Some experiences on digitisation of Cultural Built Heritage: HBIM and Open Data Hubs as new paradigms

Mattia Previtali
Politecnico di Milano, Department of Architecture, Built Environment and Construction Engineering,
Via Ponzio 31, 20133 Milano, Italy

Introduction:

- Present three experiences on digitization of Cultural Built Heritage showing the potential of HBIM

- HBIM as a single point of access to building data and meeting place for different experts working and cooperating at the same project

- Experiences will focus on potential / research aspects / challenges of HBIM for:
  - Restoration / maintenance projects
  - Decision making at city level
  - Increasing knowledge and rising awareness on Built Heritage role

BIM (Building Information Modeling)

- Shared digital representation of physical and functional characteristics of any built object (including buildings, bridges, roads, etc.) which forms a reliable basis for decisions [BS ISO 29481-1 2010]

- A rich information model, consisting of potentially multiple data sources, elements of which can be shared across all stakeholders and be maintained across the life of a building from inception to recycling [National Building Specification (NBS)]

- Building Information Modelling is digital representation of physical and functional characteristics of a facility creating a shared knowledge resource for information about it forming a reliable basis for decisions during its life cycle, from earliest conception to demolition [RIBA, CPIC]

BIM (Building Information Modeling)

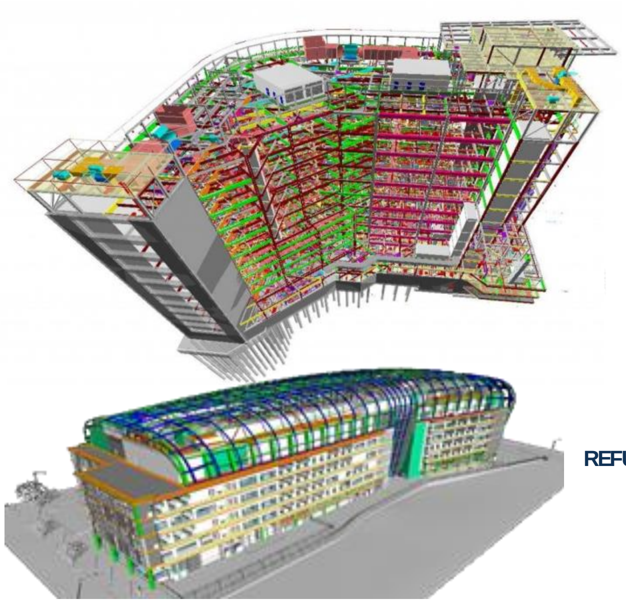
- Shared **digital representation** of physical and functional characteristics of any **built object** (including buildings, bridges, roads, etc.) which forms a reliable basis for decisions [BS ISO 29481-1 2010]

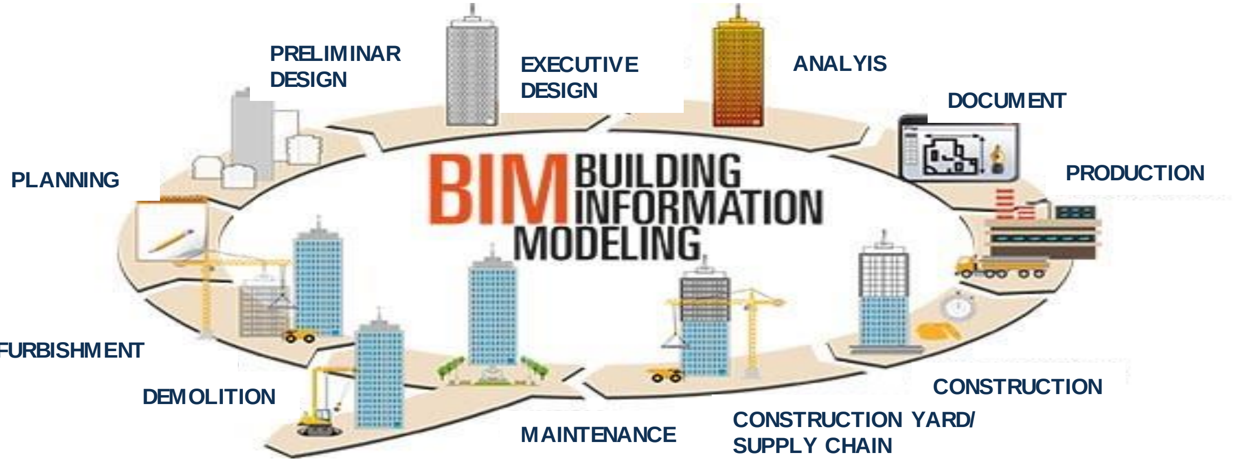
- A rich information model, consisting of potentially **multiple data sources**, elements of which can be shared across all stakeholders and be maintained across the **life of a building** from inception to recycling [National Building Specification (NBS)]

- Building Information Modelling is digital representation of physical and functional characteristics of a facility creating a **shared knowledge** resource for information about it forming a **reliable basis for decisions** during its life cycle, from earliest conception to demolition [RIBA, CPIC]

BIM (Building Information Modeling)

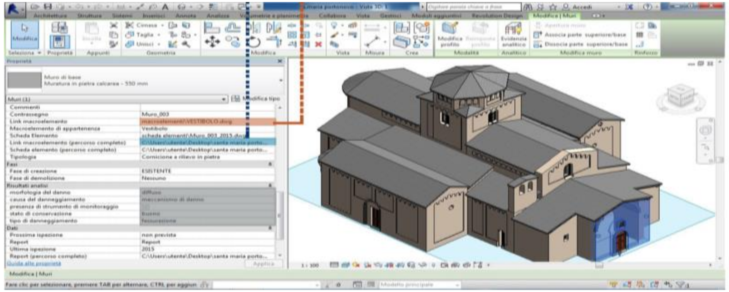
- Digital model-based process that provides insight to help you plan, design, construct and manage buildings and infrastructures



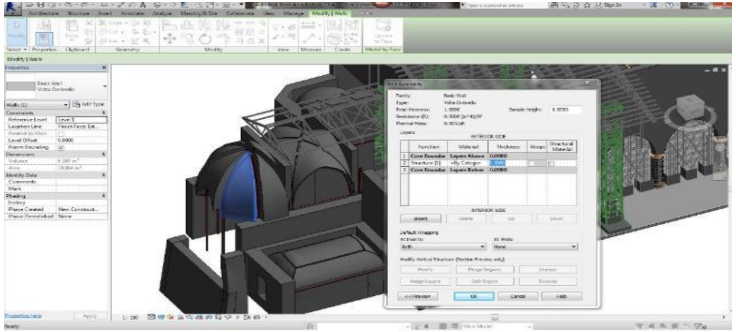


HBIM (Historical Building Information Modeling)

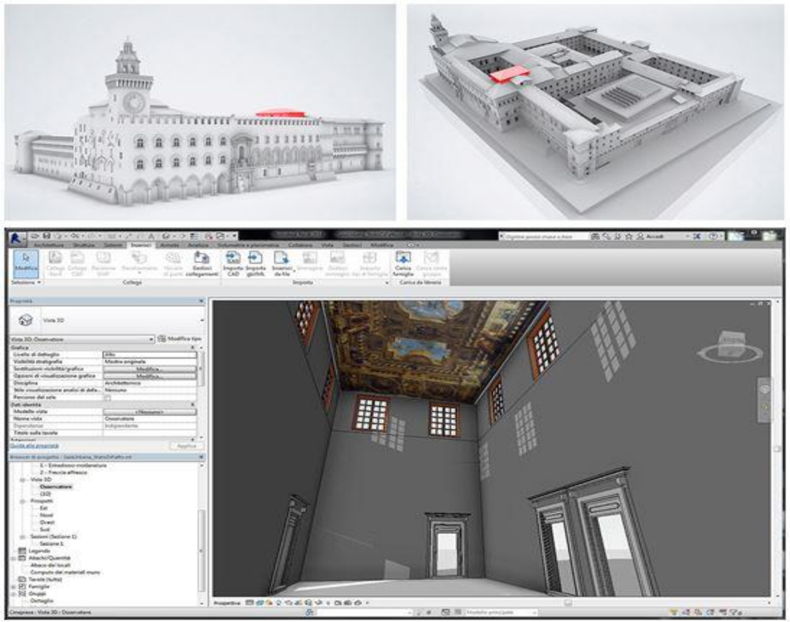
– Historic Building Information Modelling (HBIM) is a new approach for modelling historic buildings which develops full Building Information Models (BIMs) from remotely sensed data [C. Dove]



R. Quattrini, R. Pierdicca, C. Morbidoni, 2017



F. Banfi, S. della Torre, 2011

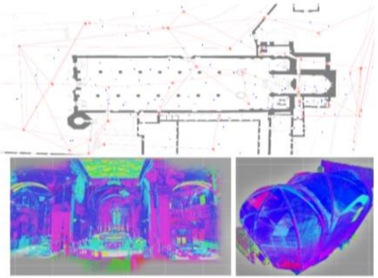


S. Garagnani, 2014

HBIM challenges

- BIM tools were primarily devoted to design and manage new buildings
- In “standard BIM” (new constructions) elements are standardized and regular
- Modelling methodologies and approaches which will document deformities, irregularities and complex geometries retaining BIM functionality

=> Define new methodologies and workflows to use BIM tools in the case of Cultural Built Heritage



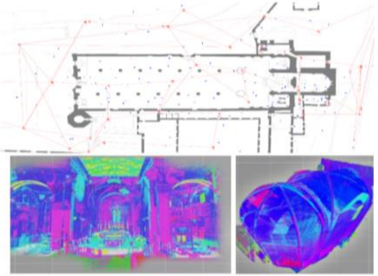
SCAN

Data Acquisition:

- Terrestrial laser scanning

- Photogrammetry

- UAV

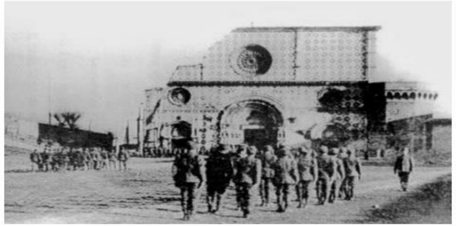


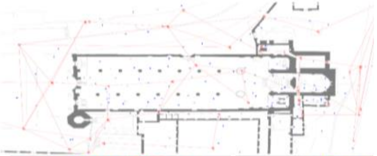
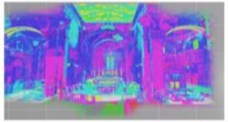
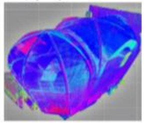
SCAN

HISTORICAL ANALYIS

Historical analysis:

- Analysis of historical data sources (written documents, images, renovation projects, etc…)



SCAN

MATERIAL ANALYIS

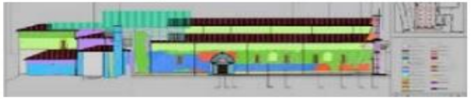
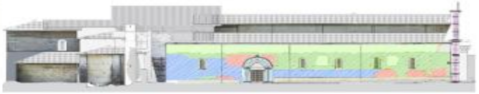
HISTORICAL ANALYIS

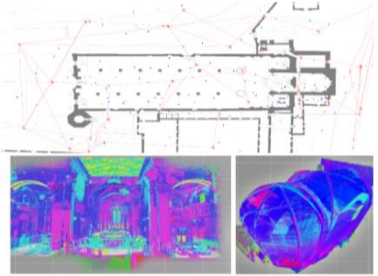


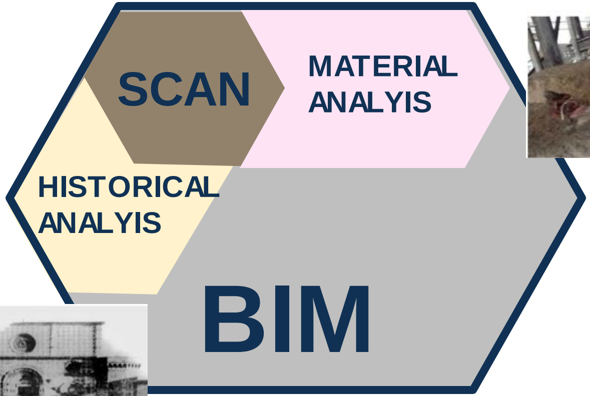

Material analysis:

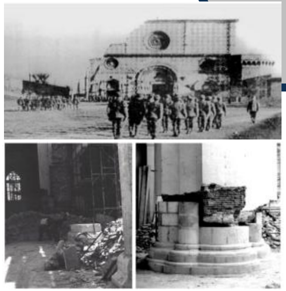
- Definition of material characteristics (mechanical, physical, etc.)
- Non-destructive tests
- Crack analysis
- Decay analysis



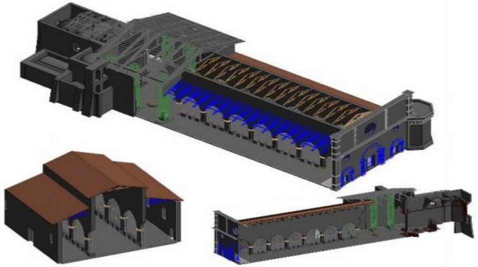


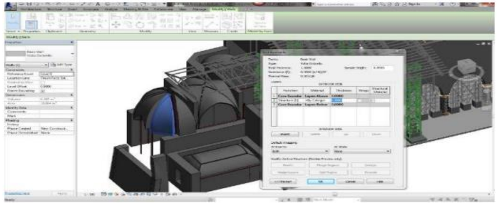




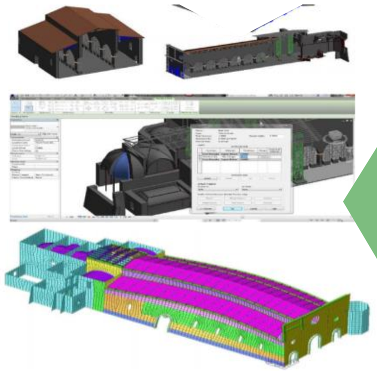
Scan-to-BIM:

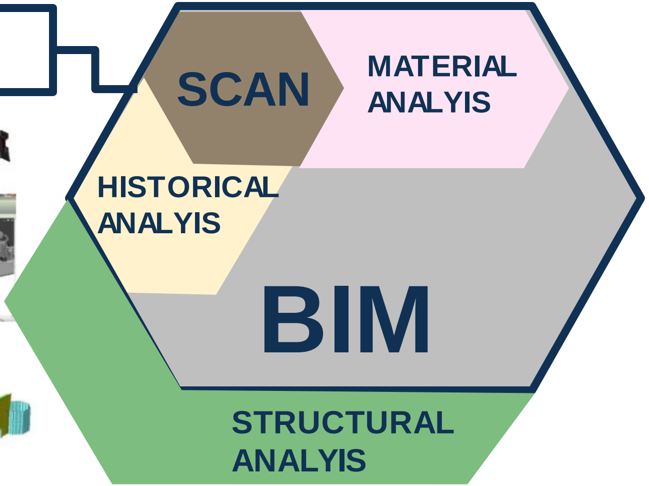
- Acquired information are combined into a unique model
- Generative modelling is used to model complex geometries retaining BIM functionality
- Free-form NURBS are combined into BIM software





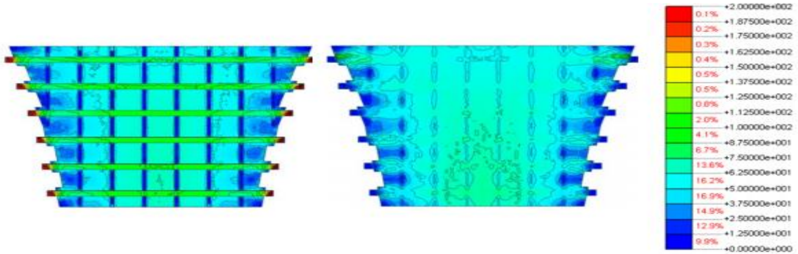
SCAN-to-BIM

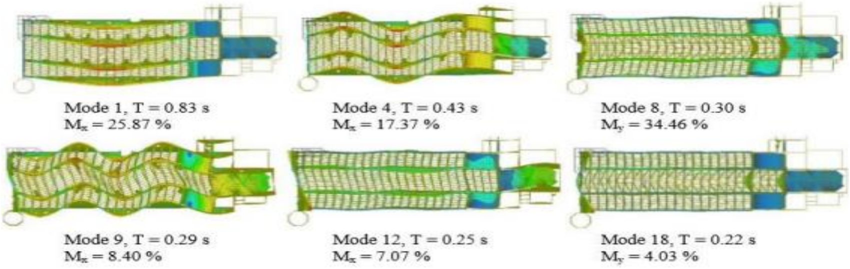




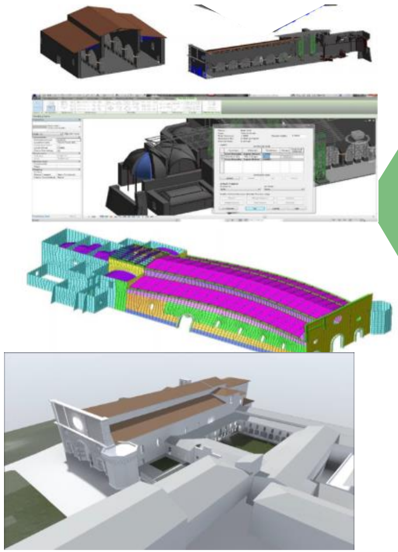
Structural analysis:

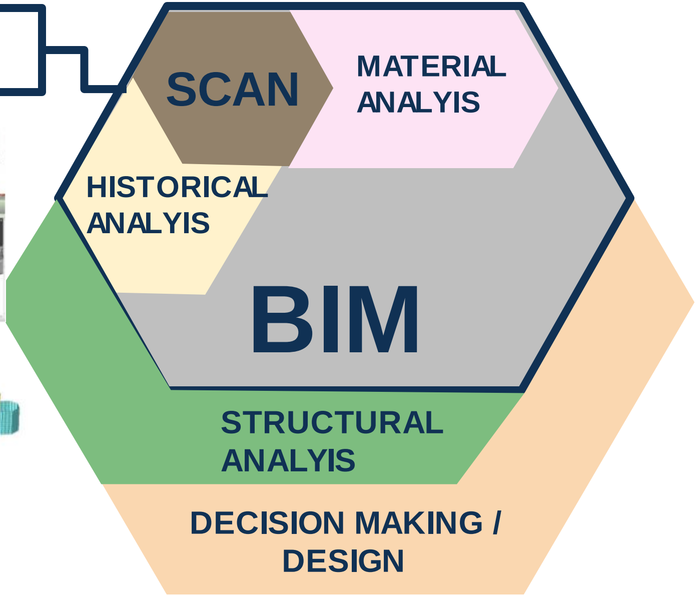
- Modal analysis and evaluation under seismic actions
- Finite-element analysis
- Definition of possible design scenarios





SCAN-to-BIM

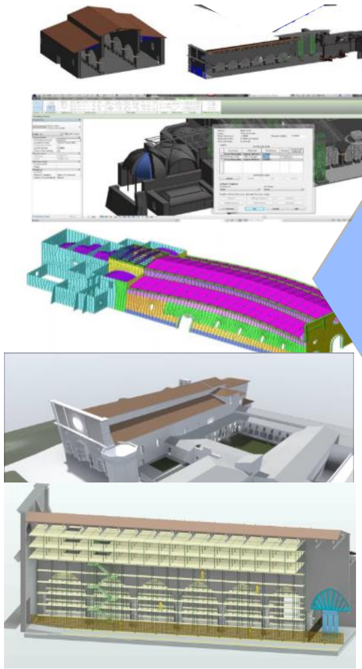


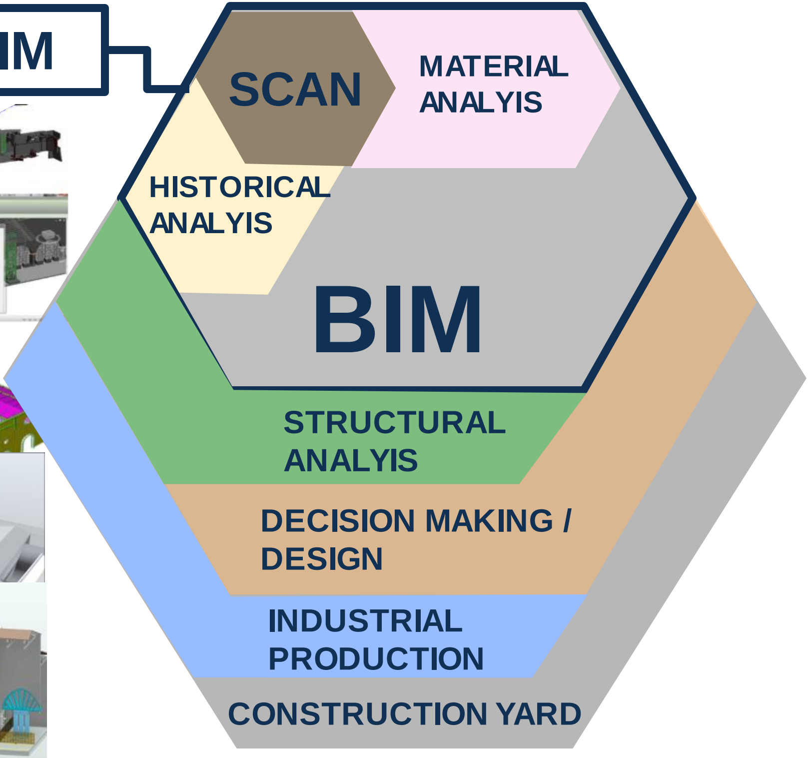


Decision Making / Design:

- Design of the restoration / maintenance intervention based on the acquired knowledge
- Design performed using BIM tools

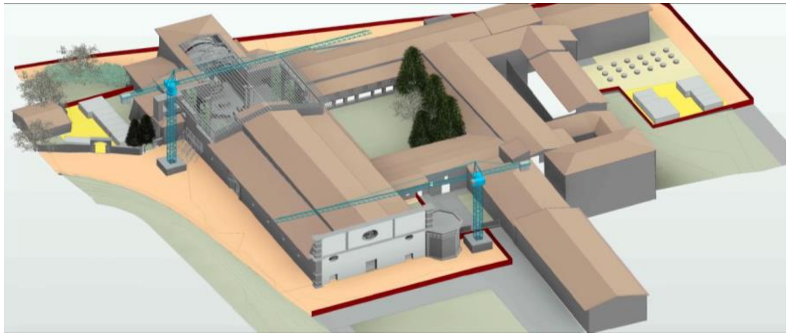
SCAN-to-BIM



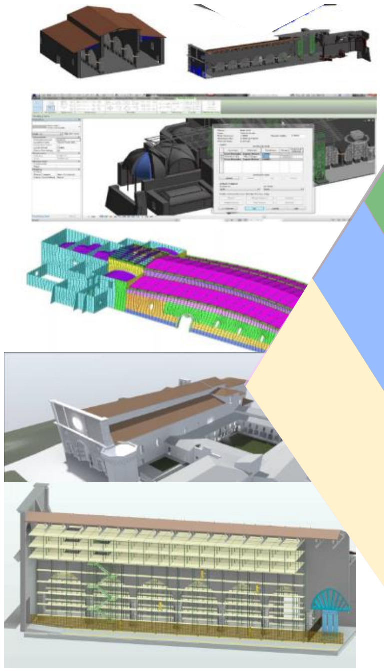


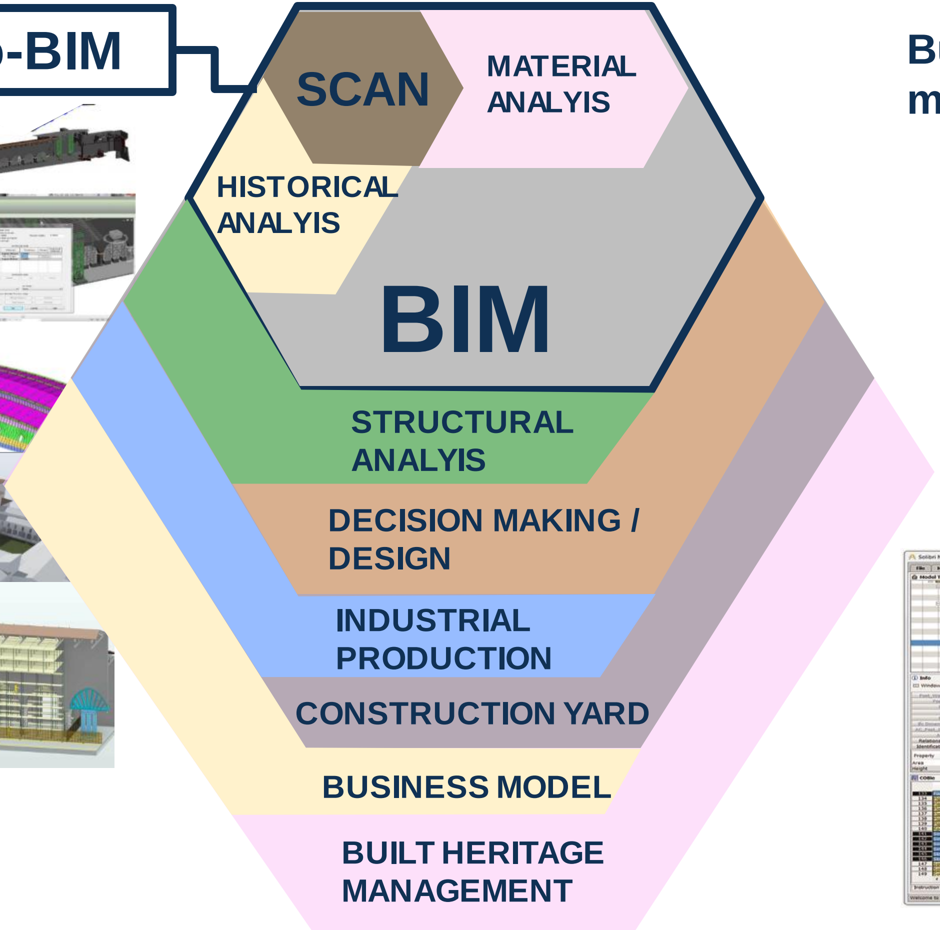
Construction Yard / Supply chain:

- Design and management of the construction yard, scheduling and work breakdown
- Management of the supply chain based on industrial production processes



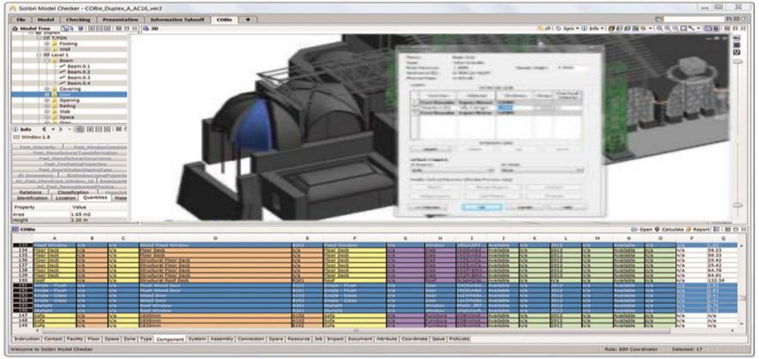
SCAN-to-BIM





Built heritage management / maintenance:

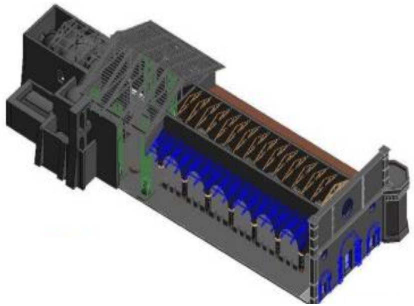
- The maintenance of the built heritage can be efficiently carried out by using BIM tools for maintenance
- Life-cycle-management and definition of planed maintenance



Presented experiences:

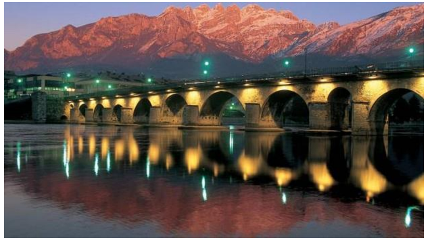
– SANTA MARIA DI COLLEMAGGIO (L'AQUILA)

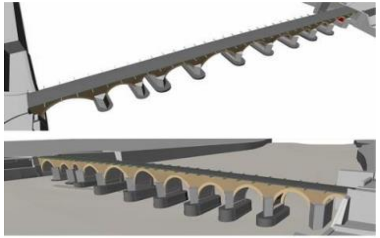
- HBIM for design of restoration work after an earthquake
- Modelling free-form surfaces retaining BIM functionalities
- BIM to FEA & BIM to construction yard



– PONTE AZZONE VISCONTI (LECCO- ITALY)

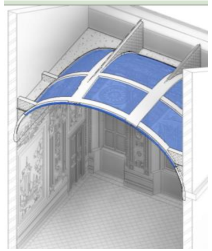
- HBIM as "live" repository of information on the bridge
- HBIM and monitoring
- BIM / GIS integration





– OPEN DATA HUB FOR HBIM MODELS

- Integration among different HBIM projects
- Database of vault systems

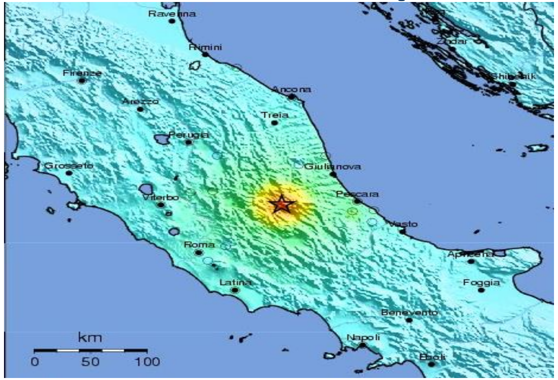


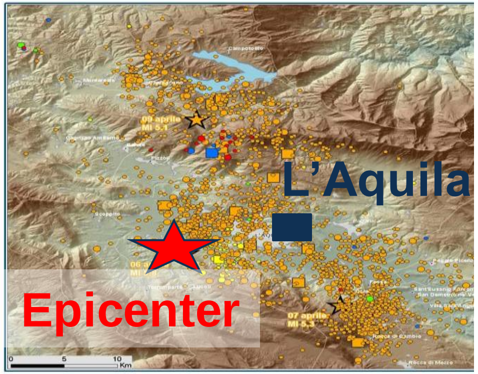
SANTA MARIA DI COLLEMAGGIO (L'AQUILA - ITALY)

April 2009

December 2017

L'AQUILA Earthquake - ITALY

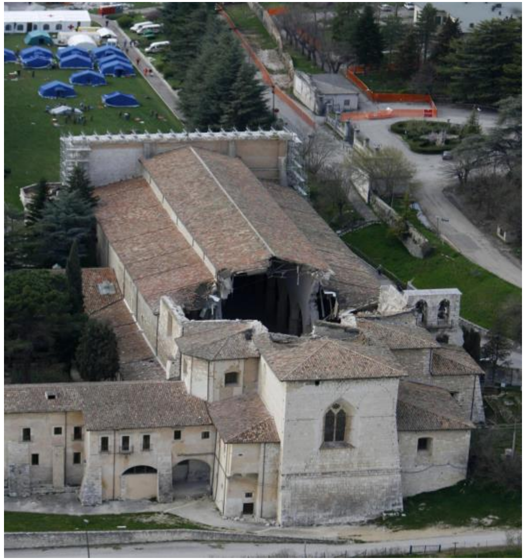




- On April 6th, 2009 at 3:32 a.m. an Earthquake (Richter Magnitude 5.9) struck L'Aquila (Central Italy): 309 victims, 65000 displaced people
- More than 10 billion euro of estimated damage, about 100 churches unusable for major collapses

L'AQUILA Earthquake - ITALY

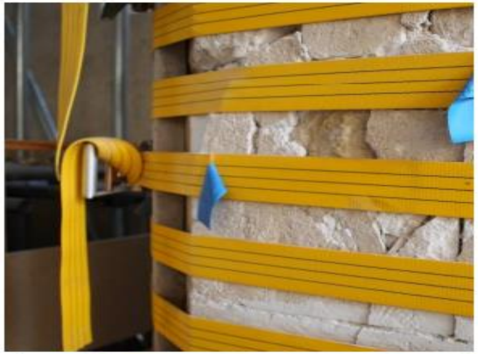




The Basilica di Collemaggio was significantly stricken:

- the dome, the transept with the central vaults and triumphal arches collapsed,
- great damage occurred to the pillars, to the apses, and to the north front

Santa Maria di Collemaggio



Some works were performed to for securing the site:

- a new steal structure was built to cover the area of the collapsed dome,
- Naves' columns were hooped to secure them,
- Carbon fiber reinforcement in the central nave

Santa Maria di Collemaggio

The aim of the rehabilitation intervention was to guarantee the safety of the elements with artistic-historical value.

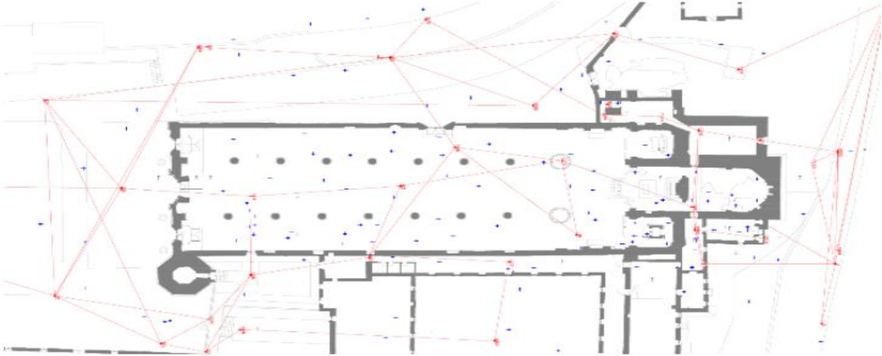
The **main interventions** to design were:

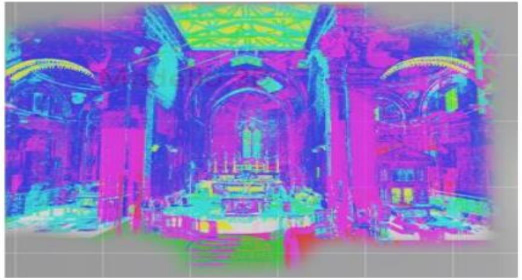
- **Rebuilding of the pillars** to increase the stiffness of the transept area in the transversal direction
- Rebuilding of a **new cross-lam roof** that increases considerably the dissipation capacity of the whole building
- **Restoration of the naves' columns**

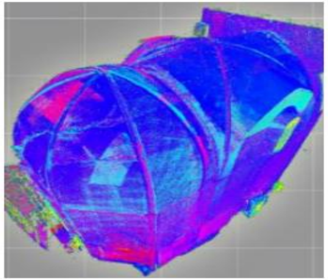
⇒ A proper **methodology** was needed in order **to preserve** both tangible and intangible **values of the Basilica** and **guarantee the safety** of the church in case of further earthquake

⇒ An **HBIM** process was evaluated as the most suitable solution to guarantee a single **repository of information** to be used **for decision making and design** of the restoration works as well as management of **restoration works**

Step 1 –Survey



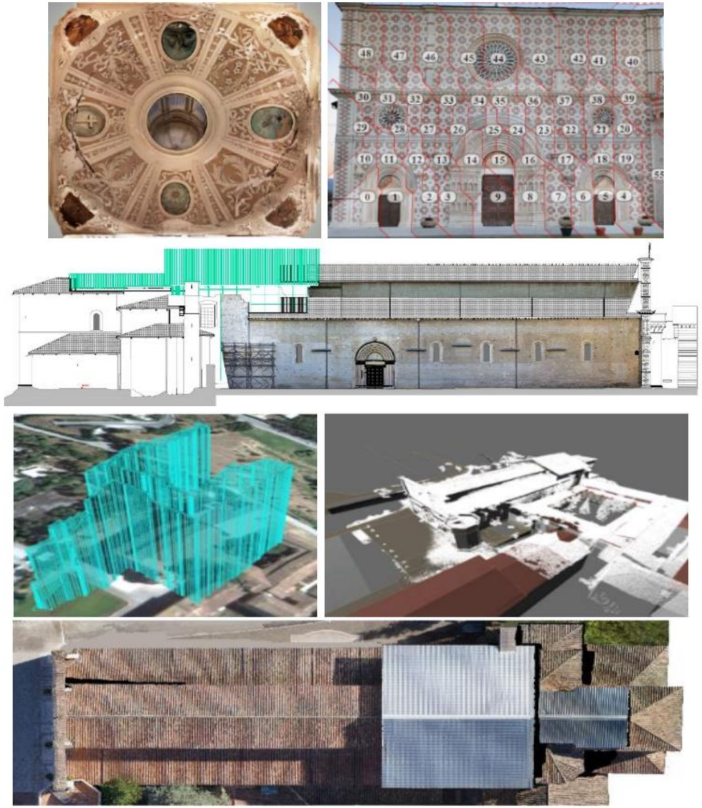




- The complexity and size required a robust geodetic network to fix the datum of the project and to remove deformations during the scan registration

- The laser scanning survey is made up of 182 scans (roughly 8 billion points) registered by means of checkerboards measured with the geodetic network and spherical targets. The final registration precision was better than ±3 mm, i.e. equivalent to the precision of the laser scanner used (Faro Focus 3D)

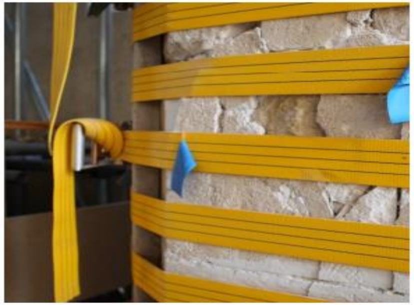
Step 1 –Survey



- Image-based methods were used to reconstruct areas where laser data did not provide a sufficient level of detail or where there was a complete lack of data (e.g. othophoto of vaults to provide a valid support to understand and interpret the structure, elements like cracks or other structural damages can be easily inspected)

- UAV photogrammetric block made up of 52 images allowed extraction of a dense point cloud to reconstruct the roof structure and provided the geometric model where the images were reprojected to obtain an orthophoto of the area

Step 2 – Ashlar analysis

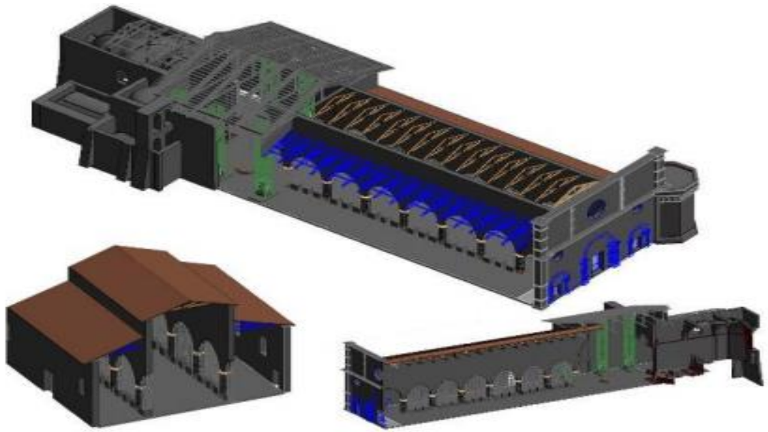


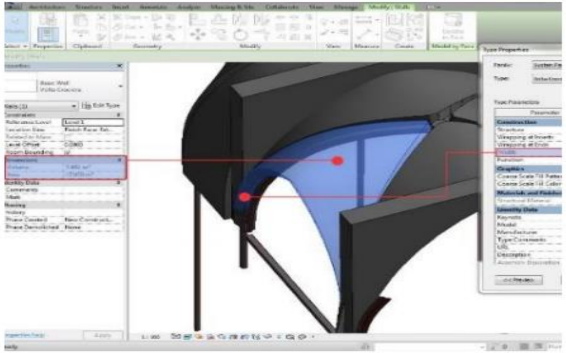
- A particular attention was paid to the geometrical and constructive analysis of the damaged medieval stone columns of the nave. They were restored in 1970 changing broken stones and inserting mortar

- Manual measurements to reconstruct the geometry and arrangement of the blocks in rows

- It is important to mentioned that a preliminary disassemble is not possible to evaluate the exact consistency of the internal part. Therefore, both survey and data interpretation provided a fundamental tool for structural engineers to plan specific intervention

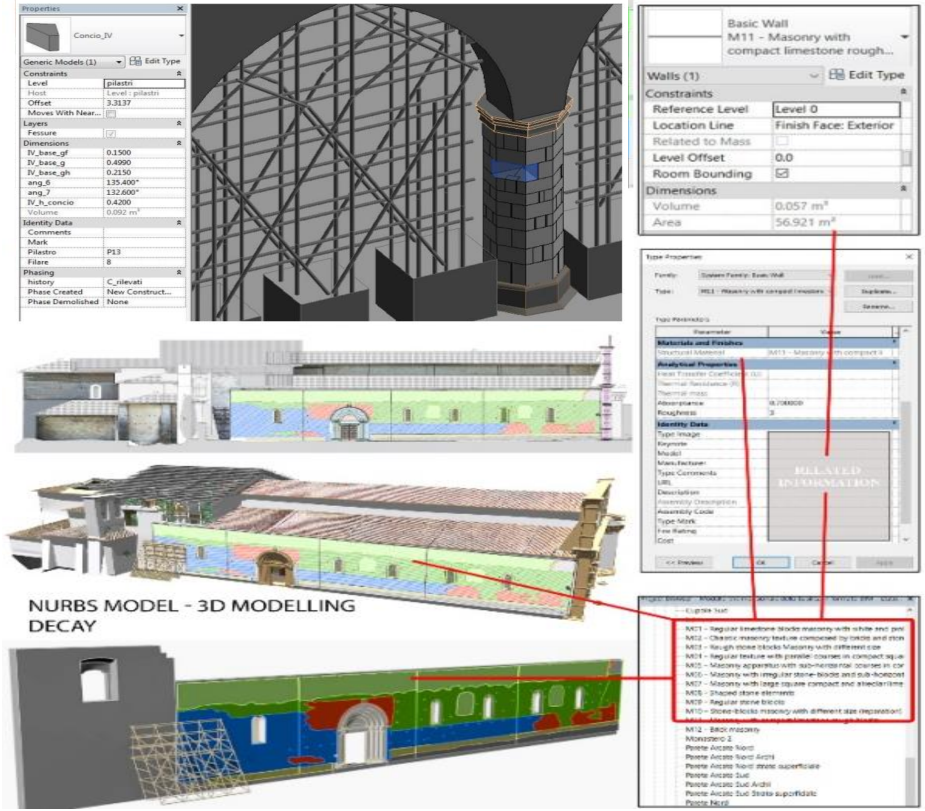
Step 3 – BIM Modelling





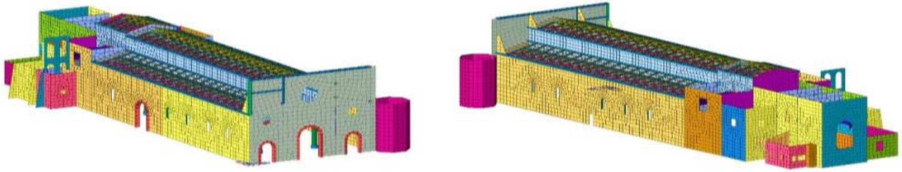
- The 3D model of the Basilica was divided in its structural elements following the constructive logic of the building: i.e. vaults, wooden elements of the cover, walls, columns, stone ashlars, and decorative elements.
- Starting from multiple point clouds, Rhino© allowed the representation of complex shapes by using NURBS (Non Uniform Rational Basis-Splines)
- The second step was the use Rhino© shapes into BIM parametric elements in order to obtain a complete parametric conversion of all the elements without losing information.
- The aim was to overcome the lack of parametric model software (i.e. Graphisoft Archicad© and Autodesk Revit©) for the management of complex and irregular shapes

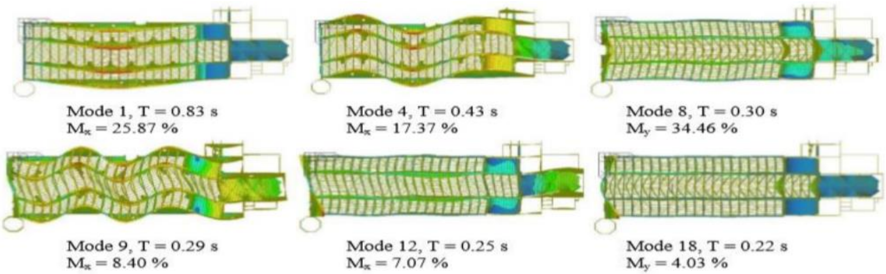
Step 4 – BIM data enrichment

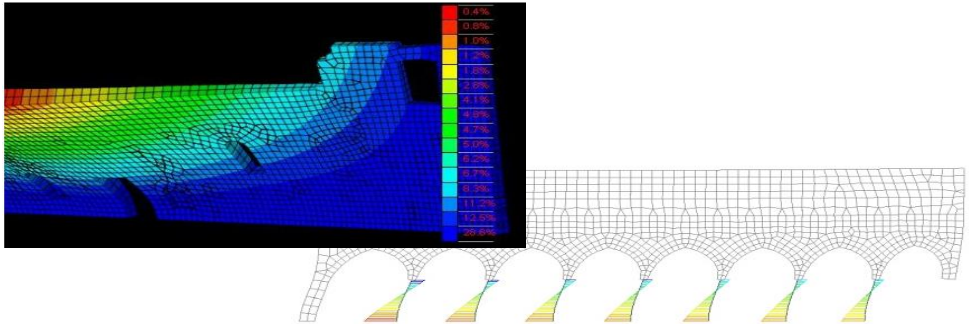


- The 3D BIM model of the Basilica was enriched with both materials and decay information
- The main reason for generating 3D BIM mapping of materials was that 2D drawings did not show real permanent deformations, specific structural deterioration, suffered damage and accurate quantification in one overall visualization
- The method is based on the integration of the thematic mappings drawings in the HBIM, and generation of 3D objects corresponding to various decay areas identified

Step 5 – Structural analysis



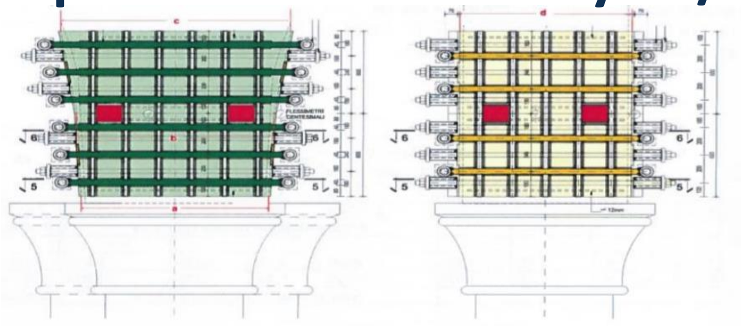




- Starting from the BIM model a set of structural analysis were carried out:
  - Modal analysis;
  - Analysis linear/non linear of the North Facade
  - Analysis of the naves’ column under horizontal action

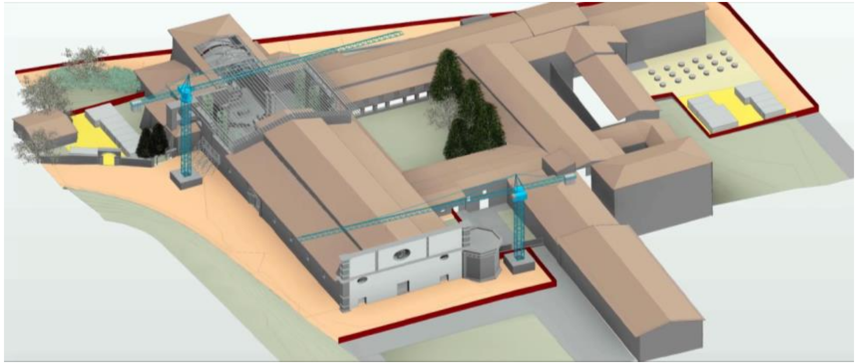
- The aim of those analysis was to design a proper intervention guaranteeing the safety of the church in case of further earthquake

Step 5 – Structural analysis / Columns



- The two lines of octagonal columns suffered deep and large cracks due to the heavy compression experienced during the earthquake
- The aim of the procedure is to disassemble and rebuild the columns without altering the state of stress of the supporting wall
- The necessity of analyzing and restoring the columns, ashlar by ashlar, led to the design of a suspension system able to support the wall's nave on behalf of the column, during its restoration.
- A clamp is assembled just above the stone capital, in order to clamp the end of the two arches converging in the column

Step 6 – The work planning and the construction site



- The economic management required a WBS for the evaluation of the cost of the restoration during the planning phase along with a continuous check to monitor the intervention. This step was based on the subdivision of the Revit© model according to the different restoration actions by using the different structural and decorative elements of the building

- Similarly the construction yard were planned and monitored using the BIM model

Step 7 – Reopening of the Church

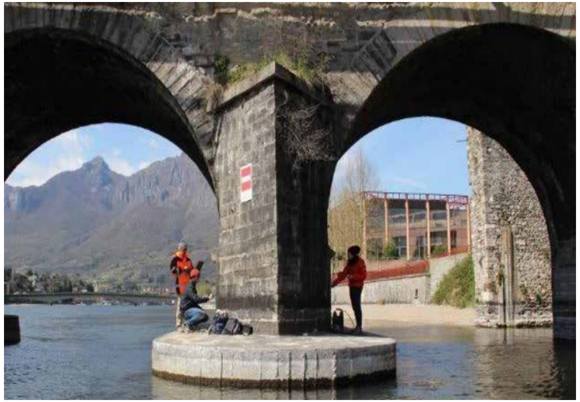
The consolidation aimed at preserving the constituent elements of the pillars (stone ashlars) as much as possible using two different types of interventions depending on the damage. The most damaged pillars were completely disassembled and replaced with provisional structures that allowed the temporary suspension of the masonry above them, and reconstruction through the replacement of the ashlars that no longer demonstrated having mechanical characteristics considered suitable.

Step 7 – Reopening of the Church

The pillars were entirely rebuilt with a reinforced concrete frame covered with stone facing and reassembled with recovered stones, along with the new triumphal arch, creating a highly resistant element that can adequately absorb the stresses of any future earthquakes. The new roofing has main warped wood and secondary, visible warped wood in the central part which extends the visual continuity with that of the nave, while the barrel vaults were restored in the side braces.

PONTE AZZONE VISCONTI (LECCO- ITALY)




PONTE AZZONE VISCONTI (LECCO- ITALY)

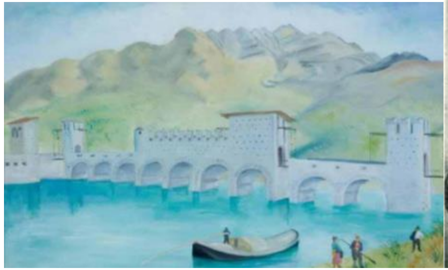
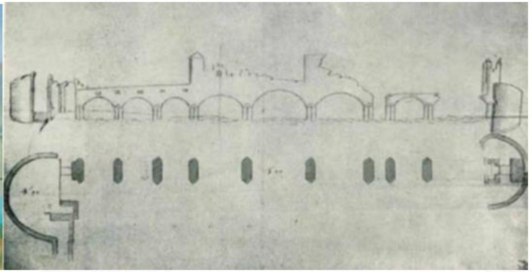
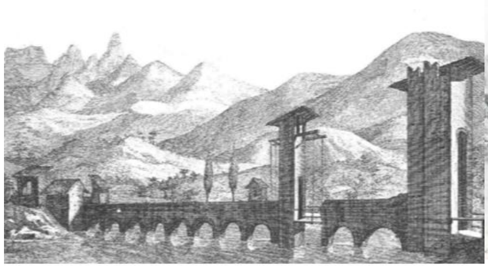
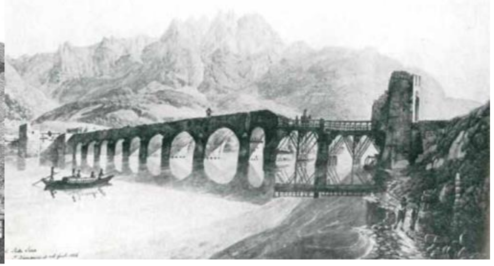
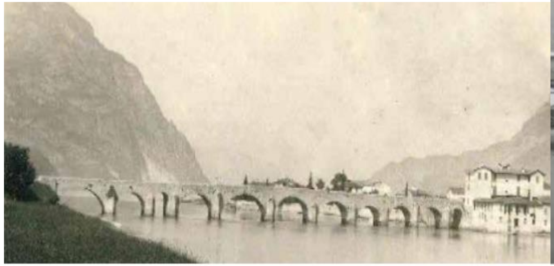
- Masonry arch bridge (**realized** by the wish of the Lord of Milan, Azzone Visconti, **between 1336 and 1338**)
- It has been for centuries (until 1955) the unique road connection between the two banks of Adda river
- It is still an important access road to the town of Lecco
- **Heavy vehicle traffic** on the bridge, so the Municipality of Lecco asked for an extensive research activity involving several disciplines, with the aim of **investigating the bearing capacity** of the bridge

⇒ Many **different experts** are working together in the project: engineers, geologists, architects, restores, and historians

⇒ A proper methodology was needed in order to work as a **"live" repository** of information on the bridge

⇒ An **HBIM** process was developed to integrate information coming from different expertise

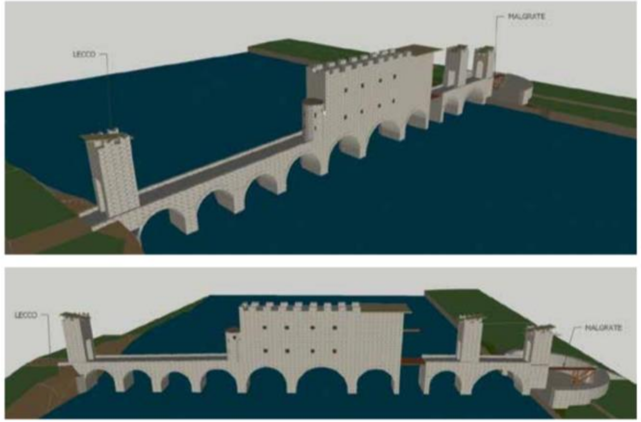
Step 1 – the Historical analyis

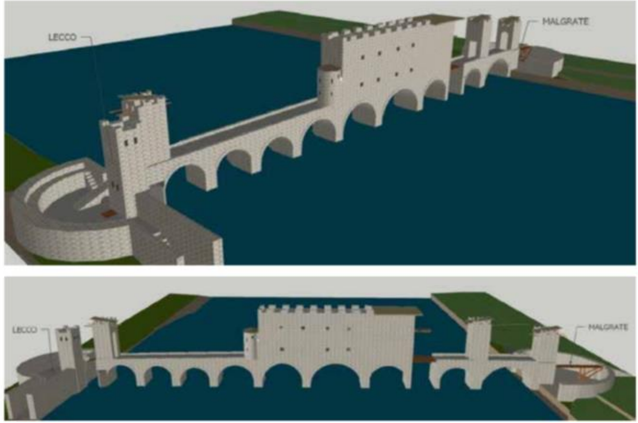

- Realized by the wish of the Lord of Milan, Azzone Visconti, between 1336 and 1338
- The bridge was later expanded into two steps (1350 and 1434) up to 11 arches to enlarge the river cross section
- The last two arches on the right side (connecting to Milan) were demolished in 1800 during the Franco-Austrian conflict
- At the beginning of the 20th century (1909–1910) the existing deck was enlarged
- In 1959 important strengthening interventions were realized

1338

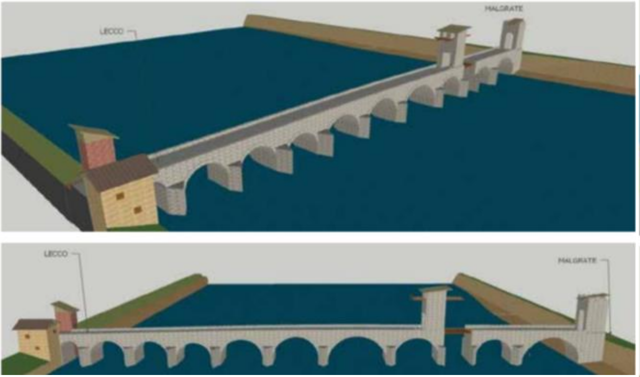
1354



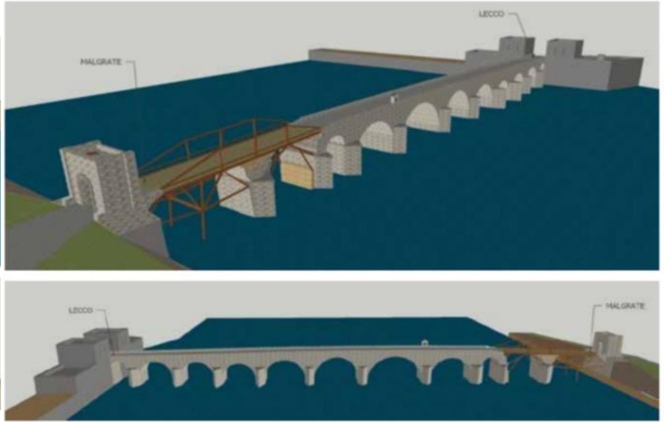
1434



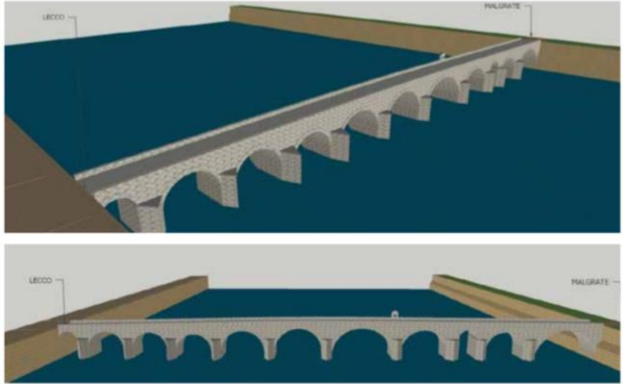
1780



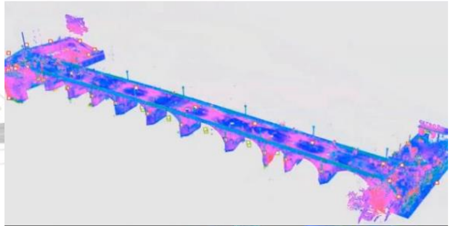
1806

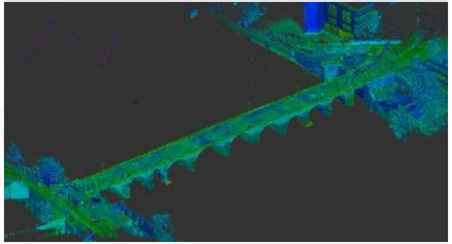


1900



Step 1 – Survey

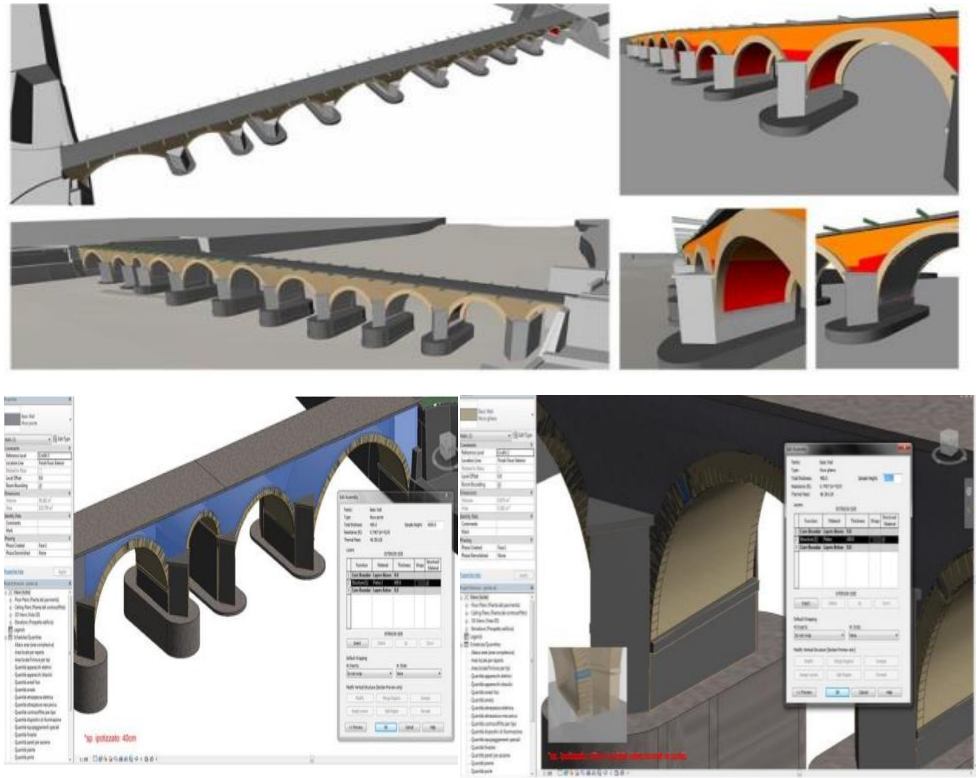




- Data were registered in a stable reference system given by a geodetic network measured with a Leica TS30. The network is made up of 6 stations and the measurement phase took one day

- 77 scans registered with the geodetic network. The instrument is a Faro Focus 3D and the final point cloud is made up of 2.5 billion points. The instrument was placed in different positions, including the road and the riverbanks. The survey of the vaults required the creation of a mobile metal structure that allowed one to capture the intrados

Step 2 – Parametric Modelling

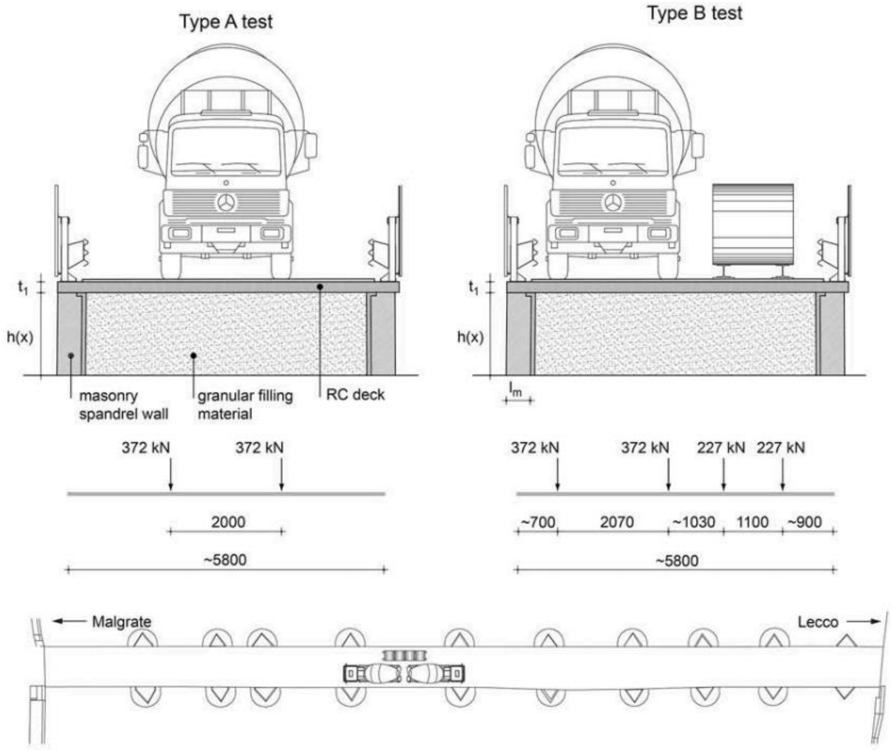


- The 3D model of the Basilica is carried out combining pure modelling tools (Rhino) and free-form complex shapes (NURBS) and parametric tools (Revit)

- Rhino shapes are converted into BIM parametric elements in order to obtain a complete parametric conversion of all the elements without losing information

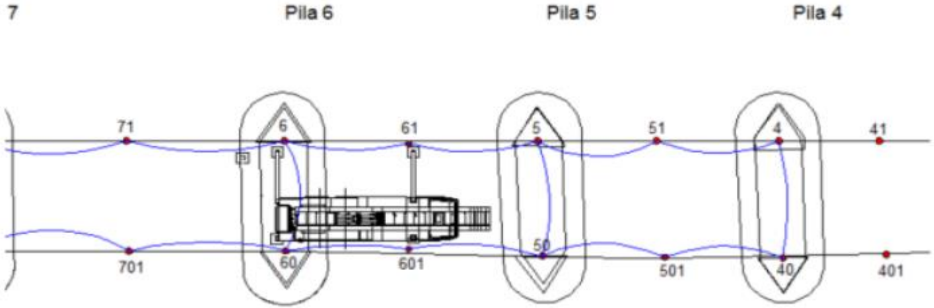
- This process allows an accurate geometric representation of the external shape surveyed with laser scanning technology and photogrammetry

Step 3 – Bridge load tests



- The load tests were designed looking to the provisions of the Italian Technical Regulations for Construction (NTC, 2008), for a first class bridge
- Application of about 1200 kN by means of truck mixers and steel coils on arch 7
- Application of about 750 kN by means of two truck mixers on arches 2, 4, 5, 6, 7, 8, 10, and 11
- The truck mixers were positioned along a lane as prescribed by the Italian code

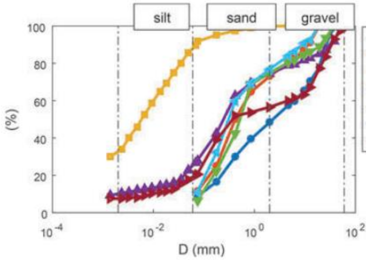
Step 3 – Bridge load tests / monitoring



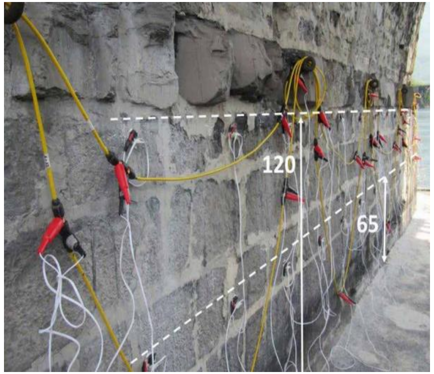
- Monitor vertical displacement under the testing and verify they were compatible with predicted ones
- A geometric leveling was established to monitor vertical movements of a set of points over the bridge during its testing phase
- The precision of heights (after least squares adjustment) was about ±0.15 mm for all tests carried out with different load conditions

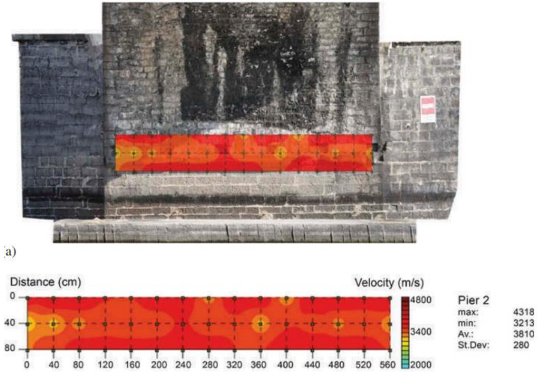
Step 4 – Mechanical characterization





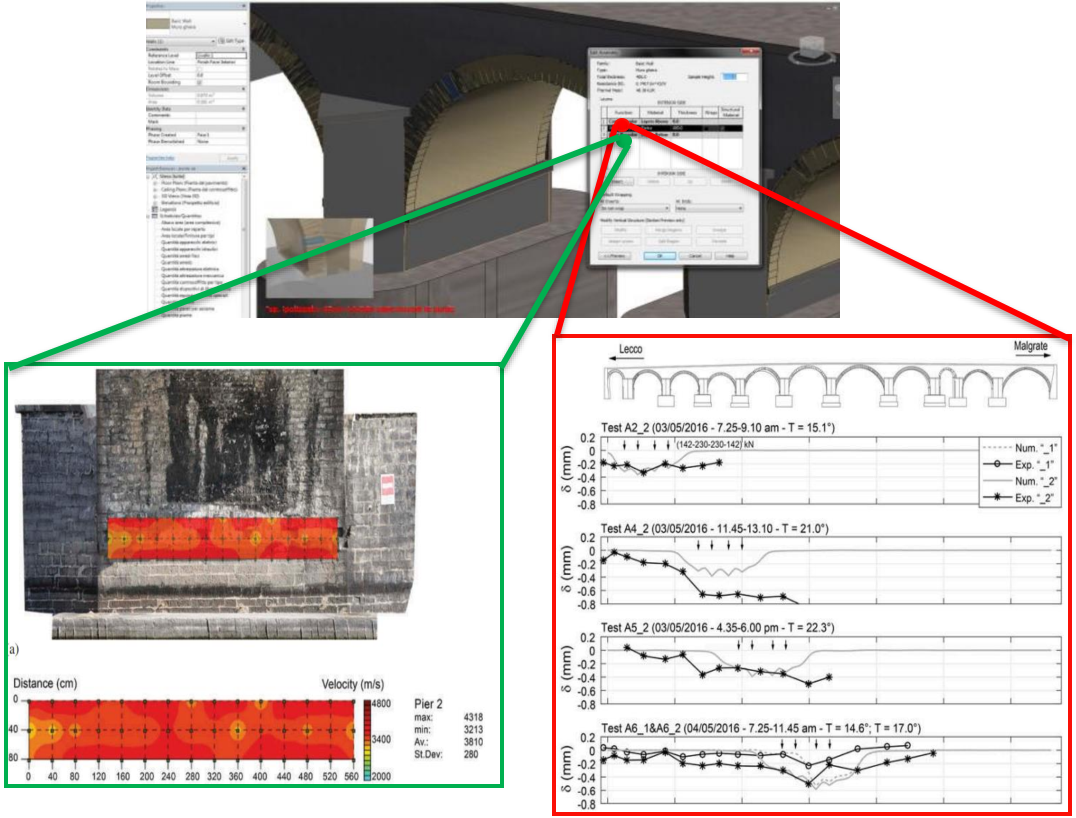
- One vertical core was drilled in piers 6, 7, 8, 9, and 10 in order to get a direct inspection of the internal filling of the piers and to investigate even the underlying riverbed





- Sonic tests were carried out on piers 2, 3, 6, 7, and 8 with the aim of investigating the mechanical characteristics and the stratigraphy of the piers in their lower part

BIMonitoring

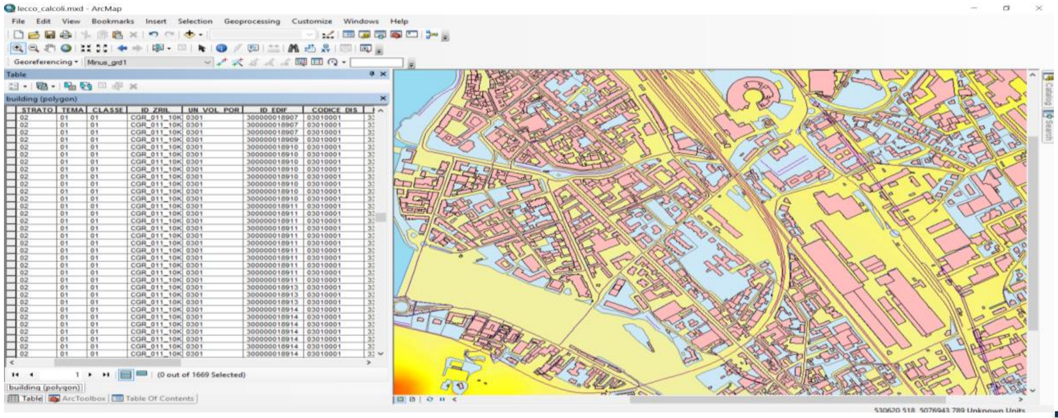


- Different numerical and graphical results were available thanks to the contribution of different specialists: displacements measured during the loading phase to assess the load capacity of the bridge, sonic tests data, coring, and mechanical characterization of specimens

- This kind of information can be directly correlated to 3D information and can be stored in different ways in the BIM, also including links to reports, images, files, etc...

BIM:
Building Information Modeling

GIS:
Geographic Information System

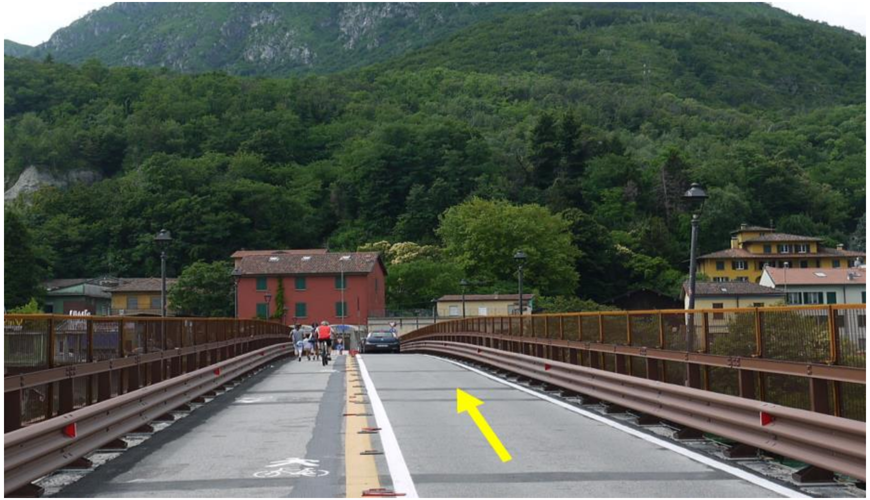


Objects (2D/3D)
+
Relatioships
+
Database

Influences on car traffic with one or two lanes of traffic

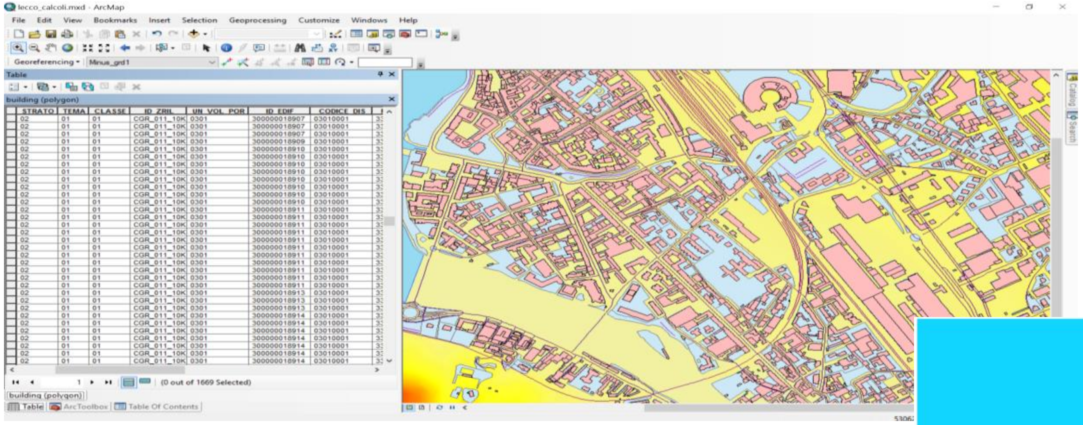
Two lines

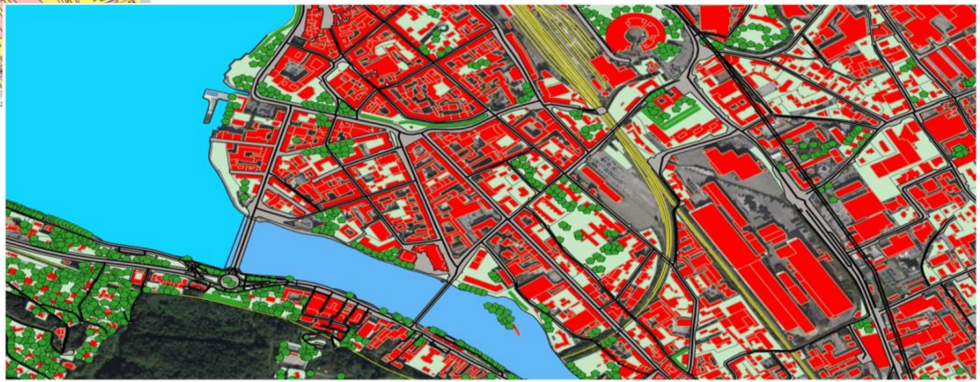
One line



Barazzetti, L., & Banfi, F. (2017). BIM and GIS: WHEN PARAMETRIC MODELING MEETS GEOSPATIAL DATA. *ISPRS ANNALS OF THE PHOTOGRAMMETRY, REMOTE SENSING AND SPATIAL INFORMATION SCIENCES*, *4*(5W1), 1-8.

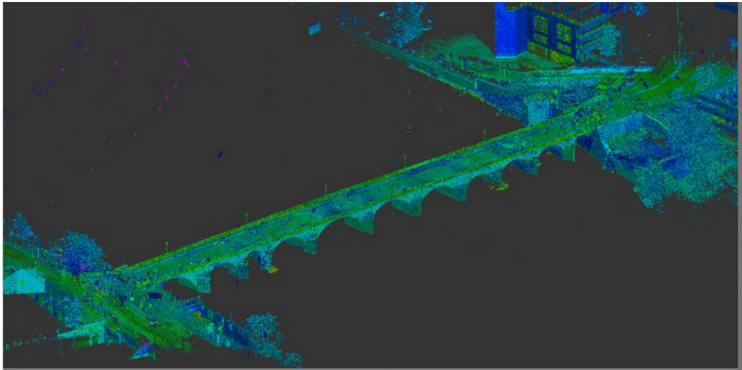
- GIS data (DBT city of Lecco):
  - buildings, roads, railways, rivers and lakes
  - most of the buildings have an approximate height and the roof is modeled with a flat surface

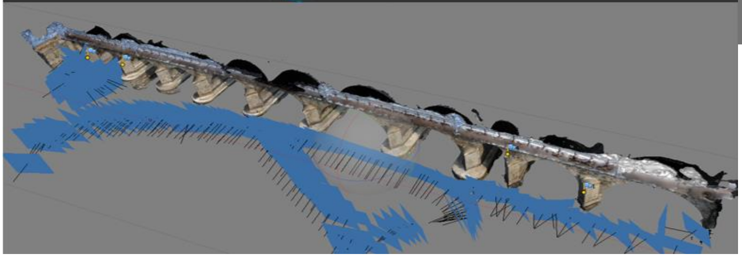


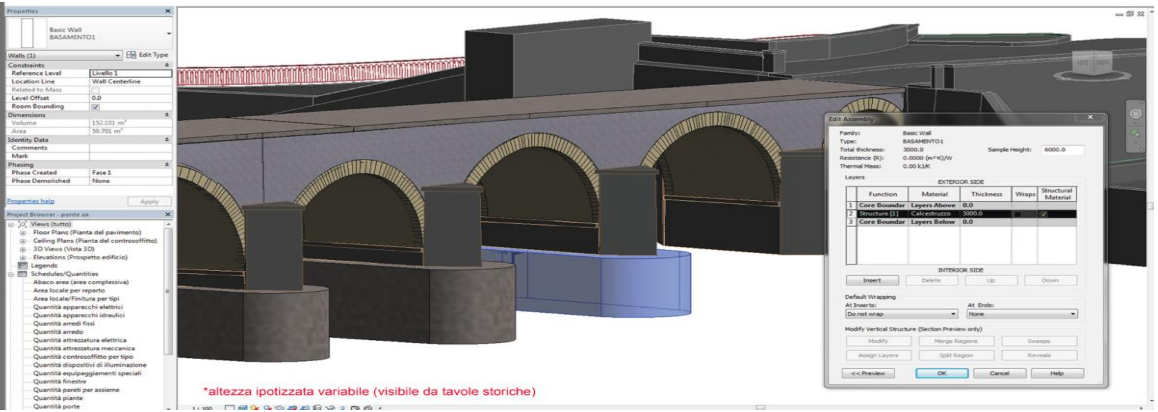


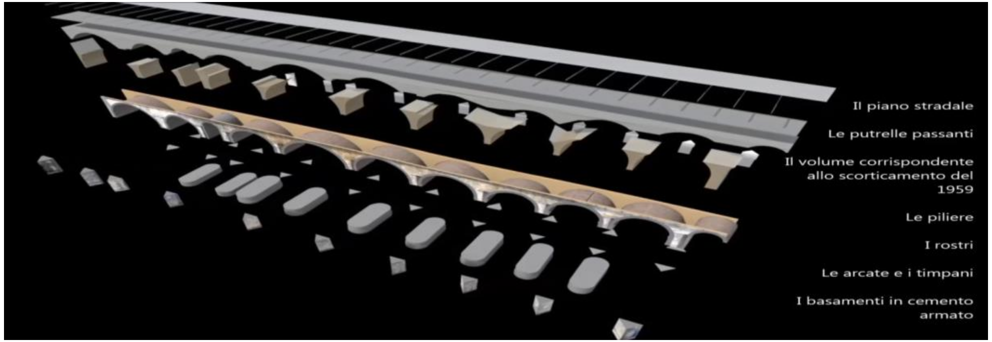
Barazzetti, L., & Banfi, F. (2017). BIM and GIS: WHEN PARAMETRIC MODELING MEETS GEOSPATIAL DATA. *ISPRS ANNALS OF THE PHOTOGRAMMETRY, REMOTE SENSING AND SPATIAL INFORMATION SCIENCES*, *4*(5W1), 1-8.

- BIM data
  - BIM model of Azzone Visconti Bridge









Barazzetti, L., & Banfi, F. (2017). BIM and GIS: WHEN PARAMETRIC MODELING MEETS GEOSPATIAL DATA. *ISPRS ANNALS OF THE PHOTOGRAMMETRY, REMOTE SENSING AND SPATIAL INFORMATION SCIENCES*, *4*(5W1), 1-8.

- GIS data (DBT city of Lecco):
    - buildings, roads, railways, rivers and lakes
    - most of the buildings have an approximate height and the roof is modeled with a flat surface
- BIM data:
    - Ponte Azzone Visconti model (scale 1:50)
- Target:
    - Simulation of traffic in transit on the bridge

- Traffic simulation:
  - Two lanes
  - A lane
- BIM-GIS integration:
  - the BIM-GIS integration is fundamental to perform an accurate analysis that takes into account the actual boundary conditions (accessibility to the bridge, traffic lights, one-way directions, etc.) not present in the original BIM model of the bridge alone

OPEN DATA HUB FOR HBIM MODELS

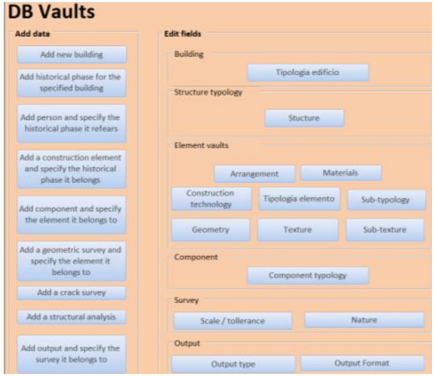
- Different HBIM models are generally not connected one to the other
- Low accessibility to a large public and lack of connection to other similar projects
- Put together information coming from different HBIM processes may reveal unexpected correlation (e.g., similar constructive technologies in different geographical areas)
- Privacy issues should be taken into account

⇒ An **Open Data Hub for HBIMs** has been conceived in order to publish and access the gained information within a geographic domain where to **meet different data sources** and **perform** different **searches**

⇒ A **“live” repository** of information fed with a crowdsourcing approach

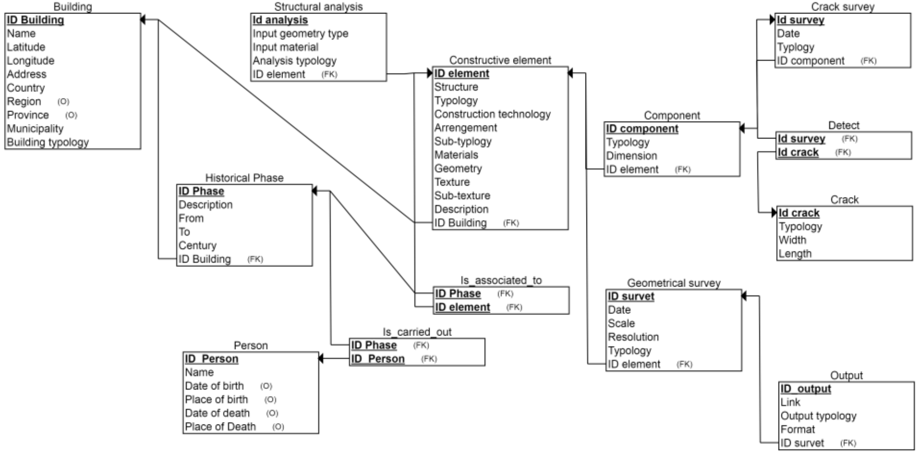
⇒ An **open updatable system** that can contribute to share information increasing knowledge and rising awareness

Step 1 – Vault Database



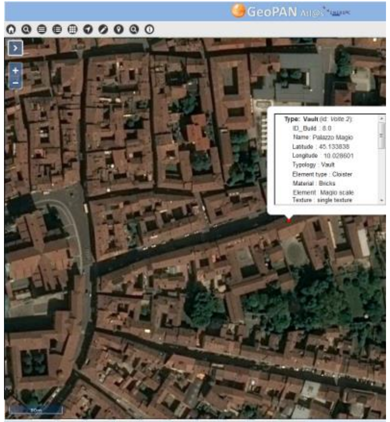
Vault Typology (construction technology)

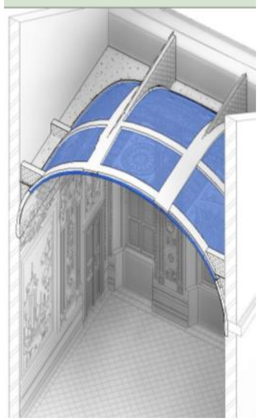
Arch and Vault	Other
Barrel	Pavillion on circular plan
Cloister	Pendentive Dome
Cloister-to Dome	Planterian
Cloister-to Trompe	Sail-Dome
Pavillion	Sail-Dome-to-Cloister
False Vault	…
Wooden Vault	
Groin	

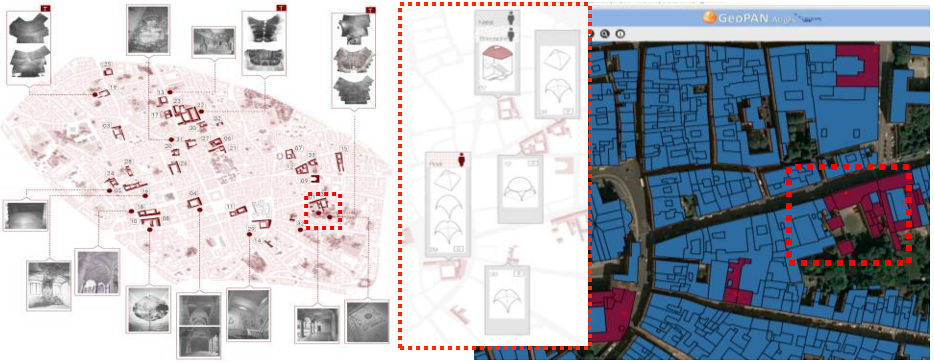


- Database of Vault typologies
- Definition of nine main entities (e.g., Building Element , Historical Phase , Constructive element, Component, 3D model, etc…)
- Conceptual model of the database is provided in the form of an Entity Relationship Diagram (ERD)
- Definition of a Vocabulary defining elements in the Data Base

Step 2 – Open GeoDB







- The database was then connected with a geographic server (GeoServer)
- Visualization of produced data through the use of OGC standards like Web Map Service (WMS, WMTS and WCS)
- Data query and analysis using the Common Query Language (CQL)
- Web link to BIM web published resources (e.g. .rte REVIT, A360 Autodesk Platform, etc.)

Conclusions:

- HBIM proved as a powerful tool for Cultural Built Heritage documentation / preservation / management
- Possibility to merge free-form and parametric modelling
- HBIM can be a meeting place among different expertise
- Interoperability plays an important role in BIM applications

Challenges:

- Improve interoperability between tools
- BIM / GIS integration not fully solved
- Definition of Open Standards for data exchange / publication on the web
- Need to define specific «user defined views» of the HBIM model

2nd INTERNATIONAL CONFERENCE OF GEOMATICS AND RESTORATION

GeoRes 2019 – www.geores19.polimi.it/

Milan, Italy (8 – 10 May 2019)

Abstract submission: 11 Gennaio 2019

Thank you for your attention !