations, abutments, piers, arches – into components [99] [MbA] 166

Table 4.6 – Breakdown of the structural sections – decks, row of bearings, joints, seismic equipments – into components [99] [MbA] 166

Table 4.7 – Outline of the identifier assigned to each structural material 167

Table 4.8 – Nomenclature of structural sections and components, together with their ID and the Annex B forms to be assigned also according to the material and structural function of each component 168

Table 7.1 – List of the *IfcTypes* and *IfcTypeEnumerations* assigned to each Revit family type modelled [AoE] 234

Table 9.1 – Input data of the 2017 and 2020 UAS surveys 270

Table 9.2 – Output data of the 2017 and 2020 UAS surveys 270

Table 9.3 – Main components of the monitoring network placed upon the Temple of Neptune 273

Table 9.4 – List of the measuring points initially envisaged for the monitoring system set up and their eventual installation 274

Table 9.5 - A detailed list of the measuring points distinguished according to type, components of the detected displacement and presence or absence of DAQ.....................276

Table 11.1 – The table shows the variation of x, y, and z coordinates in the translation from the Global Georeferenced System (EPSG: 32633 for the columns marked with *) to the Local One...310

Anna Sanseverino **Application of BIM methodology for structural inspection and maintenance** *SDS ICAR 17*