



**UNIVERSITÀ  
DI PARMA**

UNIVERSITÀ DI PARMA

Dottorato di ricerca in Ingegneria Civile e Architettura

Ciclo XXX

# From survey to analysis for Cultural Heritage management: a new proposal for database design in BIM

Coordinatore: Chiar.mo Prof. Andrea Carpinteri

Relatore: Chiar.mo Prof. Riccardo Roncella

Tutor: Chiar.ma Prof.ssa Cristiana Achille

Chiar.mo Prof. Andrea Zerbi

Dottoranda : Nazarena Bruno

Anni 2014/2017



*A mio fratello Michele  
regalo unico e prezioso della mia vita*



# Table of contents

## Introduction

XVII

## SECTION I

### From 3D model to information management: state of the art and literary review

<b>1. The Building Information Modelling (BIM)</b>	<b>1</b>
1.1. BIM definition	2
1.2. BIM methodology	5
1.2.1. Maturity levels	8
1.2.2. BIM documents	10
1.3. Data management with BIM: potentials and limits	12
1.4. The use of BIM worldwide	19
1.5. Towards a common legislation	21
1.5.1. The ISO standards	21
1.5.2. European legislation	25
1.5.3. LOD definition	27
1.5.4. Level Of Accuracy (LOA)	32
1.6. Interoperability	34
1.6.1. IFC	35
1.6.2. COBie	38
1.6.3. gbXML	40
1.6.4. The actual interoperability degree	41
1.7. The BIM adoption in Italy	42
1.7.1. UNI 11337	44
1.7.2. INNOVance	49
1.8. BIM tools	51
<b>2. Historic BIM for Cultural Heritage documentation</b>	<b>55</b>
2.1. Importance of HBIM for Cultural Heritage documentation	56
2.2. State of the art: methodologies and technologies	59
2.2.1. Geometric survey and data elaboration	61

2.2.2. 3D modelling	63
2.2.3. Semantic enrichment and database design	70
2.3. Open questions in Cultural Heritage application	71
2.3.1. Survey and data management	73
2.3.2. Semantic classification: shared vocabularies and object libraries	76
2.3.3. Parametrization of complex 3D objects	79
2.3.4. Modelling of irregularities	81
2.3.5. Database structuring and data sharing	83

## SECTION II

### The HBIM application for Cultural Heritage management: the case study of Parma Cathedral

<b>3. Research overview</b>	<b>91</b>
3.1. Materials and methods: the HBIM as Information System	91
3.2. Regulations on Cultural Heritage safeguarding	94
3.3. Application to a real case study: Parma Cathedral	96
3.3.1. Historical and architectural features	96
3.3.2. The history of restorations and actual problems	99
<b>4. Integrated survey</b>	<b>105</b>
4.1. Methodology: multi-resolution and scalability	105
4.2. Integrated survey campaign	108
4.2.1. Topographical survey	108
4.2.2. Laser scanner survey	111
4.2.3. Photogrammetric survey	115
4.2.4. Survey validation	119
4.2.5. Photogrammetric survey of details	124
<b>5. 3D Modelling</b>	<b>131</b>
5.1. Methodology and technical choices	131
5.2. Semantic classification	134
5.3. Data processing	139
5.4. Parametric modelling of repeated objects: examples	141

5.5. Strategies for irregular shape modelling: examples	146
5.6. 2D and 3D mapping	154
5.7. Model validation and Level of Accuracy	157
<b>6. The HBIM application</b>	<b>161</b>
6.1. Database design	162
6.1.1. Reasons for an ad-hoc database for Cultural Heritage	163
6.1.2. Database requirements and data analysis for Parma Cathedral	166
6.1.3. Database design: conceptual and logical models	170
6.2. Technologies and software adopted	185
6.2.1. .NET Framework	185
6.2.2. SQL Server, Entity Framework Technology and Asp.NET	187
6.2.3. WPF controls	190
6.3. Integration with Autodesk Revit	193
6.3.1. Database connection	195
6.3.2. Get element information and data entry	196
6.3.2.1. General information form	199
6.3.2.2. Problem form	205
6.3.2.3. Damage form	208
6.3.2.4. Intervention form	211
6.3.2.5. Survey and model metadata forms	214
6.3.3. Queries and thematic visualization	217
6.3.4. 3D mapping starting from 2D orthophotos	222
6.3.5. Survey metadata entry	226
6.4. Data sharing and application usability	229
6.4.1. Web application characteristics and functionalities	229
6.4.2. Mobile application implementation	231
<b>Conclusions</b>	<b>237</b>

## APPENDIX A

### The use of BIM worldwide

A.1. Scandinavian countries: Norway, Denmark, Sweden and Finland	243
A.2. The United Kingdom	246
A.3. Other European Countries	250

---

A.4. The United States	252
A.5. Canada	255
A.6. Australia	256
A.7. The BIM adoption in Asia	258

## APPENDIX B

### Survey instruments technical references

B.1. Leica C10 Scan Station	263
B.2. Topcon Image Station IS203	265
B.3. Leica GPS1200 - GX1230 GG	267
B.4. Nikon D3x digital camera	269
B.5. SenseFly Albris drone	271

## APPENDIX C

### Data entered in the database

C.1. Semantic classification of the elements	279
C.2. Problem list and description	284

<b>Bibliography</b>	289
---------------------	-----

---

# List of figures

Page 6	Figure 1. Relation between data and methodology. Model made by Brian Barbini and Stefano Gagliardotto. From: [222]
8	Figure 2. Comparison between traditional delivery method and IPD method. From: [9]
9	Figure 3. Bew-Richards "BIM Wedge" Maturity Model. From: [34].
11	Figure 4. Diagram representing the information cycle in the BIM environment according to regulations PAS 1192-2: 2013. It represents the information cycle and should be read from the top right. From [48].
14	Figure 5. The bar charts show the impact of the use of BIM on some key points of the construction process. The research was conducted by Dodge Data & Analytics on 23 construction projects of complex buildings. [112]
16	Figure 6. Limits in the use of BIM. SmartMarket Brief: BIM Advancements No. 1 [113]. The graph combines frequency and negative impact of factors that impede BIM success on projects.
17	Figure 7. The MacLeamy Curve comparing the efforts and resources required for the traditional design process with those determined by the BIM approach.
18	Figure 8. SWOT analysis of the BIM process. Personal elaboration according to [223].
20	Figure 9. Level of BIM adoption in selected countries. Personal elaboration based on the data provided by [216],[217],[182] and [184].
20	Figure 10. Percentage of contractors at High/Very High BIM implementation Levels (by Country). Form: [185].
21	Figure 11. Future use of BIM. From: [207]
22	Figure 12. Graphic summary of the level of BIM adoption and of the informce regulation worldwide.
26	Figure 13. Member States of the EU BIM Task Group. From: [128]
28	Figure 14. Comparison of LOD cclassification systems in the various standards [63].
30	Figure 15. Graphical illustration of Level of Development classification [[241].
31	Figure 16. Classification of Detail Level (GRADE) based on AEC (UK) BIM Protocol v. 2.0.
33	Figure 17. The LOA classification provided by USIBD.
33	Figure 18. Example template for assigning LOAs to elements, highlighting Suggested, Accepted or Special values [297].
36	Figure 19. IFC Technical principles. [73]
37	Figure 20. IFC Data architecture with conceptual layers [162]
39	Figure 21. Organisation of data in COBie format. Image taken from Strategy Paper for the Government Construction Client Group From the BIM Industry Working Group – March 2011 [3].

- 41 Figure 22. NBS National Report 2015 and 2016. [217][218].
- 43 Figure 23. Level of BIM adoption in Italy. Comparison between Italian Report 2015 and Italian Report 2016. Personal elaboration based on [15][161][236].
- 46 Figure 24. On the top the Information process of construction, on the bottom the Information organization of the work according to UNI 11337-1.
- 48 Figure 25. Example of LOD of a wall. UNI 11337-4
- 50 Figure 26. Informative flow from construction product and building. Image from [235].
- 57 Figure 27. Numeber of visitors and gross earnings in € at Italian Cultural Heritage sites. From: Statistics office of the Ministry of Cultural Heritage and Tourism (MIBACT), 2016.
- 59 Figure 28. Comparison between the BIM process for new buildings and for existing ones.
- 60 Figure 29. HBIM process conceptual schema. The main issues and contributions of geomatics disciplines are highlighted.
- 61 Figure 30. Typical workflow for survey and data management. Personal elaboration according to literature analysis
- 64 Figure 31. Summarizing table of main modelling techniques and their main classification. a from [90]; b from [180]; c from [103]; d from [116]; and from [245].
- 65 Figure 32. Elements of a mesh surface. From: [239]
- 65 Figure 33. Control vertices in a Nurbs surface. From: [http://www.3dmax-tutorials.com/CV\\_Surface.html](http://www.3dmax-tutorials.com/CV_Surface.html)
- 66 Figure 34. Solids BRep and Solids CSG. From: [http://engineeronadisk.com/notes\\_design/solidsa3.html](http://engineeronadisk.com/notes_design/solidsa3.html)
- 67 Figure 35. Parametric object example.
- 71 Figure 36. Database synchronization with BIM models . From: [181]
- 77 Figure 37. "Morphological cuttings of the analysed object according to two different analyses: the vocabulary of the architect and the construction techniques". From: [103]
- 78 Figure 38. "Four «points of view» on the studied object elaborated starting from the same morphological cutting". From: [103]
- 79 Figure 39. "The instantiation of the primitive: under-constraint deformation of geometrical atoms". From: [103]
- 81 Figure 40. Visual and numerical results of the deviation between laser-scanner point clouds and parametric models of the South Altar using Geomagic Design X. From: [180]
- 82 Figure 41. Automatic procedure for modelling irregular non-vertical walls by Dore et al. [117].
- 82 Figure 42. The mass modelling workflow implemented by Bitelli et al. [56]
- 83 Figure 43. Levels of accuracy for building documentation. [297]
- 85 Figure 44. Semantic qualification of a3D representation in NubesVisum. From: [104].

---

85	Figure 45. The implemented plug-in inside Rhinoceros Nurbs Modeller and the web viewer. From: [136].
86	Figure 46. Web 3D visualization of the building enriched with semantic data. From: [246]
92	Figure 47. HBIM process. For each phase, the main feature to take into account are pointed out.
94	Figure 48. Screenshots of SICaR. Personal elaboration.
97	Figure 49. The Parma Cathedral. From: <a href="http://www.up.aci.it">www.up.aci.it</a>
98	Figure 50. Summary of main works in Parma Cathedral. Sources: [58];[247]; [7]; [152] and [237].
100	Figure 51. Main restoration works (grey) and surveys (blu). Sources: [58];[152]; Archival documents preserved at Sabap [265]-[273]. Personal elaboration. Sabap = Soprintendenza Archeologia Belle Arti e Paesaggio per le province di Parma e Piacenza.
107	Figure 52. Parma Cathedral example views.
109	Figure 53. Topographical network points monographs: examples.
109	Figure 54. Topographical network of traverses.
112	Figure 55. Scan stations configuration.
113	Figure 56. The detail survey design: the figure highlights, for each scan, the area of the building detected with a resolution equal or better than 5 mm.
114	Figure 57. The complete point cloud after registration.
115	Figure 58. Acquisition environment: narrow streets around the Cathedral and many occlusions due to the Cathedral conformation.
117	Figure 59. Imaging geometry of the photogrammetric acquisition.
119	Figure 60. Orthophoto of the Cathedral main façade overlapped to the drawings of the photogrammetric survey made by FOART in 1989. (In the previous page).
120	Figure 61. Map of displacement between two registered point clouds.
121	Figure 62. GCP (red) and Check points (yellow) location on the south facade. (Orthophoto integrated with FOART façade representation).
121	Figure 63. Photoscan report on GCP locations and error estimates.
123	Figure 64. Map of displacement [m] between DSM and laser scanner point cloud.
125	Figure 65. The Giulio-Claudio statuary exhibited in the Archaeological Museum of Parma.
125	Figure 66. The antique decorated bronze exhibited in the Museum of Parma.
126	Figure 67. Typical camera network characterizing the sculptures photogrammetric surveys.
127	Figure 68. Bare 3D models of the statuary.
128	Figure 69. A: the Drunken Hercules ("Ercole Ebbro") statuette. B: Image block geometry for the bronzes surveys. C: Comparison map [mm] between two different reconstructions of the object.

---

132	Figure 70. Diagram of the implemented methodology.
134	Figure 71. Semantic level classification.
135	Figure 72. Functional areas schema.
136	Figure 73. Hierarchical aggregation schema.
137	Figure 74. Semantic classification: Level 3, Level 4 and material classification.
142	Figure 75. Parametric model of the tapered arch window.
143	Figure 76. Parametric model of the tapered window with cornice.
144	Figure 77. Parametric profile of the attic base.
144	Figure 78. a: Columns of the apse loggia. b: parametric model of the loggia's columns.
145	Figure 79. Parametric model of the capital.
145	Figure 80. Parametric model of the decorative element.
146	Figure 81. In place direct modelling of the apse close window.
147	Figure 82. Blending operation for wall modelling.
148	Figure 83. Wall by face (mass element) workflow. (It continues on the next page).
149	Figure 84. Wall by face (NURBS surface). Workflow. (It continues on the next page).
151	Figure 85. Summary of the three tested methodologies.
152	Figure 86. Comparison maps [mm] between the Veleia and Boulogne Hercules.
153	Figure 87. Blender UV-texture mapping process: on the right the 3D model and the identified seams used for subdividing the mesh; on the left the unwrapped UV-maps of each parts.
154	Figure 88. Textured 3D models of the statuary.
156	Figure 89. Example of 2d mapping on orthophoto.
157	Figure 90. GIS mapping process.
159	Figure 91. False colour map of displacement between Revit model and laser scanner point cloud.
165	Figure 92. Hierarchical relationship sample. From: [181]
168	Figure 93. "Problem Form". Form for problem evaluation according to [251].
168	Figure 94. "Damage Form". Form for damage evaluation according to [251].
169	Figure 95. "Program Form". Form for intervention program according to [251].
169	Figure 96. "Inspection Form". Form for collecting data during the inspections, according to [251].
171	Figure 97. Entity-Relationship schema.

---

174	Figure 98. Database structure according to semantic classification.
179	Figure 99. Level of Knowledge according to available information. Table C8A.1.2 [91]
182	Figure 100. Class diagram which represents the survey database structure.
182	Figure 101. Schematic example of a survey process.
184	Figure 102. Relational model of the implemented database. (In the next page).
186	Figure 103. Visual overview of the Common Language Infrastructure (CLI). From: [2]
186	Figure 104. .NET Framework component stack. From: [2]
187	Figure 105. System architecture.
188	Figure 106. Entity Framework scenarios for database interaction. From [125]
189	Figure 107. Implemented class diagram.
190	Figure 108. Diagram of interactions within the MVC pattern. From [193]
192	Figure 109. Data binding schema [304].
193	Figure 110. Direction of the data flow [304].
194	Figure 111. DuomoAddin in Revit ribbon panel.
195	Figure 112. Database List in RevitDBServer.
196	Figure 113. Connect DB workflow.
196	Figure 114. Database connection, ribbon panel action.
197	Figure 115. Get element information workflow.
197	Figure 116. Element information window WPF layout.
200	Figure 117. Database graphical model. The table to which general form refers are highlighted.
201	Figure 118. General information interface.
203	Figure 119. Dialog window for metadata association.
204	Figure 120. "Link element on the model" function workflow.
204	Figure 121. "Add file to element" function workflow.
205	Figure 122. "Show file preview" function workflow.
206	Figure 123. Database graphical model. The table to which problem form refers are highlighted.
207	Figure 124. Problem Form interface.
208	Figure 125. "Change problem db context" workflow.
209	Figure 126. Database graphical model. The table to which damage form refers are highlighted.

---

210	Figure 127. Damage form interface.
212	Figure 128. Database graphical model. The table to which intervention form refers are highlighted.
213	Figure 129. Conservation Intervention form interface.
215	Figure 130. Database graphical model. The table to which Metadata refers are highlighted.
217	Figure 131. Model Metadata Form. (In the previous page).
217	Figure 132. Survey metadata form. (In the previous page).
218	Figure 133. Query and theme interface.
219	Figure 134. The use of query builder for selecting the elements to query.
219	Figure 135. The use of query builder for defining the conditions of the query.
220	Figure 136. The answer to the query in the DataGrid.
221	Figure 137. Theme interface and and example of model thematic mapping.
222	Figure 138. "Create Parts" and "Divide Parts" Revit tools example. a. Original wall, b. Wall divided into parts after "create Parts" command, c. Wall with a part divided into sub parts after "Divide Parts" command.
223	Figure 139. "Create parts" function workflow. Orange text boxes refer to the actions performed by the user.
224	Figure 140. Image Reference System.
225	Figure 141. Example of 3D mapping created.
226	Figure 142. Survey metadata entry implemented interface.
227	Figure 143. Add survey data interface.
227	Figure 144. Add instrument interface.
227	Figure 145. Add process interface.
228	Figure 146. Data entered into the interface.
228	Figure 147. The Figure shows the information associated to the selected item (in this case the Process "Dati per Calge" and the highlighted nodes connected to it.
230	Figure 148. Implemented web interface.
233	Figure 149. From top left to right down: 3d model viewer, Google Cardboard VR, Holographic view, AR visualization.
234	Figure 150. Interactive map for the virtual tour of Parma.
235	Figure 151. Panoramic view examples.

# List of tables

Page 8	Table 1. Comparison between the traditional and the BIM work methodologies. Personal elaboration..
16	Table 2. Advantages of using BIM for the different actors involved. [33]
44	Table 3. The eight different parts of the UNI 11337.
47	Table 4. The 7 LOD degrees defined by the Italian UNI 11337.
110	Table 5. Horizontal coordinates network adjustment stats.
110	Table 6. Altimetric coordinates network adjustment stats.
112	Table 7. Maximum admissible distances from the object in order to ensure 5 mm resolution, according to the C10 Scan Station performance.
116	Table 8. GSD variability.
119	Table 9. Residuals of the scan registration on the basis of the topographical network.
120	Table 10. Stats on the deviation between two registered point clouds.
122	Table 11. Check points residuals.
123	Table 12. Stats on the deviation between DSM and laser scanner point cloud.
124	Table 13. Stats on the deviation between DSM and laser scanner point cloud, focusing on the side chapels area and on the upper part of the transept.
167	Table 14. Principal data required by BPCM 9 February 2011. Personal elaboration.
172	Table 15. BIM Element Entity.
172	Table 16. General Info Entity. Grey data are common for all semantic levels, orange data refer to architectural element, green data refer to building.
173	Table 17. Material Entity
173	Table 18. Owner Entity.
173	Table 19. Semantic Levels Entity.
173	Table 20. Element Class Entity.
173	Table 21. Element SubClass Entity.
174	Table 22. Soil Structure Entity.
174	Table 23. Problem Entity.
175	Table 24. Problem Class Entity.

---

175	Table 25. Anomaly Entity.
175	Table 26. Inspection Entity.
176	Table 27. Action Entity.
176	Table 28. Damage Entity.
176	Table 29. Conservation Intervention Entity.
177	Table 30. Work Entity.
177	Table 31. File Entity. In Grey common data, in Orange data referred to raster files and in Green data about files that are survey data.
177	Table 32. Polygon Entity.
178	Table 33. Model Metadata Entity.
181	Table 34. Personal elaboration of the Level Of Knowledge (LC) classification according to [91].
183	Table 35. Survey Entity.
183	Table 36. SurveyData Entity.
183	Table 37. Process Entity.
183	Table 38. Instrument Entity.

# List of acronyms

AEC	Architecture, Engineering and Construction
AGC	Association of General Contractor
AIA	American Institute of Architects
AIM	Architectural Information Modelling
AMCA	Air Conditioning & Mechanical Contractors' Association
API	Application Programming Interfaces
AR	Augmented Reality
BCA	Building and Construction Authority
BCF	BIM Collaboration Format
BDS	Building Description System
BEP	BIM Execution Plan
BIM	Building Information Modelling
B-Rep	Boundary representation
BS	British Standard
BSDD	buildingSMART Data Dictionary
BSI	British Standards Institution
CAD	Computer-Aided Design
CanBIM	Canada BIM Council
CEN	European Committee for Standardization
CH	Cultural Heritage
CIBSDR	China Institute of Building Standard Design & Research
CIOB	Chartered Institute of Building
CLR	Common Language Runtime
COBie	Construction Operations Building Information Exchange
COBIM	Common BIM Requirements
CoRENet	Construction Real Estate Network
CORS	Continuous Operation Reference Station
CRC	Cooperative Research Centre
CSG	Constructive Solid Geometry
CTS	Common Type System
D.lgs	Decreto legislativo (legislative decree)
DBFMO	Design-Build-Finance-Maintain-Operate

---

DIBS	Danish Digital Building Initiative
DIN	German Standardisation Institute
DLL	Dynamic-link library
DM	Decreto Ministeriale (Ministry Decree)
DPCM	Decreto Presidente del Consiglio dei Ministri
DPR	Decreto Presidente della Repubblica
DRM	Data Relationship Model
EF	Entity Framework Technology
EIR	Employer's Information Requirements
EUPPD	European Union Public Procurement Directive
FC	Fattore di confidenza
FCL	Framework Class Library
FM	Facility Management
gbXML	Green Building Extensive Markup Language
GCP	Ground Control Points
GDL	Geometric Descriptive Language
GIS	Geographic Information System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GSA	United State General Services Administration
GSD	Ground Sampling Distance
GUI	Graphic User Interface
HBIM	Historic Building Information Modelling
HTML	HyperText Markup Language
HVAC	Heating, Ventilation and Air Conditioning
IAI	International Alliance for Interoperability
IBC	Institute for BIM in Canada
ICP	Iterative closest point
ICT	Information & Communication Technologies
ID	Identifier
IDM	Information Delivery Manual
IDM	Information Delivery Manual
IFC	Industry Foundation Classes
IFD	International Framework for Dictionaries
IPD	Integrated Project Delivery
ISO	International Organization for Standardization
ISTAT	Istituto nazionale di statistica
IT	Information Technology

JFCC	Japan Federation of Construction Contractors
LCA	Life Cycle Analysis
LDM	Logical Data Model
LKG	Level of Knowledge – Geometry
LKM	Level of Knowledge – Material
LKS	Level of Knowledge – Structure
LOA	Level of Accuracy
LOD	Level of Development
LOI	Level of Information
LOR	Level of Reliability
lv	Level
MEP	Mechanical, Electrical and Plumbing
MIBACT	Ministero dei beni e delle attività culturali e del turismo
MIDP	Master Information Delivery Plan
MLTM	Ministry of Territory, Transport and Maritime Affairs
MVC	Model-View-Controller
MVD	Model View Definition
NASA	National Aeronautics and Space Administration
NATSPEC	National Specification System
NBIMS	National Building Information Modelling Standard
NBS	National Building Specification
NCB	National Computer Board
NIST	National Institute of Standards and Technology
NURBS	Non-Uniform Rational B-Splines
ORM	Object-Relational Mapper
PAS	Publically Available Specification
PDOP	Position Dilution Of Precision
PPS	Public Procurement Service
PSB	Singapore Productivity and Standards Board
RDBMS	Relational Data Base Management System
RFI	Request For Additional Information
RGB-D	Red Blue Green and Depth
RIBA	Royal Institute of British Architects
RICS	Royal Institution of Chartered Surveyors
RMS	Root Mean Square
RS	Reference System
SABAP	Soprintendenza Archeologia, Belle Arti e Paesaggio
SD	Standard Deviation

---

SDK	Software Development Kit
SICaR	Sistema Informativo per i Cantieri di Restauro
SIS	Swedish Standards Institute
SQL	Structured Query Language
STA	Swedish Transportation Administration
TC	Technical Committee
TLS	Terrestrial Laser Scanner
TOF	Time Of Flight
TS	Total Station
UAS	Unmanned Aerial System
UAV	Unmanned Aerial Vehicle
UI	User Interface
UNI	Ente nazionale italiano di unificazione
URI	Uniform Resource Identifier
USACE	United States Army Corps of Engineers
USIBD	US Institute of Building Documentation
VA	Department of Veterans Affairs
VR	Virtual Reality
w.r.t.	with respect to
WCF	Windows Communication Foundation
WF	Windows Workflow Foundation
WPF	Windows Presentation Foundation
XAML	Extensible Application Markup Language
XDS	XML Defining Schema

---

# Introduction

In recent years, there has been an increasing diffusion of the BIM (Building Information Modelling) methodology, mainly thanks to the introduction of regulations and standards that impose or at least regulate its use. Italy, thanks to the recent publication of the new UNI 11337:2017 standard, is also moving towards a progressive adoption of the BIM in public contracts.

BIM must be considered as a comprehensive methodological approach that allows managing, in a coherent and coordinated way, all phases of a building lifecycle. It is therefore not simply a design tool and can also be applied to existing buildings.

In recent years, in fact, users are gradually starting using BIM also for interventions on existing buildings. However, in the field of Cultural Heritage, the use of BIM is very limited and remains the prerogative of universities and research centres, while in the professional sector it is almost not adopted.

The reasons for this disparity can be traced back to the difficulties involved in setting up a BIM of historic buildings.

The realization of an information system for Cultural Heritage knowledge and preservation has to take into account several aspects that are not relevant in a BIM for new constructions. First of all, the HBIM implementation process is opposite: it starts indeed from the actual object, and not from an ideal design, and arrives at the model, i.e. an abstraction of the reality.

In addition, the time dimension and the lifecycle concept are different. For new buildings, the lifecycle is linear. It starts from the design and, through construction, operation and maintenance phases, goes to the end, represented by the demolition of the building

itself. This lifecycle has a limited duration in time, corresponding to the service life of the building. Conversely, the service life of cultural assets is essentially limitless. The cultural, historical and artistic importance of the asset is so great that it calls for an eternal life of the artefact. The lifecycle, thus, is cyclical because the asset is subject to a periodic and recurring succession of inspections, maintenance, restoration and replacement activities. In addition, the whole history of the building has to be taken into account and added to the information about the building actual state. For these reasons, the time dimension in a Historic BIM is completely different, having to manage several diachronic and multi-temporal information.

Another point of difference is the uniqueness of historic building. Each building is different from the others and has peculiar features and singularities that make it a *unicum*. Trying to devise standard and fixed methodologies is pointless, since, in addition to the general problems and characteristics shared by all the historic assets, each building has its specific features and problems that cannot be dealt with in a standard way. This aspect involves at the same time general features (such as history, construction phases etc.), semantic information and geometric shapes, that are often irregular and/or deformed. Thus, in the Cultural Heritage analysis, standardized approaches are not useful, while general guidelines and flexible/customizable tools are a more effective solution.

Finally, the sharing of building documentation (semantic and geometric data) and information system usability are key points. The conservation actors (restorers, historians, etc.) are not specialists of the AEC industry and are reluctant to use BIM software or databases. Therefore, in order to make HBIM really used in practice, these systems have to be simple and user friendly. In addition, building documentation has to be shared extensively and directed at different categories of users, from the practitioners and restorers to historians and to the entire community of people. In fact, dissemination also plays an important role in promoting Cultural Heritage.

Despite the difficulties mentioned above, the use of BIM for documentation and management of historical buildings would certainly have positive effects. In fact, as shown by literature, BIM greatly simplifies the management of the time factor in building documentation. It makes it possible to handle coherent and coordinated data relating to different time phases, to highlight and separate the different construction phases, as well as to keep track of all the performed or scheduled interventions. It also provides a single access point for all the available data, constituting a sort of unique and searchable archive.

Moreover, BIM offers support for analyses (structural, energetic, cost calculation and so on), thanks to the interoperability with specialized software. Finally, BIM can be used as a promotion tool, exploiting the 3D model and the associated information for promotion and dissemination activities, involving a much broader community of users.

Due to these features, BIM represents an effective tool for supporting scheduled maintenance and conservation activities, which are an increasingly important instrument for safeguard and conservation of Cultural Heritage. Preventing the onset of risk and damage situations helps to limit the invasiveness of restoration interventions and avoid situations of danger for the asset.

Especially in a country rich in historical sites and monuments, such as Italy, investing in research and development of instruments aimed at protecting and preserving Cultural Heritage represents a great opportunity both from a cultural and economic point of view.

In this context, the implementation of a BIM for historical building documentation can be a big challenge but, at the same time, a technological improvement that enables a better and deeper knowledge of these assets. The hope is that, in the near future, the use of this technology in the Cultural Heritage field will improve, contributing to the solution of the many problems still present.

The thesis project led to the realization of a HBIM application aimed at restoration and maintenance of historic buildings. The system presented here, thanks to a specific database, compliant with the currently in force Italian regulations, allows storing and querying the data necessary for the description of historical buildings. The application has been conceived as standalone but it can be integrated into main BIM software (at the moment the experimentation has been limited to Autodesk Revit) and consulted via a web interface.

In its implementation, the main aspects related to survey, modelling and database design have been addressed, identifying central features and problems and trying to give an original contribution with regard to some outstanding issues.

Database design and system usability, in particular, have been the most investigated aspects. In fact, if the themes related to surveying and modelling are widely investigated in literature, there are still few studies concerning the organization of semantic data, system usability and data sharing.

The thesis is organized as follows. Chapter 1 will address the birth, development and use of BIM methodology from a general point of view, analysing the specific regulations

in this regard and the real level of application. Chapter 2 will instead focus on the specific use of BIM for Cultural Heritage, which is an innovative and still underdeveloped research field.

The second part of the thesis is focused on the description of the developed HBIM application for the Parma Cathedral. Chapter 3 will refer to the general methodology adopted and describe the case study, the problems it presents and the reasons for its choice. In Chapter 4, the issues relating to the integrated survey performed and the procedures for its validation will be dealt with. An excursus will be presented in Chapter 5 about the modelling techniques adopted for the HBIM realization and the difficulties related to the accurate modelling of complex and deformed geometries. Finally, Chapter 6 will describe the implemented application, the database design and the development of additional features with respect to the ones offered by traditional commercial BIM software. In the same chapter, system integration with Autodesk Revit and web applications will be also described







# SECTION I

From 3D model to information  
management: state of the art and  
literary review



# The Building Information Modelling (BIM)

In the history of architecture and engineering, activities such as design, survey or analysis have taken advantage of instruments for representing and describing the reality. Both in the transition from a design idea to a built building or, on the contrary, from an actual building to its in-depth analysis, reality is too complex to be described as-it-is and needs to be simplified, decomposed, schematized, in other words, modelled.

The model (from the Latin *modellus*, *modulus* diminutive) is precisely an abstraction of reality, a simplified representation derived from the identification of rules and norms that represent the essence of reality. A correct model does not distort the reality, but recognizes its characteristics and includes rules, by which reality can be represented with different degrees of simplification.

In the architectural field, the model has almost always been considered a scaled-down and simplified geometric representation of the building. This conception derives from ancient legacies related to the custom of making models with clay, wax or, predominantly, wood, in order to prefigure the shape of the building under construction. It is the case of Renaissance Brunelleschi's models for the dome of Santa Maria del Fiore in Florence or Michelangelo's models for the St. Peter's Cathedral in Rome. These models accompanied the two-dimensional paper drawings and provided a more immediate representation of the designed architecture in the three dimensions.

The architecture had been described through traditional two-dimensional drawings (plants, elevations and sections) accompanied by three-dimensional plastic models until the 1970s, when the progressive development of personal computers led to the replacement of traditional manual design with computer aided design (CAD). The

increasing development of these tools makes possible today the 3D digital modelling of any shape and size [142].

If the model is considered in a wide sense, i.e. as an abstraction of reality, not only the geometric features but even the semantic ones have to be considered. In this context, to take into account all the information that describes a building, it is necessary to produce and link to the geometric model many textual, thematic and descriptive data. The capability to archive, analyse, visualize and query semantic data associated with geometric elements in a coherent and coordinated way, facilitates and improves knowledge of the building.

This is the logic behind information systems, which can be applied at different scales: from the territorial, to the building, up to the single object. At the architectural scale, an example of information system, which is becoming more and more popular today, is the Building Information Modelling (BIM).

BIM allows the interrelated and consistent management of all data about a building (drawings, survey data, documents, images, analyses) during its lifecycle. The use of BIM is indeed advisable in design, management and maintenance phases and is acquiring great importance also in the management and preservation of historic buildings.

The chapter will deal with BIM diffusion and application based on a literary review. In particular, it will address the birth, development and use of BIM methodology, analysing the specific regulations in this regard and the real level of application.

## 1.1. BIM definition

---

The origin of BIM is commonly attributed to Charles Eastman and to some other researchers at Carnegie-Mellon University in Pittsburgh (USA) that in 1974 developed what they called the Building Description System (BDS) [121], i.e. a software capable of:

*"... interactively defining elements... deriv[ing] sections, plans, isometrics or perspectives from the same description of elements... Any change of arrangement would have to be made only once for all future drawings to be updated. All drawings derived from the same arrangement of elements would automatically be consistent... any type of quantitative analysis could be coupled directly to the description.... cost estimating or material quantities could be easily generated... providing a single integrated database for*

*visual and quantitative analyses... automated building code checking in city hall or the architect's office. Contractors of large projects may find this representation advantageous for scheduling and materials ordering." [122]*

With this paper, Eastman introduced the system known today as BIM (Building Information Modelling or Building Information Model), which today seems to represent the future for the architecture, engineering and construction industry (AEC industry), changing the way of designing, constructing and managing the building.

Despite the increasing diffusion of the BIM, there is still confusion on what the BIM is and what its functions and purposes are. To clarify what it is and to define the direction that will be followed in this thesis, some definitions are reported below, distinguishing, in particular, between the BIM as a process (Modelling) and the BIM as an object (Model).

**BIM as a process: Building Information Modelling/Modeling.** It represents all the actions performed during the whole building lifecycle by the stakeholders involved [222]. These definitions are provided by the main international institutions for BIM standardization. The emphasis is mainly on the concepts of "digital model", "accurate and reliable definition of reality", "information sharing", "support for decision", "integrated process", "building life cycle management" and "collaborative work". These are the key concepts of the BIM methodology and the most innovative aspects that, as shown in the following paragraphs, will lead to an increasing BIM adoption and development.

*Shared digital representation of physical and functional characteristics of any built object [...] which forms a reliable basis for decisions. [ISO standard, ISO 29481-1:2010(E)]*

*Building Information Modeling (BIM) is one of the most promising developments in the architecture, engineering and construction (AEC) industries. With BIM technology, an accurate virtual model of a building is constructed digitally. When completed, the computer - generated model contains precise geometry and relevant data needed to support the construction, fabrication, and procurement activities needed to realize the building. BIM also accommodates many of the functions needed to model the lifecycle of a building, providing the basis for new construction capabilities and changes in the roles and relationships among a project team. When implemented appropriately, BIM facilitates a more integrated design and construction process that results in better quality buildings at lower cost and reduced project duration. [Eastman et al., 2008, p. 1]*

*BIM or Building Information Modelling is a process for creating and managing information on a construction project across the project lifecycle. [...] BIM is a way of working. BIM is information modelling and information management in a team environment, all team members should be working to the same standards as one another. BIM creates value from the combined efforts of people, process and technology.*

[NBS, National Building Specification for the UK]

*Building Information Modeling is the development and use of a multi-faceted computer software data model to not only document a building design, but to simulate the construction and operation of a new capital facility or a recapitalized (modernized) facility.*

[GSA BIM Guide Series 01: Overview, p. 3]

**BIM as model: Building Information Model**, i.e. a digital representation of an artefact, considered in its physical and functional characteristics. The artefact is decomposed into its semantic components, represented as digital objects with relationships, attributes and properties [222]. These definitions focus, instead, on the digital model of the building, rather than on the whole methodology. The BIM model is not a simple 3D representation of the building, but becomes an information model from which all the needed information can be obtained.

*One of the key outputs of this process is the Building Information Model, the digital description of every aspect of the built asset. This model draws on information assembled collaboratively and updated at key stages of a project. Creating a digital Building Information Model enables those who interact with the building to optimize their actions, resulting in a greater whole life value for the asset.*

[NBS, National Building Specification for the UK]

*A Building Information Model is a digital representation of physical and functional characteristics of a facility. As such, it serves as a shared knowledge resource for information about a facility forming a reliable basis for decision during its life cycle from inception onward.*

[NBIMS-US, National BIM Standard–United States]

*The resulting Building Information Model is a data-rich, object-based, intelligent and parametric digital representation of the facility, from which views appropriate to various users' needs can be extracted and analyzed to generate feedback and improvement of the facility design.*

[GSA BIM Guide Series 01: Overview, p. 3]

Therefore, BIM is not a simple software, nor just a three-dimensional model, since 3D modelling software allows to represent only the objects geometric features, without managing topological relationships nor associated information.

BIM is neither a standard nor a protocol, but it can be considered a coordinated process to achieve better design and construction quality, optimize engineering production chain and reduce errors and costs [46].

According to these definitions, in the present thesis, BIM will be considered as a process between designers, managers, engineers, architects, customers who can exchange information through a common language and a common tool [141].

## 1.2. BIM methodology

As seen before, BIM must be considered as an entire methodological approach and as a new process of modelling/translating reality into an information model. BIM makes it possible to manage in a coherent and coordinated way the entire building lifecycle (design, construction, management, operation, maintenance and demolition), making collaborative the work of the stakeholders.

According to Eastman et al. [123], the essential elements that contribute to the definition of the BIM are: a three-dimensional object-oriented parametric model of the building, a relational database containing all the information about the building and the data exchange flow between the actors involved in the building process.

The 3D model consists of individual constructive elements represented by "intelligent" objects, i.e. objects that "know" what they are and that are associated with graphic attributes, data and parametric rules. In other words, each object has associated information that describes its properties and behaviour in relation to other objects. The use of parametric objects ensures the overall consistency of the model, since the information are non-redundant and are updated simultaneously in all model views

(plants, elevations, sections, schedules and quantities, tables, 3D views).

The database governs the entire BIM architecture, containing element's semantic definition, rules and relations that govern parametric behaviour and all the thematic attributes that can be associated to the model. It is updated and implemented over time, making it possible to manage

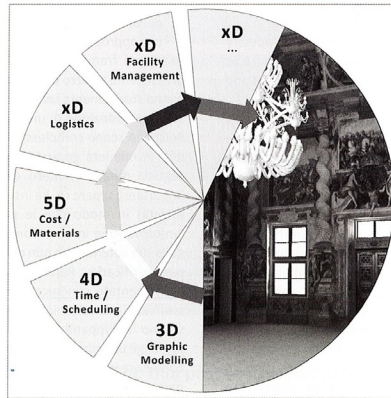


Figure 1. Relation between data and methodology. Model made by Brian Barbini and Stefano Gagliardotto. From: [222]

time dimension, fundamental for properly represent the building during its life cycle. There are potentially no limits to information that can be related to the model and, for this reason, some authors describe BIM as a xD methodology (Figure 1), i.e. capable of managing n dimensions in addition to the third (spatial) and fourth (temporal) ones. [222][32][186].

Information exchange between stakeholders, collaborative work and interoperability between platforms are essential issues, without them it is not possible to talk about BIM. These elements let the BIM to become methodology rather than a simple intelligent model.

The BIM revolution lies precisely in the virtualization of the process that encompasses all aspects and disciplines, allowing architects, engineers, clients, contractors, suppliers and builders to collaborate in a more efficient and precise way [33].

The advantage of the BIM is to facilitate mutual information exchange, making available a common database shared by all actors, upgradeable and implementable over time, from which it is possible to retrieve the information necessary for specific works, being sure about its consistency.

This new way of working is well described in the National Building Information Modeling Standard of the American NBIMS Committee, of which an extract is given below [202]:

*Imagine for a moment all of the individual actors in all of the phases of a facility's lifecycle. Imagine all of the actors, working in familiar ways within their own specialty areas, are able to gather information, explore options, assemble, test, and perfect the elements of their work within a computer-based model before committing their work to be shared with or passed on to other, to be built, or to be operated imagine further that when it becomes necessary to share or pass a bundle of information to another organization, which may or may not be using the same tools, or to move it on to*

*another phase of work, it is possible to safely and almost instantaneously (through a computer-to-computer communication) share or move just the right bundle of information without loss or error and without giving up appropriate control. In this imaginary world the exchange is standardized across the entire industry such that each item is recognized and understood without the parties having to create their own set of standards for that project team or for their individual organizations. Finally, imagine that for the life of the facility every important aspect, regardless of how, when, or by whom it was created or revised, could be readily captured, stored, researched, and recalled as needed to support real property acquisition and management, occupancy, operations, remodeling, new construction and analytics.*

Through the use of BIM, the approach to the design, construction and management changes and becomes much more collaborative and shared. The Delivery Process becomes Integrated Project Delivery (IPD), as defined by the American Institute of Architects (AIA) [9]:

*Integrated Project Delivery (IPD) is a project delivery approach that integrates people, systems, business structures and practices into a process that collaboratively harnesses the talents and insights of all participants to reduce waste and optimize efficiency through all phases of design, fabrication and construction. Integrated Project Delivery principles can be applied to a variety of contractual arrangements and Integrated Project Delivery teams will usually include members well beyond the basic triad of owner, architect and contractor. At a minimum, though, an Integrated Project includes tight collaboration between the owner, the architect, and the general contractor ultimately responsible for construction of the project, from early design through project handover.*

Since this is a completely new and different methodology compared to the traditional one, an initial investment in people training is necessary. In addition, new and ad hoc regulations and legislation are required: given the strong interdisciplinary feature of the BIM process, shared standards and common languages are needed in order to guarantee dialogue between all the actors involved.

Project Factor	Traditional Delivery	Integrated Delivery
<b>Team</b>	Fragmented, assembled on "as-needed" or "minimum necessary" basis, very hierarchical, controlled	Integrated team entity of key stakeholders, assembled early in the process, open, collaborative
<b>Process</b>	Linear, distinct, segregated, knowledge gathered "as-needed", information hoarded, silos of knowledge and expertise	Concurrent and multi-level, early contributions of knowledge and expertise, information openly shared, trust and respect
<b>Risk</b>	Individually managed, transferred to the greatest extent possible	Collectively managed, appropriately shared
<b>Reward/Compensation</b>	Individually pursued, minimum effort for maximum return, often first cost-based	Team success tied to project success, value-based
<b>Communication/Technology</b>	Paper-based, two dimensional, analog	Digital, virtual, Building Information Modeling, 5+ dimensional
<b>Agreements</b>	Encourage unilateral effort, allocate and transfer risk, no sharing	Encourage, foster, promote and support multilateral open sharing and collaboration, risk sharing

Figure 2. Comparison between traditional delivery method and IPD method. From: [9]

<i>Traditional methodology</i>	<i>BIM methodology</i>
Geometric entities	Parametric objects
Technical drawings (plans, elevation, sections etc.)	Unique model from which all the desired views are extracted
Lack/omission/error of information	Information consistency
Manual updating	Automatic updating
Information are retrieved from separate documents	Information are retrieved from a single database
Repeated and sequential work	Collaborative work
Multidisciplinarity	Interdisciplinarity
Distinct management of phases	Contextual management of the entire life cycle

Table 1. Comparison between the traditional and the BIM work methodologies. Personal elaboration..

### 1.2.1. Maturity levels

Today, as it can be seen in the next paragraph (§ 1.4), Great Britain is the reference country for the transition from CAD to BIM. It is the leader in standard definition and process standardization.

In order to illustrate the progressive process of transition from CAD to BIM and clarify the achieved level of development of the new technology, the **British Standards Institution (BSI)** [67] introduced in 2013 the concept of *Maturity Model* i.e. a sequence of levels of maturity in the use of BIM [34].

It is a classification in four different levels (from Level 0 to Level 3) that aim to define recognizable milestones in the BIM adoption process. These levels move from 2D CAD drafting to 'full' collaborative working and corresponds to different improvements from a technical and collaborative point of view. For each level, proper tools, techniques and

standard references are specified, as shown in Figure 3.

The four levels refer to increasing standardisation, sharing and information requirements.

**Level 0** means no BIM adoption: design documents are produced only by 2D CAD drawing and the outputs are supplied in paper or electronic version. On the contrary, levels 1 to 3 show different degrees of development in modelling, collaboration and exchange of fully integrated or interoperable data.

Specifically, **Level 1** refers to better information management and establishes the methodology for managing production, distribution and quality of information for construction. This includes information generated through 2D and 3D CAD systems, in a collaborative way, providing a common data environment and possibly some standardised libraries.

**Level 2** refers to a 3D environment, managed through separate “BIM” tools related to the different disciplines, with data linked together. At this level, the BIM is considered as 4D (time management) and 5D (cost management). Great Britain has reached this level of maturity since 2016, requiring that all centrally founded public projects, both building and infrastructure construction, deliver BIM data for the entire project lifecycle.

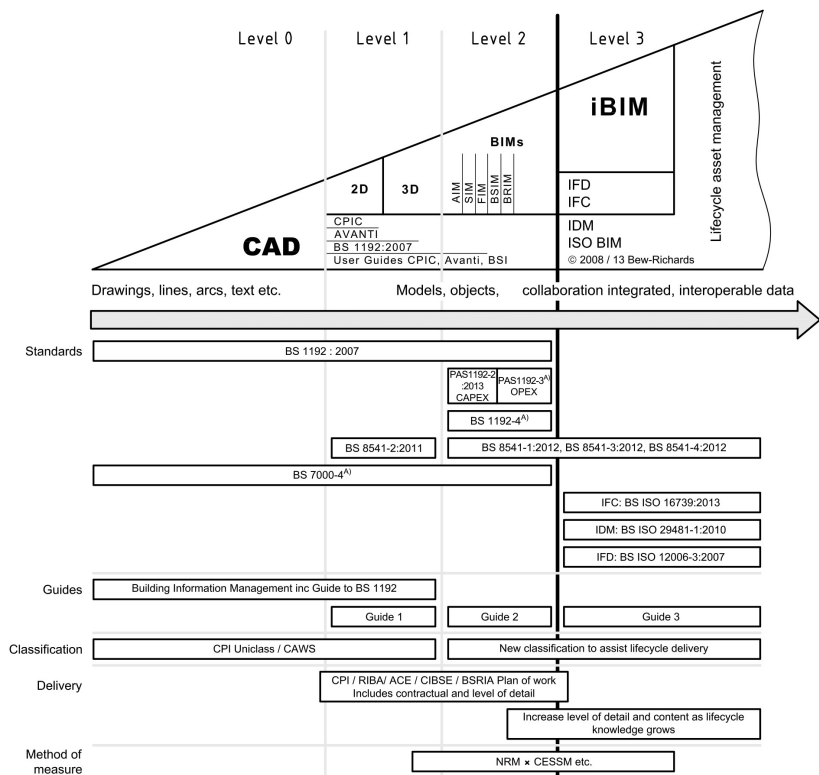


Figure 3. Bew-Richards “BIM Wedge” Maturity Model. From: [34].

**Level 3** refers to a fully open and fully interoperable process through the use of IFC and IFD formats<sup>1</sup>. Data management takes place on the basis of a collaborative server and can be considered as an iBIM or integrated BIM involving the various engineering processes.

Therefore, analysing in detail the standards issued by the BSI, which, as it can be seen from the graph, define the transition from one level to another, these standards are divided into British Standard (BS) and Publically Available Specification (PAS). BSs are more general standards, they are Code of Practice that establish global standards. The PASs are more specific and implementing, while remaining consistent with the respective British Standards. These rules have been and will be of fundamental importance for the development of the BIM in the UK and in all countries that intend to follow this direction. A summary of the available standards is provided in Appendix A.2.

### 1.2.2. BIM documents

As said before, collaborative work is key point of BIM methodology. For a truly collaborative work, standard compliance and proper organization of information are mandatory. In order to guide through the process of delivering and operating buildings with BIM, the British Government commissioned two guidance documents: PAS 1192-2 and PAS 1192-3. PAS stands for Publically Available Specification and enables an emerging standard to be rapidly developed in response to the industry need about the adoption of BIM and the digital approach to building.

Part 2 is about the delivery phase of a building, whilst Part 3 is about how a building is managed and operate once it's in use. PAS1192-2:2013 is the reference standard for BIM Level 2 implementation, indicates the main documents to be produced and requested in all the BIM process stages.

Central to both documents is the process map shown in Figure 4. This map explains project deliver: information is stored in graphical and non-graphical form in the one shared ares called Common Data Environment, i.e. a collaborative work sharing environment, an archive and work management system [260]. The ownership of the information remains with the person who produced it, but it can be easily shared and reused for planning the construction phase, producing estimates and calculations,

.....  
1. For interoperability format, see paragraph 1.6

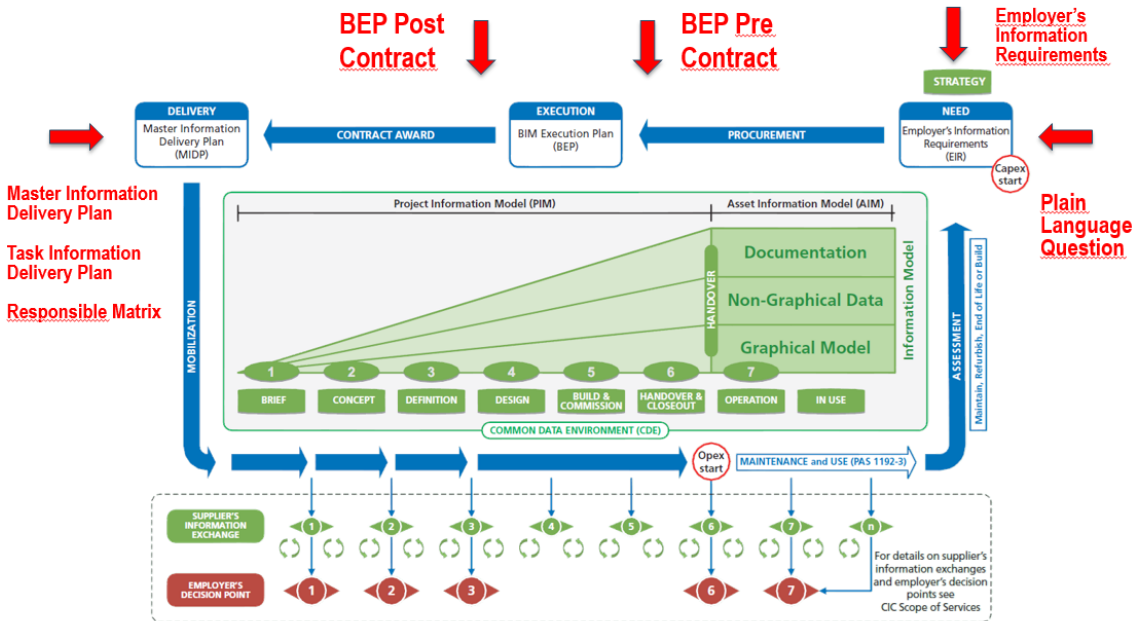


Figure 4. Diagram representing the information cycle in the BIM environment according to regulations PAS 1192-2: 2013. It represents the information cycle and should be read from the top right. From [48].

facility management etc. [229].

The information increases in richness as the project stages progress until the point of handover where that complete data set is passed to the building operator. The dataset is called **Project information Model** in the delivery phase and **Asset Information Model** in the operational phase.

The whole process is supported by some documents, of which only a brief description is provided here, referring to PAS1192-2 for additional specifications [48]. The building process starts at the outset of capital expenditure on an asset with the **Employer's Information Requirements (EIR)** where the strategy for meeting the customer's needs is determined. The EIR sets out the information that the customer will require to run the new facility and to make decisions about its development during the project delivery process. On this document procurement can occur and the **BIM Execution Plan (BEP)** can be created. The BEP explains how the information modelling aspects of the projects will be carried out and is a key document for all parties.

Following the process of Contract Award, the **Master Information Delivery Plan (MIDP)** is produced. This sets out the information to be prepared, who needs to prepare it and the protocols and procedures for its production and release. It can only be developed from the BEP and the EIR.

From these foundation documents, the project team can mobilise and commence the project delivery process, building the information model in full alignment with the customer's needs and requirements.

At the point of handover, operating expenditure commences and the asset management phases begin. These periods are governed by PAS 1192-3, as said before.

All the documents are organized in order to specifically define everything that concerns the BIM process, such as: objectives, project milestones [229], strategies and actions [260], information about models, drawings, specifications, construction site working hours [229], responsibilities for information deliverable [53], suppliers and human resources identification [260] and so on.

So the intention is not to leave anything to the free interpretation of the individual professional studio, but to define and standardize the whole process, so that it is common and shared.

By possessing a data rich information model, the customer and the end user are able to assess the performance of their built asset. This allow them to be better informed when renewing their assets and commencing the delivery again in te future.

The cycle is supported by continual information exchange between the project team and key customer decision points throughout.

### 1.3. Data management with BIM: potentials and limits

---

On the basis of the analysis made above, it can be seen that the BIM methodology has considerable potentials, which can be summarised as follows:

- **Unique project management.** Each model view (two-dimensional, three-dimensional or schedules/quantities) is simultaneously and automatically updated according to the model changes. This results in a reduction of the time needed to update the documents and of errors, thanks to the perfect consistency between the documents.
- **Real-time clash detection.** Thanks to the 3D model visualization, it is possible to verify interferences between individual components. In this way, it is possible to avoid variations during the construction to address problems that could not be assessed during the design phase.

- **Adjustment of the level of detail and content according to the representation scale.** In traditional drawing, different representations and data are used depending on the design phase to which they refer (preliminary, detail, construction) with increasing levels of detail. The use of BIM allows to define a unique object and to visualize it with different level of detail depending on the design phase to which it refers, thanks to the definition of parameters and properties for each object that regulate the type of representation associated with each level of detail.
- **Unique relational database** that allows managing the entire construction process in a coherent and coordinated way. This enables better organisation and retrieval of information and ensures overall consistency of the project.
- **Collaborative work.** The work can be divided into sub-projects (work sets), so that the various actors can work on the portion of the project they are responsible for. These sub-projects refer to the global model and are, therefore, always coherent and coordinated, avoiding inconsistencies and interference.
- **Time management.** The possibility of managing the fourth dimension within the project allows the same BIM model to be used for the entire life cycle of the building, from the first decisional phase to the demolition phase, keeping track of all the transformations that have taken place.

These potentialities (as evidenced by the research of numerous authors, [123] [222] [33]) result in concrete advantages both in the management of the building life phases and in benefits for the individual actors involved.

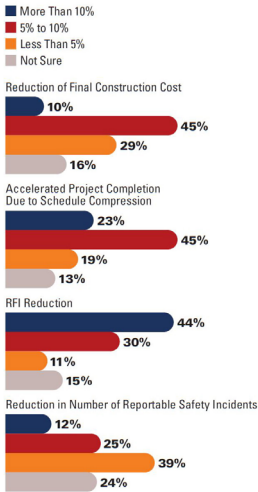
As an example, the results of some surveys, carried out by Dodge Data & Analytics and reported in the 2015 Smart Market Report [112], are given below (Figure 5).

In the left bar chart, the interviewees (engineers, architects, owners and contractors) had to express the percentage improvement, linked to the use of BIM, in the reduction of costs, schedule, request for additional information (RFI) and incidents. The second graph shows, on a scale from 1 to 10, the percentage of respondents who considered high or very high the impact of the BIM in some selected areas. The third graph evaluates the BIM process: respondents had to select the BIM processes they thought contributes the most to the success of complex projects. The graph shows the first seven processes indicated by the interviewees with the relative percentages divided by type of respondents.

From the survey, it emerges that BIM really improves outcomes on complex building

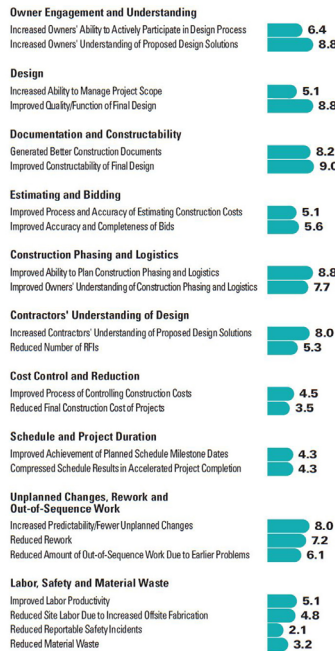
**Metrics for the Impact of BIM on Cost, Schedule, RFIs and Safety (Among Those Rating Medium or Higher BIM Impact on These Outcomes)**

Dodge Data & Analytics, 2015



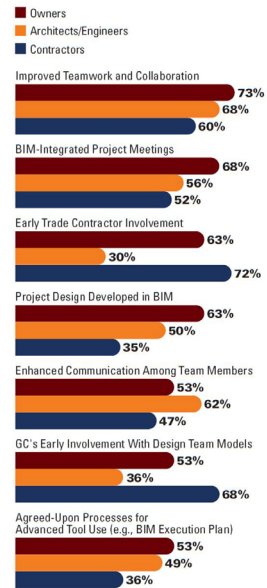
**Impact of BIM on Complex Project Outcomes (Percentage of High and Very High Ratings, Converted to a 1–10 Scale)**

Dodge Data & Analytics, 2015



**Project Processes That Contribute Most to the Success of Complex Projects (According to Owners, Architects, Engineers and Contractors)**

Dodge Data & Analytics, 2015



projects. The main BIM benefits indicated by stakeholders are constructability improvements and better design understanding. This reflects on schedule acceleration and completion and, then, final construction costs reduction [112].

**The use of BIM in the design phase**

In the design phase, there are advantages associated with better project management thanks to the three-dimensional visualization that allows a global and coordinated view of the building. It allows for the preliminary verification of interference (clash detection), guaranteeing process consistency and design error reduction [123].

A better management of the project is made possible also thanks to the interdisciplinary collaboration of designers who can manage in a coordinated and shared way the same project model [123].

Moreover, already at the preliminary design stage, it is possible to compare different design solutions and make realistic estimates of both the construction and management costs, thus establishing the most economical, functional [32] and sustainable project [123].

These possibilities, combined with the capability of planning logistics and construction

Figure 5. The bar charts show the impact of the use of BIM on some key points of the construction process. The research was conducted by Dodge Data & Analytics on 23 construction projects of complex buildings. [112]

phases [33], result in significant advantages during the construction site phase, reducing delays and variations.

### **The use of BIM in the construction phase**

The construction process can be simulated directly within the BIM model by showing the progress states of the works [123]. This allows predicting and planning logistic and safety management on the construction site [33]. The “virtualization” of the construction process makes it possible to solve better and more quickly any problems that occur on site: the BIM prefigures scenarios, strategies and the effect that a modification will have on the whole project (in terms of interference, costs, appearance, etc.) [123].

Compared to the traditional methodology, the BIM aids the component fabrication: parametric objects can be exported and used as a basis for manufacturing by means of numerical control machines [123] and can be listed and catalogued in schedules/quantities, providing total control over quantities and their correct position in place.

In addition, the model portability allows viewing the project on different devices directly on site and to update it based on the progress of the work [33].

Thanks to the continuous synchronization between the project and the really built work [123], the final model will contain all the building data, constituting the basic documentation for the consequent operational management.

### **BIM for facility management**

BIM methodology is useful also in the operation phase, since it provides a complete and constantly updated model which represents the unique access point to all building information.

In the traditional process, information is contained in a number of separate documents, often difficult to manage in an interrelated way. In the BIM environment, all data are referred to the model and can be retrieved by selecting elements in the scene.

In addition, the recent development of smartphone and tablet applications, which display the three-dimensional models and implement augmented reality, increases the portability of the model, which can then be directly displayed on site during maintenance operations. All this results in easier maintenance and management from both a spatial and economic point of view [33], [123].

Therefore, summarizing, the BIM methodology leads to numerous advantages in terms of time saving and preliminary error detection, which lead to economic positive effects and to quality and functionality improvements.

BIM application	Owners	Designers	Contractors	Facility managers
Enhanced viewing	x	x	x	x
Project validation		x		
Collaborative work		x		
Assessment of project options	x	x	x	
Cost estimation	x	x	x	
Sustainability analysis	x	x		
Quantity evaluation		x	x	
Logistics management	x		x	
Time planning		x	x	
Feasibility analysis		x	x	
Building performance analysis	x	x	x	x
Building management	x			x
Project marketing	x			

Table 2. Advantages of using BIM for the different actors involved. [33]

However, despite these undoubted advantages, the BIM methodology also presents some limitations, partly due to the recent use of these instruments on a large scale.

The SmartMarket Brief: BIM Advancements No. 1 [113] identifies some obstacles to BIM success. First of all, the low level of team interest/support and the low level of collaboration. Since BIM is a completely new methodology, different from the traditional approach, one of the main barriers to the implementation of the BIM is the lack of qualified personnel able to govern the process completely. In fact, specific technical skills are needed for the use of new platforms and, above all, expertise able to manage the changed overall organization of work that becomes shared, collaborative and interdisciplinary [123], are required. It is therefore necessary to invest in personnel training, plan the whole process and organise the work in a completely different way [222]. The training process involves not only technicians but also employers, in order to abandon initial reluctance and understand the potential of the BIM approach. All this takes time and a significant initial economic investment.

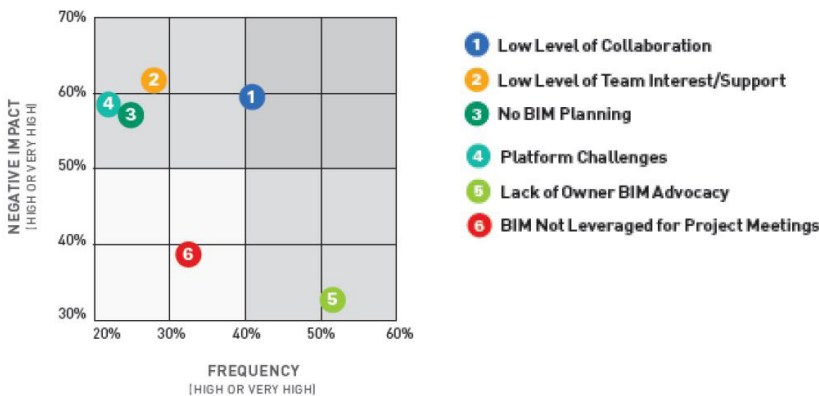


Figure 6. Limits in the use of BIM. SmartMarket Brief: BIM Advancements No. 1 [113]. The graph combines frequency and negative impact of factors that impede BIM success on projects.

The MacLeamy curve (Figure 7) compares the efforts and resources required for the traditional design process with those determined by the BIM approach. Compared to the traditional methodology (which concentrates the efforts in the construction and documentation phase), BIM anticipates the peak of the efforts to the preliminary design phase. BIM therefore does not allow reducing the design efforts (note that the peaks of the two curves are almost identical) but anticipates these efforts to the initial phases, where the costs related to design variations are significantly lower. The diagram shows that despite a strong initial investment, the final return is certainly advantageous.

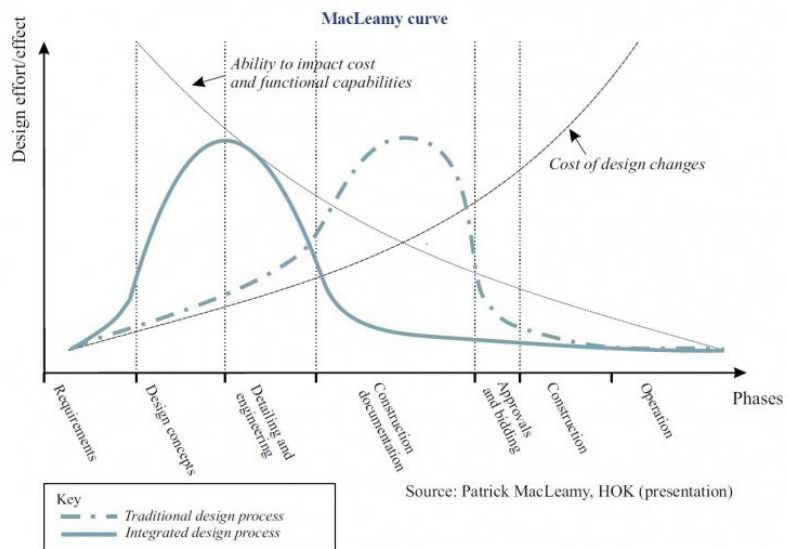


Figure 7. The MacLeamy Curve comparing the efforts and resources required for the traditional design process with those determined by the BIM approach.

In addition to the lack of qualified personnel and high initial costs, major obstacles to the BIM implementation include technical, operational and legal issues. In fact, there is a lack of collaborative work processes and regulatory standards to which refer [33]. Regulations and guidelines about the use of BIM (see paragraph 1.5) are being issued, but other improvements have to be made to reach full interoperability.

As far as the interoperability is concerned, there are indeed still exchange problems between models realized with different platforms, which do not guarantee the integrity of all information and the concrete exchange of data [123][33].

In addition, there are legal and contractual problems. The first risk is related to the lack of rules that determine and protect the ownership of BIM data [33][222]. As the BIM is a collaborative process, all the actors involved can access data produced by others and the intellectual property rights have not yet been unambiguously established. To date,

it is regulated through internal agreements between the parties involved in the same project.

As well as intellectual property has not been defined, the responsibility for the correctness of the data entered has not even been regulated too [33]. It is a still open question, very important when errors or inaccuracies occur.

Despite the persistence of problems and difficulties related to the use of BIM, this methodology, seems to represent the future of the construction sector and the virtuous goal that administrations are moving towards.



Figure 8. SWOT analysis of the BIM process. Personal elaboration according to [223].

## 1.4. The use of BIM worldwide

In recent years, the knowledge and use of BIM has become increasingly widespread. Starting from its initial applications, dating back to the early 2000s, BIM is increasingly becoming a market leader in the AEC Industries (Architecture Engineering and Construction Industries) all over the world, establishing itself as the methodology of the future.

Its development is periodically documented by research institutes that investigate the evolution of the adoption of this technology, its effects and the initiatives undertaken by single countries for its progressive adoption. The main references are the reports produced by McGraw Hill Construction (since 2015 Dodge Data & Analytics) under the patronage of the US Department of Veterans Affairs and the national and international reports of the National Building Specification for the UK (NBS), owned by the Royal Institute of British Architects (RIBA).

From these reports, the following aspects stand out:

- A progressive increase in the number of countries approaching the use of BIM
- An increase in the concrete use of BIM in construction projects
- Increasing maturity and experience in the use of this technology.

Leaders in the adoption of the BIM are the most developed countries, such as the United States, Canada and Western Europe (in particular Scandinavian countries and the United Kingdom), but also new markets such as Australia, Brazil, Japan, New Zealand and South Korea are working on drafting standards and guidelines [185]. Finally, emerging countries such as China, India, Malaysia and the Middle East are also taking the first steps towards the BIM adoption. [148][262][276].

Not only the number of countries that know and promote BIM adoption is growing, but also the real use of BIM in construction projects and the level of maturity and awareness about its use are increasing [185]. In the United States, for example, it grew from 28% in 2007 to 71% in 2012 [182], and also in countries such as Great Britain and Canada the trend is positive [207] (Figure 9).

This positive progression is now set to raise again, as highlighted in the International Report prepared by NBS in 2016 [207], which shows a projection of the future use of BIM over the next five years. In all the analysed countries (UK, Canada, Denmark, Czech Republic and Japan), respondents expect that, within the next 5 years, the BIM adoption will reach 80% of projects; in particular, in the UK, Canada and Denmark the projections

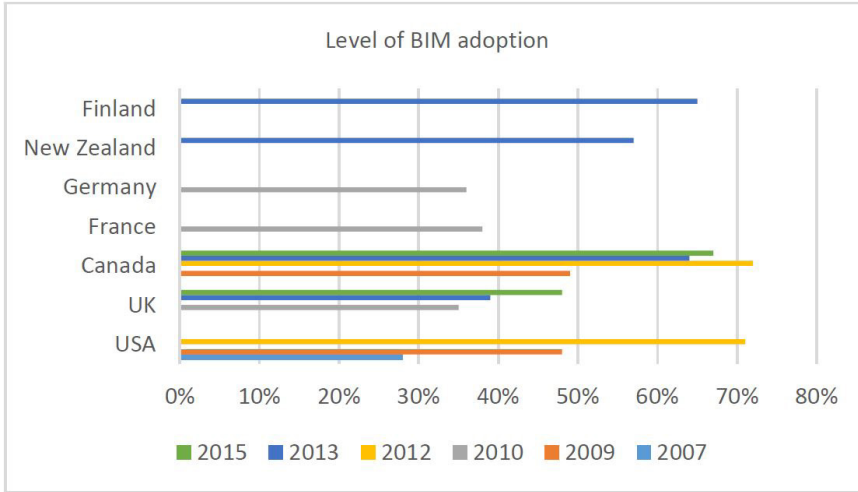


Figure 9. Level of BIM adoption in selected countries. Personal elaboration based on the data provided by [216],[217],[182] and [184].

Source: McGraw Hill Construction, 2013

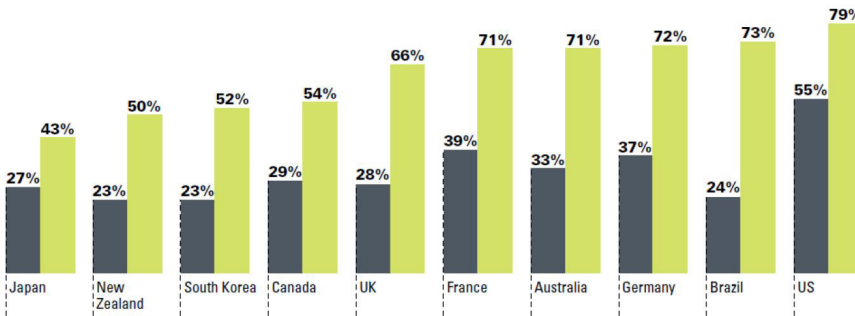


Figure 10. Percentage of contractors at High/Very High BIM implementation Levels (by Country). Form: [185].

are even more optimistic, with an expected substantial expansion within 3 years or less. The growing use of BIM is mainly due to the emergence of many relevant legislation and to the interest of public administrations, which have sometimes imposed, or at least regulated, its use. In countries such as Finland, Denmark, Norway, the United Kingdom, Singapore, South Korea and Australia, BIM has become legally mandatory. Other countries, such as the United States and the Arab Emirates, have adopted policies promoted by organizations or public authorities, while others countries are beginning to adopt guidelines and strategies for the future, such as China, France, Germany, Hong Kong, Japan, Malaysia and New Zealand [185].

Among the main publications about the countries policies in relation to the BIM adoption, there are the McGraw Hill Smart Market Reports [185][183], the research conducted by Cheng & Lu [87] and by Anna Osello [222], in a worldwide context, and by Chiara C.

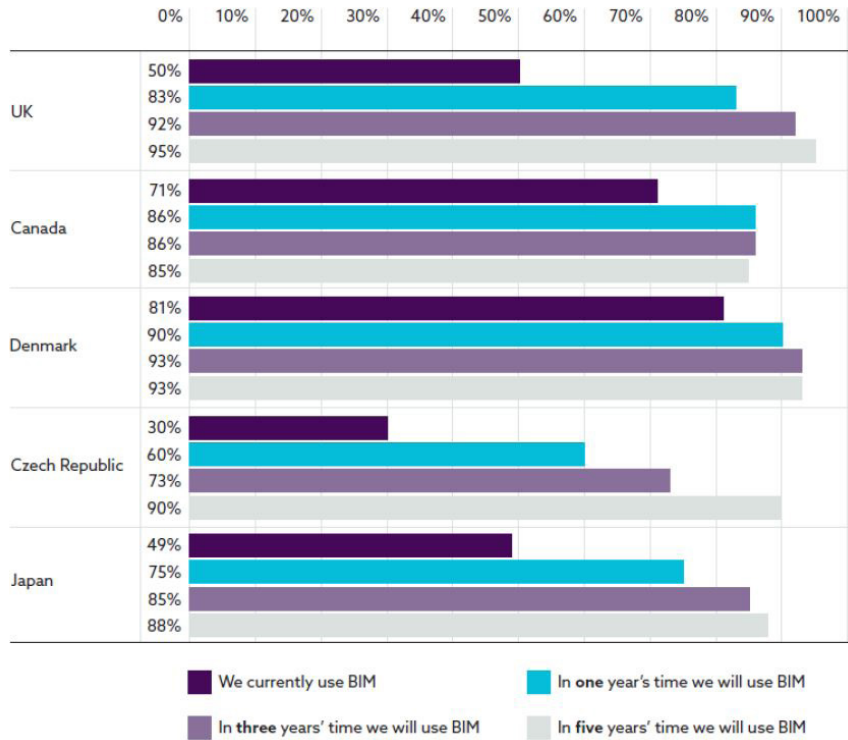


Figure 11. Future use of BIM.  
From: [207]

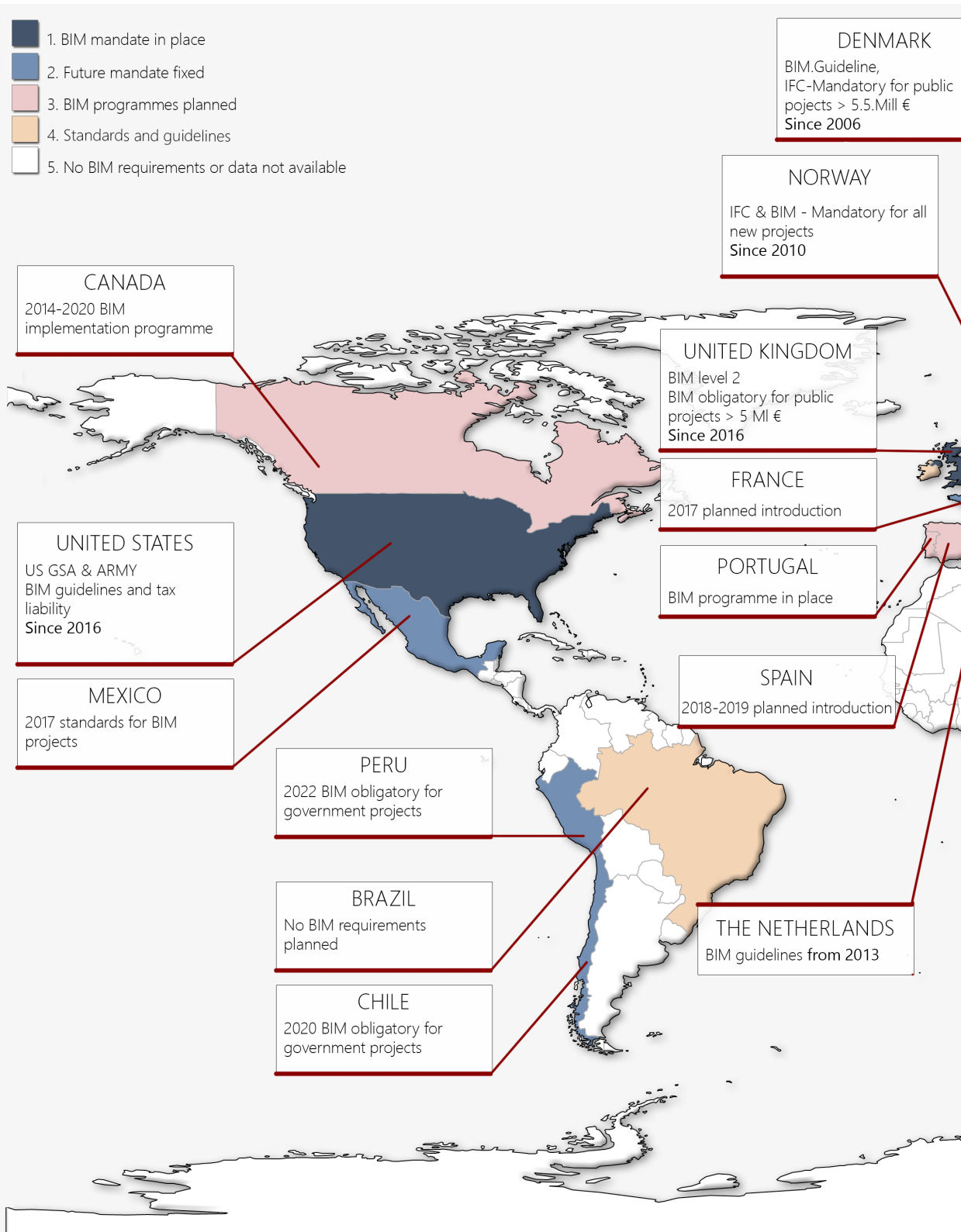
Rizzarda [261] with reference to the European context. A graphic summary of these studies is shown in Figure 12 and in Appendix A the history of the BIM adoption in the main countries is presented.

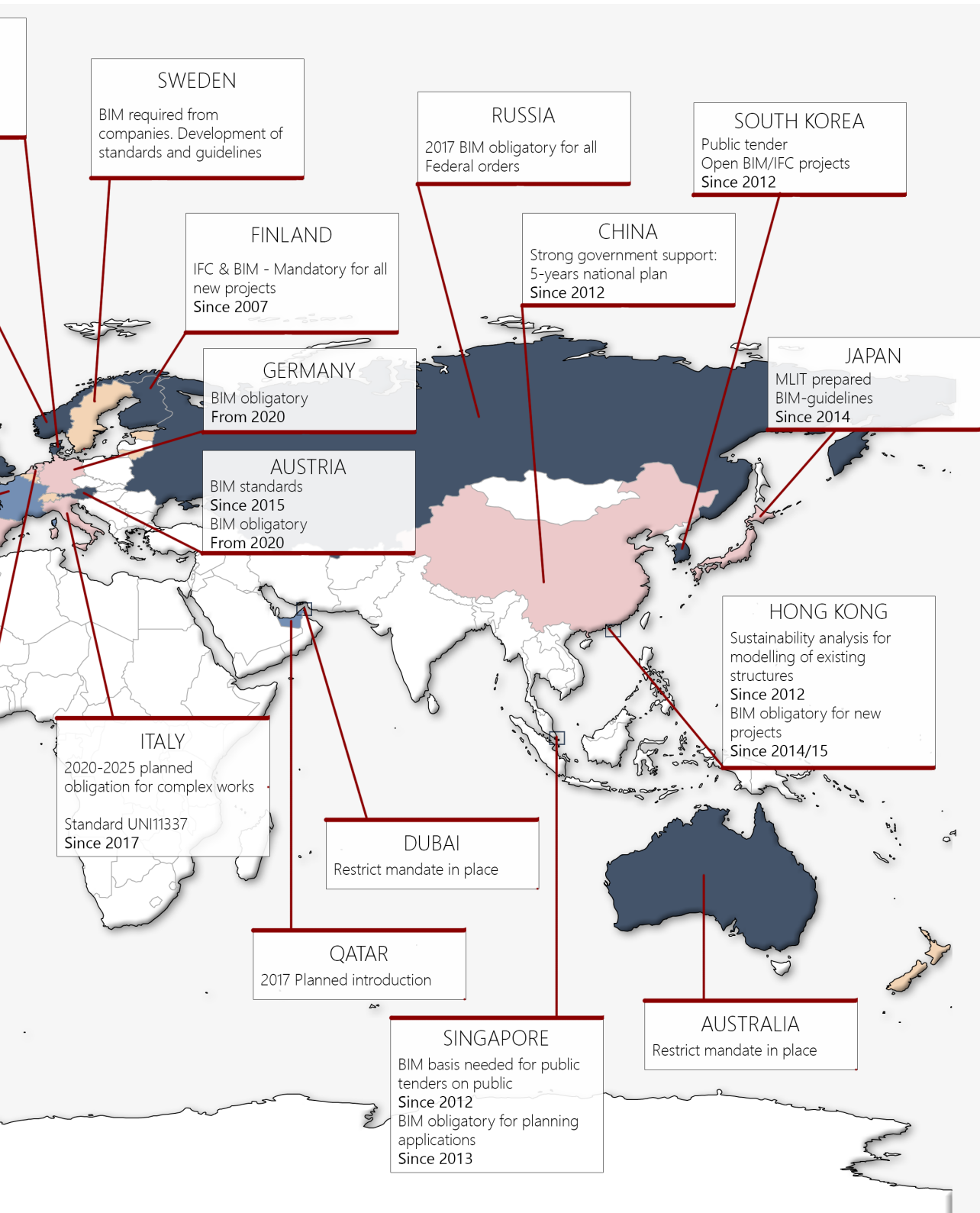
## 1.5. Towards a common legislation

### 1.5.1. The ISO standards

The ISO Technical Committee 59 (ISO/TC 59) *Buildings and civil engineering works* deals with the production of international standards on topics ranging from terminology, IT organisation in construction and civil engineering processes, geometric requirements for buildings, building elements and components, including modular coordination, general rules for joints, tolerances and requirements and performance. The Committee's rules also cover current and essential issues such as sustainability, accessibility and lifespan.

Figure 12. Graphic summary of the level of BIM adoption and of the informce regulation worldwide.





Therefore, the commission contributes to sustainable development, by addressing the quality and performance of buildings and describing how these problems can be integrated into the life cycle of the built environment [167].

In this context, the ISO/TC 59/SC 13/WG 13 "Information Management" working group, promoted and coordinated by Great Britain, is working on the theme of BIM. The working group is composed by spokespeople of Great Britain, Italy (represented by Alberto Pavan and Angelo Ciribini), Germany, USA, Australia, Austria, Japan, Norway and Netherlands.

To date, the ISO standard for BIM includes:

- ISO STEP 10303 *Standard for the Exchange of Product model data*
- ISO 12006-2:2015 *Building construction -- Organization of information about construction works -- Part 2: Framework for classification*
- ISO 12006-3:2007 *Building construction -- Organization of information about construction works -- Part 3: Framework for object-oriented information*
- ISO/TS 12911:2012 *Framework for building information modelling (BIM) guidance*
- ISO 16354:2013 *Guidelines for knowledge libraries and object libraries*
- ISO/DIS 16739-1 [Under development] *Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries -- Part 1: Data schema using EXPRESS schema definitions*
- ISO 16757-1:2015 *Data structures for electronic product catalogues for building services -- Part 1: Concepts, architecture and model*
- ISO 16757-2:2016 *Data structures for electronic product catalogues for building services -- Part 2: Geometry*
- ISO/DIS 19650-1 [Under development]: *Organization of information about construction works -- Information management using building information modelling -- Part 1: Concepts and principles*
- ISO/DIS 19650-2 [Under development] *Organization of information about construction works -- Information management using building information modelling -- Part 2: Delivery phase of assets*
- ISO 29481-1:2016 *Building information models -- Information delivery manual -- Part 1: Methodology and format*
- ISO 29481-2:2012 *Building information models -- Information delivery manual -- Part 2: Interaction framework*

The new ISO 19650 [233] standard is under development, drawing largely on the British (BSI) standard PAS 1192, especially in its parts 2 and 3, which concern BIM information

management in design, construction, management and maintenance phases.

The standard will be structured in 4 parts:

- Part 1: Concepts and Principles;
- Part 2: Delivery phase of the assets;
- Part 3: Operational phase of assets;
- Part 4: Server based systems.

On the basis of PAS 1192, it provides for the introduction of documents and documents, such as the EIR (Employer's Information Requirement) and the BEP (BIM Execution Plan), which will transform the contract process and the project delivery approach. It should contain, in addition, an initial proposal for the definition of levels of detail both for model and information (LOD and LOI) divided into: Brief, Concept, Design, Definition, Built and Commission, Handover and Close-up, Operation and In-use, End of Life [233].

The final publication, at least of the first two parts, is expected in 2017.

## 1.5.2. European legislation

In 2014, the European Parliament introduced the BIM on a regulatory level with the *European Union Public Procurement Directive* (EUPPD 2014/24), inviting the 28 EU member states to "encourage, specify or impose", through specific legislative measures, the use of the BIM as a reference standard for all public projects by 2016 [129].

The aim of the Directive is to reduce the economic waste associated with the construction of public works and the greenhouse gas emissions, derived from both the construction and maintenance processes of the building.

As seen above, many countries have already made efforts in this direction and the EU BIM Task Group was set up to bring together and coordinate these national initiatives in a common European approach. In fact, the EU BIM Task Group wants to prevent that the excessive diversification of standards and regulations across the European countries lead to problems and restrictions on competition in the European single market [218].

The EU BIM Task Group [128] is composed of several public sector representatives, such as public real estate owners, construction and infrastructure operators and representatives of the 21 States (Austria, Belgium, Denmark, Estonia, Finland, France, Germany, Ireland, Iceland, Italy, Lithuania, Norway, Netherlands, Poland, Portugal, Czech Republic, Slovakia, Slovenia, Spain, Sweden, United Kingdom).

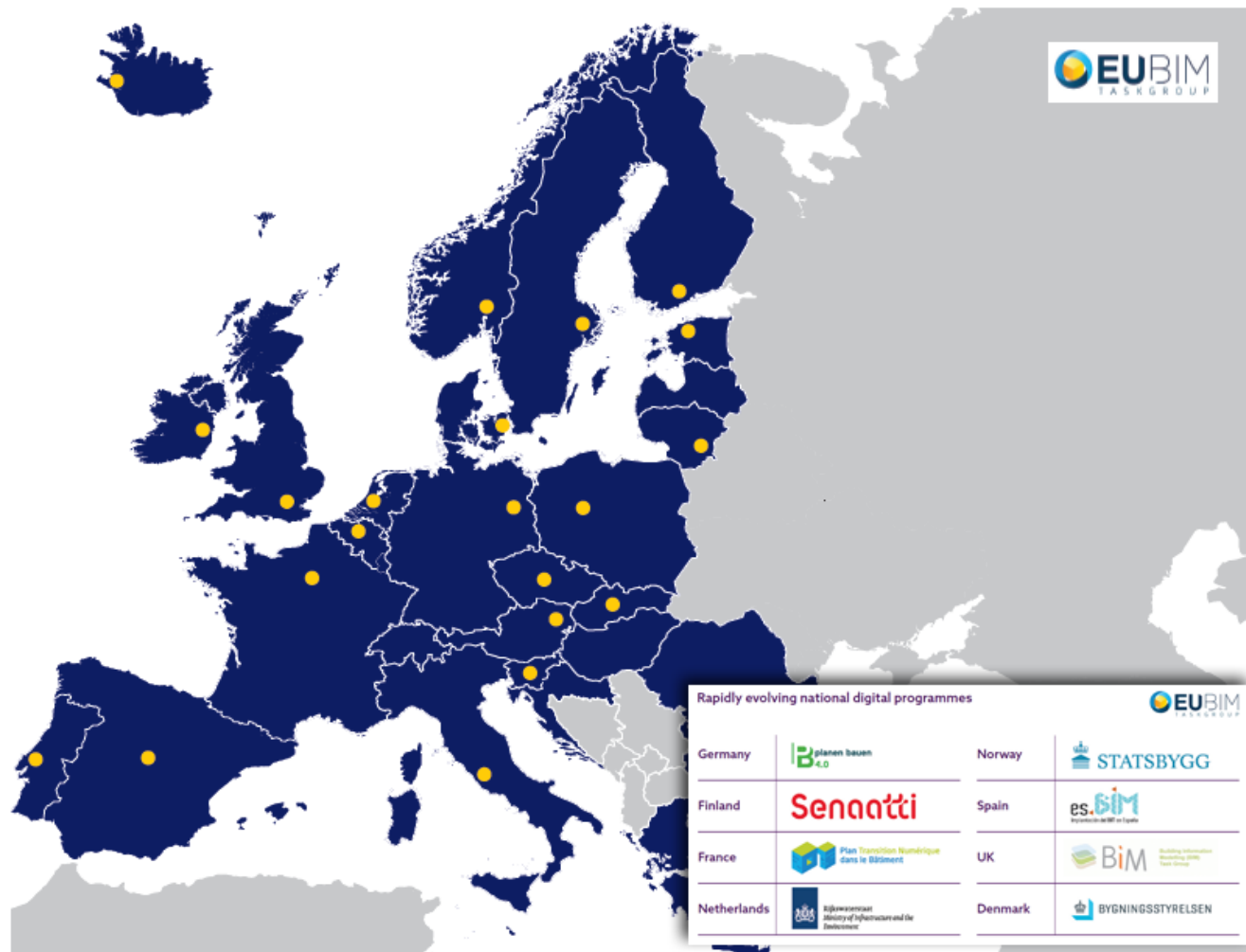
The objective of the group is to produce guidelines (*Handbook for the introduction of Building Information Modelling by the European Public Sector*) containing the general principles for the correct introduction of a digital approach (of which the BIM is part) in public works projects and national strategies.

The *Handbook* (latest version 6 July 2017 [187]) aims to identify the common principles and best strategies already implemented in the BIM field, making them the basic know-how for the entire European Union, thanks to which create an open and competitive digital single market for construction.

As far as standards at European level are concerned, the CEN (European Committee for Standardization) Technical Board BT CEN/BT/WG 215 "Building Information Modeling" is responsible for standardisation activities in the BIM field, whose respective technical committee is CEN TC/442 "Building Information Modeling".

The table is promoted and coordinated by Norway and includes Italy (Pavan, Romano,

Figure 13. Member States of the EU BIM Task Group.  
From: [128]



Re Cecconi, Odorizzi), France, Austria, Germany, Great Britain, Spain, Netherlands, Denmark, Belgium, Czech Republic, Estonia, Portugal, Sweden and Finland [233].

The working group is active on the implementation of ISO standards on:

- BIM Information Delivery Manual (IDM) - ISO 29481 parts 1 and 2
- Industry Foundation Classes (IFC) - ISO 16739
- International Framework for Dictionaries (IFD) - ISO 12006 parts 2 and 3.
- The new version of ISO 19650 part 1 and 2

Currently published standards are [82]:

- EN ISO 12006-3:2016 *Building construction - Organization of information about construction works - Part 3: Framework for object-oriented information* (ISO 12006-3:2007)
- EN ISO 16739:2016 *Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries* (ISO 16739:2013)
- EN ISO 29481-2:2016 *Building information models - Information delivery manual - Part 2: Interaction framework* (ISO 29481-2:2012).

The publication of the other draft standards is expected by 2019.

### 1.5.3. LOD definition

There are still different views on the concept of LOD, depending on the reference standard and, principally, on its interpretation as “Level of Detail” or “Level of Development”. LODs have been the subject of various discussions and a complete and exhaustive analysis has been carried out by Marzia Bolpagni [63], whose contribution has been taken as a reference for the drafting of this paragraph.

The acronym LOD was first introduced in 2004 by Vico Software (a company now acquired by Trimble) to indicate the “Level of detail” and establish the progressive reliability of the information over a period of time.

In 2008, AIA introduced five “Development Levels” (LOD100-LOD500) in the E202™ -2008 *Building Information Modeling Protocol Exhibit*, then updated in 2013. Based on these specifications, starting from 2013, the BIMForum is publishing annually the *Level of Development Specification*, which has become the benchmark for national guidelines for countries such as Australia, Canada, Singapore, Singapore, China, Taiwan, Germany and France.

Other countries have developed their own national specifications. For example:

- New Zealand has defined the LOD as “Level of development” based on the 2013 AIA protocol, but defines it as the sum of four aspects: “Level of detail” (LOd), “Level of accuracy” (LOa), “Level of information” (LOi) and “Level of coordination” (LOc);
- Denmark has instead developed since 2007 a different classification system based on 7 “Information levels” (0-6) for geometric and non-geometric elements. This classification was implemented in 2009 in the *Australian CRC National BIM Guidelines* and in 2014 in the *Nederlandse BIM informatieniveaus*, despite in these countries the AIA LOD definition was the dominant system in use;
- UK introduced in 2009 (*BIM Protocol of the AEC (UK)*) the classification of LOD as Level of Detail/Grade, providing four level of detail (G0-G3) referred only to geometric and graphical aspects.

An important contribution to the LOD definition, was given by the UK PAS1192-2:2013, which introduced the “Level of Definition” concept. It provided a new seven-level classification (1-7) that represents both the Level of Model Detail (LOD) for graphic content and the Level of Model Information (LOI) for information content. This concept was taken up in 2015 in both the *NBS BIM Toolkit and the AEC (UK) BIM Technology Protocol*, while the *CIC BIM Protocol* (2013) refers only to Detail Levels.

The English approach is followed by the *BIMForum guidelines*, which in 2015 include both Element Geometry and Associated Attribute Information.

Despite these main references, a unique and shared definition of LOD does not yet exist. Each national country has its proper classification. Figure 14 shows a summary of the main national classifications taken from M. Bolpagni’s contribution.

Nevertheless, regardless of the individual national classifications, it is important to highlight the general difference between LOD as the “Level Of Detail” and LOD as the “Level Of Development”. LOD as Level of Development is a measure of the reliability of information represented by a BIM element. It is not just a measure of the amount of information, nor it is a measure of the quantity and accuracy of the graphic information. A LOD table can be considered as a measure of the certainty and reliability of information [241].

Today, the most exhaustive classification is the one expressed by the BIM Forum Level of Development Specification 2016 which adopts the following subdivision [45][143]:

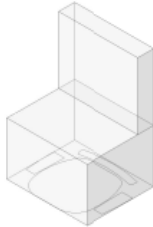
Figure 14. Comparison of LOD classification systems in the various standards [63].

Source	Title	Authorship	LoX System	Levels
BIPS 2007	3D Working method	Parties/ Responsibility	Information Level	- - 0 1 2 3 4 5 6 -
CRC 2009	Object data levels	Responsibility	Object data levels/Level of Detail	- - - A B C - D E -
Department of VA 2010	BIM Object/Element Matrix	Model Element Author	Level of Development (LoD/LOD)	- - - 100 200 300 - 400 500 -
Vico Software 2011	Model Progression Specification	-	Target Level of Detail/Level of Detail	- - - 100 200 300 - 400 500 -
NATSPEC 2011	NATSPEC BIM Object/Element Matrix (BOEM)	Model Element Author (MEA)	Level of Development (LOD)	- - - 100 200 300 - 400 500 -
HKIBIM 2011	BIM Model Specification	-	Level of Detail	- - - - - - - - - -
NYC DDC 2012	Object Requirements	-	› Model Level of Development/ › Level of Development (LOD) › Model Granularity	- - - 100 200 300 - 400 500 (?) -
PennState University 2012	BIM Information Exchange- Level of Detail Matrix	Model Element Author (MEA)	Level of Development (LOD)	- - - 100 200 300 - 400 500* -
USC 2012	-	-	Level of Detail (LOD)	- - - 100 200 300 - - - -
US Army Corps of Engineers 2012	USACE BIM Minimum Modeling Matrix (M3)	-	› Level of Development (LOD) › (Element Grade/Grade (A, B, C, +))	- - - 100 200 300 - - - -
AIA E203™ 2013	Model Element Table	Model Element Author (MEA)	Level of Development (LOD)	- - - 100 200 300 - 400 500 -
BCA 2013	BIM Objective and Responsibility Matrix	Model Author Model User	Level of Detail	- - - - - - - - - -
PAS 1192-2 2013	-	-	› Level of model Definition › Level of model Detail (LOD) › Level of model Information (LOI)	- - 1 2 3 4 - 5 6 7
CIC 2013	Model Production and Delivery Table (MPDT)	Model Originator	Level of Detail (LOD)	- - 1 2 3 4 - 5 6 7
BMVBS 2013	-	-	Level of Development (LOD)	- - - - - - - - - -
BIM 2014	Matrix and Project Template	Aspect-model	Information Level	- - 0 1 2 3 4 5 6 -
AEC (CAN) 2014	Information exchange worksheet or modelling matrix	Responsibility	Level of Development (LOD)	- - - 100 200 300 350 400 500 -
Le Moniteur 2014	-	-	Level of Detail/ Level of Development (LOD)	- - - 100 200 300 - 400 500 -
BCPP 2014	-	-	Level of Development (LOD)	- - - 100 200 300 - 400 500 -
			Level of detail (LOd)	- - - - - - - - - -
			Level of accuracy (LOa)	- - - - - - - - - -
			Level of information (LOi)	- - - - - - - - - -
CBC 2014	-	-	Level of Detail (LOD)	- - - 100 200 300 - 400 500 -
BIM Taiwan 2014	-	-	Level of Development Level of Completeness Level of Detail	- - - 100 200 300 350 400 500 -
ABEB-VBA 2015	LOD Description	-	Level of Development (LOD)	- - - 100 200 300 350 400 500 -
D&R 2015	-	-	Level of Development (LOD)	-100 0 - 100 200 300 - 400 500 -
BIMForum 2015	LOD 2015 Element Attributes Tables	Model Element Author (MEA)	› Level of Development (LOD) › Level of Detail › Element Geometry › Associated Attribute Information	- - - 100 200 300 350 400 500 -
NBS BIM Toolkit 2015	NBS BIM Toolkit	Responsibility	› Level of Detail (LOD) › Level of Information (LOI)	- - 1 2 3 4 - 5 6 7
AEC (UK) 2015	-	-	› (Level of Definition) › (Level of Information (LOI)) › Grade/Level of Detail (LOD)	- - 1 2 3 4 - 5 6 -
SZGWS 2015	-	-	LOD	- - - 100 200 300 - 400 500 -
USIBD 2016	-	-	Level of Development Level of Accuracy	- - - 100 200 300 - 400 500 - 10;20;30;40;50

Comparison of the classification system used within different LoX systems v2.1 (Bojipagni & Cimbinii, 2016)

# LEVEL of DEVELOPMENT

**LOD 100      LOD 200      LOD 300      LOD 400      LOD 500**



Concept (Presentation)

Design Development

Documentation

Construction

Facilities Management

<b>DESCRIPTION:</b>
Office Chair
Arms, Wheels
<b>WIDTH:</b>
<b>DEPTH:</b>
<b>HEIGHT:</b>
<b>MANUFACTURER:</b>
Herman Miller, Inc.
<b>MODEL:</b>
Mirra
<b>LOD:</b>
100

<b>DESCRIPTION:</b>
Office Chair
Arms, Wheels
<b>WIDTH:</b>
700
<b>DEPTH:</b>
450
<b>HEIGHT:</b>
1100
<b>MANUFACTURER:</b>
Herman Miller, Inc.
<b>MODEL:</b>
Mirra
<b>LOD:</b>
200

<b>DESCRIPTION:</b>
Office Chair
Arms, Wheels
<b>WIDTH:</b>
700
<b>DEPTH:</b>
450
<b>HEIGHT:</b>
1100
<b>MANUFACTURER:</b>
Herman Miller, Inc.
<b>MODEL:</b>
Mirra
<b>LOD:</b>
300

<b>DESCRIPTION:</b>
Office Chair
Arms, Wheels
<b>WIDTH:</b>
685
<b>DEPTH:</b>
430
<b>HEIGHT:</b>
1085
<b>MANUFACTURER:</b>
Herman Miller, Inc
<b>MODEL:</b>
Mirra
<b>LOD:</b>
400

<b>DESCRIPTION:</b>
Office Chair
Arms, Wheels
<b>WIDTH:</b>
685
<b>DEPTH:</b>
430
<b>HEIGHT:</b>
1085
<b>MANUFACTURER:</b>
Herman Miller, Inc
<b>MODEL:</b>
Mirra
<b>PURCHASE DATE:</b>
01/02/2013

(Only data in red is useable)

practicalBIM.net © 2013

Figure 15. Graphical illustration of Level of Development classification [[241].

- LOD 100**

The elements of the model with this level of development can be represented graphically through a symbol or other generic representation that shows the existence of the object but does not necessarily faithfully represent its shape, size and precise location. All information in the LOD 100 is approximate
- LOD 200**

Model elements represent generic systems or objects approximating their shape, size, location and orientation. Non-graphic information can be associated to the model via links to external references.
- LOD 300**

At this level of development, model elements represent specific systems objects or assembly, defined by shape, quantity, size, location and orientation. Non-graphic information may also be attached to the Model Element, but dimensions, shapes, quantities and positions can be measured directly on the model without the need for external references.
- LOD 350**

This level of development differs from the previous one since it is possible to

integrate parameters of relation with other elements present in the model. Distances, lengths, constraints and so on can be measured directly on the model without the need for specific external documents.

- **LOD 400**

In addition to the dimensional data already addressed by the previous levels, assembly data, installation instructions and manufacturing characteristics are also included at this level of development.

- **LOD 500**

The LOD 500 provides for the on-site check of the elements, confirming their shape, quantity, size and position.

The Level of detail is instead a measure of the amount of information provided. Therefore, being only a measure of quantity, all the information provided is relevant and can be considered reliable.

The GRADE classification proposed by the *AEC (UK) BIM Protocol v. 2.0* is as follows:

- **GRADE 0 - Schematic diagram**

Symbolic placeholder representing an object. It may not be scaled and may not have all the correct dimensional values. It is particularly used for electrical symbols that can never be represented by a 3D object.

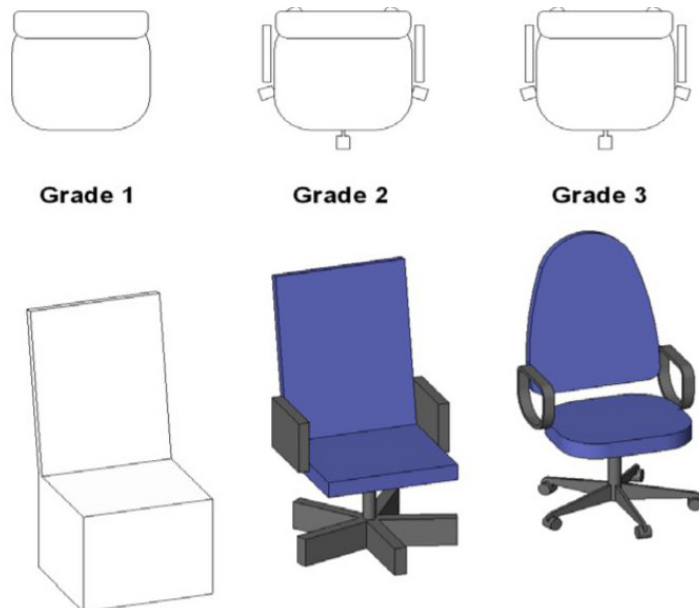


Figure 16. Classification of Detail Level (GRADE) based on AEC (UK) BIM Protocol v. 2.0.

- **GRADE 1 - Conceptual**

Simple placeholder with sufficient level of detail to make it a recognizable object. The dimensions represent the bounding box dimensions and the material is uniform.

- **GRADE 2 - Defined**

The object contains relevant metadata and technical information and the model resolution allows identifying different materials and components. The two-dimensional representation is consistent with the representation scale. This is the level of detail sufficient for most projects.

- **GRADE 3 - Realistic**

The information content shall be equal to Grade Level 2. It differs only by the definition of the 3D model, which presents more details.

## 1.5.4. Level Of Accuracy (LOA)

*"Everything should be made as simple as possible,  
but not one bit simpler."*

Albert Einstein

In addition to the Level of Development, especially in the documentation of existing buildings, particular importance is assumed by the accuracy of the model compared to the existing.

The US Institute of Building Documentation (USIBD) has defined a specific classification of Levels of Accuracy (LOA) [297] in terms of standard deviation, determined by comparing different datasets or independent measurements. Following the LOD classification, 5 different accuracy classes corresponding to different ranges have been identified, as shown in Figure 17.

LOA have to be applied to each single element and not to the whole project, so within the same model there may be elements with different LOA, depending on how the element was surveyed and how it was modelled.

For each element, therefore, there are a Measured Accuracy Level (representing the accuracy of the survey carried out) and a Represented Accuracy Level (i.e. the level of deviation of the data from the real, after processing and modelling operations).

USIBD guidelines subdivide the model elements into 7 categories (A - Substructure; B - Shell; C - Interiors; D - Services; E - Equipment & Furnishings; F - Special Construction

LOA10 >>> LOA 20 >>> LOA 30 >>> LOA 40 >>> LOA 50  
 Low >>> High

Level	Upper range	Lower range
LOA10	Defined by user	5 cm
LOA20	5 cm	15 mm
LOA30	15 mm	5 mm
LOA40	5 mm	1 mm
LOA50	1 mm	0

Figure 17. The LOA classification provided by USIBD.

& Demolition; G - Building Sitework) based on the CSI UniFormat™ classification. For each category, distinguishing between “Standard” buildings or “Cultural assets”, the “Suggested”, “Accepted” or “Special” accuracy levels are indicated (Figure 18). The “Suggested” LOAs (yellow) are based on generally-accepted standard deviations and/or recognised deviations in industry standards. “Accepted” LOAs (white) generally have an accuracy that is outside the most commonly used range but, depending on a case-by-case evaluation, may be considered appropriate. Finally, “Special” LOAs (grey) are generally considered as having a standard deviation that is higher than accepted in the industry for the respective building system or sub-system and are usually not used. The classification in “Suggested”, “Accepted” or “Special” changes between standard buildings and cultural heritage, being more restrictive for the latter.

Figure 18. Example template for assigning LOAs to elements, highlighting Suggested, Accepted or Special values [297].

Field of application  Standard  Heritage

Dimensional units  Imperial  Metric

Level 1	Level 2	Level 3	CSI UniFormat™ 2010
<b>A SUBSTRUCTURE</b>			
	A10		Foundations
	A1010		Standard Foundations
	A1020		Special Foundations
	A20		Subgrade Enclosures
	A2010		Walls for Subgrade Enclosures
	A40		Slabs-on-Grade
	A4010		Standard Slabs on Grade
	A4020		Structural Slabs on Grade

Measured Accuracy		SSSSS			
X	Absolute	If Absolute - describe reference frame here			
	Relative	If Relative - describe measure of relativity here			
<b>Level of Accuracy (2 σ std dev)</b>					
	5cm	15mm	5mm	1mm	Upper Range (Metric)
	5cm	15mm	5mm	1mm	Lower Range(Metric)
<b>LOA10</b>	<b>LOA20</b>	<b>LOA30</b>	<b>LOA40</b>	<b>LOA50</b>	(A, B, or C)
					Validation
					Note
					Exposed surface

**LEGEND**

- Suggested (Most commonly utilized)
- Accepted (Commonly utilized)
- Special (Special case - may exceed most applications)

## 1.6. Interoperability

As seen above, BIM represents a methodology in which data exchange and collaborative work are the fundamental pillars. Therefore, in order to truly use the BIM as a lifecycle methodology and not only as an intelligent model aiming at simplifying the design phase, it is necessary to create the legal and technical prerequisites to make the work really collaborative [222].

The issuing of standards and guidelines represents a clear intervention in this direction. In fact, shared procedures and methods, as well as standardized documents, are the basis for creating common language and *modus operandi* between the stakeholders. In this context, interoperability becomes a fundamental requirement.

Interoperability [284][231] is important both between the different BIM software (software BIM authoring), and between different disciplines, in order to standardize the workflow, integrate and exchange data without loss of information and make collaborative the work at the various levels of the design/management chain: architectural, technological system, energy, structural, management etc.

Interoperability therefore requires [74]:

- A clear and open workflow so that all project stakeholders can participate without limitations deriving from the specific software used
- The creation of a common language that allows public administrations to compare projects in a transparent way, evaluating the quality of services offered and relying on data quality
- The possibility of using design data throughout the building life cycle, avoiding multiple entries, which are often a source of errors
- The possibility for all software vendors to compete on a level plain field.

All stakeholders involved in the construction process (owners, designers, facility managers and software houses) will be able to benefit from this shared way of working, as efficiency in the transmission of information and standardization of procedures allows considerable economic savings [76]. This will therefore have important economic benefits for the entire AEC industry.

The interoperability issue is discussed very much in Scandinavian countries, where governments already require the adoption of open formats for project submission. Moreover, the issue will become more and more topical with the progressive improvement of BIM adoption in the various countries: the BIM Maturity Level 3, to

which Denmark and Great Britain are already projected, focuses on increasing the quality of data exchange and improving open BIM adoption.

The need for data exchange between software is not a new concept; the affirmation of DXF and IGES formats for the transfer of vector graphic data between different software was a response to this need. However, in BIM environment, in addition to graphic information, also semantic data related to each individual object have to be exchanged. New exchange formats such as IFC, gbXML and COBie were thus implemented.

### 1.6.1. IFC

One of the most active institutions in the production of open formats for data interoperability is BuildingSmart International. The company was established at the end of 1994 as a consortium of 12 private companies under the name of Industry Alliance for Interoperability. Since 1995, participation has been extended to all interested parties, becoming in 1997 the International Alliance for Interoperability (IAI) [123]. In 2008, it assumed the current name of BuildingSmart International to better reflect its proper objectives, i.e. to allow information sharing throughout the life cycle of any building, among all participants, regardless of which software application they use [74]. BuildingSmart International has developed five international open standards for this purpose, which have also been drawn on ISO and CEN standards [300][74].

- **Data Standard – Industry Foundation Class (IFC)**

It is the basic “operating system” that allows data and information exchange. It is a structured data model, a system for describing and classifying both geometric components and attributes. It is an open, public and independent data format from any software platform. It has been implemented by ISO 16739 and the latest release is IFC4.

- **Mapping of Terms – International Framework for Dictionaries (IFD)**

It includes the buildingSMART Data Dictionary (BSDD) and it is aimed at unambiguously defining terms, entities, products and processes of the construction industry. By providing common, unambiguous and shared definitions of objects and properties, IFD makes available the shared basic language that is indispensable for common understanding and information exchange without difficulty. This standard has been implemented by ISO 12006-3.

- **Process Standard – Information Delivery Manual (IDM)**

IDM is the standard for defining information exchange processes. Collaborative work involves the exchange of a large amount of information between different professionals and, in order to make the work efficient, each actor involved in the process has to know what and how much information to provide and in what moment of the process share that information.

The purpose of the IDM is also to ensure that the exchanged data is communicated correctly so that it is correctly interpreted by the target software. The IDM standard (transposed in the international standard ISO 29481) defines the processes and related information flows throughout the entire life cycle of the building.

- **Process Translation – Model View Definition (MVD)**

It is linked to the Information Exchange Manual (IDM) and represents the translation in the computer language of the specifications indicated in the IDM. In other words, it represents the software specifications and requirements for implementing an IFC interface.

- **Change Coordination – BIM Collaboration Format (BCF)**

It is a “simplified” standard based on the XML schema that encodes messages to allow communication between workflows of different BIM software.

IFC standard can be used to exchange data throughout the life cycle of a building and, from version 4, it has also been extended to infrastructure. From a technical point of

Function	Name	Standard
Describes processes	IDM Information Delivery Manual	ISO 29481-1 ISO 29481-2
Transports information/ data	IFC Industry Foundation Class	ISO 16739
Change coordination	BCF BIM Collaboration Format	BuildingSmart BCF
Mapping of terms	IFD International Framework for Dictionaries	ISO 12006-3 bSDD
Translate processes into technical requirements	MVD Model View Definitions	BuildingSmart MVD

Figure 19. IFC Technical principles. [73]

view it is defined in the EXPRESS data specification languages, defined by ISO 10303-11, and XML Defining Schema (XDS), defined by the XML W3C Scheme Recommendation [162].

All objects in the EXPRESS language are called entities and are organized into a four conceptual architecture: resource layer, core layer, interoperability layer and domain layer (Figure 20).

At the lowest level there are the basic entities definitions. Basic entities are non-specific and reusable entities, such as geometry, topology, materials, measurements, actors, roles, properties etc. They are then composed to define objects commonly used in the construction industry, such as generic walls, windows, structural elements, process elements, construction elements, building elements, management elements and generic elements, called "Shared Building Elements". At the upper level there are specific elements, with their own characteristics, used for specific uses. Objects are then defined

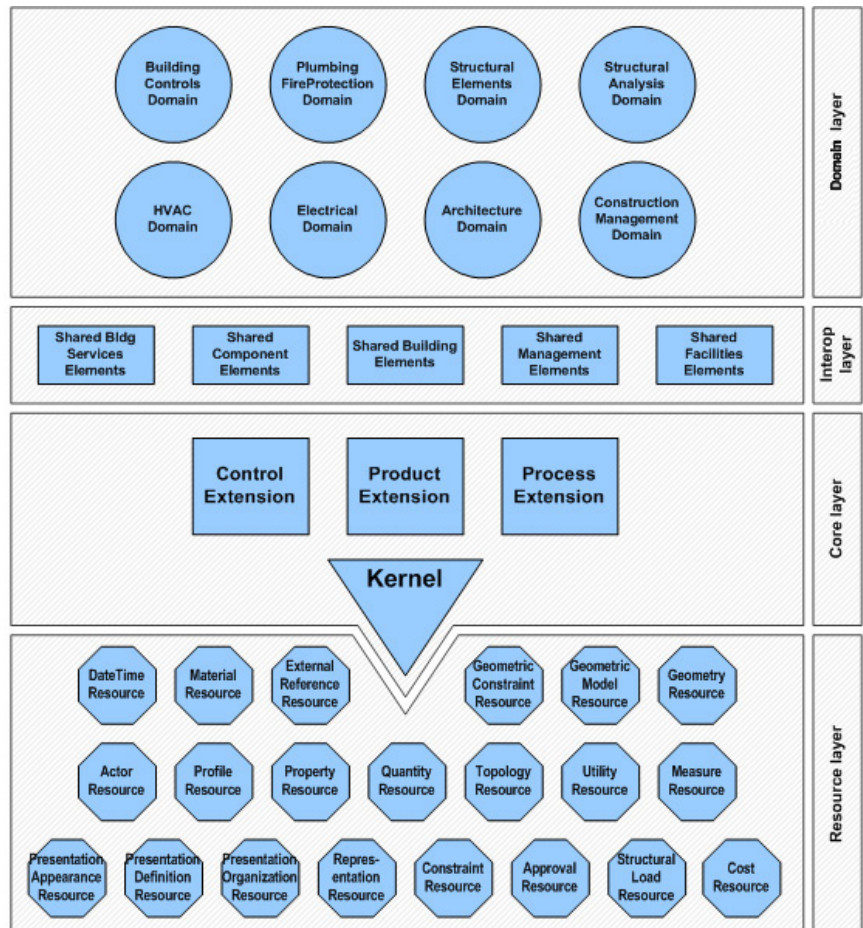


Figure 20. IFC Data architecture with conceptual layers [162]

by a hierarchical structure comparable to a tree structure. A wall in IFC format is defined as follows [123]:

*IfcRoot* → *IfcObjectDefinition* → *IfcProduct* → *IfcElement* → *IfcBuildingElement* → *IfcWall*

At each tree level, the defined attributes and relationships increase. For example, the *IfcRoot* level assigns only a global id and other identifying information; *IfcObjectDefinition* inserts the wall in a more aggregated context and identifies the components of the wall; *IfcProduct* defines the position of the wall and its shape; *IfcElement* indicates the relationship between the wall and others objects (e. g. wall limitation ratios, definition of internal spaces) and reports the openings that the wall hosts.

In this way, the IFC allows managing the geometry of objects, relationships, object properties and meta-properties, i.e. all metadata that allows handling information over time, changes, controls, constraints etc. [123].

The IFC interfaces with all the software involved in the building's life process: architecture software, energy analysis simulation software, plant engineering software, construction management software, data server, development tools, facility management software, three-dimensional modelling software, GIS software, 3D displays and structural calculation software [73].

## 1.6.2. COBie

COBie (Construction Operations Building Information Exchange) [3] is a non-proprietary format for sharing mainly non-geometric data about a building. It is designed for the exchange of information needed by facility management. The format was developed in 2008, thanks to the collaboration of the US Department of State, US Army Corps of Engineers (USACE), NASA and Veterans Association, in order to ensure that the owner/operator/resident of the building receives all relevant information in the most complete and useful way possible, replacing the large amount of paper data.

The latest COBie version is the 2.4, contained in the *National Building Information Modeling Standard (NBIMS-USTM) Version 3.0 - Information Exchange Standards; Construction Operation Building information exchange (COBie) – Version 2.4 2015*.

COBie is a spreadsheet-based format, typically a Microsoft Excel spreadsheet, designed to be opened and displayed in the various building design, construction and management software. Its versatility and simplicity allows it to be used by companies

of very different sizes and levels of experience in the Information Technology sector, allowing everyone to have easy access to information. This is not a format for editing and entry information, but only improves its accessibility and usefulness for the end user. The objective of COBie is to structure and rationalise the information that is (or should be) available at all times, in order to facilitate its subsequent re-use [3].

Therefore, the information exchanged in COBie format relates to the structure, levels or sectors, spaces and areas that constitute the building. They are then detailed with information on the systems and products actually installed, spare parts, warranties and maintenance requirements.

The structure (Figure 21) is considered as a unitary system called “facility”, which is then broken down into floor and space floors. “Zones” can be used to represent other collections of spaces for functional purposes, such as access, cooling, fire control, etc.

The physical components of the structure are assigned to the individual spaces and are grouped by “type”, i.e. by product type. As well as “zones”, “systems” are additional functional groups of components.

Every type is then associated with “spare” and “jobs” necessary to keep the asset alive and working [3].

The use of COBie has been found useful and efficient in many scenarios, including documentation of existing facilities throughout the life cycle.

COBie allows the association of a series of additional information to the objects that make up the structure:



Figure 21. Organisation of data in COBie format. Image taken from Strategy Paper for the Government Construction Client Group From the BIM Industry Working Group – March 2011 [3].

- **Contacts:** all actors involved and their roles, including designers, consultants, contractors, subcontractors and suppliers who provide information and who provide warranties and maintenance services
- **Documents:** all documents, including meetings, projects, deliveries, with any associated URI (Uniform Resource Identifier)
- **Attributes:** values with name, description and units
- **Connections:** connections between components
- **Coordinates:** location of floors, spaces and components in three-dimensional space
- **Problems:** conflicts between objects

To date (2017) COBie has been included in the design and construction contracts in the United States, UK and Singapore.

### 1.6.3. gbXML

Green Building Extensive Markup Language (gbXML) [145] was created in 1999 to facilitate the transfer of building information stored in CAD models, allowing interoperability between various drawing tools and between engineering analysis software. In particular, gbXML has been designed for the exchange of information on the energy consumption of a building.

Today, the scheme is supported by the AEC industry and major software houses working on the BIM. In addition, thanks to the export and import capability in more than 40 modelling and engineering analysis tools, it has become a standard industry scheme. Its use greatly simplifies the transfer of information from and to architectural and engineering models, thus reducing the time and, therefore, the cost of designing sustainable and energy-efficient buildings.

In particular, the possible sustainable building analyses are:

- whole building energy use and costs
- water use and costs
- carbon emission
- heating and cooling load analysis
- renewable energy
- HVAC equipment sizing

- Lighting analysis
- CFD analysis
- Fire analysis
- Solar/shading analysis
- HVAC system analysis (air and hydronic)

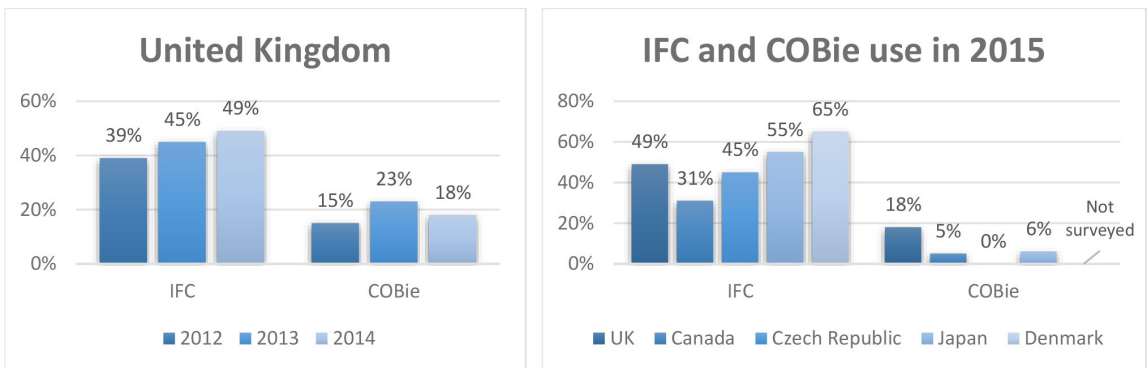
This language allows exchanging data about 3D and 2D geometry, space boundaries and information about thermal ad emission properties, fire properties, energy power and efficiency, HVAC equipment, water use, lighting and controls, ventilation requirements and so on. In other words, all data about the LCA (Life Cycle Analysis) and energetic analyses. The current version is the 6.01 released in November 2015

### 1.6.4. The actual interoperability degree

Despite the existence of different interchange formats that facilitate data transfer between different software platforms, full interoperability is not yet achieved. Looking at the results of the NBS surveys carried out in 2015 [217] and 2016 [218], it appears that the prevalence of IFC use is increasing, while COBie is still largely underused or even unknown (Figure 22).

This low diffusion of interoperable formats can be traced back to the problems that often affect their use. As testified by various literature contributions [174][288][231][222], problems can arise both w.r.t. geometry (errors in the maintenance of the original shape, impossibility of modification), and w.r.t. information content (loss of attributes, incorrect transfer of information, modification of the category of the element and consequently of the parameters assignable), as well as w.r.t. the parametric properties of objects and

Figure 22. NBS National Report 2015 and 2016. [217] [218].



their relations.

Compatibility with the IFC system depends heavily on the conversion processes implemented by the different BIM software, that, being different, can lead to unwanted geometric transformations and semantic errors [231].

Another problem relates to the adaptability and extensibility of the IFC format. It is required a great amount of time to implement the scheme, in a compliant way, with the newest technologies and construction methods. In addition, the IFC format is not simply extensible for people who are not highly familiar with the EXPRESS language. These weaknesses make often the IFC use an impractical solution [231].

Therefore, despite the research is making significant progress in the implementation of reliable interoperable schemas and the governments are working to make the creation of open BIM mandatory, today the interoperability is not yet total and further efforts must be made to reach the BIM Maturity Level 3.

## 1.7. The BIM adoption in Italy

The knowledge and the use of BIM in Italy are scarcely developed. A survey made by ANCE in 2016 shows that 70% of respondents know BIM but only a small part of them actually use it [195]. Nevertheless, the economic value of contracts relates to BIM in considerable. The BIM Italian Report 2015 [15] shows, indeed, a global amount of 1 mld € and a positive increment up to 2.6 mld € in 2016, thanks to the contribution of the Brenner Tunnel (1.3 mld € without considering the tunnel) [161].

From these reports (for the complete stats see Figure 23), results that the main part of BIM projects are public procurement (58%) and only 42% are due to private projects, demonstrating that the public sector is already more sensitive to the use of BIM methodology [161].

Another important improvement toward BIM adoption and alignment of the Italian AEC industry with European standards, is the new D.Lgs. n.50/2016 "Codice dei contratti pubblici". It implements the European Directives 2014/23/UE, 2014/24/UE and 2014/25/UE and introduces the use of Building Information Modelling.

The Code – Article 23, paragraph 13 - states that contracting authorities can require the adoption of BIM for new construction, restoration and requalification activities, principally for complex works, endorsing the use of open formats in order to not limit

the competition between software vendors [109].

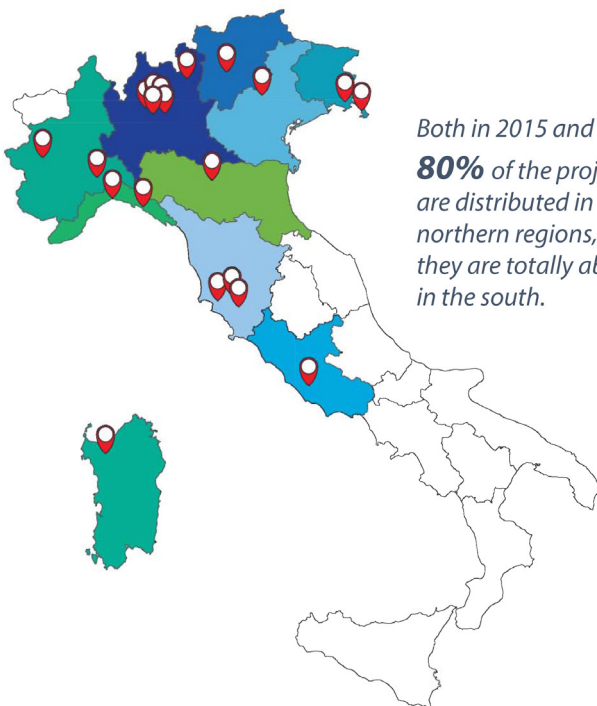
The Decree for implementation is now in public consultation and envisages that from 2019 the contracting authority will have to use BIM for all “complex works” worth more than one hundred million Euros. Gradually the obligation will be extended to buildings with a smaller amount [107]:

- from 2020 to works worth over 50 million €,
- from 2021 to buildings over 15 million €,
- from 2022 to above 5.22 million € (current EU threshold for public works),
- from 2023 to all the works over one million € and up to cover all public works (including those that cost less than one million euros) in 2025.

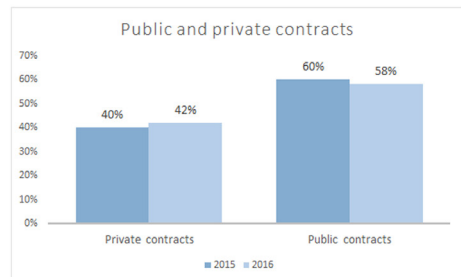
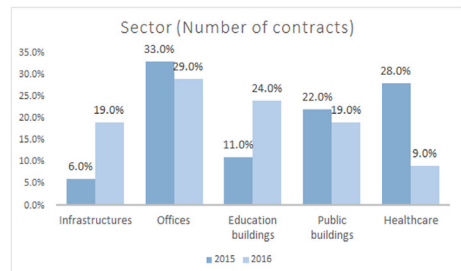
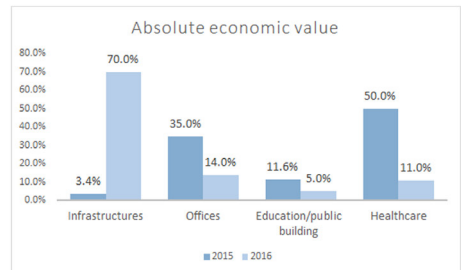
The expression “complex works” identifies works characterized by high technological content or by a significant interconnection of architectural, structural and technological aspects and projects with great executive difficulties or requiring a high level of knowledge, in order to avoid time and cost overrun [107].

Figure 23. Level of BIM adoption in Italy. Comparison between Italian Report 2015 and Italian Report 2016. Personal elaboration based on [15] [161][236].

Total investment amount:  
 2015 1 mld €  
 2016 2.6 mld €



*Both in 2015 and 2016  
 80% of the projects  
 are distributed in the  
 northern regions, while  
 they are totally absent  
 in the south.*



### 1.7.1. UNI 11337

In support of this transition to digital, the Italian organization for standardization UNI is working to define standards about digitization: the UNI 11337 series. The aim of the standard is to facilitate the transition from standard process to digital process, ensuring the correct adoption of BIM methodology.

The new UNI standard modifies the original UNI 11337 published in 2009 and is organized in eight different parts, as shown in the table below.

Part	Title	Code	Status
Part 1	<i>Models, documents and informative objects for products and processes</i>	UNI 11337-1:2017	Current
Part 2	<i>Designation and classification criteria for models, products and processes</i>	UNI 11337-2	Under Drafting
Part 3	<i>Models of collecting, organizing and recording the technical information for construction products</i>	UNI/TS 11337-3:2015	Current
Part 4	<i>Evolution and development of information within models, documents and objects</i>	UNI 11337-4:2017	Current
Part 5	Informative flows in the digital processes	UNI 11337-5:2017	Current
Part 6	<i>Guidance to redaction the informative specific information</i>	UNI/TR 11337-6	Under Approval
Part 7	<i>Requirements of knowledge, skills and competence for the figures involved in the digital management of the information processes</i>	UNI 11337-7	Under Drafting
Part 8	<i>Integrated Processes of Information Management and Decisions</i>	UNI 11337-8	Under Drafting

Table 3. The eight different parts of the UNI 11337.

The **Part 1** introduces the BIM methodology and can be applied to any construction works. In particular, it defines codification criteria for construction products and works, activities and resources, and gives proper definitions for concepts such as information,

information content, instruments for information transmission and digital object [291]. Its aim is to lead the construction process in the transition to the digital process. To define the degree of progress achieved, the standard defines 5 levels of maturity of the digital process [21]:

- *Level 0 = not digital*  
The transfer of information is carried out in a non-digital way, mainly on paper.
- *Level 1 = basic*  
Information is shared through digital and non-digital documents, but contractually the required support remains paperwork.
- *Level 2 = elementary*  
Contents are produced in a digital way, but contractually the required support remains paperwork accompanied by digital model for graphic information.
- *Level 3 = advanced*  
Information exchange is done through graphical information models and digital documents. In order to facilitate information interoperability, data can be organized according to informative templates defined by UNI 11337-3:2015.
- *Level 4 = excellent*  
Data exchange is done through information models.

So, in order to facilitate this transition to the digital, the standard provides for a review of the entire construction process (from the concept stage to demolition). This new "Informative process of construction" (*Processo informativo delle costruzioni*) (Figure 24) is organized in four "stages" (planning, design, production, management) divided into eight "phases" that concern the production and management of information contents, relating to the whole life cycle of an asset. It is a cyclical process that starts from the employer's requirements until the end of the building lifetime [232].

Not only the informative process was reviewed, but also the infrastructure work was decomposed into several informative layers (*Scomposizione informativa dell'opera*) [232]:

- *Process*: it refers to information about activities, means, equipment and human resources involved in the different stages of the construction, i.e. concept, construction, manage and maintenance;
- *Space*: it deals with information about spaces and function;
- *Construction site*: it concerns information about territory, ambient and landscape of building location;

- *Building/infrastructure*: it deals with architectural, technological, constructive and system information.

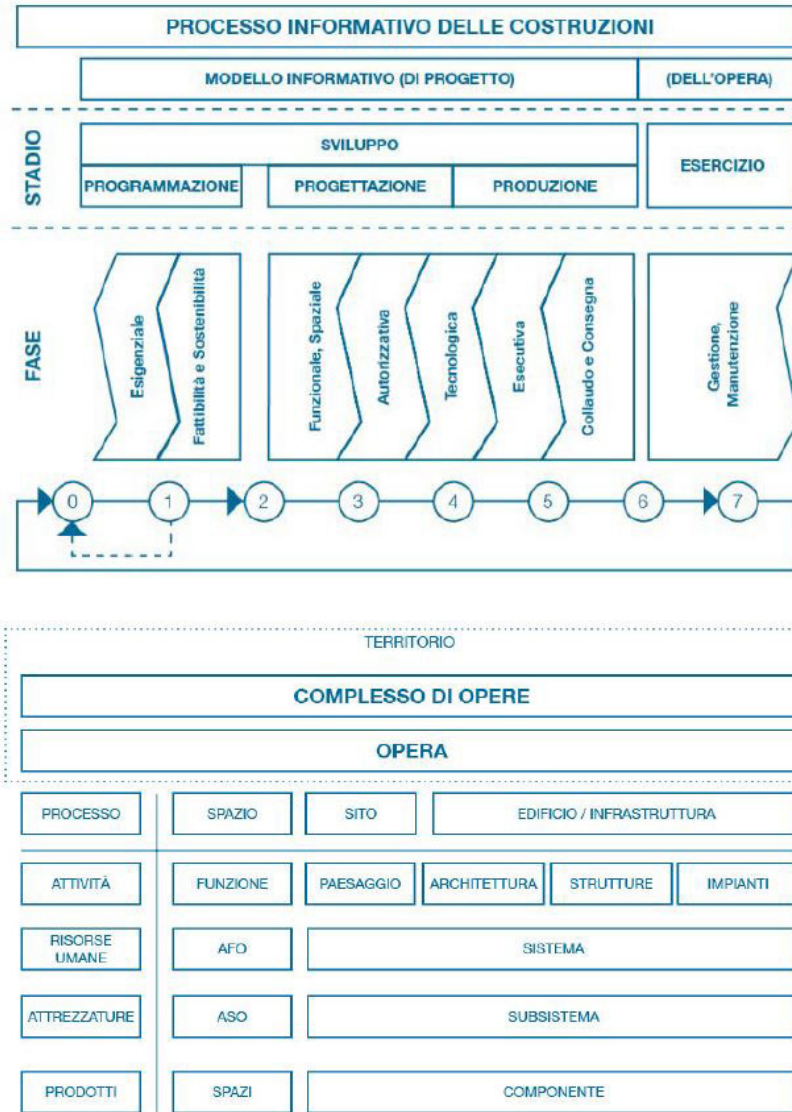


Figure 24. On the top the Information process of construction, on the bottom the Information organization of the work according to UNI 11337-1.

The **Part 4** of the standard specifies scope and characteristics of any phase of the process (0-7) according to UNI 11337-1 and defines the level of development (LOD) of objects and processes [291].

In analogy with the UK and US classification, LOD is intended as Level of Development of both graphic and informative attributes. Thus, LOD can be seen as the sum of LOG

(Level of Graphics, which defines the consistency of graphic information) and LOI (Level of Information, referred instead to non-graphic attributes).

Unlike the previous LOD classifications, the Italian standard defines 7 LOD degrees, indicated with capital letters A to G. Each level refers to a specific maturity of the object:

LOD	NAME	CHARACTERISTICS
<b>LOD A</b>	<i>Symbol</i> Oggetto simbolico	<ul style="list-style-type: none"> <li>• Symbolic 2D or 3D representation</li> <li>• Not geometric representation</li> <li>• Qualitative and quantitative information is indicative</li> </ul>
<b>LOD B</b>	<i>Generic obj</i> Oggetto generico	<ul style="list-style-type: none"> <li>• Generic geometric representation or generic placeholder</li> <li>• Qualitative and quantitative information is approximate</li> </ul>
<b>LOD C</b>	<i>Defined obj</i> Oggetto definito	<ul style="list-style-type: none"> <li>• Defined geometric representation</li> <li>• Qualitative and quantitative information is generic and can be referred to similar entities</li> </ul>
<b>LOD D</b>	<i>Detailed obj</i> Oggetto dettagliato	<ul style="list-style-type: none"> <li>• Detailed geometric representation</li> <li>• Qualitative and quantitative information is specific for many defined similar products</li> <li>• There is information related to specific construction systems, maintenance etc.</li> </ul>
<b>LOD E</b>	<i>Specific obj</i> Oggetto specifico	<ul style="list-style-type: none"> <li>• Specific geometric representation</li> <li>• Qualitative and quantitative information is specific for a single system</li> <li>• There is information related to construction, assembly, installation, maintenance</li> </ul>
<b>LOD F</b>	<i>Constructed obj</i> Oggetto eseguito	<ul style="list-style-type: none"> <li>• As-built representation</li> <li>• Qualitative and quantitative information is specific for the real product</li> <li>• Information about specific maintenance, management, reparation and substitution</li> </ul>
<b>LOD G</b>	<i>Updated obj</i> Oggetto aggiornato	<ul style="list-style-type: none"> <li>• Updated representation</li> <li>• Historical representation during the life cycle</li> <li>• Information about specific interventions carried out</li> </ul>

Table 4. The 7 LOD degrees defined by the Italian UNI 11337.

The specific LOD required does not depend on the construction process stage, but it is established by the employer during the procurement phase. If necessary, intermediate classes can be specified with the lower reference letter and an integer from 1 to 9 (e.g. LOD A.01, LOD A.02... LOD A.09).

In this classification, the main difference with respect to previous classifications is the introduction of the LOD G, intended as a life-cycle LOD. This LOD, representing the

evolution of the object during its lifetime and the transformation occurred, represents a further in-depth level after the as-built one, indicated by LOD F. This further development constitutes a novelty in the international regulatory framework.

Another innovation is the implementation of four different classification scales, according to the specific construction work addressed:

- General LOD (for buildings and new construction works)
- LOD for restoration
- LOD for infrastructure and territorial works
- LOD for means and equipment

In particular, for the purpose of this thesis, very important is the introduction of the specific LOD classification for restoration. In this context, LOD F is required to document the current situation and the LOD G for the subsequent management activities. Simplified models (LOD D and E) are allowed for specialist activities such as structural, energetic and computational analyses. LOD F includes information about management, maintenance and/or repair interventions to be executed in a scheduled program. All the actual, individual and significant interventions of management, maintenance, repair, replacement and decays occurred in time have to be included in the LOD G.

This high demand for detail, as explained in the norm, is necessary as cultural assets

Figure 25. Example of LOD of a wall. UNI 11337-4

proprietà C.1 Esempio di LOD parete						
LOD A	LOD B	LOD C	LOD D	LOD E	LOD F	LOD G
<b>Geometria</b> Elemento architettonico verticale o pseudoverticale rappresentato mediante un simbolo 2D.	<b>Geometria</b> Solido generico per rappresentazione elemento architettonico verticale o pseudoverticale con forma, spessore e posizione approssimata.	<b>Geometria</b> Elemento architettonico (sistema e sottosistema) verticale o pseudoverticale rappresentato con ingombri calcolati secondo la normativa tecnica.	<b>Geometria</b> Elemento architettonico verticale o pseudoverticale rappresentato mediante un solido avente dimensioni pari alle dimensioni reali. Sono modellate tutte le stratigrafie.	<b>Geometria</b> Elemento architettonico verticale o pseudoverticale rappresentato mediante un solido avente dimensioni pari alle dimensioni reali. Sono incluse tutte le stratigrafie, i dati specifici del trionfo dei materiali e le finiture.	<b>Geometria</b> Oggetto parete. Come LOD E (rilievo di quanto eseguito).	<b>Geometria</b> Oggetto parete. Nuovi interventi: come LOD F (con aggiornamenti) Manutenzione e gestione su elementi esistenti: come LOD G o D (a parlar da).
<b>Oggetto</b> Grafica 2D (linee e campiture 2D)	<b>Oggetto</b> Solido 3D	<b>Oggetto</b> Solido 3D strutturato	<b>Oggetto</b> Solidi 3D complesso	<b>Oggetto</b> Solidi 3D complesso	<b>Oggetto</b> Solidi parete completa	<b>Oggetto</b> Solidi parete
<b>Caratteristiche</b> - Posizionamento di massima	<b>Caratteristiche</b> - Semplici geometrie di ingombro	<b>Caratteristiche</b> - Spessore - Lunghezza - Larghezza - Volume - Definizione dei materiali - Definizione stratigrafie principali - Definizione del sistema architettonico	<b>Caratteristiche</b> - Definizione stratigrafie dettagliate - Spessori componenti - Struttura - Isolamento - Camera d'aria - Sottofondo supporto - Finitura - Dettagli costruttivi - Dettaglio dei componenti per gruppi e senza riferimenti a singoli prodotti	<b>Caratteristiche</b> - Tipofiniture interna - Superficie finitura interna - Tipofiniture esterna - Superficie finitura esterna - Composizione Materiale/Componente - Presenza certificazioni - Capacità strutturale - Trasmissione vapore - Valore R - Valore U - Valore assorbimento - Trasmissione acustica - Dettaglio dei componenti con singolo prodotto - Informazioni di montaggio - Materiale di supporto - Schede tecniche singoli prodotti	<b>Caratteristiche</b> - Manuale di manutenzione - Classificazione (UNI 8290, CSI, etc.) - Certificazioni di prodotto - Certificato di omologazione - Sistema parete finito	<b>Caratteristiche</b> - Data di manutenzione

are characterized by high degree of singularity and specificity, with specific details and features that are very influential to address design choices. This specific legislation, in a country so rich in historic and monumental buildings (such as Italy), does not surprise. On the contrary, an implementation of this standard with specific sections dedicated to restoration, discussed also in the international technical committees, is desirable.

The latest published part is the fifth one (**Part 5**), which defines roles, requirements and workflows required for the production, management and transmission of information and their connection and interaction in digitized construction processes. Significant is the clarification of the minimum content for the "Capitolato Informativo" (equivalent to the *Employer Information Requirement - EIR*) and for the "Offerta e/o Piano per la gestione informativa" (equivalent to the *Bidding BOS execution plan pre-contract Award* and *BIM execution plan - BEP*). The introduction of these documents and the definition of the Informative flows in the digital processes is important because it makes compliant the Italian legislation with the English PAS, being a step forward in the international framework [292].

## 1.7.2. INNOVance

As said before, all the efforts of public administrations for the progressive adoption of digital technologies in the AEC sector, are aimed at rationalizing information flows that link the different phases (design, build, operate, management, maintain, demolish or reuse) and the actors involved in the process itself (owners, designers, contractors etc.) [235].

Rationalization consists of standardised and organized data, shared vocabularies and definitions, proper exchange of information in order to reduce errors, misunderstandings, waste of time and costs overrun. It is indeed important that communication of information is simple and guarantees the correct interpretation of the information [235]. The research project INNOVance [163] leads in this direction. It is funded by Ministero dello Sviluppo Economico and is realized with the cooperation of 16 partners, including universities, professional associations, research centres and software houses. It is the first Italian BIM interoperable platform for the AEC sector and aims at ensuring correct exchange of structured information during the whole life cycle process among all the actors. The principal objectives of INNOVance can be summarized as follow [234]:

- Development of a unique classification system for products, services, activities and resources;
- Standardized datasheet for collecting informative attributes;
- Creation of a common database to store and share information among all actors involved;
- Creation of a web portal for exchanging information in a user-friendly and smart way.

The core system is the relational database that contains all technical, scientific and economic information useful to the construction chain. The database is articulated in [234]:

- *Space Functional System*, which allows to describe the whole work and its subdivision into homogeneous functional areas, homogeneous spatial areas and spaces;
- *Technological Construction System*, which collects information about construction products, elements and assembled systems;
- *Technological System*, which is articulated in products, subsystems and systems;
- *Process System*, which contains workings, equipment and human resources;
- *Anthropic Environmental System*, which collects information about the environment and its artificial changes.

Each of these schemes is divided in Assembled System, Installed Element and single component and products.

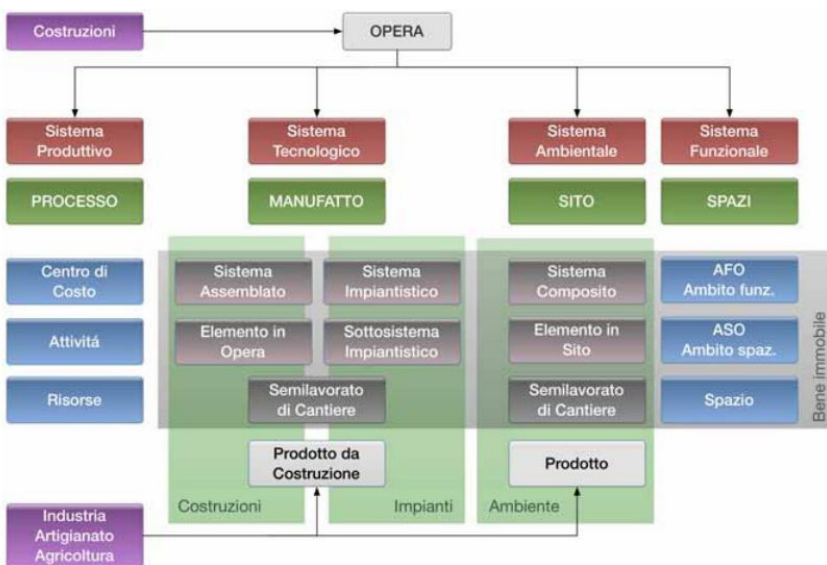


Figure 26. Informative flow from construction product and building. Image from [235].

INNOVance is based on a classification schema that allows identifying buildings and objects with different levels of complexity, identifying them clearly and uniquely. Each element in the database can be described through [163]:

- a unique name based on 7 fields, useful for defining the object with a unique code and a name. The code consists of 7 key words related to: Category, Typology, Normative Reference, Performances, Geometry, Dimension and Physical and chemical characteristics;
- a standardized technical datasheet, prepared in agreement with professionals, manufacturers and construction companies, containing all the information of that element, broken down by thematic areas;
- a BIM object (available in the main extensions currently used by software houses and in IFC and xml format)
- optional additional dossiers, more detailed than the technical file, for example concerning site construction, commissioning, maintenance, sustainability, etc.

All these data are accessible through the INNOVance web portal [164]. Users can create new objects, with coded denomination and proper technical datasheet; search for, download, and manage information about INNOVance objects, including pre-formatted views; manage a project from the initial stages up to construction and disposal; access and share INNOVance objects, with related information; download standard BIM objects to use in own projects or load objects in one of several compatible formats [163].

The portal is conceived for all user categories, including practitioners, manufacturers, vendors, building contractors, owners, public administrations, building managers and so on, and, for each of these users, the system has specific functions.

## 1.8. BIM tools

---

Since BIM is a methodology that involves all building life cycle phases, it is incorrect to identify BIM as a specific commercial software. BIM relates data, information, models, works and analysis made with different software and by practitioners of different technical areas, during the building chain. Therefore, BIM has to be considered as many different dedicated tools, interconnected and able to interoperate, communicate and exchange information.

As demonstrated in the *Environmental Scan of BIM Tools and Standards* published by the Institute for BIM in Canada in 2011 [159] there are many open or commercial tools and technologies available to support BIM implementation. This survey lists 79 commercial tools used in the AEC industry, organized according to the different stages of building life: planning & design, construction and operation.

BIM tools have to supply different functionalities, such as preliminary design and feasibility, BIM authoring, BIM analysis, shop drawing and fabrication, construction management, quantity takeoff and estimating, scheduling, file sharing & collaboration, etc. [54]. So there is a wide range of solutions available and the choice depends on the particular technical area of reference, strong/weak points of each software, specific needs and different skills of practitioners. In such a varied context, interoperability becomes fundamental to exchange data and information, avoiding the monopoly of a particular software house.

In BIM workflow, regardless of the specific software house, the main role is achieved by BIM modelling software, i.e. environments where intelligent building components can be modelled and analysed, producing worksheets and building documents. In addition, there are many other applications that are part of the BIM process by carrying out calculations and performing specific tasks (structural calculations, energy analysis, site management, etc.), starting from the more general models that will then integrate with new information [142].

The major modelling software currently in use are Autodesk Revit, ArchiCAD (Graphisoft), Bentley MicroStation, AllPlan (Nemetscheck), Edificius (Acca Software), DigitalProject, GenerativeComponents and VectorWorks [177][142].

All the contents in this chapter show how the BIM is a valuable tool for managing the information model at the scale of the building, but a hint about the use of the BIM for data management at the urban scale has to be done. There is indeed a lack of connection between elements/data at building scale and data at urban scale, generally represented by GIS (Geographic Information System). The integration of BIM and GIS could represent an opportunity for improving knowledge about building and its surrounding. For a deep knowledge of a building, it is important to understand also its relationship with the context and the characteristic of urban/landscape environment in which it is located. This information can be acquired and analysed through GIS, increasing data amount related to the single building.

On the other hand, being able to generalize and extend data gained from the single building (such as performance analyses, energy consumption etc.) to the entire urban

context, could give an overall view of global dynamics at the urban level.

For these reasons, many researches are in progress, aiming at assuring BIM and GIS data connection and interoperability [225][62][298]. In particular, this interconnection can help historical researches and activities of protection and enhancement of architectural heritage [36], or performance/energy analyses focused on the sustainable development of smart cities [227][225].



# Historic BIM for Cultural Heritage documentation

As far as historical buildings are concerned, it is important to understand if and how the BIM could be a real benefit for the study of these assets. In fact, historical buildings have different characteristics compared to new buildings. They are a unicum and are composed of elements which are similar but different from each other.

Therefore, the question is how a standard approach, such as the BIM process outlined in the previous Chapter, may be suitable to describe a historical asset in all its aspects, from modelling, to management and analysis of information.

At a first glance, a BIM process designed for new constructions is unsuitable for historical buildings, since the process is, in a way, opposite w.r.t. the one for new construction works and has different aims.

Although the principal aims of a Historical BIM are not design and construction phases management, HBIM is very useful for enriching the knowledge about the building, documenting the asset and monitoring its health conditions. In this context, historical and time dimensions are the main features to take into account.

This Chapter examine in depth the use of BIM in the Cultural Heritage field, considering the BIM as an information system at the architectural scale. In fact, it is just as an information system and not as a tool for standardization and increase of productivity, that BIM plays a key role in cultural asset documentation. BIM can be seen as a common point of access and management of all building information over time and, in this respect, it can facilitate restoration and maintenance work on the artefact.

Starting from the consideration that laws and regulations are almost non-existent (except the recent Italian UNI 11337-4:2017, which introduces specific LODs for restoration

works), the Chapter will analyse the main publications and studies in this field, in order to understand strengths and weaknesses of BIM for Cultural Heritage documentation. In particular, paragraph 2.1 will analyse the usefulness of BIM application in the Cultural Heritage field and paragraph 2.2 will show the main methodologies and techniques available today for converting reality into information models. Then, attention will be paid to how these techniques can be extended to Cultural Heritage and what are the still open questions, especially about the semantic classification of historical elements, the modelling techniques and the database design phase (paragraph 2.3). In all paragraphs, some methodological considerations will be made on how the accuracy of the survey and of the model influences the final results and the reliability of any analysis and query performed on the model, since geomatics has a central role in considering this issue.

## 2.1. Importance of HBIM for Cultural Heritage documentation

---

Italy is undoubtedly the country that holds the greatest part of world Cultural Heritage. It is the first country for number of UNESCO World Heritage Sites, 53 sites (48 cultural sites and 5 natural sites), coming before Spain (44), Germany (42), France (42) and China (36) [290]. Moreover, Istat (Istituto Nazionale di Statistica) sources note that Italy has a great number of museums or similar institutions, quantifiable in 1.7 institutes per 100 km<sup>2</sup> and about one every 12,000 inhabitants [168].

According to the statistics office of the Ministry of Cultural Heritage and Tourism (MIBACT), there are 203 state museums and 250 monuments and archaeological sites with paid or free admission in Italy in 2016. The number of visitors in 2016 was 45'521'194, with an increase of 3.94% compared to 2015 and 22.37% compared to 2012. The same argument applies to gross earnings that reach 174 million euros [189].

It is therefore obvious that the incomes directly linked to visits to cultural assets and to all the satellite activities (such as accommodation facilities and businesses) have positive economic repercussions for our country. Cultural Heritage is an important resource for economic growth, employment and social cohesion, offering the opportunity to revitalize urban and rural areas and to promote sustainable tourism. It also enriches the individual life of citizens, with benefits for the cultural and creative sectors [97].

Knowledge, preservation and conservation of cultural assets, in addition to promotion

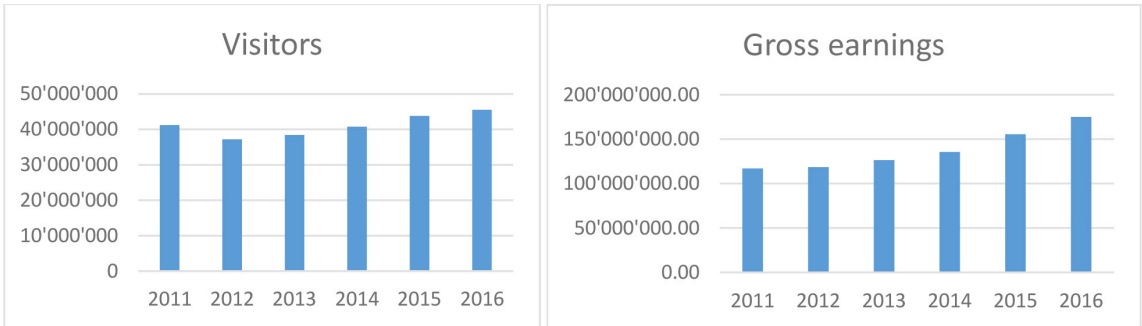


Figure 27. Number of visitors and gross earnings in € at Italian Cultural Heritage sites. From: Statistics office of the Ministry of Cultural Heritage and Tourism (MIBACT), 2016.

of activities, are very important matters and the first steps for Cultural Heritage valorisation. Safeguarding and preserving historic heritage guarantees a remarkable economic return and should represent a large investment field in our country.

Cultural assets knowledge and conservation requires the interrelated analysis of different information (spatial, geometric, historical, thematic, temporal etc.). To manage this heterogeneous and multi-layered information, information systems have taken a crucial importance. In fact, these tools allow for managing both spatial/geometric and thematic data, relating heterogeneous data collected from different datasets and handling the temporal dimension. The possibility of managing simultaneously all these data and, combining them, deriving additional information enhances heritage documentation.

In Europe some examples of information systems for collecting data about cultural assets have already emerged. It is the case of the *Kist o Riches* by the School of Scottish Studies developed by the University of Edinburgh in 2015 or the *CultureSampo* promoted by the Helsinki University of Technology in 2015. Italy too has its web information system, *SICarweb* [279], for documentation, design and management of restoration sites. It integrates the geometric representation of the assets and their respective thematic maps, essential for restoration, with the management of heterogeneous information organized in a database on dedicated tabs [6].

BIM too can be used for describing historical buildings. In fact, BIM represents an information system at architectural scale and makes it possible to manage semantically enriched three-dimensional models [277], having positive impact in the analysis of historical buildings. The first Historic Building Information Modelling (HBIM) was realized by Murphy et al. [197][198]. They introduced the acronyms HBIM and defined it as “a novel solution whereby interactive parametric objects representing architectural elements are constructed from historic data, these elements (including detail behind the scan surface) are accurately mapped onto a point cloud or image-based survey” [197].

Other important pioneer projects in the use of BIM or information systems for Cultural Heritage documentation are the Architectural Information Modelling (AIM) developed by Pauwels et al. [230], the NUBES Project implemented since 2007 by the research group of Livio De Luca [103][104] and the projects conducted by Attar et al. [24] Fai et al. [132], Arayici [19] and Boeykens et al. [61].

The use of BIM for restoration works, as demonstrated by literature, has many advantages that can be summarized as follows:

- Documentation of the building over time
- Outlining of the different construction phases [68] [285]
- Support for analyses of structural and material deterioration evidences
- Virtual reconstruction of destroyed buildings on the basis of historical documentation [103] [105]
- Support for Augmented Reality applications and web sharing, useful for promoting the asset and for assisting maintenance works on the building [136][5]
- Support for ordinary maintenance programs [136]
- Keeping track of all intervention occurred
- Having a unique database that collects all data about the building [132][16]
- Integrated and interdisciplinary management of information
- Support for structural behaviour and FEM analyses [220][117][140][96]
- Support for energy analyses [68] [24] [144]
- Making quantitative esteems
- Integration of BIM and GIS data for deeper knowledge both of building and its surrounding [115][84][274].

Above all, the documentation function is crucial; it is the basis for every action on the building, from promotion to maintenance, restoration and renewal. HBIM can be seen as a unique archive that includes all information about the asset and as an information system at architectural scale.

Thus, the use of BIM for documenting existing buildings, in particular historical ones, can be a big challenge but, at the same time, a great opportunity for a better and deeper knowledge of these assets. The hope is that, in the near future, the use of this technology in the Cultural Heritage field will improve.

## 2.2. State of the art: methodologies and technologies

The creation of BIM for existing buildings follows an opposite process with respect to new construction one, starting from the existing and arriving, through the survey, modelling and information enrichment, to the digital model.

The entire process can be detailed as outlined in the flowchart below (Figure 28) and, summarizing, it is composed of a preliminary survey phase and a consequent modelling phase, of both geometric (3d modelling) and semantic data (database design and implementation).

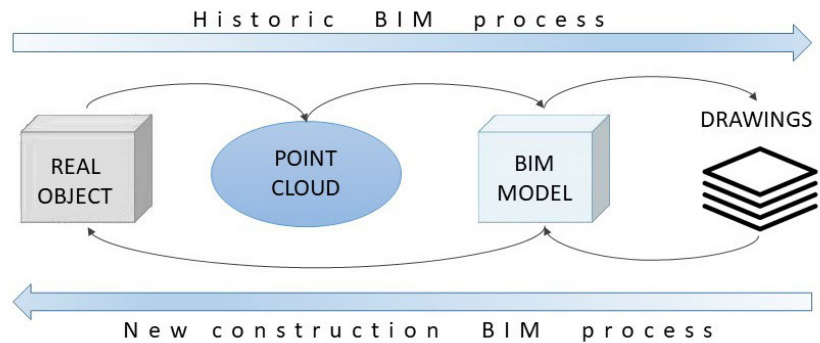


Figure 28. Comparison between the BIM process for new buildings and for existing ones.

Today there are different consolidated techniques available in each of these fields, but in order to analyse historical assets, not all the methodologies are suitable. In particular, there are several issues to be taken into account, such as the accuracy and reliability of the survey, the adherence of the model to reality, time and historical data management and so on. The aim of this part of the thesis is to investigate costs and benefits of the available techniques, both in terms of reliable application and correctness of the results, and to highlight the geomatics contribution in the debate about these themes.

To correctly document cultural heritage buildings, a preliminary phase of study, in which building characteristics are assessed and BIM final purposes are set up, is crucial [114]. Both geometrical survey and in-depth historical and archival research have to be performed since, on the one hand, historical data are essential to have the basic knowledge of the building past but, on the other hand, these documents are often lacking or incomplete and, in any case, not as exhaustive as expected. For this reason, the building is always document of itself and can be deeply known through accurate

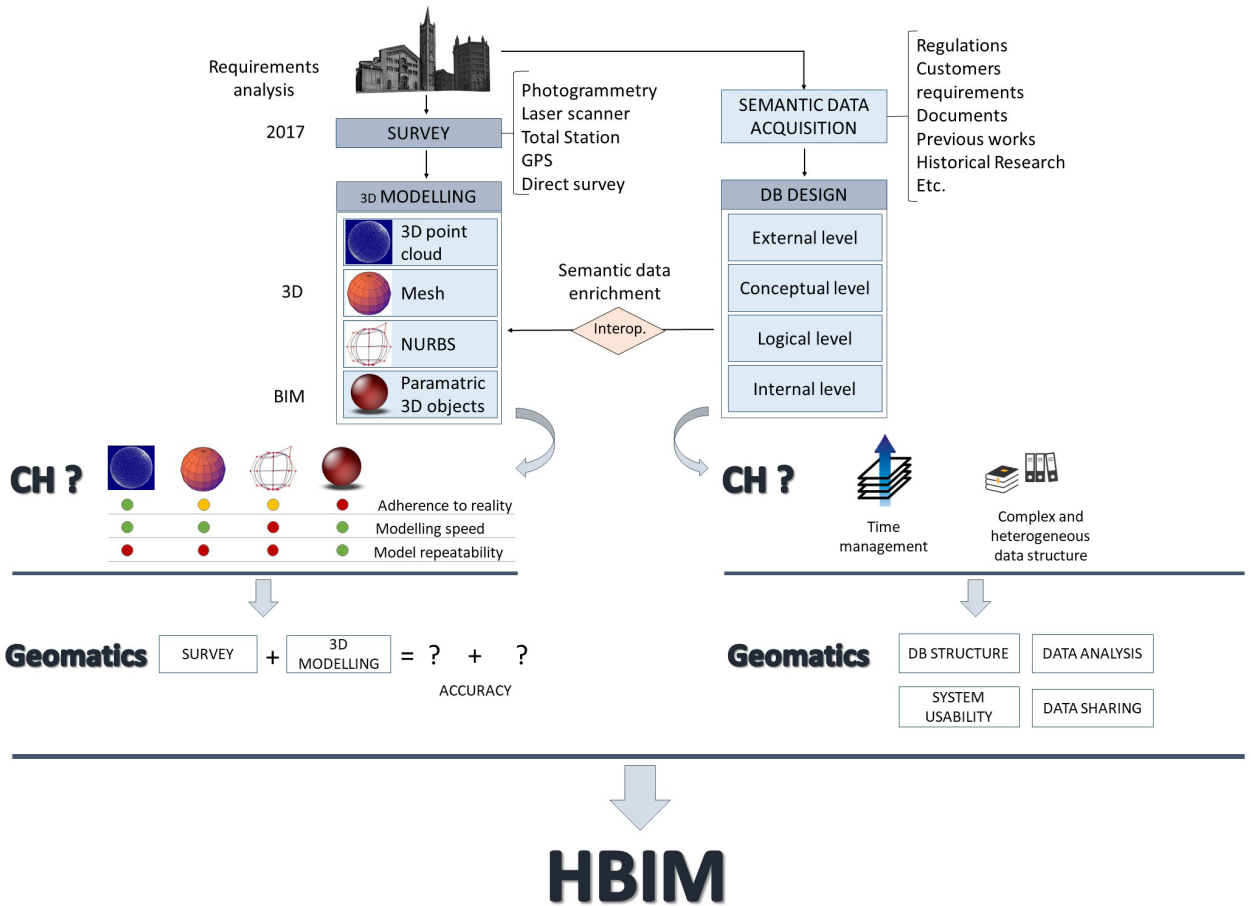


Figure 29. HBIM process conceptual schema. The main issues and contributions of geomatics disciplines are highlighted.

spatial, geometrical, material and structural analyses [140].

Geometrical survey and data elaboration are deeply investigated in literature [81] [41][5][135][140][210] and, to date, the workflow is well-established (paragraph 2.2.1). On the contrary, semantic data acquisition (paper-based document digitising and relational database design [132]) is less investigated, with only a few literature references (paragraph 2.2.3).

In general, the most discussed issues, in HBIM implementation, concern the survey data processing (paragraph 2.2.1) and the modelling phase (paragraph 2.2.2).

Geomatics is involved especially as far as survey and model accuracy are concerned. They indeed influence the final results and the reliability of any analyses and query performed on the model. Moreover, the database design, with particular respect to database organization, system usability and query and data sharing. All the above

mentioned are key issues for our specific disciplines. The thesis will address all of them and in particular the last ones.

### 2.2.1. Geometric survey and data elaboration

The real world (in this case represented by the building) is so complex and, in order to create a model of it, it is essential to know how to simplify the reality, thus a preliminary phase of study is important.

As far as the general workflow is concerned, from the analysis of literature [81][135][79][37][140][252][253][153][57], the most agreed upon and consolidated process is summarized in Figure 30.

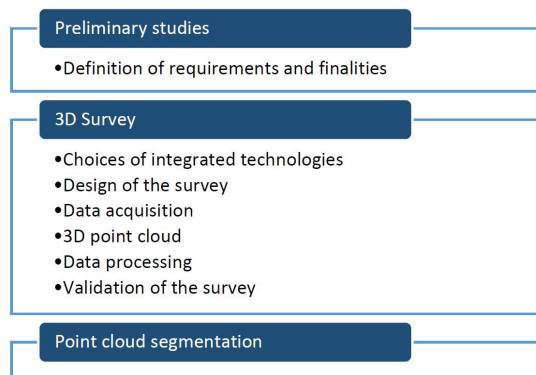


Figure 30. Typical workflow for survey and data management. Personal elaboration according to literature analysis

Geometric and spatial data are generally acquired through integrated survey [81], since integration allows obtaining different products (such as orthophotos, dense point clouds, discrete highly precise measures) and overcoming the specific limitations of each technique, having more complete results [43][263][137]. Moreover, the integration of multiple techniques speeds up and optimizes survey acquisitions and produces multi-scale and multi-functional data [5], increasing the available products.

In the field of geomatics, there is a large body of literature on instrumental surveys and the acquisition techniques are well-established. The main techniques available today include total station and GNSS surveying, terrestrial laser scanning (TLS) and photogrammetry [81].

Today, the use of Unmanned Aerial Vehicle (UAV) equipped with high-resolution cameras or even lightweight TOF laser scanners [114] for Cultural Heritage documentation is emerging. In particular UAV are used for documenting archaeological sites [100],

monitoring and damage assessment, and in general for surveying not directly accessible heritage, overcoming difficulties (such as occlusions and roof survey) that affect surveys from ground level in an efficient and inexpensive way.

As far as survey for BIM implementation is concerned, there are not regulations or specific guidelines. To the best of the author's knowledge, the only guideline that deals with laser scanning and photogrammetric data acquisition for BIM implementation is the *GSA BIM Guides Series 03: BIM Guide For 3D Imaging* [294]. This guide summarizes pros & cons, suggests examples of applications and gives guidelines for instruments use, reduction of errors and data processing. Nevertheless, as it dates back to 2009, this document is no longer exhaustive up-to-date, due to the many improvements occurred in these fields. .

Thus, in this regard the principal reference is the scientific literature, which represents the most advanced and exhaustive documentation in this respect.

Today the research is mainly focused on these principal aspects:

- Management of big survey datasets
- Multi-resolution survey
- Automatic point cloud segmentation.

The primary outcome of integrated surveys, in particular laser scanning and photogrammetry, is a dense and big point-cloud, i.e. a collection of 3D data points in a given coordinates system that describes the building.

The point cloud describes the geometric complexity of the object but, semantically speaking, each point is equal to the other and the point cloud model is not a semantic model [275]. Thus, in order to produce an object-oriented model with semantic information, the point cloud must be segmented, grouping points that share a spatial similarity [242] and giving semantic connotation to each part.

The two principal issues here are the geometrical identification of elements and the enrichment with semantics data of each geometrical shape.

Many researches and algorithms have been developed for the automatic identification of specific elements, such as geometric primitives, façades, walls, pipes, as summarised in Previtali et al. 2013 [242].

Interesting results have been obtained especially in façade segmentation and automatic modelling. Methods are presented in Müller et al. [196], who implemented the automatic modelling of building façades starting from a single rectified image through the identification of horizontal and vertical straight lines; by Boulaassal et al. [64],

who, working on laser scanning point clouds, extracted the main lines that define the façade and the openings; by Pu and Vosselman [244] who worked on planar element identification and classification of building features, and by Previtali et al. [242] who identifies the main façade elements, reconstructs 3D vector models and enriches data with semantics, using a classification tree.

These methods work on rather simple and planar surfaces using algorithms designed for small-scale point clouds or RGB-D images (Red Blue and Green images with associated Depth values).

However, laser scanning survey produces generally large-scale point clouds that represent the entire building. A recent paper on segmentation of large-scale point cloud at once is presented by Armeni et al. [20], that proposed a method for semantic parsing the point cloud of an entire building through a hierarchical approach. They, starting from the raw coloured point cloud of an indoor space, first divided it “into semantic spaces (e.g., hallways, rooms), and then further parsed those spaces into their structural (e.g. floor, walls, etc.) and building (e.g. furniture) elements” [20].

### 2.2.2. 3D modelling

There are several modelling techniques and commercial software that can be used to represent a building, starting from survey data. Up to date, the ways for representing a 3D model can be summarized in: mesh surfaces, NURBS (Non-Uniform Rational B-Splines) surfaces, B-Rep (Boundary representation), CSG (Constructive Solid Geometry) and parametric objects. The main modelling techniques are reverse modelling, direct modelling, generative modelling and object oriented modelling [288] and can be classified in: parametric or non-parametric, global or local and surface or volumetric representation [156].

Parametric modelling allows for describing the model with a finite number of parameters, non-parametric models are created starting from geometric primitives and working with modelling operators. Global representations refer to the description of the entire object through the same model, local representations are considered when the object is decomposed in portions and each element/part is modelled by itself. Surface representation refers to shapes description and volumetric representation refers to geometric solids or parametric objects [156].

Figure 31 shows the relationship between 3D representations and modelling techniques and is used as basic schema for this paragraph.

Modelling technique	Parametric	Non-parametric	Local	Global	Surface representation	Volumetric representation
Reverse modelling (MESH)		X		X	X	
Direct modelling: NURBS		X	X	X	X	
CSG		X	X			X
Generative modelling	X		X		X	
Parametric object oriented modelling	X		X			X

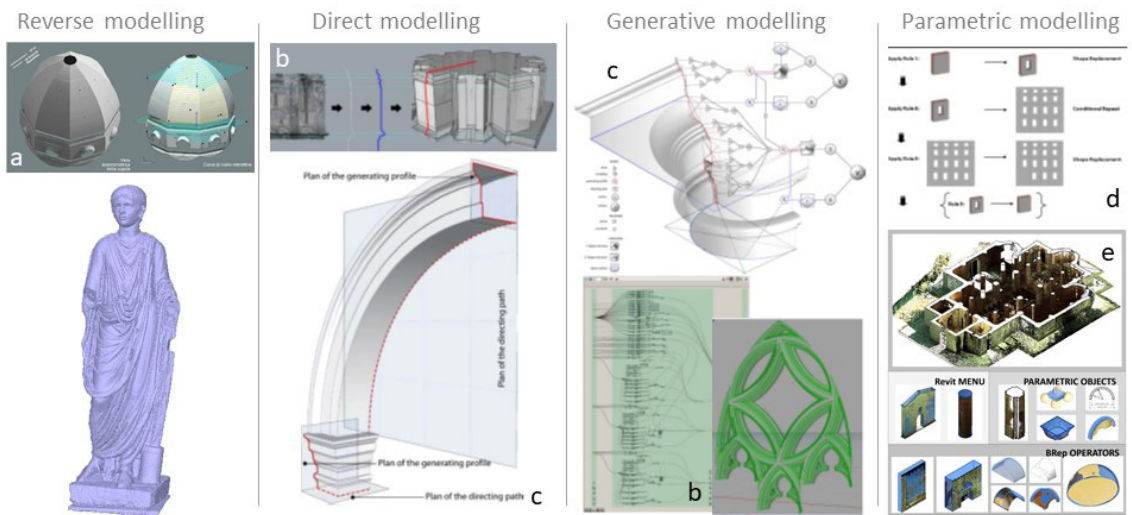


Figure 31. Summarizing table of main modelling techniques and their main classification. a from [90]; b from [180]; c from [103]; d from [116]; and from [245].

## Ways for representing a 3D model

### Mesh surface

Mesher [239] are surfaces described by a collection of vertices, edges and faces that defines the shape of a polyhedral object. Generally, faces are triangles, quadrilaterals or other simple convex polygons.

There are many ways for representing a mesh, according to the specific method used to store the vertex, edge and face data. A detailed analysis of the different types of data storage is out of the scope of this work, but it is necessary to underline that in general meshes require high storage capabilities.

Mesher can represent complex objects that cannot be described by simple geometric rules. However, they approximate curved surfaces and the quality of the approximation depends on the size of the polygons. Smaller polygons fit better the surface but make

the final model bigger.

In addition, it is difficult to perform many geometric operations on mesh surfaces and editing is not easy.

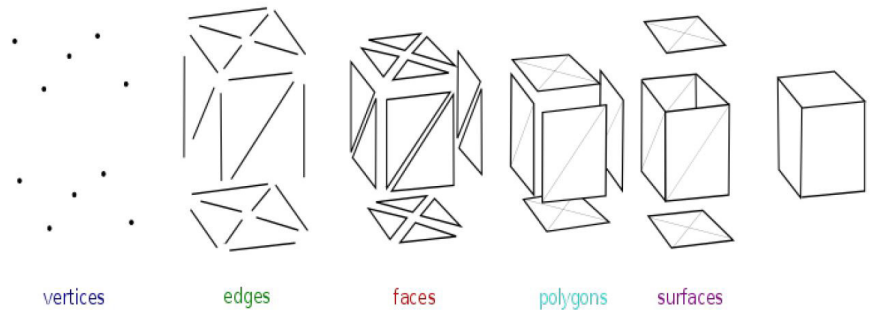


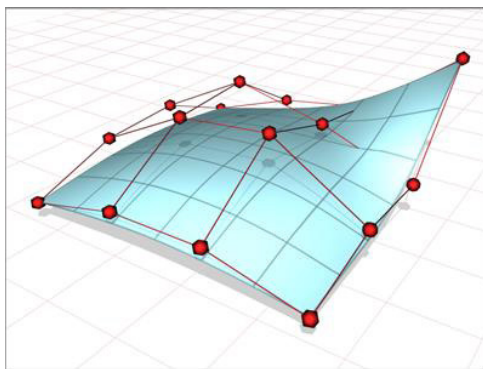
Figure 32. Elements of a mesh surface. From: [239]

**NURBS surface**

NURBS (Non-Uniform Rational B-Splines) [254] are mathematical representations of geometry, which accurately define any form: from a simple line, circle, arc or curve to the most complex solid or surface free or organic 3D shape.

A NURBS curve is defined by four features: degree, control points, knots, and estimation rule. Degree is a positive integer (usually 1-5) that defines the curvature of the curve. The control points are a row of points at least equal to (degree + 1). Each control point is associated a weight that represents its ability to attract the curve. Bar some exceptions, the weights are positive numbers. When the control points of a curve all have the same weight (usually 1), the curve is called "non-rational". Otherwise, it is called rational.

Knots are a row of numbers equal to (degree + N-1), where N represents the number of control points. This sequence of numbers, that specifies the parametric definition of the curve, is also called "node vector". Control points and knots control the curve's shape and can be directly manipulated to change its smoothness and curvature.



The estimation rule is a mathematical formula that assigns a number to each point. The NURBS estimation rule is a formula for degree, control points, and nodes. It calculates the so-called basic B-spline functions. BS letters in NURBS acronym are for "base spline". The number with which the estimation rule starts is

Figure 33. Control vertices in a Nurbs surface. From: [http://www.3dmax-tutorials.com/CV\\_Surface.html](http://www.3dmax-tutorials.com/CV_Surface.html)

called “parameter”. The estimation rule can be considered as a “black box” that receives a parameter and generates the position of a point. The degree, nodes and control vertices determine how this “black box” works [254].

NURBS can describe curved surfaces very well and the editing can be done changing the position or the number of knots and control points. Compared to the meshes, NURBS reduces also the memory usage when storing shapes, allow flexible and accurate design of a large variety of shapes and can be evaluated reasonably quickly by numerically stable and accurate algorithms.

### B-Rep (Boundary representation)

B-Rep can be considered as an extension to the wireframe model. It represents a solid shape bounded by its surface and has its interior and exterior. [65] It represents shapes using limits (boundaries) between connected surface elements. It is a vector graphics format that represents only the edges of a solid, then coating the surfaces obtained with textures to represent their final shape. In a B-rep there is topological and geometric information. Topological information provides the relationships among vertices, edges and faces and include orientation of edges and faces. Geometric information is usually equations of the edges and faces [65]. As far as geometric modelling is concerned, B-Rep is very flexible and allows Boolean operations, extrusion (or sweeping), chamfer, blending, drafting, shelling, tweaking and other operations [66].

### CSG (Constructive Solid Geometry)

CSG [95] is a representation of volume-based 3D objects. In this approach, the forms are constructed from a family of elementary geometric solids, which are called primitive, such as the parallelepiped, the cylinder, the sphere, the cone, etc. In order to build complex volumes from these elementary ones, volumes are combined using Boolean operations (union, difference, intersection), so, compared to B-Rep modelling, CGS is less flexible since allows only Boolean operations.

The process leading to the final solid can be arranged in a pattern called the CSG tree: each leaf represents a solid and every node corresponds to a Boolean operation, while at the top there is the final object.

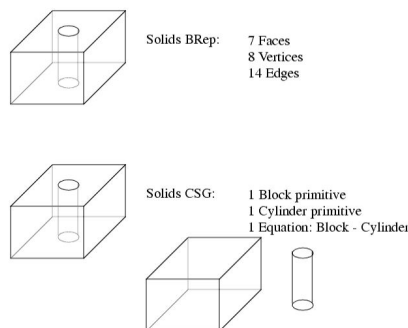


Figure 34. Solids BRep and Solids CSG. From: [http://engineeronadisk.com/notes\\_design/solidsa3.html](http://engineeronadisk.com/notes_design/solidsa3.html)

### Parametric objects

Parametric objects describe a model with a finite number of parameters, such as length, height, thickness, radius etc. In this way, the model is not unique, but is repeatable and editable in any step by simply changing the parameters. The model is “intelligent” and can be adapted to many specific cases, speeding up the modelling phase. Parameters are useful for describing the rules that determine the geometric shape of the object, the topological relation with other object in the model and constraints.

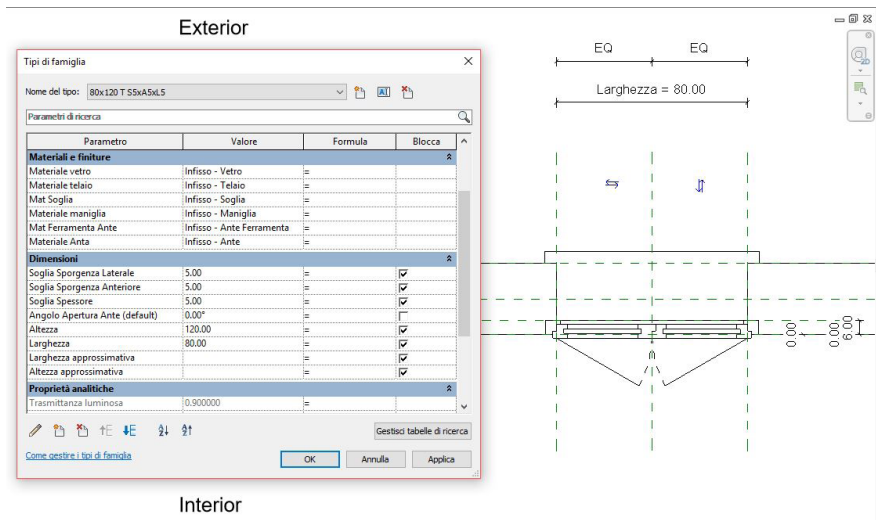


Figure 35. Parametric object example.

The use of one or another technique depends on the object features and on the modelling needs.

## Modelling techniques

### Reverse modelling

Reverse modelling implements automatic tools that translate the point cloud in a polygonal mesh surface. It is the quickest and most accurate way to model a surface starting from the point cloud and Reverse modelling software (such as Geomagic [146], MeshLab [188]) provide algorithms that automatize these operations.

### Direct modelling

Direct modelling is performed through modelling software (such as Rhinoceros [255], 3D Studio Max [26], Maya [27]) in which it is possible to create graphic primitives or two-dimensional sections from the point cloud and model using them as guides. Generally,

NURBS, B-Rep and CGS are produced. It is a time-consuming process since it requires the extraction of contours and discontinuity lines, deconstructing the global surface into its generative shapes. Therefore, the comprehension and the abstraction of the geometrical structure of the object to model is mandatory. Moreover, each element is unique and, even for similar elements, it is necessary to restart the modelling process [288] from the beginning. Consequently, modelling in this way is very time-consuming, since it is indispensable to perform several task (e.g extract many different horizontal and vertical sections to define all profiles) necessary for reconstructing complex shapes.

### **Generative modelling**

Generative modelling works with NURBS and allows for creating parametric models, starting from a sequence of commands. In this way it is possible to create also complex shapes. This is the case, for instance, of tools such as Grasshopper [151] (plug-in to Rhinoceros) or Dynamo [120] (plug-in to Revit). Generative modelling is defined by Tedeschi [286] as an algorithmic modelling approach where “the goal achievement is always related to a proper detection and resolution of the different problems associated to a specific operative range. The resolving procedure is usually tied to the decomposition of the problem in a number of simpler steps that ensure an efficient management of the process with traceability and transmissibility of the involved phases. This type of approach, combining cognitive mechanisms and human reasoning, is transferable to the pc with algorithms”.

Once the object has been decomposed into its generative shapes and the geometric rules for its construction have been identified, a sequence of operations can be set that allows the semi-automated modelling of the object. In this way elements with similar shapes and geometric rules but different proportions and dimension, can be modelled automatically simply changing the parameters [288].

In the cultural heritage field, studies have been made especially about Gothic architectural elements. These elements are, in fact, characterized by complex but recurrent geometric shapes, thus the generative modelling approach has considerably accelerated the modelling phase [180][155][124].

### **Parametric object oriented modelling**

Parametric object-oriented modelling is based on the use of pre-modelled objects collected in libraries. This is the typical approach of BIM software (such as Autodesk Revit [31], ArchiCAD [150], Allplan [208], VectorWorks [299]) which uses simple and regular

objects to describe the entire building. These objects are “intelligent” since they have semantic definition, relate with other objects according to specific rules and topological constraints and are associated to an internal database containing all information and parameters useful for their definition.

All these methods are now consolidated and, today, the main fields of research refer to implementation of automatic modelling strategies and to definition of instruments and techniques for realization of more and more accurate models.

Automation is needed above all to speed up time-consuming direct modelling operations and reduce the human intervention in the process [287]. To this aim, Barazzetti et al. [38] found a semi-automated methodology for creating NURBS from point clouds and use them as basis for parametric modelling [38]. This approach allows for discontinuity lines detection through NURBS curves and the creation of a NURBS curve network to densify discontinuity lines. NURBS surfaces are created interpolating these curves.

Another interesting research has been made by Garagnani et al. [141]. Their implemented plug-in, GreenSpider, lays out points in space, as if they were nodes of an ideal network in Revit environment. In this way, these detected points can be used for tracing interpolating splines, in order to model surfaces (also irregular ones) with accuracy.

There are also several software, plugins and academic researches that work on automatic recognition of points cloud elements and automatic modelling of parametric objects [287][242][116].

However, while the Barazzetti’s and Garagnani’s approaches work on irregular shapes and have been developed to manage complex objects, the algorithms implemented for parametric modelling work on simple and repetitive elements, so they are not applicable to the field of cultural assets.

As far as the modelling phase into BIM environment is concerned, parametric object-oriented modelling is almost exclusively used.

Meshes, in fact, are useful for describing free form objects, ensuring an acceptable and reliable fitting of the model to the point cloud, but they are not suitable for representing an entire BIM model. A mesh model is big and is a global representation of the entire object (in this case a building), thus it is difficult to segment it in its specific components. A mesh is, in fact, a surface while a building is composed of objects, with a proper thickness and volume. For this reason, their use is limited to description of single free form objects, then imported into the BIM environment. However, this operation is not always permissible and many BIM software do not allow direct mesh insertion or cause

many losses of its features [288].

As far as NURBS are concerned, they can be imported into BIM more easily: nonetheless NURBS are still scarcely used, because they cannot be created through an automatic modelling procedure (such as meshes) and consequently require a long direct modelling process. There are examples of BIMs made only with NURBS objects (NUBES project [103] and BIM3DSG system [250]) but, in those cases, an ad hoc information system was created without working within commercial BIM software.

In fact, commercial tools have many interoperability problems and constraints [288], which limit the possibility of importing objects modelled with other software.

### 2.2.3. Semantic enrichment and database design

Literature references about semantic data and HBIM model enrichment are not many. In most cases, the issue of qualitative historical data is ignored or not deepened. In fact, the digital processing of historical data (such as photographs, blueprints, archival documents and plans, original drawings, sketches, texts etc.) is generally discussed in other disciplines and is often unrelated to BIM [176].

These documents are generally paper-based and so they have to be digitised and organized in a relational database architecture [132]. Nevertheless, there are not guidelines or consolidated procedures that specify what data have to be searched, how to digitize and organize them in a relational database in order to preserve their features, nor what information should be associated with the BIM.

Generally, database design is a topic in information technology or in GIS. Database structure and data organization are extensively treated, even for historical data [69]. In BIM, semantic data are arranged in the integrated database, by inserting parameters, i.e. attribute associated to BIM elements. Nevertheless, parameters are commonly linked to the element in a 1:1 relationship and the relational complexity is lost. Hence, in order to simplify data exchange and management, it is necessary to link external databases (Access, MySQL, SQLserver or PostgreSQL) with BIM software (Figure 36).

As presented in [181], there are several commercial solutions available for synchronizing BIM models and external database. They are, for instance Ideate – BIMLink [160], WhiteFeet Tools [302], Trelligence – Affinity [289], CodeBook [93], Nosyko dRofus [213] and Onuma Planning System [219].

This remarkable software development reveals a considerable interest in the link

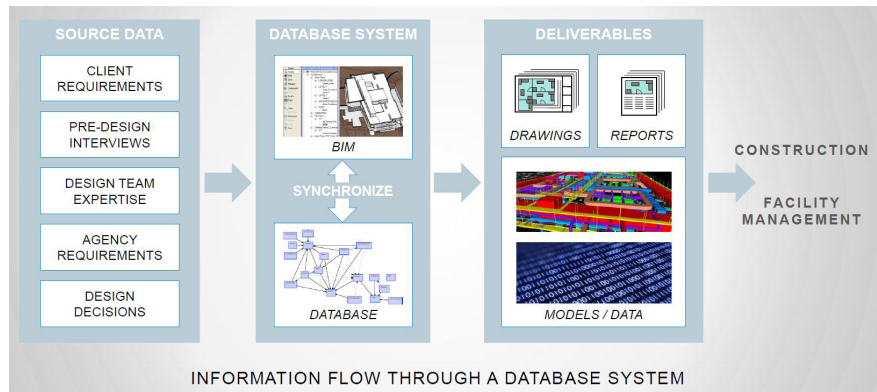


Figure 36. Database synchronization with BIM models . From: [181]

between BIM and external databases, which is becoming a real need for easier data management.

Nevertheless, investigations on how to structure the associated database, which in the field of cultural assets involves considerable difficulties, are not widespread. Only recently the topic of semantic data management has been addressed in experimental projects such as Batawa Project [132], BIM3DSG SYSTEM [250], or in case studies [246]. In addition, the creation of ontologies for the classification of BIM elements, both for new buildings and for historic buildings [245][138][246][114] is gaining considerable interest. Due to the innovative feature of these projects, it is not possible to speak of an established state of the art. Rather, several issues have been risen and first answer attempts made, that deserve a more accurate analysis (see paragraph 2.3.5).

## 2.3. Open questions in Cultural Heritage application

Despite the increasing interest in BIM adoption for new construction and the undeniable pros that BIM can produce even in the Cultural Heritage field (paragraph 2.1), studies about HBIM are still few and are prerogative of universities and research institutes, while professional works are almost unknown. BIM is, in fact, principally associated to new construction works and only in the last years its use is spreading to existing buildings too [300], while in the field of cultural heritage documentation BIM is seldom applied. This is due, on the one hand, to the lack of public and government investments in this direction. Laws and regulations on the matter refer mainly to new constructions: only

the recent Italian UNI 11337-4:2017 addresses Historic BIM, introducing specific LODs for restoration works.

On the other hand (and probably the main reason for poor adoption), HBIM implementation faces more problems than ordinary BIM, due to the particular characteristics of historical buildings.

First of all, the necessity of starting from surveyed data and not from a project. In a project all data are known by the designer, who has the control over the project, so over the BIM model too. Starting from an existing building, in particular historical one, all this information is lacking (paragraph 2.3.1). At the beginning, the BIM author has no knowledge of the building. It is necessary to analyse and understand the building, acquire sufficient and exhaustive data for correctly document it and find a way for decomposing the complexity of the reality for creating the 3D model (paragraph 2.3.2). In addition, historical buildings are complex, are characterised by irregular and often deformed shapes and elements. These characteristics affect both the modelling and the database design phases: deformed and irregular elements hardly fit into parametric modelling based on libraries and historical data are very heterogeneous, so difficult to be standardized and organized into a relational database (see, for instance, paragraphs 2.3.3, 2.3.4, 2.3.5).

In addition, there is the problem of BIM system usability. In fact, especially in the field of historical buildings, tools for building management have to be simple and user friendly (paragraph 2.3.5).

In a so complex panorama, there are many levels of deepening and methods to devise a BIM model fitting the design goal. This choice depends on the purpose of the HBIM, the specific needs and the requested outputs. These key aspects influences all the BIM implementation phases: the survey, the modelling and the database design [114].

At the same time, for HBIM, it is necessary to take into account that the life of a cultural asset is longer than the nominal life of a common building: in fact, considering the cultural assets as almost eternal, their maintenance continues over time.

Today, the needs of tomorrow are not known and, consequently, a HBIM must be structured to respond to its current purpose and, at the same time, must be capable to accommodate future (re-)implementation to meet new requirements.

All these problems will be examined in detail in the following paragraphs, reporting the state of the art and the many still open questions.

### 2.3.1. Survey and data management

The main critical aspects to take into account, as far as survey is concerned, are the accuracy and the reliability of the surveyed data and the management of big data.

Nowadays, especially in Cultural Heritage field, there is an increasing spread of image- or Lidar-based 3D reconstruction and modelling tools [210]. The use of expeditious techniques, often by non-specialists of the geomatics disciplines, provides apparently good results, but with little or no information about quality and metric correctness. An accurate, properly detailed and correctly executed survey should be planned according to its specific purpose. The quality of the survey defines the quality of the resulting 3D model and, so, the quality of the analyses performed on it.

The a-posteriori validation of the survey result becomes a non-trivial aspect [81][210]. The survey design aims indeed at foreseeing and guaranteeing an overall quality of the acquired data, suitable for the survey specific requirements. Nevertheless, a validation of the survey through comparison with other data (e.g. check points) measured via independent techniques is mandatory before starting the modelling phase.

For existing building, especially historical ones, accessibility problems or preservation constraints limit the knowledge of the building. For example, it is difficult to find out how an element has been constructed or the specific materials employed and their properties, without performing destructive analyses [6]. In addition, ancient architects built according to their experience and empirical rules, so constructive and design documents, as intended today, are missing. Historical documents and treatises can help in defining these characteristics, but a deep knowledge of the building itself, possible for new construction, is very hard to reach.

Knowledge can be improved for example by integrating the actual survey with the information gathered from historical drawings, by simple visual analysis or by analogy and comparison with coeval buildings and constructive techniques. Obviously, these different sources provide a different level of reliability, which has to be known before modelling, especially in a parametric model, where geometric, structural and material parameters have to be defined.

At a conference presentation [44] Bianchini et al. introduced a new parameter, the Level of Reliability (LOR), associated to the elements of the 3D model. It certifies the reliability of the data used for the model, in other words, the degree of knowledge of the object before the modelling phase.

No other literature references to the topic have been found: however, this topic is

certainly of great interest and criteria for defining a level of “pre-modelling” knowledge should be further investigated.

In this respect, metadata that certifies the quality of the survey and the degree of knowledge of the building acquire great importance.

If, on the one hand, performing a highly accurate and detailed survey is always preferable, especially for modelling purposes, the great amount of survey data to be managed is one of the main problems the BIM implementation. Point clouds acquired by laser scanners are composed of millions of points and this makes data importing and visualization often hard and very time consuming. Moreover, having a high detailed point cloud is not suitable for BIM implementation due to BIM software characteristics and their incapability of easily modelling the complex shapes of historical building. As there is always a loss of information during the conversion from point cloud to parametric elements starting from a reduced point cloud could be, in many cases a better choice [114].

On the other hand, the reduction of the amount of points might cause a loss of details that, due to the importance of accuracy and detail richness in historical heritage documentation, might not be generally accepted.

Thus, it is necessary to balance level of detail and completeness with data manageability, considering the final purpose of the survey and the building characteristics.

A very consolidated way of working is to design the survey so that it has resolution more or less constant across the building and adequate to the required level of detail. Many scans are performed in order to reduce occlusions and avoid resolution reduction due to the distance from the scanning station [135]. Then, these data are processed, eliminating excessive point cloud overlapping and filtering point, in order to have a manageable dataset.

This method has many pros, first of all the great documentary value and the accuracy. A high and homogeneous accuracy allows precise and exact analyses with a high level of reliability. This approach is very useful to acquire all possible information and having the certainty that these data can be used in future. It is the case of buildings with precarious stability conditions, heritage sites that have to be (digitally) available to future generations, unsafe working conditions or constraints on data acquisition time, and so on.

However, despite these undeniable pros, all these data have to be managed and with the actual hardware and software performances, it is often expensive. The point cloud obtained is big and, in many areas, redundant. Historic architectural buildings have,

in fact, complex and varied shapes, interchanging smooth parts (e.g. a planar wall) and more detailed ones (e.g. a capital). Thus, the homogeneous resolution can lead to redundancy of information in some areas and lack of data in others. To correctly manage all these points, reduce and filter them, many algorithms have been developed. They allow for point reduction according, for example, to object curvature, in order to preserve high resolution in rich detailed areas and delete redundant points in planar surfaces.

A different methodological approach is the multi-resolution technique [114][172], where a global manageable model ("container") hosts other, more detailed, models guaranteeing the adequate level of detail where required. A global survey of the asset at low resolution is performed and then detailed with high resolution scans of areas with a complex features.

This approach, however, requires an in-depth preliminary knowledge of the building, a clear initial semantic parsing of the elements and the precise knowledge of survey and model purposes. In addition, the acquisition phase is very time consuming and for buildings with a great amount of decorative elements, it is not advantageous, because too many detailed scans have to be acquired.

In addition to the point clouds, there are all the other documents and information necessary for describing the building. Therefore, the total amount of different data that have to be organized and manipulate is even greater.

Also literature references about HBIM model enrichment are not many. For example, as reported by Fai et al. [132] "BIM is not discussed in Robin Letellier's Recording, Documentation, and Information Management for the Conservation of Heritage Places (2007), considered by many as the standard reference for heritage documentation. Nor is BIM mentioned in Metric Survey Specifications for Cultural Heritage [42]".

Trying to summarize what arises from literature, the problem of big data management is real and, to date, not adequately solved. Many strategies are being developed, but each of these has pros and cons not negligible. The most common opinion is that the most proper approach has to be defined case by case, taking into account:

- Survey purposes, goals, specific analyses required and representation scale
- Amount of data obtained and management capabilities
- Acquisition times
- Complexity of the building to survey.

### 2.3.2. Semantic classification: shared vocabularies and object libraries

The semantic classification of architectural elements, before the modelling phase, is a fundamental step in order to avoid create objects meaningless from an architectural point of view [103]. However, semantic classification is not always easy and poses difficulties connected to the great variety of architectural elements. For each component, there are many different typologies, which differ according to historical period, architectural style and geographic area. The same object can have different names, materials or constructive techniques with typical and specific features.

For example, vaults can be barrel, cross, ribbed, cloister, fan and can be realized starting from semi-circular, pointed, segmental or bucket arches. Columns have different dimension and proportion on the basis of architectural orders, and in particular capitals, although they have common semantic features, are very different in details.

Therefore, there would be the necessity to create a common shared vocabulary in which all elements are defined. This vocabulary has to take into account all specific feature of architectural elements and, at the same time, represent the unique basis for a common language, essential for real interoperability in the Cultural Heritage field [114].

Examples of shared libraries referred to historical components are shown in the research of Murphy et al. [198][199], De Luca et al. [103][102] and Apollonio et al. [18]. They worked with classical architectural elements and established libraries and modelling strategies based on rules and semantic classification gained from treatises.

The main part of the works involves elements of classical architecture, better identifiable and realized according to specific rules and proportions, while searches about more irregular architectures such as Romanesque or Gothic buildings are almost missing [245]. In this context, an interesting study is proposed by Quattrini et al. [245][246]. They, in a research involving the Romanesque Church of Santa Maria at Portonovo (Ancona, Italy), focused on the geometric shapes and on the structural module (pillar, column and vault) in developing ontologies and shared libraries starting from the surveyed elements. These libraries have been used in similar architectures and allowed research in architectural proportions.

From a normative standpoint, instead, there are no rules that define a classification of historical elements and libraries. Even the new Italian UNI 11337/2017 and the libraries proposed by the recent INNOVance Project [163], are just about new buildings.

Another problem in semantic classification, is the non-perfect accordance between geometric, semantic and material description.

From a geometric point of view, elements are often defined by a profile that is used as a basis for modelling through functions such as extrusion, revolution, sweeps and so on. Thus an element, such as a Doric capital, can be seen as a single surface obtained through the revolution of its profile.

However, from a semantic and architectural point of view, a capital is not a simple surface. It is indeed a solid and is composed of specific elements, with proper names, proportions and geometrical rules (cimbia, astragal, collar, ovule, abacus, etc.). Therefore, from a bare semantic point of view this should be the correct classification. Nevertheless, often the morphological cutting according to vocabulary classification contrasts with the physical and material division of the elements [103] and in many cases there is a commingling of structural and decorative elements, which complicates the identification of the main elements. Semantic elements often do not correspond to separate physical elements and there are ambiguities between the semantic definition and the physical/material division (Figure 37).

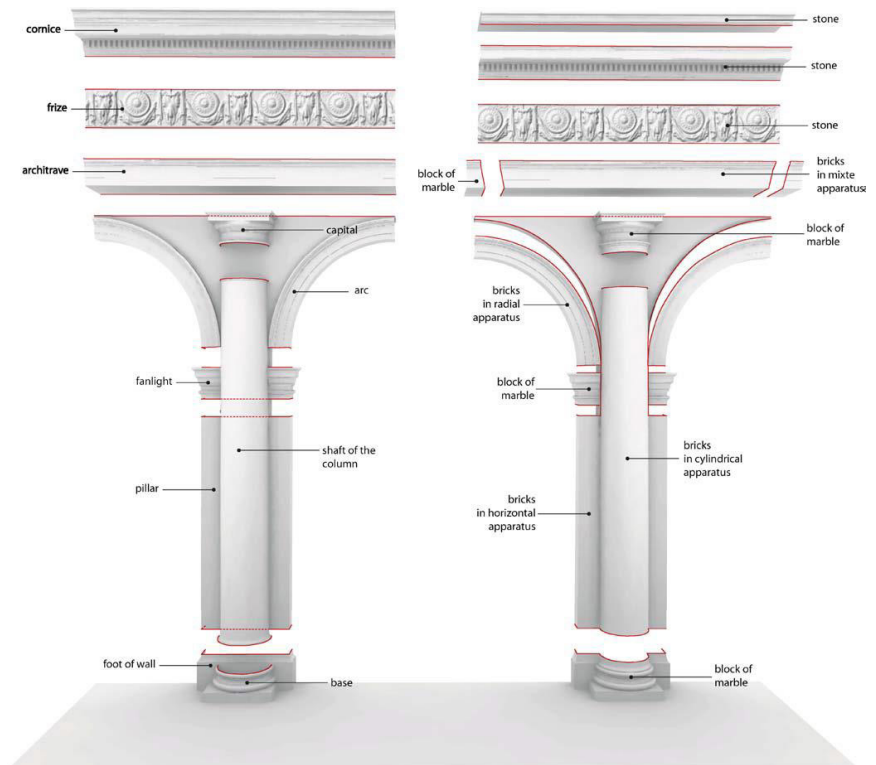


Figure 37. "Morphological cuttings of the analysed object according to two different analyses: the vocabulary of the architect and the construction techniques". From: [103]

To overcome these difficulties, De Luca et al. [103] introduced the “point of view” analysis of the building, distinguishing between construction techniques/materials and vocabulary (Figure 38). They distinguished between four different points of view starting from the same morphological cutting, superimposing the information according to the sculpture, the mouldings, the order and materials. In this way, it is possible to analyse completely the structure accessing all the available data.

Nevertheless, semantic classification is still an open field of research and there is not an absolute correct way of working. The process is difficult and it is hard to recognise and name automatically and in a correct way the elements that constitute a historical building. The manual approach, at the current state of the art, remains the most efficient, although it is the most time consuming.

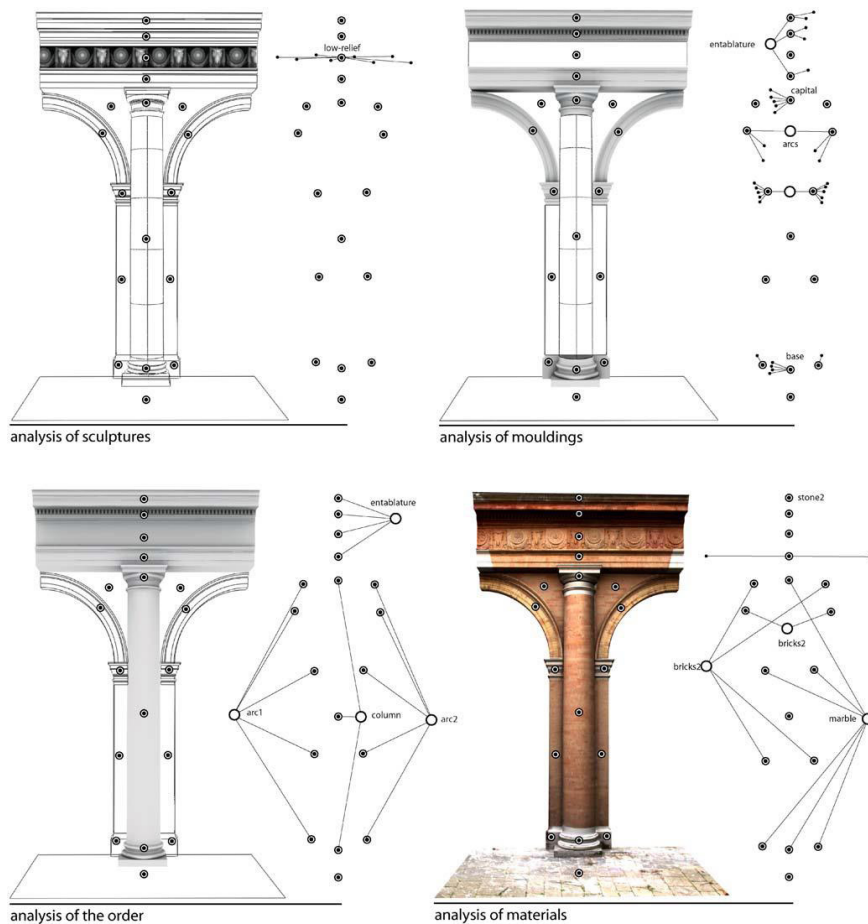


Figure 38. “Four «points of view» on the studied object elaborated starting from the same morphological cutting”. From: [103]

### 2.3.3. Parametrization of complex 3D objects

The advantages of parametric modelling (both generative and object oriented) are evident: it speeds up modelling phase allowing the user to replicate and modify object dimensions by changing the value of some parameters.

In addition, BIM software uses almost exclusively parametric objects, since their “intelligence” allows associating attributes and connecting elements through topological and hierarchical relationships. BIM software provide even the ability to model using traditional direct modelling tools, or import objects modelled externally, but with many interoperability problems [288] and losing the intelligence relationship with the elements.

In this context, one of the most crucial aspects in implementing an HBIM is the lack of libraries of historical architectural elements. As mentioned above, with reference to the semantic classification, because of the great variety and heterogeneity of elements, there are no common libraries already made, as instead occurs for new constructions.

So there are two main issue:

- How the historical elements have to be parameterized to create library items: what rules have to be applied and what the admissible level of automation is
- How the modelled object can be modified to fit the survey data.

The first researches, using parametric surfaces, have been made since 2006 by De Luca et al. [106][103] and Chevrier et al. (2009) [88]. They create parametric objects starting from the point cloud. In order to fit the model to the real shape of the object, De Luca et al. [103] developed a modelling methodology that subdivides the basic profile gathered from treatises into geometrical atoms (mouldings). Each atom can be edited individually through partial deformations in the two directions (x and y) in order to instantiate the object fitting the actual form correctly (Figure 39).

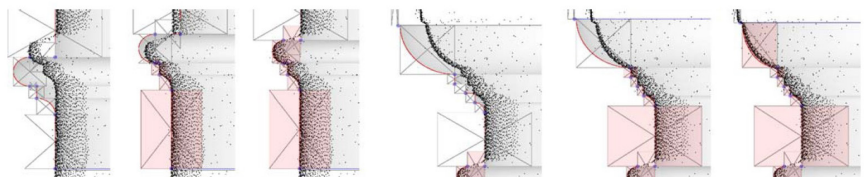


Figure 39. “The instantiation of the primitive: under-constraint deformation of geometrical atoms”. From: [103]

As far as parametric objects are concerned, Murphy et al. [198] were pioneers in this context. Starting from laser scanning and photogrammetric survey, they modelled specific structural elements and manually mapped them onto the 3D surface model

associating information about methods of construction and material makeup. Their studies in this field evolved until the development of GDL (Geometric Descriptive Language) scripts for automatically creating parametric objects and automatic mapping the 3D object onto the survey data [117].

Also their object library is based on historical data derived from treatises and architectural pattern books and, generally, it is the most followed approach, as demonstrated by Apollonio et al. [18].

Other researches concern, instead, the parametrization of elements that are not compliant to the geometrical rules of the classic architectural orders. It is the case of the studies developed by Fai et al. [132][131][130], Baik et al. [35], Oreni et al. [221] who modelled vaults and roofs, Santagati et al. [275] who took into account Gothic portals, and Quattrini et al. [245][246] who worked on Romanesque architectural elements.

Nevertheless, parametric object modelling is not flexible and imposes many constraints that limit the accuracy of the model and its conformity to surveyed data. Especially in the field of cultural assets, this causes many problems and limitations on the correctness of the modelling of objects, which are often irregular or deformed. Parametric objects, in fact, are "standard" and are suitable for new construction, where elements are regular, straight, orthogonal and standardized. In the Cultural Heritage field nothing is equal, standard and regular, so this approach is dangerous, because it can lead to excessive simplification of the elements.

Therefore, a reflection arises spontaneously: considering the BIM as information system at the building scale, the kernel is the association of thematic data and attributes to geometric and spatial elements. In other words, a BIM could be a collector of all information about a building, a three-dimensional way for representing it and a process for knowing and analysing it. Thus, in the Cultural Heritage field, how is it correct to approximate the representation of a building to privilege parametric modelling?

In this case, BIM is not a design instrument, there is not the necessity of modifying the project and verifying the effects of these changes, as it happens in new construction. The principal aim of a Historical BIM is documenting the state of the asset and supporting its maintenance and restoration. Each historical architectural element is a *unicum*, it does not change and it is slightly different from other elements.

Parameterization of the elements is certainly useful in preserving topological relationships and ensuring constraints between elements (for example: a window must be hosted by a wall, the roof and the wall must be continuous), but, working with unique and irregular architectural elements, parametrization does not facilitate the modelling operations.

For these reasons, it is author's opinion that the final aim of the model, the characteristics of the object and the LOD required determine what modelling technique has to be adopted.

To correctly merge in a unique model elements modelled with different techniques and with different software the new direction of development must look at concrete interoperability; an interoperability that allows data exchange (without loss of information) and thematic data association.

### 2.3.4. Modelling of irregularities

Working on historical buildings, the attempts to create parametric models, as seen in the previous paragraph often is not sufficient and a model based on families of pre-modelled elements hardly fits the actual form of the object.

Thus, how is it possible to model all these irregularities?

There are several class of problem to take into account. First of all, the capabilities of the available software. BIM tools are conceived for new construction and, generally, do not allow "mistakes" such as out of plumb of the walls, not perfect planarity, off axis lines etc. All these irregularities can be solved more easily with direct modelling tools, but this causes interoperability problems. In addition, creating a high accurate model results in very long modelling times and unmanageable size models.

From the literature analysis many hints arose.

Some authors [180][135][134] use NURBS (both with direct modelling and procedural modelling) and mesh surfaces, in particular for free form object such as statuary or embellishment (Figure 40). In these cases, the level of accuracy achieved is high, but as the authors emphasize [288], integrating these models into parametric BIM software is still a difficult task and many data or editing capability are lost.

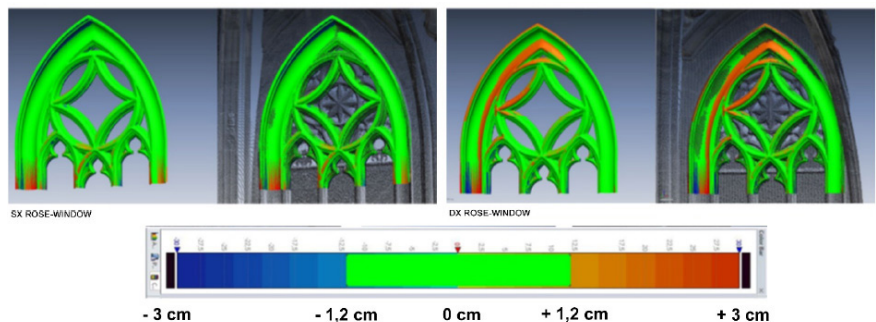


Figure 40. Visual and numerical results of the deviation between laser-scanner point clouds and parametric models of the South Altar using Geomagic Design X. From: [180]

Other researches try to manage deformation into BIM software environment. The more common workflow concerns the extraction of multiple cut section of the object that are used as references for adapting the parametric model.

Dore et al. [117] developed procedural rules for modelling building façades and external building geometry implementing a prototype plug-in for ArchiCAD BIM software (Figure 41). Horizontal cut sections are created at different height and the user can select a group of sections which are used to automatically create the irregular wall surface.

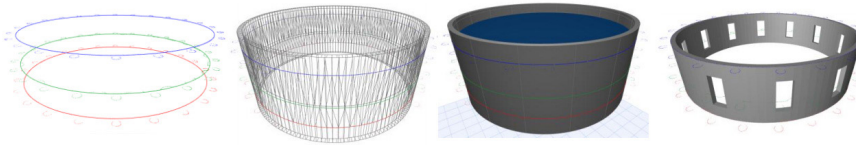


Figure 41. Automatic procedure for modelling irregular non-vertical walls by Dore et al. [117].

Bitelli et al. [56] developed a two-steps procedure for modelling horizontal and vertical irregularities entirely into Revit environment. They manually drew on the point cloud the main reference section lines that defines the irregular shape of the church. Then, using the mass modelling tool, a solid mass was created by which the parametric wall family was generated (Figure 42).

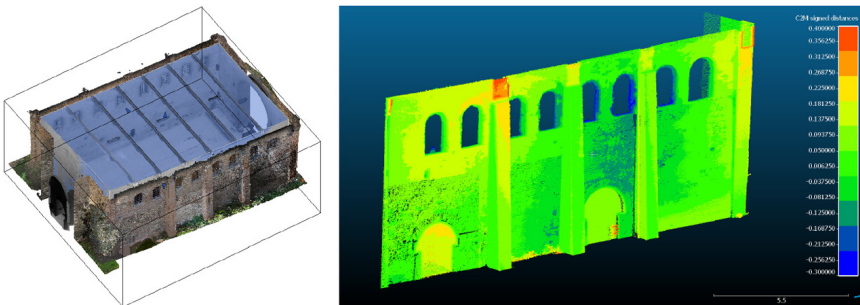


Figure 42. The mass modelling workflow implemented by Bitelli et al. [56]

Quattrini et al. [245] used, instead, B-rep operators, such as revolution, extrusion etc., for directly modelling in place the more complex geometries.

Barazzetti et al. [38][220][39] used an automatic procedure for extracting NURBS curves from 3d point cloud. Then this curve network allows for creating a NURBS surface that is turned into parametric BIM objects.

Brumana et al. [68] did not use multiple cut sections to reconstruct the deformations but combined two different layers: a regular layer (wall) modelled with the software parametric tools, and a deformed layer attached to it, which represents the deformations.

Castagnetti et al. [81] worked with the traditional approach creating 3D solid primitives

through NURBS and LOW-POLY meshes. They transformed the point cloud into triangulated mesh and, then, converted it into solid element. These solid objects have been imported into BIM environment. They are not parametric object and the morphological characteristics were added to each element as attributes.

Despite these studies, the modelling of irregularities is still an open task and, above all, the acceptable level of approximation is still not defined. Apart from the USIBD guidelines [297], that indicates different levels of accuracy, there are no specific regulations in this regard.

Level	Upper Range	Lower Range
LOA10	User defined	5cm *
LOA20	5cm *	15mm *
LOA30	15mm *	5mm *
LOA40	5mm *	1mm *
LOA50	1mm *	0 *

Figure 43. Levels of accuracy for building documentation. [297]

*\*Specified at the 95 percent confidence level.*

As it can be seen from the investigated research, the key factors are the representation scale and the purpose of the model, even to avoid having totally unmanageable model unusable for requested analyses [114]. The representation scale entails a defined tolerance and therefore, according to it, the admissible level of accuracy is defined.

### 2.3.5. Database structuring and data sharing

The data available to describe a building are many: photographs, archival documents, technical reports, historical drawings, information gathered directly from the asset itself, etc. In such context, database design phase addresses three main classes of problems:

- Identification of information and documents required and consequent data acquisition
- Data organization into a relational database
- Interoperability with the database and usability.

First of all, data retrieval is not always easy. Historical data are, generally, paper based and not digitised, thus their discovery and accessibility are more difficult. In addition, when the available data are historical archival documents, many other issues arise, especially related to their actual usability. They are indeed affected by preservation and conservation regulations, such as reduced consultation, diffusion and copy limits and so on.

In addition, there are semantic and standardisation problems. Available data are many and heterogeneous; they are different in typology, structure, organization, format, content, date, source etc., and therefore their standardization and organization in a rigid structure is far from easy. In addition, the methodology of approaching historical assets is not unique and not fully standardisable, since each historical product has specific characteristics and singularities that differ from other's.

Thus, it is difficult to organize historical information in standard and rigorous framework, such as the relational tables of a database that is the basis and the core of information systems.

In addition, the procedures to build the information system itself, in Cultural Heritage field are not unique and it is not possible to fix standards and rigorous processes, but it is rather useful to trace common guidelines and reference methodologies, which should be flexible and adaptable to specific requirements [6].

This because, on the one hand, historical data have to be preserved and not forced into logical organization too far from their proper one and, on the other hand, each historical building and each element that composes it, is unique and has specific features and history.

Another non trivial aspect is the multi-temporality of information and the need to have a system usable for diachronic analyses. Historical data are, in fact, by their nature multi-temporal and, in addition, conservation is a continuous activity that requires constant updating of information and continuous collection and processing of different data.

Moreover, the multi-scale aspect has to be taken into account. In this regard, two hints of reflections emerge.

The former concerns how it is possible to break down the building and to what level of detail the information should relate. In other words, what are the main entities of the information system. Thus, a semantic classification of the building is required not only for modelling purposes but also for the semantic data enrichment.

The latter, instead, refers to what information has to be associated to each level of the building classification and what is the level of detail of the information. As well as for new constructions, the Levels of Development (LOD) indicate the level of detail and reliability of both the geometric model and the associated information, in the Cultural Heritage field, this aspect does not find correspondence. The UNI 11337 that, as pointed out in paragraph 1.7.1, introduces specific LODs for restoration, does not specify in detail the required information (how much) and semantic content (what). Thus, in this context, there are no references that define what information is needed to document an asset:

practitioners refer to what the Superintendence or other authorities require to properly document the state of a building.

In most of the literature concerning the BIM, all these aspects are not dealt with. On the contrary, literature on historical databases or historical information systems made on historical maps [69][170][190], address these issues more in detail. Indeed, in such research, the historical nature of the investigation is very much taken into account.

With reference to BIM, the heart of the matter does not change. Only the scale changes, while problems and resolution methodologies remain and can be extended to the BIM field too.

One of the best samples of information system at the architectural scale is the NUBES project developed by De Luca et al. [103][104].

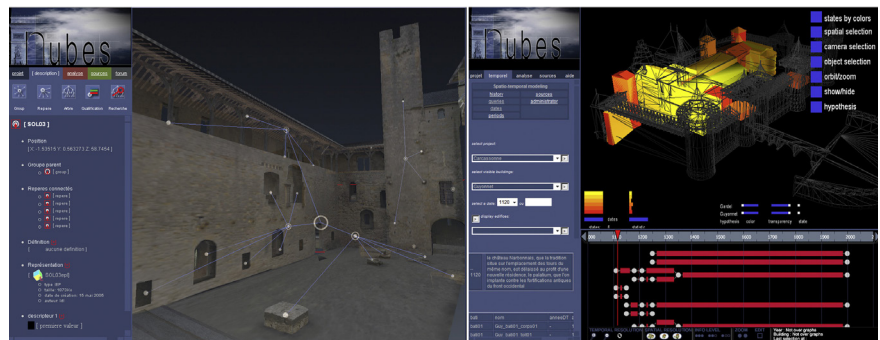
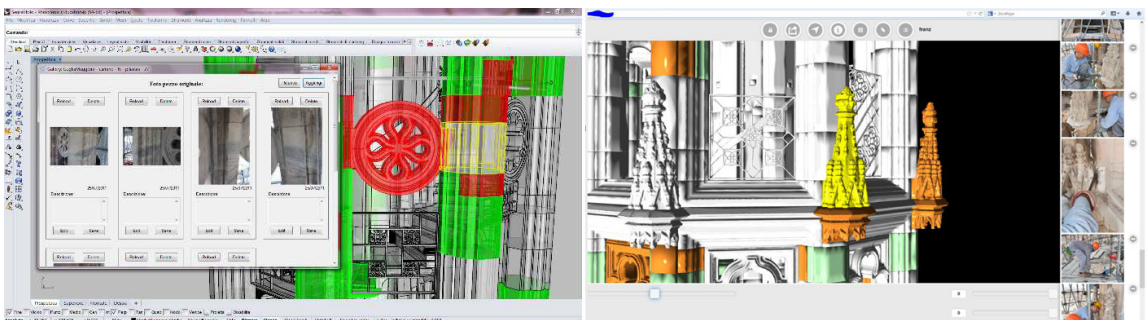


Figure 44. Semantic qualification of a3D representation in NubesVisum. From: [104].

This system allows for 3D buildings representation, taking into account shape, dimension, conservation state and hypothetical transformations in time, and for collecting and associating heterogeneous information. It represents an integrated framework, based on web technologies, able to manage and connect data about Cultural Heritage building, in order to describe, analyse and document the assets.

Figure 45. The implemented plug-in inside Rhinoceros Nurbs Modeller and the web viewer. From: [136].

In the last years, in the field of BIM, an interesting research is being conducted by Fassi et al. [136][250]. They implemented a web-based system for archiving and management



of all the information about the Milan Cathedral and other historical monuments, with the purpose of supporting maintenance activities. Their database hosts the 3D models (in different format and level of detail), information and files (such as photo, video, documents, dwg, etc.) associated with the objects, maintenance and restoration activities with their relative information and files. It gives solution to problems of managing of big, high resolution and heterogeneous 3D models, ensuring data and information sharing. Another research has been presented by Quattrini et al. [245][246]. They modelled an ontology with the main information needs for the building and a methodology that, using the BIM existing platforms and semantic-web technologies, make the user able to explore the 3D model and the associated semantic data.

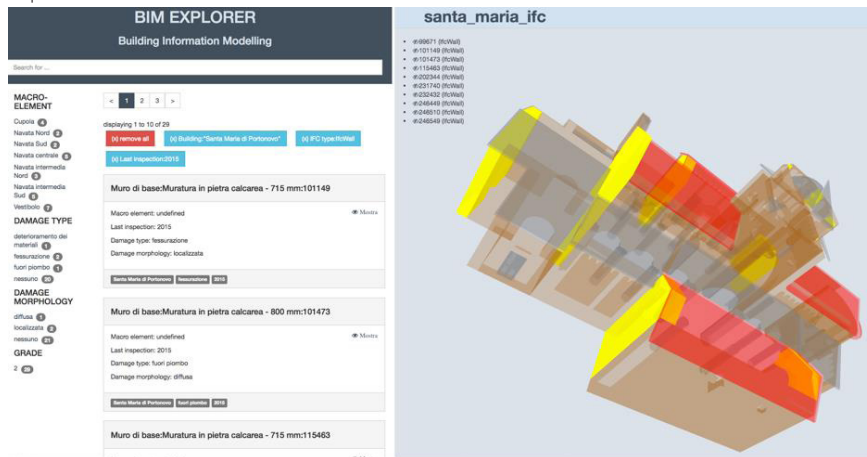


Figure 46. Web 3D visualization of the building enriched with semantic data. From: [246]

All authors emphasize the need to use web application to share the information, both geometrical and semantic. In fact, despite the presence of tools that allow the interaction between BIM software and external databases (see paragraph 2.2.3), all these solutions are commercial ones, thus posing constraints and limiting data exchange and interoperability with other tools.

To date, complete interoperability between software has not yet been achieved [288] and often, transferring the model from one platform to another, inconsistencies, such as loss of information or errors in data, occur. This weakens the reliability of the model, undermining the initial efforts made to obtain an accurate model. In fact, producing a good model that addresses all the accuracy and reliability requirements discussed previously in this chapter, is worthless if it cannot be shared properly.

The use of web applications, allows being free from any software platform (at least in the visualization and usage phase). The user is not obliged to install any specific software since all the information can be accessed through the browser. In this way,

interoperability issues are overcome.

In addition, web applications simplify the usability of the system. Usability is indeed another issue to take into account. Especially in the field of historical buildings, there is the need for a tool that can document the building over time, acting as a single collector of all information and data useful for restoration or maintenance. This tool should be unique and easy to use. This is because the actors involved in conservation (such as restorers and historians) are not specialists of the AEC industry and are reluctant to use commercial BIM software or databases. Therefore, in order to make BIM application really used in practice, these systems have to be simple and user friendly.

The latest development frontier is going to the sharing of the model through smartphone apps and Virtual (VR) and Augmented Reality (AR), with promotion and valorisation purposes. Prototypical examples are presented by Di Benedetto et al.[110] and Barazzetti et al. [41], that show how complex, scientifically correct and accurate models can be turned into manageable mobile apps, in order to involve not only expert operators of the Cultural Heritage field but the entire community, preserving, in any case, the value and the quality of the data provided.

After this brief overview of the main fields of research and of the main projects realized, some consideration exposed by Fassi et al. [136] will be reported as chapter conclusion. These considerations, in the author's opinion, well summarize and highlight the direction that research in the field of Cultural Heritage should undertake.

*"The main first idea was to break away from the commercial software that nowadays are unsuitable for the multi-faceted world of Cultural Heritage [... going to] the realization of a highly customizable system able to easily adapt itself to the different cases allowing to work with different type of objects, different representation scale and resolutions, also simultaneously showing and sharing different type of information and managing different and unique maintenance operations. [...] The second key aspect is a consideration about the operators working in Cultural Heritage field. [...] The system should be easy to use and easy to learn even for non-experts. It should have a user-friendly interface and should be used with common devices. [...] The third consideration is that a digital 3D model is expected to become the representation of the future. [...] Digital 3D models should be dynamic and eternal, that means [they] should be forever upgradeable and modifiable in the future; [they] should be "for everybody", i.e. visualized and used easily by different operators and "from everywhere" that means that a digital 3D model should be shared and used in a collaborative way."*





## SECTION II

The HBIM application for Cultural  
Heritage management: the case study of  
Parma Cathedral



### 3.1. Materials and methods: the HBIM as Information System

---

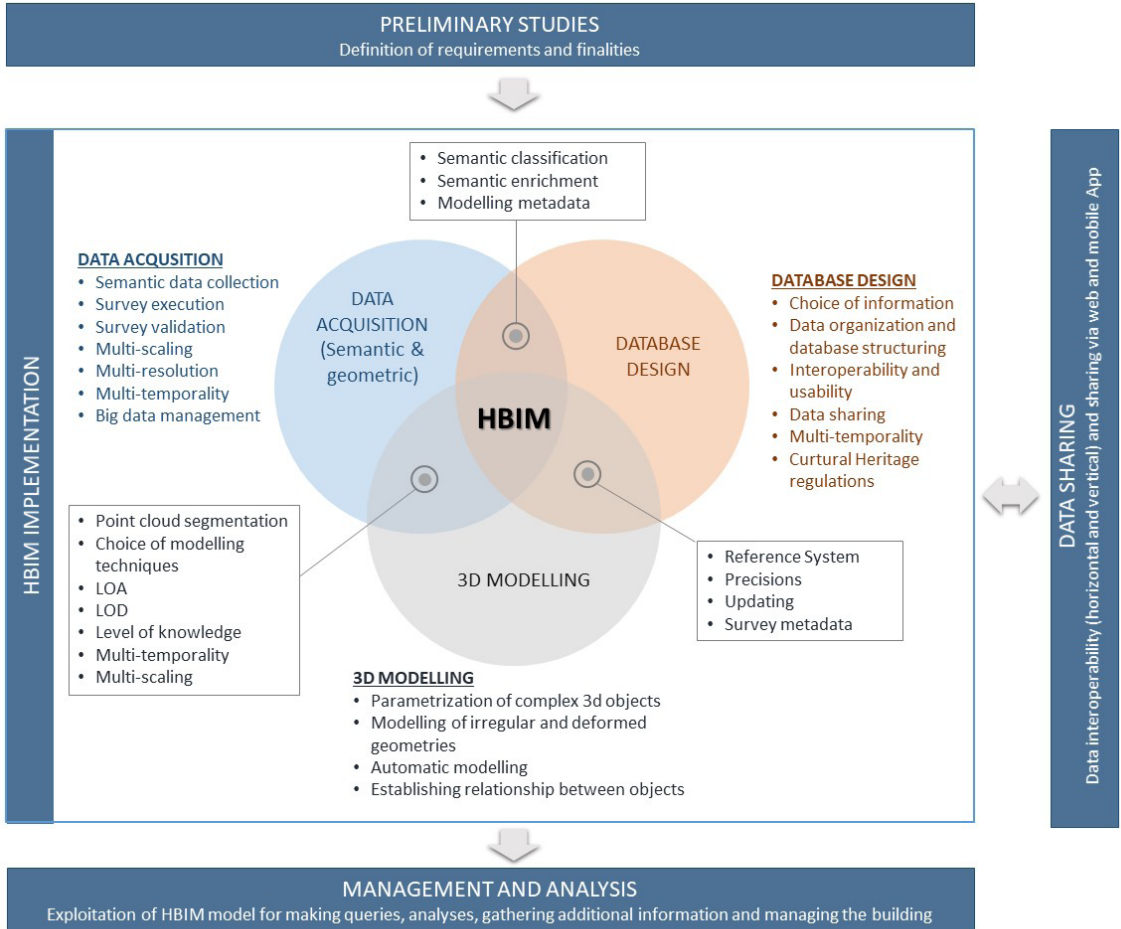
The first part of the thesis addressed the definition of BIM and HBIM concepts highlighting the state of the art and the open fields of research. In this complex panorama, the disparity between the BIM adoption for new construction and historical building clearly emerges, with a predominant use in the field of new constructions. Many problems are the reason of this disproportion. First of all, the absence of solution tailored to meet the needs of cultural heritage field: commercial solutions are unable to manage complex and real based shapes and are not conceived for maintenance operations and restoration activities.

There are not specific regulations and, in general, there is not yet a shared awareness of the importance of BIM in Cultural Heritage and, therefore, there is no commitment to act in this regard by providing *ad hoc* solutions for cultural assets.

The thesis intends to give an original contribution on this topic.

BIM implementation is an integrated process which addresses survey, modelling, database design and data entry. Especially in the cultural heritage field, the creation of a BIM is not a linear process, but an integrated and circular one.

As shown in the figure below (Figure 47), survey, modelling and database design influence each other. For example, the accuracy with which the survey is performed and the achieved level of knowledge of the object influence the quality of the model (in terms



of accuracy and adherence to reality) and of the database (in terms of organization of information and data contained). Moreover, incorrect database design invalidates the quality of the model because it does not allow a correct semantic enrichment.

Figure 47. HBIM process. For each phase, the main feature to take into account are pointed out.

The thesis investigates the three aspects related to the survey, modelling and database design from a methodological point of view and presents the results obtained in the application to a real case study represented by the Parma Cathedral.

The most investigated aspect is the database design since right now, as seen from the bibliographic analysis, it is the less addressed field and, in the author’s opinion, one of the most important, on which to invest for the creation of an effective and useful tool for Cultural Heritage conservation.

The thesis project led to the realization of an HBIM application to support restoration

and maintenance of historic buildings. The BIM has been understood as an information system on the architectural scale and as an interrelated and integrated process of all three components illustrated in Figure 47. For each of the three phases, the main features and problems have been identified, trying to give an original contribution to the solution of some outstanding issues.

Particular attention has been paid to the regulations currently in force on BIM and Cultural Heritage, in order to understand what could be common points and hints for an integrated use .

In addition, a stand-alone system was created that can be integrated with the main commercial BIM software and can also be used via web. In such application usability, flexibility and customized implementation according to specific needs are a priority and the choice of a specific BIM software would have limited the flexibility and scope of use of the system. The project goal was to ensure easy access to data, easy use of the system, performance of data analysis and sharing of semantic data and three-dimensional model, essential for the actual use of the system by practitioners.

Other research topics investigated, of high interest in geomatics, were survey accuracy, traceability and data testing in BIM.

In fact, the final accuracy of the model is influenced by both the quality of the data surveyed and the modelling operations carried out. For this reason, since the information system is based on the 3D model, for a correct use of the data obtained from it, it is important certifying its accuracy and reliability. Metadata on survey and modelling methods, on the accuracy obtained and on the correspondence of the model to reality, are a first instrument for monitoring data quality and the basis for a rigorous and scientific analysis of the object under investigation.

Therefore, a protocol to enter the quality of the survey in the database linked to the geometric model, and let the user to verify at any time the correctness of the product he is working on, has been set up.

The first phase of the work involved the analysis of the regulatory requirements and specific needs that the Parma Cathedral presents. Then the acquisition of both geometric and semantic data, through instrumental survey and documentary and normative analysis, were performed.

On the basis of the data acquired, always working in an integrated way between the need for modelling, documentation, accuracy, data manageability and system usability, the three-dimensional model of the Parma Cathedral has been created and the information system has been implemented.

### 3.2. Regulations on Cultural Heritage safeguarding

In Cultural Heritage field, the Italian reference regulation is the *Code of Cultural Heritage and Landscape* (D.lgs 42/2004). The code provides for the protection and preservation of cultural assets, considered as “coherent, coordinated and scheduled study, prevention, maintenance and restoration activities”<sup>1</sup>.

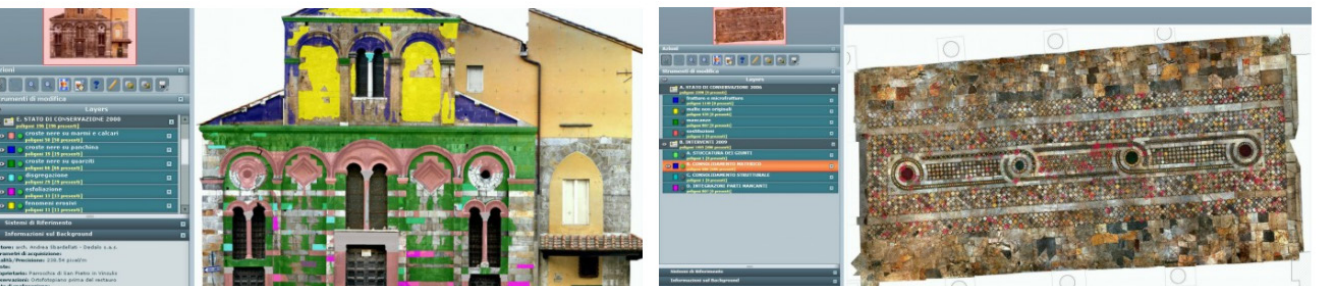
All these concepts have long evolved in time and, without entering the long question of specific definitions and philosophical approach to restoration interventions, today it is worth pointing out that the scheduled maintenance approach is becoming an increasingly important protection activity. In fact, dealing with architectural heritage, preventing damage and diffusion of pathological situations is even more important: a structured practice of inspection, diagnostic and maintenance activities would help to limit costs and the invasiveness of restoration interventions, and, above all, an accurate cure of historic buildings would avoid the risk of losing a unique and unrepeatable heritage.

For these reasons, the scheduled conservation methodology, which starts from the preventive maintenance, has become a normative requirement.

The *Code of Public Contracts*, starting from its 1994 version (Law n. 109/1994), introduces the Maintenance Plan as a required document in the executive design. The actual *Code of Public Contracts* (D.lgs n. 50/2016) confirms this requirement, recognizing the importance of the strategic planning of the activities in terms of rationalizing public investment. On the basis of the *Implementing Regulations of the Code of Public Contracts*<sup>2</sup> (DPR 207/2010, Art. 240), the principle of scheduled maintenance is extended also to protected buildings.

The maintenance plan is defined as the complementary document to the construction design that includes, plans and schedules the maintenance of the intervention, in order to maintain its functionality, quality characteristics, efficiency and economic value (DPR

Figure 48. Screenshots of SICaR. Personal elaboration.



207/2010, Art. 38) [99]. For Cultural Heritage buildings, the scheduled maintenance becomes scheduled conservation [251] and focuses on the knowledge of the building and on the need of an integrated evaluation of the elements of vulnerability, the risks arising from use and environmental hazards.

In particular, the code underlines the centrality of the maintenance plan and the final scientific report (*Consuntivo scientifico*), i.e. the technical report that concludes every activity on a building, certifying and describing the specific executed works and the still open issues, in order to address future interventions.

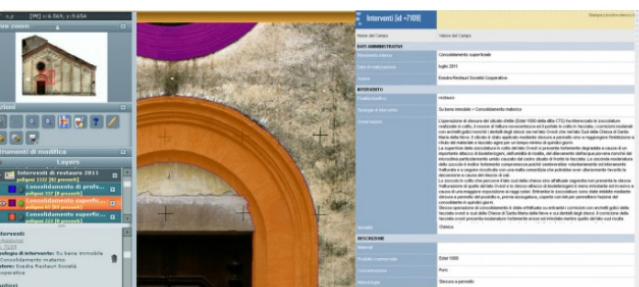
The regulation states that it is necessary to document the state of the asset and keep track of all the intervention occurred, the solved issues, the still open ones or those that might arise. In this way, the regulation wants to set up a broad basic knowledge, in order to prevent any problems and schedule future actions.

This descriptive document is associated with the need to collect and organize all the information that comes from preventive activities and maintenance works, as well as previous restorations. The constant monitoring of the asset conditions and the progressive collection of data related to all the events that affect the asset, are essential to evaluate the severity of the degradation phenomena, foreseeing their emergence and course.

Therefore, an information system that collects, archives, processes, uses and updates all archive data, the information available on the asset, and the information generated during the maintenance plan management would be of great help for proper safeguarding of the asset.

Some relevant example used as national information systems *Risk Map* [258] and *SICaR* [278] can be connected to this context.

*Risk Map* is an information system developed by the Istituto Superiore per la Conservazione e il Restauro. Its aim is the damage risk assessment for real estate. It is an alphanumeric and cartographic database system, able to explore, overlap, and process information about potential risk factors for Cultural Heritage. The risk is evaluated statistically, considering two main factors: the *Individual Vulnerability*, that indicates



the level of exposure to the aggression by territorial environmental factors, and the *Territorial Danger*, i.e. the level of potential aggressiveness of a given territorial area. The system returns a thematic map that shows the location of the real estate and data on territorial riskiness and vulnerability maps.

*SICaR* is an information system for restoration works promoted and funded by Tuscany Region from 2003. At present it is adopted by the Italian Ministry of Cultural Heritage and Activities and Tourism to manage restoration works. The system is capable to georeference documentation in vector, raster and alphanumeric formats. Technical information produced during the restoration (methods, materials and tools used in the intervention, chemical, physical, petrographic analyses, etc.) can be linked to data (textual, iconographic, video) about the asset (general and historical information, constitutive materials, working techniques, state of conservation, etc.), referring them to the area of interest. In this way, *SICaR* guarantees a unified view of damaged surfaces, actions carried out and associated information, and reports quantitative data and statistics, providing effective decision support in cost and time planning and subsequent monitoring.

## 3.3. Application to a real case study: Parma Cathedral

---

### 3.3.1. Historical and architectural features

The history of Parma Cathedral has been discussed in many studies and historical researches [248][247][194][179], and, especially as far as its early construction stages and its original conformation are concerned, critics disagree for the lack of certain documents. In particular, the foundation date remains unclear, but thanks to recent analyses and accurate surveys, performed in recent years after important restoration works (2006), discoveries have been made, highlighting previously unseen aspects of the early construction lifetime [58].

It is common opinion that the construction of the cathedral started in the second half of the XI century, at the will of Cadalo (antipope and bishop of Parma from 1046 to 1072), and was completed under the direction of Matilde of Canossa. This is evident in

the strong stylistic discontinuity between the presbytery and the naves: the former has features comparable to the imperial Rhine architecture, such as elementary volumes and well-defined geometries (traceable, for example, in the Speyer Cathedral), while the latter presents different forms, less emphatic and closer to Lombard architecture. This can be related to a change in the workers, due to the religious and political revolution that took place in Parma in 1104, when the city passed from imperial to papal influence under the guidance of Matilde of Canossa [58].

During its lifetime, the church has been subject to changes, additions, damages and repair works. The most important event that influenced the cathedral conformation was the strong 1117 earthquake, which caused the collapse of many parts: the roof and, consequently, the vaults of the central nave, the top of the side walls and of the façade. The post-earthquake reconstruction led to the elevation of the lateral buttresses and to the reconstruction of the vaults on a rectangular plan, less thrusting than the previous sexpartite vaults (maybe) based on a square plan [70].

Figure 49. The Parma Cathedral. From: [www.up.aci.it](http://www.up.aci.it)

In the following centuries, lateral chapels and vaults over the gallery were added in order to increase the stability of the cathedral and contrast the transverse thrusts of the



vaults of the nave.

The main steps and interventions in the history of Parma Cathedral can be summarized as shown in Figure 50.

At present, the plan of the cathedral is based on a Latin cross with three naves, composed by seven bays. Both the nave and the aisles are covered by a cross vault system while the gallery has barrel vaults. The cross section of the structure is completed by the lateral chapels, built during the XVI century.

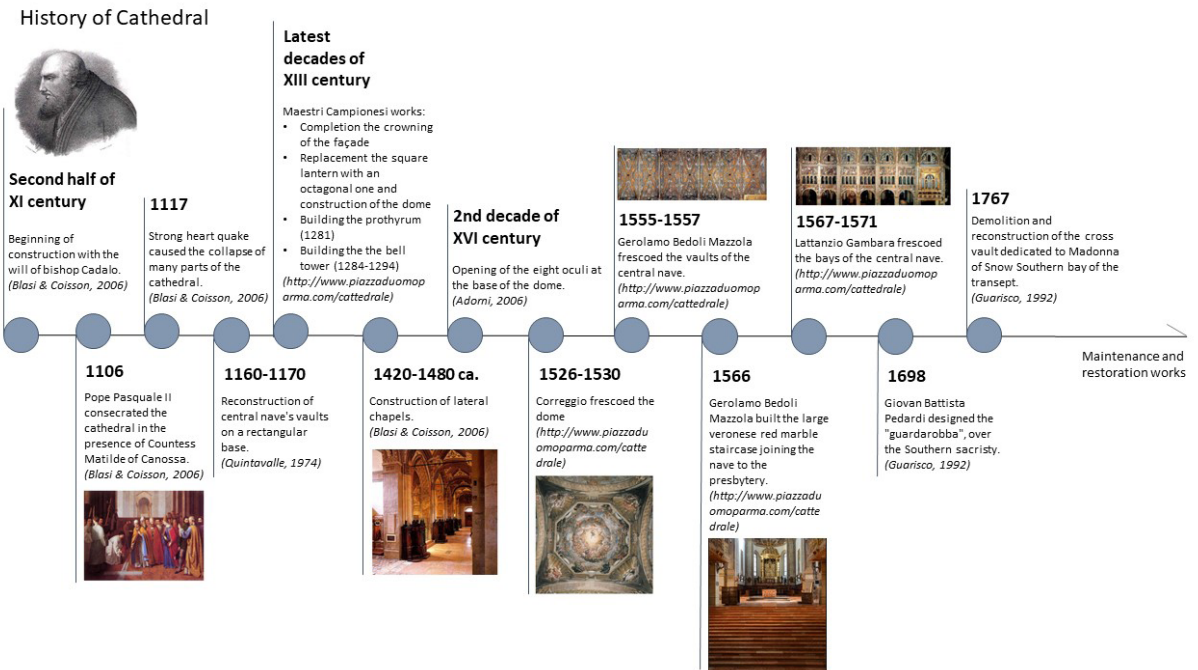
The transept and the choir rise up to the nave and a majestic red marble staircase connects the two liturgical areas. The transept has five domed aisles (two of which are not visible externally since they are included into the sacristies) and the crossing is covered by a dome that rises on an octagonal tambour.

Particularly interesting is the crypt, which is built under the transept and the choir. It retraces the structure of the upper presbytery and is divided into four squared modules of 3x3 cross vaulted bays [58].

As far as the paintings are concerned, remarkable are the fresco "Assumption of the Virgin" made by Correggio for the dome between 1526 and 1530, the frescoes of the nave's vaulting made by Gerolamo Bedoli Mazzola from 1555 to 1557 and the frescoes of the bays realized by Lattanzio Gambara in the years between 1567-1571 [237].

Externally, the cathedral is chiefly built of bricks, although, as evidenced by some plaster

Figure 50. Summary of main works in Parma Cathedral. Sources: [58];[247]; [7]; [152] and [237].



remains, it had to be entirely plastered. Lesenes and corners are instead made of stone, especially sandstone and limestone, while the embellishments have various materials including terracotta and marble.

The façade is gabled with protruding prothyrum and three levels of galleries, the latter of which follows the pitched roof. As far as material are concerned the façade is faced with stones (principally sandstone and limestone), many of which replaced over time for advanced states of degradation and unwholesome 19th century stylistic restorations.

The façade is a little behind the two originally planned bell towers, of which only the south one has been realized, whereas the north one remains unfinished.

Despite the Romanesque origins, the dome frescoed by Correggio, the paintings of the nave made by Lattanzio Gambara, as well as the baroque embellishment, altars and decorations all contributed to the formation of a mixed feature within the medieval basilica [152].

### 3.3.2. The history of restorations and actual problems

The works on the cathedral have occurred since XVI century and last today. Initially the interventions aimed to the cathedral completion (see, for instance, modifications and additions made during XV and XVI centuries), then they addressed its conservation and restoration for contrasting the progressive decay.

Of great importance are the seventeenth- and eighteenth-century works on the dome roof in order to stop water infiltrations that were damaging frescoes and, then, to solve structural problems [152].

Structural problems have always affected the cathedral, in particular the central nave and the crypt. They are principally due to the high thrusts of the vaults of the central nave and the weight of the dome, which cause a considerable out-of-plumb in the side walls and the subsidence of the structures under the dome. For this reason, in 1775 the walls of the central nave were further raised and the roof was replaced in order to avoid that the deformed trusses laid directly to the extrados of the underlying vaults [152].

The first restoration interventions were realised during the XIX century, when the normal practice was to perform stylistic restoration, which involved reconstructions, substitutions and renewal to reach, as Viollet-le-Duc said, "a condition of completeness which may never have existed at any given time". Therefore, under the direction of architects as

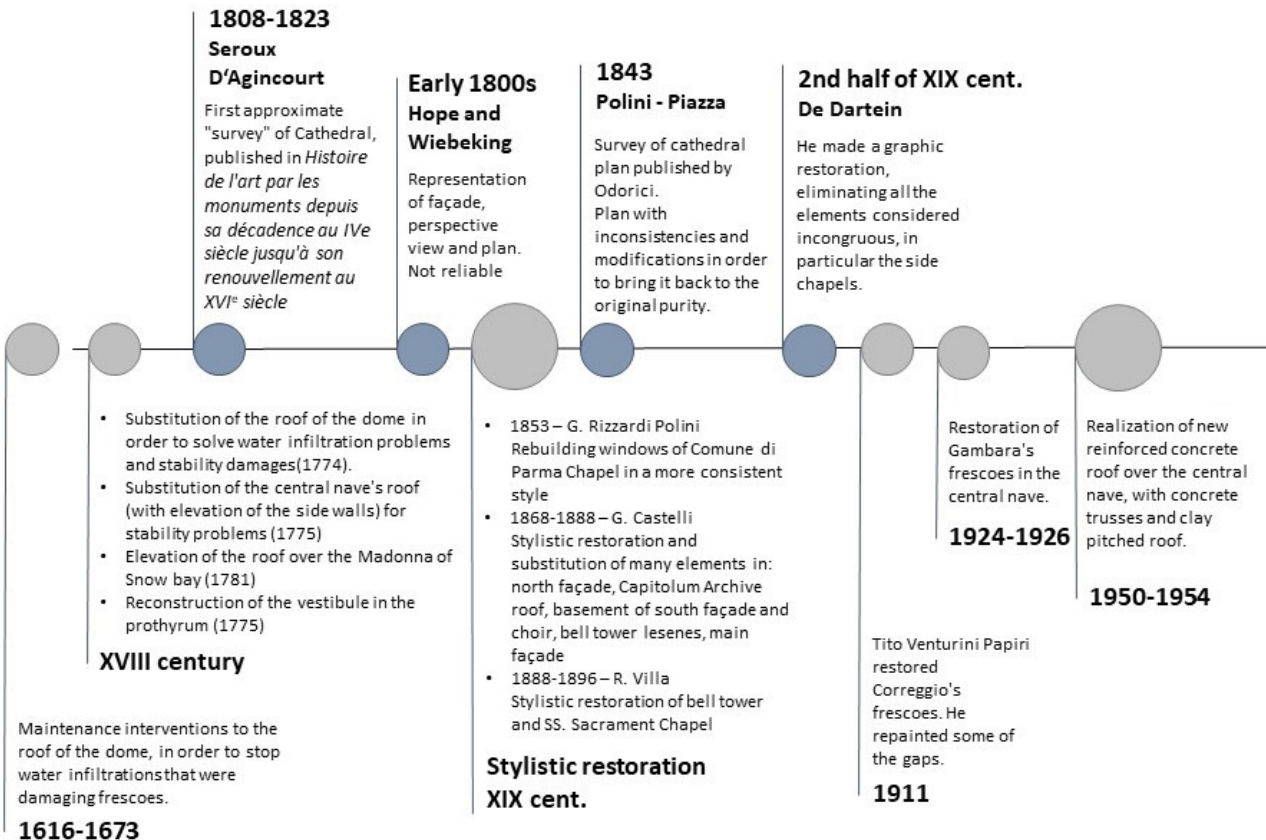
Giuseppe Rizzardi Polini, Pietro Bandini, Ernesto Piazza, Raffaele Villa and Gaetano Castelli, the cathedral of Parma was subject to radical intervention to harmonize the complex appearance and restore the lost gothic image [58].

The main interventions concerned [152]:

- the rebuilding of windows in the Comune di Parma Chapel in a more consistent style,
- the stylistic restoration and substitution of many elements in north façade, Capitulum Archive roof, basement of south façade and choir, bell tower lesenes, main façade
- the stylistic restoration of bell tower and SS. Sacrament Chapel
- the substitution of many stones affected by a high level of decay.

At this time the first drawings of the cathedral were realized, among which D'agincourt's,

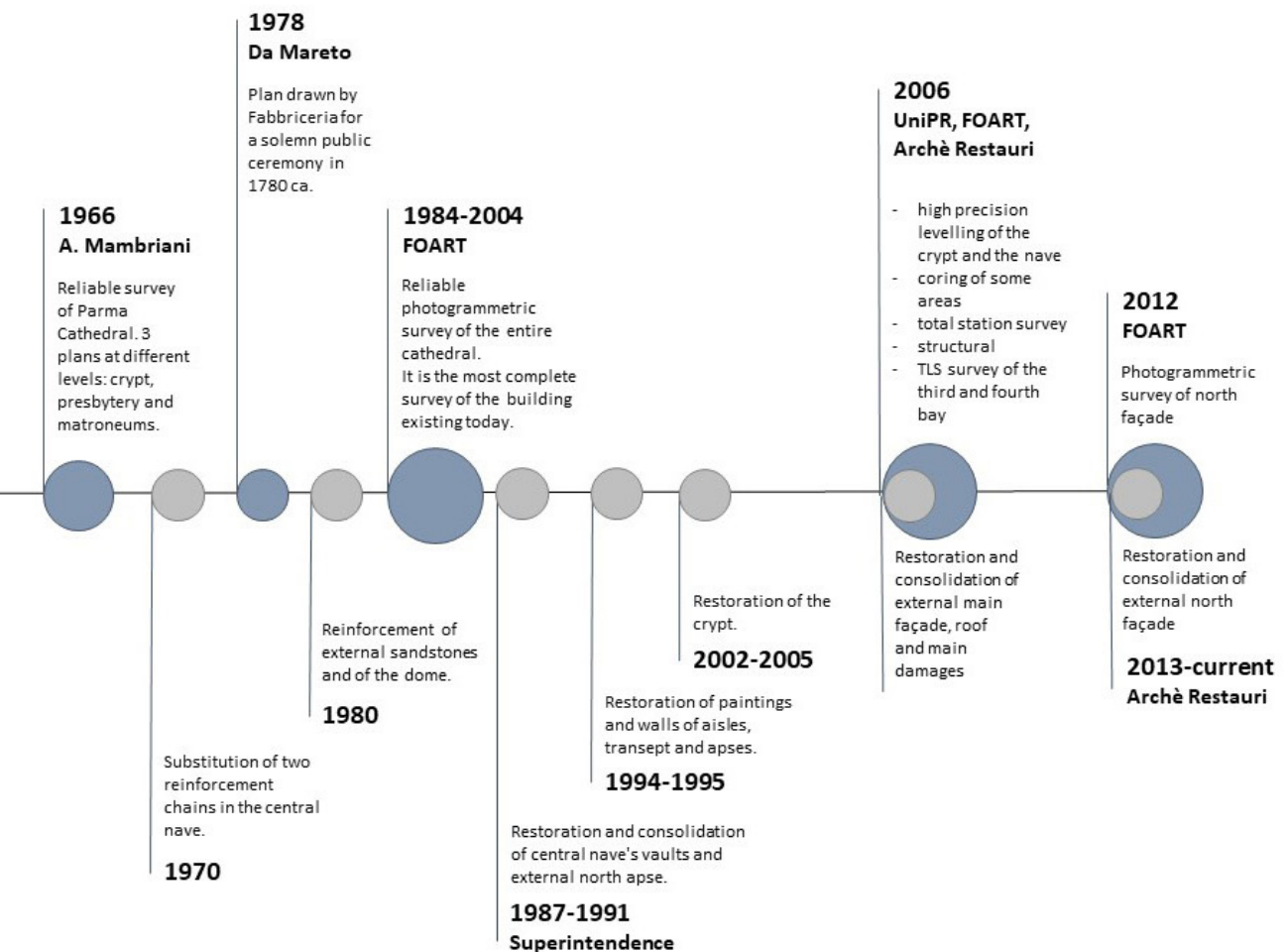
Figure 51. Main restoration works (grey) and surveys (blu). Sources: [58];[152]; Archival documents preserved at Sabap [265]-[273]. Personal elaboration. Sabap = Soprintendenza Archeologia Belle Arti e Paesaggio per le province di Parma e Piacenza.



Hope's and Wiebeking's publications, in which they represented elevations, plans and perspective views, which, however, are not totally reliable. Another representation is the "survey" made by De Dartein in the second half of XIX century. He, according to the contemporary stylistic restoration, represented the cathedral without the side chapels, which were considered inconsistent, making a graphic restoration of the cathedral to bring it back to the "original purity" [152].

Other "style" interventions followed World War II, until the clamorous substitution in 1950 of the timber framework in nave roof with a new reinforced concrete roof composed of concrete trusses and clay pitched roof [58].

Surveys and more suitable restorations were made from the 1980s. Particularly worth mentioning is the photogrammetric survey conducted by FOART s.r.l. between 1984 and 2004. They made reliable and accurate survey of the entire cathedral, representing plans, elevations and cross and longitudinal sections. This is the most complete survey



of the building existing today.

A restoration campaign lead by the Superintendence in the years 1987-1991 [282] carried out cleaning, damage removal, consolidation, strengthening and preservation of the east façade, in particular the apse, and of the vaulting frescoes.

Another remarkable restoration and survey campaign was carried out in 2006 [58] with the collaborative work of many specialists in the fields of restoration, structural engineering, instrumental and precise survey, geomatics, geotechnics, chemistry, biology, petrography, physics and cultural heritage.

Many accurate investigations on the structure and on materials were performed concerning:

- high precision levelling of the crypt and the nave
- coring of some areas in order to obtain the composition of the foundation subsoil
- total station survey of the out of plumb of the pillars in the central nave
- structural monitoring with inclinometer and crack gauges installed on the main cracks
- TLS survey of the third and fourth bay (starting from the façade) in order to verify the serious deformation of the vaults shown by the previous photogrammetric survey
- chemical, physical and biological analyses of the stones in the main façade.

The principal restoration works concerned cleaning, damage removal, consolidation, strengthening and preservation of the main façade and structural reinforcements of the roof and of the crypt columns.

Actually (2017) further restoration activities are in progress in the north façade in order to consolidate the masonry.

The material decay of the stones and decorative elements in the façades is one of the most relevant problems that interests the cathedral. In fact, most of the stones are made of limestone or sandstone, very sensitive to atmospheric agents, and tend to delaminate and crumble. This is dangerous both for the integrity of the buildings and for the safety of people. These are the reasons because of nineteenth-century massive substitutions and to date continuous interventions.

Other important problems relate to the structural asset. In particular survey data analysis has highlighted a rotation of the main façade outwards (15-20 cm), consistent out of plumb in the side walls and main piers of the arches that reaches values of about 20 cm, caused by the high thrust of vaulting not sufficiently contrasted in time. A loss of shape in the arched structures has followed, with a large lowering in the crown of the arches,

which also affected the overlying cross vaults [70].

Soil settlements due to the weight of the dome and supporting structures caused the progressive lowering of the area under the dome and differential settlements between this area and the surrounding ones, which lead to an evolving structural deformation in time [70].

As continuous restoration and maintenance works are required, the Cathedral is a suitable case study to implement the methodology proposed in Cultural Heritage buildings.



## 4.1. Methodology: multi-resolution and scalability

---

Documentation of Cultural Heritage sites is a truly interdisciplinary activity, where surveyors, historians, architects, restorers, facility managers, town planners, structural engineers, etc. are involved. 3D survey and 3D restitution are particularly significant since they convey more information than the 2D representation and provide a global view of the object under investigation. Laser scanner and photogrammetry allow acquiring, rapidly and with a fair automation level, a great deal of real world data at high resolution. Thus, the 3D models obtained by restitution increasingly correspond to reality, being however the user able at any time to reduce the complexity of the information returned, according to the scale of representation or the aim of the survey. The goal might be just the documentation – consider for example the establishment and population of 3D digital libraries in order to ensure that heritage sites are (digitally) available to future generations [98][37] – rather than preservation, restoration [154][220], promotion [41], rebuilding, maintenance and monitoring [68][43], etc.

In the Parma Cathedral case, the HBIM main goal is support maintenance and restoration works. A preliminary accurate 3D survey of the asset is therefore necessary.

Survey planning considered the following main points:

- Final purpose of the survey: the goal was to obtain a global 3D model of the Cathedral that can be used for HBIM implementation and as the basis for new

detailed local surveys or further analyses. Thus, the final model has to be, at the same time, manageable (for its usage in a BIM environment) and finely detailed in order to adequately document the architectural details. To reach this, the survey outputs have to be of manageable size but with the proper resolution for appreciating the embellishment.

- BIM modelling software: for the global model and BIM implementation, the commercial software Autodesk Revit was chosen (see paragraph 5.1). This software handles point clouds with variable performance depending on the cloud size and hardware characteristics, thus manageable point clouds are advisable. In addition, it is important to consider that during the modelling phase much survey information is lost since Revit is not particularly suited to the modelling of irregular and deformed elements.
- Survey implementation in time: to the present survey campaign, the Cathedral was partially accessible. In particular, the north side was under restoration and was totally covered with scaffolding. In addition, in order to constantly monitoring structural and material health, additional survey campaigns will succeed in time and their consistency and comparability are mandatory for correct monitoring actions.
- Location: the Cathedral is located in the historic centre of Parma and overlooks Piazza Duomo. Another square (Piazzale San Giovanni) is present in the south-east corner, while, on the remaining sides, the Cathedral is surrounded by narrow streets (see Figure 52).
- Levels of architectural details: the Cathedral (Figure 52) exterior presents bare brick walls with details and embellishment centered in the capitals, in the decorative mouldings and in the galleries, so the survey should have different resolutions to avoid redundancy and overabundance of information in some areas and lack of data in others.
- Output: particular attention in the HBIM model should be put on representing the material degradation of the external façade with orthophotos and collecting all information useful for restoration in the database. The focus was on the informative and qualitative aspects of the model in order to have a data collector of previously unorganized data. Restitution was planned for a nominal average scale of 1:50, reserving the 1:100 scale for less accessible areas and 1:20 for some peculiar details.

Integrated survey techniques, multi-resolution and scalability were identified as key elements to fulfill the above listed goals.

Integration allows indeed overcoming the specific limitations of each technique, having

more complete results [43]. As shown in chapter 2, many authors underline that to reach the best result in terms of accuracy and completeness of the models it is important to perform an integrated survey, which takes into account total station, GPS, terrestrial laser scanning (TLS) and close range photogrammetry techniques combined together. In addition, integration is useful to achieve the best result with less effort and to have as much comprehensive and complete documentation as possible. The specific survey campaigns will be described in detail in the next paragraphs but, in general, the survey was organized in order to implement it in time and use the most appropriate method at any time.

Multiresolution is a suitable approach to manage the huge amount of data that generally comes from such survey and to have, at the same time, a correct overview and an adequate level of detail. The survey design showed that for a homogeneous resolution coverage a high number of scans at different levels would have to be performed. This would take a lot of work time before having a global documentation as required. Thus, in order to not overload TLS data, very time consuming and with very heavy output, a global survey of the whole cathedral at medium resolution (average resolution on the object  $6\div 7$  mm) was performed, detailing then with high resolution surveys (TLS or photogrammetry) the specific areas under investigation or the ones with a complex

Figure 52. Parma Cathedral example views.



level of fine details.

Finally, scalability has great importance. Scalability has to be considered both as progressive survey implementation in time (acquiring consistent, comparable and commonly referred additional data for specific analysis) and as the ability of managing the time dimension by comparing data acquired in different epochs on the same building portion. Comparing data acquired at different times can be useful for monitoring purposes, which represent an increasingly field of research in TLS applications [70][140]. To this aim, it is mandatory to have a common database, reliable and shared references and metadata that document survey works.

## 4.2. Integrated survey campaign

### 4.2.1. Topographical survey

A stable and georeferenced topographical network, to which refer all future measures has been established. The station points of the topographical network were located all around and inside the cathedral. The network has been designed in order to:

- be stable and sufficiently redundant
- ensure intervisibility between stations
- ensure a homogeneous coverage all around the cathedral
- support all survey campaigns of the Cathedral, including the crypt and matroneums.

In order to make the reference system stable and lasting, outdoor station points have been marked with steel nails while indoors, not to spoil the marble pavement, well defined floor features, such as edges or veins, were selected and monographed (Figure 53).

Twenty-two stations were materialized, as shown in Figure 54 and surveyed.

The survey of the topographical network has been carried out twice: both with the Topcon Image Station IS2 total station and Leica C10 laser scanner (see Appendix B for technical description), in order to achieve greater accuracy on the final adjustment, thanks to the redundancy and robustness of observations [70].

In such networks, total station (TS) survey is mandatory. High TS angular and distance measure precisions assures accurate determination of the network points and the establishment of a rigid reference system. The laser scanner was used as a topographical

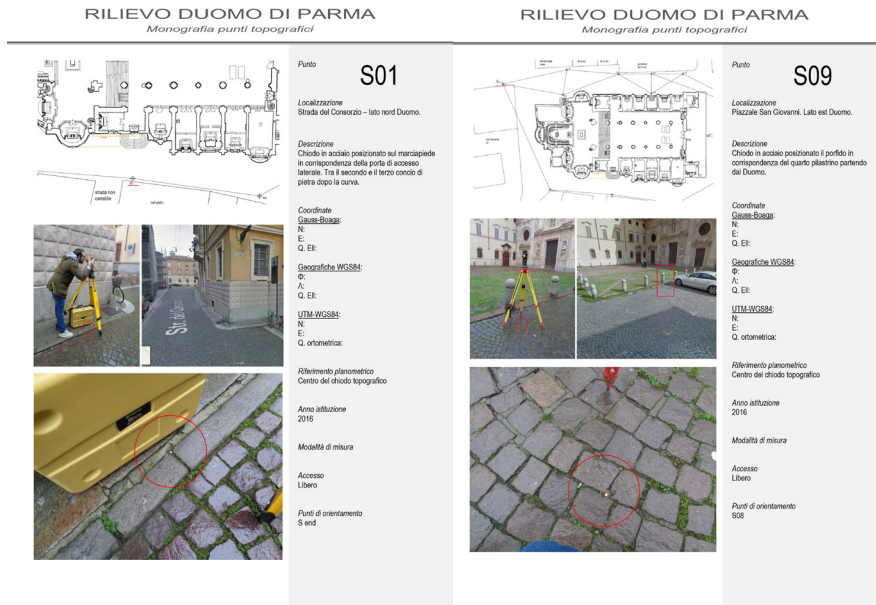


Figure 53. Topographical network points monographs: examples.

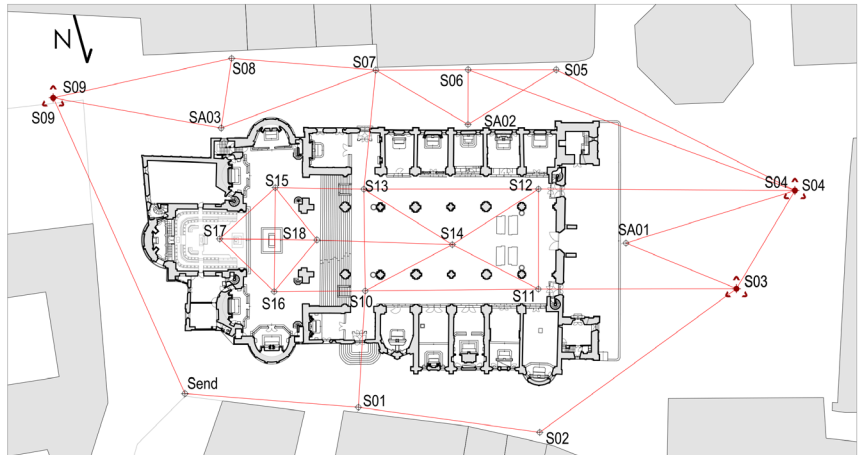


Figure 54. Topographical network of traverses.

instrument, measuring from each scan station all the network points signaled with HDS targets. This method is commonly used for scan registration if targets positioned on the building surface or algorithm for registration of common scan areas are not used. Distance laser scanner observations have been exploited here not only for scan registration, but also to strengthen the global adjustment, reducing uncertainty and increasing reliability.

Total station and laser scanner observations were adjusted through rigorous least

squares minimization with the software Calge [139] separating horizontal and altimetric coordinates. The final value obtained for sigma naught was  $\sigma_0 = 1.8$  (for horizontal coordinates) and  $\sigma_0 = 2.8$  (for altimetric coordinates), with mean accuracy of local coordinates of station points of ca. 2.1 mm, which can be considered acceptable for most modelling and monitoring activities if very high precisions are not required.

<b>STATION HORIZONTAL COORDINATES AND ORIENTATIONS PRECISIONS</b>			
	RMS (SD)	MAX (SD)	
X coordinate [mm]	1.4	2.0	
Y coordinate [mm]	1.6	2.8	
Orientation [cc]	25.5	55.7	
<b>Residuals</b>			
$\sigma_0 = 1.8$			
Equations: 325	Unknowns: 131	Constraints: 3	Redundancy: 197

Table 5. Horizontal coordinates network adjustment stats.

<b>STATION ELEVATION PRECISION</b>			
	RMS (SD)	MAX (SD)	
Z coordinate [mm]	1.17	1.49	
<b>Residuals</b>			
$\sigma_0 = 2.8$			
Equations: 139	Unknowns: 22	Constraints: 1	Redundancy: 118

Table 6. Altimetric coordinates network adjustment stats.

The topographical network was georeferenced with a GPS survey of three vertices (vertices S03, S04 and S09, as shown in Figure 54), placed in the two squares at the opposite corners of the cathedral (Piazza Duomo and Piazzale S. Giovanni) to warrant an acceptable PDOP and, so, a reduction of the georeferencing error.

The GPS coordinates were obtained through 4 hours static session with respect to a station of the CORS (Continuous Operation Reference Station) network Netgeo about 9 km away and then transformed in a local Cartesian reference system with origin in the midpoint between the GPS stations.

Since the average accuracy of the GPS points can be estimated in ca. 1 cm in (E, N) coordinates and about 1.5÷2 cm in elevation, network georeferencing was performed without scale changes, due to the topographic network better inner precision, by the following steps:

1. Rotation and translation, without scale variation, of the previously adjusted network, to fit the new GPS coordinates. This will minimize residuals with respect to all GPS

measurements

2. Azimuth calculation between the GPS stations.
3. Planimetric adjustment of the topographic network by constraining the position of the first (S03) GPS station on the coordinates that derive from the roto-traslacion at step (1), and by fixing the azimuth calculated in step (2).

As far as the altimetric adjustment is concerned, it has been done, shifting all the coordinates by the orthometric height of point S03, since it was the reference point used for planimetric adjustment.

## 4.2.2. Laser scanner survey

As far as the laser scanner is concerned, the Leica Geosystem C10 scan station was used, a Time of Flight laser scanner widely used for architectural survey (see appendix B.1 for technical description). In this specific application, being the Cathedral mainly made of brick with presence of sandstone and limestone, no problems occurred related to material reflectance.

The survey design took into account the complete coverage of the object, trying to avoid occlusions, computing the adequate resolution to properly document the object and the possibility of integration with other survey techniques.

As said before (paragraph 4.1), the survey was realized with a multi-resolution approach, so two different scan phases have been designed: a global survey and a detailed survey. The global survey aimed at generally documenting the cathedral, having a complete survey of its main volumes and assuring interviews of scan stations. For these reasons, 19 scans were performed taking advantage of the topographic network points as shown in Figure 55.

The scans were acquired all around the Cathedral, in the nave, in the transept and in the choir. As explained in the paragraph 4.1, the scans were acquired with medium resolution, which means (considering scans overlapping) an average resolution of 6÷7 mm on the object. The scans carried out in the area of the presbytery (S15, S16, S17, S18) were instead acquired at high resolution, i.e. 2÷3 mm on the object, due to the high level of detail in the presbytery area.

The detail survey was designed considering:

- a representation scale ranging from 1:50 to 1:20

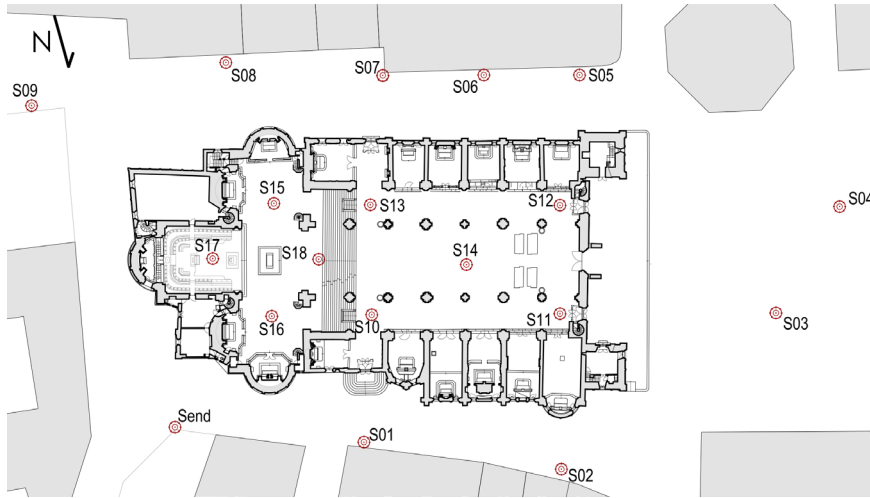


Figure 55. Scan stations configuration.

- surface discontinuities, such as overhangs, undercuts and curved shapes
- the Cathedral height (26 m for the central nave and transept, 43 m for the dome)
- the constraints due to the narrow streets surrounding the Cathedral

As the admissible drawing error for the representation scale 1:50 is 1 cm, a point cloud resolution not less than 5 mm is necessary. Since the C10 Scan Station (see Appendix B) at “ultrahigh-resolution” set up delivers 1 point/2 cm at 100 m, the scanning distance should have been lower than 25 m (Table 7).

At those distances, the instrument precision (2mm) ensures that tolerances required from the representation scale are met.

	Medium resolution 1 point/10 cm at 100 m	High resolution 1 point/5cm at 100 m	Ultrahigh resolution 1 point/ 2 cm at 100 m
Maximum distance admissible for a 5 mm object resolution	5 m	10 m	25 m

Table 7. Maximum admissible distances from the object in order to ensure 5 mm resolution, according to the C10 Scan Station performance.

As shown in Figure 56, additional scans referred to the topographic network were introduced to compensate for the resolution reduction proportionally to the distance increase. The restitution from TLS survey was anyway limited to a height of 18 meters, to document only the parts with greater level of detail such as external semi-circular apses. To maintain a resolution better than 5 mm and limit incidence scan angles, an estimated height limit of 18 meters from ground level stations has been fixed. As orthophotos of the whole edifice are anyway needed as well as roof restitution, scanning from scaffolds

has been ruled out and a UAV photogrammetric survey (see paragraph 4.2.3) has been foreseen for building elements above the 18 m limit.

TLS data were registered in Cyclone, the data processing software produced by the laser scanner manufacturer, as it allows registering clouds on the basis of a known coordinate dataset and not just point cloud co-registration or target detection.

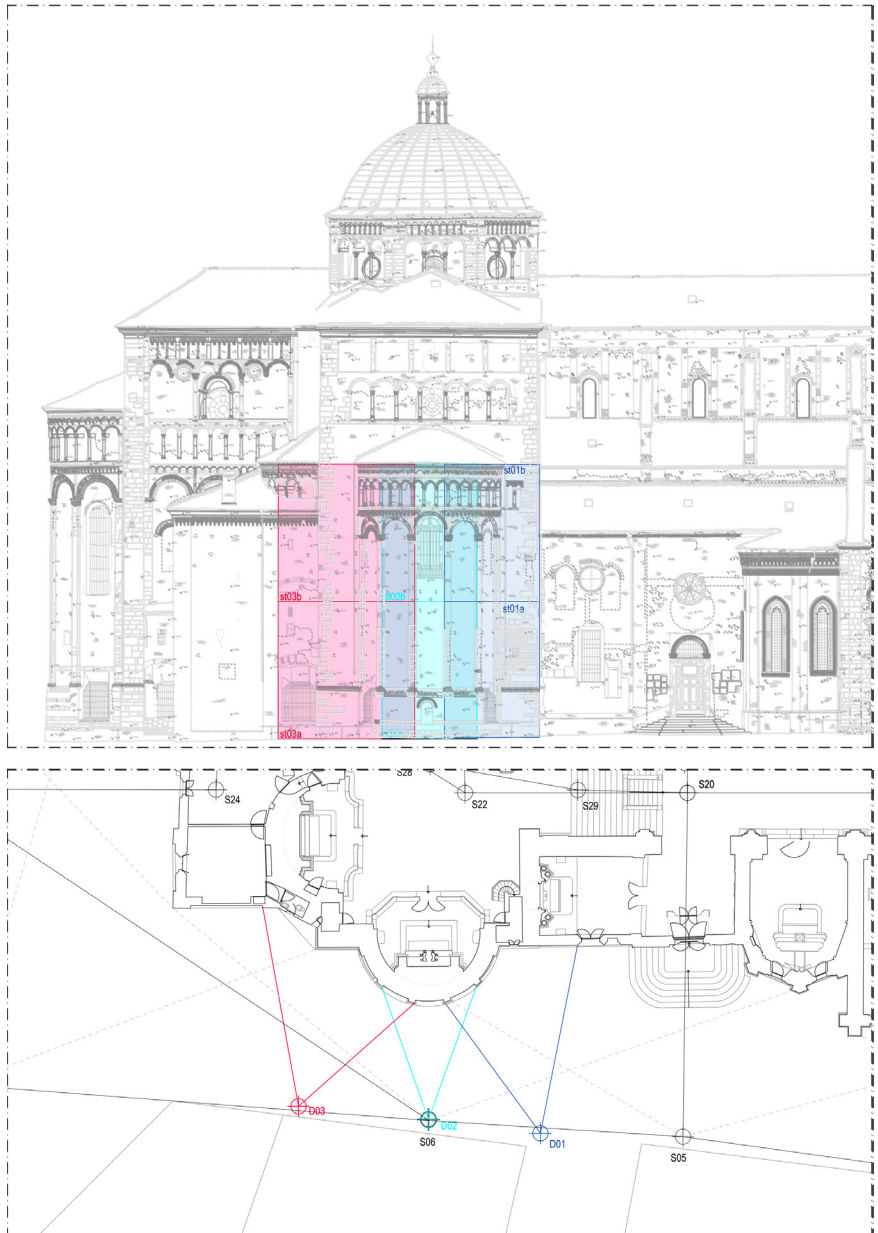


Figure 56. The detail survey design: the figure highlights, for each scan, the area of the building detected with a resolution equal or better than 5 mm.

The registration process computes the optimal overall alignment transformations for the clouds such that the constraints (tie- and reference-points coincidence) are satisfied as closely as possible. In this specific case, C10 Scan Station has been used in the same fashion of a traditional total station and the registration on the basis of a known coordinate dataset topographically surveyed (§ 4.2.1) was used. At each scan station, a backsight and a foresight reading were taken towards the previous and next station respectively. In addition, all the visible stations have been measured, increasing the redundancy of observations and network robustness. In this way, Cyclone was able to automatically recognize as constraints these target and, since they had known coordinates, use them as control-points for cloud registration.

The registration provided satisfying results, with an average residual of 2 mm and a standard deviation of 1 mm, in accordance with the tolerance of the representation scale. The registered point cloud of the cathedral is shown in Figure 57.

Figure 57. The complete point cloud after registration.



### 4.2.3. Photogrammetric survey

Although laser scanning is widely used in historical building surveys, where complex irregular objects require a full 3D description, limits in precision range, resolution and geometric and radiometric accuracy or and portability [149] might emerge.

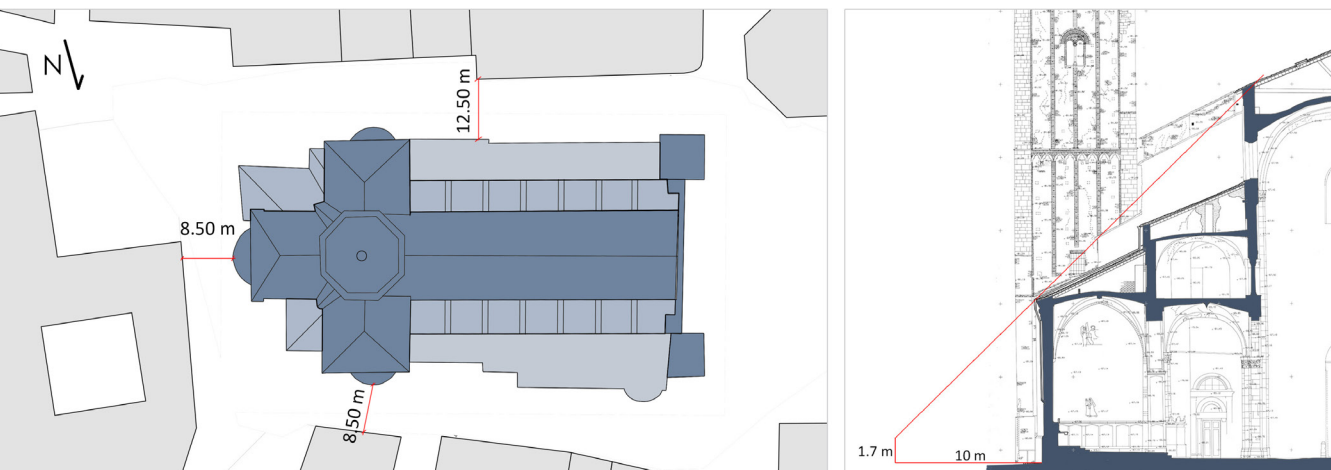
Photogrammetry, on the other hand, has become more and more popular thanks to innovative algorithms that automate image block orientation and 3D model reconstruction [263] and to the improvements of digital camera sensor resolution, providing a comparatively much cheaper but reliable solution for data acquisition.

Photogrammetry is a very versatile technique, delivering a wide range of products, from orthophotos to 3D Digital Surface Models etc., and object scales. In fact, the same hardware can deal with building-scale surveys or very small archaeological artefacts surveys: in [249] a survey with accuracy range from 5-20 mm to 0.05 mm is presented. In the Parma Cathedral survey, photogrammetry provides an essential integration to TLS, though image acquisition presents numerous difficulties. As it can be seen in Figure 58, ground level images are affected by many occlusions. Moreover, the narrow streets around the Cathedral dictate oblique imaging in order to frame the upper part of the façades, with large variations in image scale from the base to the top of the façade. This in turn cause a progressive decrease of accuracy and resolution from the lower to the upper parts.

An Unmanned Aerial System (UAS) would provide a much better imaging geometry, and would be beneficial for detection of the areas not visible from the ground level, with reduction of occlusions and for the roofs survey.

As specific equipment, the Albris of Sensefly [11] (see Appendix B.5 for technical description) was chosen. It allows capturing still and thermal imagery in a vertical angle

Figure 58. Acquisition environment: narrow streets around the Cathedral and many occlusions due to the Cathedral conformation.



of 180°, thus imagery ahead, above and below the drone. In addition, thanks to its on-board navcams and ultrasonic sensors, the Albris provides a visual and proximity feedback, particularly suitable for critical areas, such as historical city centres and cultural assets.

However, at this time, the survey with the drone has not yet been possible for issues related to authorization to fly in the city centre. Therefore, for the moment, only images from ground have been taken, suitable to model the building up to the level of the lower eave (side chapels and apses).

A Nikon D3x (resolution 6048x4032 pixel, pixel size 6  $\mu\text{m}$ ) mainly with 35 mm optics (Appendix B.4) has been used. The site constraints (narrow streets, high façades with many depth changes) prevented using longer focal lengths; 35 mm can be considered a good compromise between the wide field of view requested, ground resolution and the reduction of optics distortion as well as other photographic issues.

From the photogrammetric block design resulted that in order to reach a precision adequate for 1:50 representation scale ( $\sigma_z = 1 \text{ cm}$ ), the images had to be captured at a distance of about 17 m from the object and with a baselengths of 7 m. However, excepting the main façade, the maximum shooting distance is less than 17 m (see Figure 58). Thus, the image sequence was captured with a distance variable from 8.5 m to 17 m, trying always to keep the longest distance available, in order to detect a larger part of the façade, without inclining too much the camera. The baselength between subsequent frames has been adjusted in order to have a constant overlap not less than 80%.

The Ground Sampling Distance (GSD) varies therefore from 1.4 mm to 5.15 mm (in the upper part of the main façade). As the GSD at an object distance of 17 m is 2.9 mm, only the areas with a smaller GSD were considered for modelling.

[mm]	Main façade Dist. 17 m, H=28.5 m	South façade Dist. 12.5 m, H=11 m	South Transept Dist. 12.5 m, H=26.9 m	East Apse Dist. 8.5 m, H=26.9 m	North Transept Dist. 8.5 m, H=26.9 m
GSD min	2.91	2.14	2.14	1.46	1.46
GSD max	5.15	2.53	4.56	4.31	4.31

Table 8. GSD variability.

The images sequence was captured moving the camera all around the Cathedral, making two or three strips (according to the façade height) to document the entire vertical surface (see Figure 59).

Lighting conditions were not optimal since the acquisition were made in a very sunny

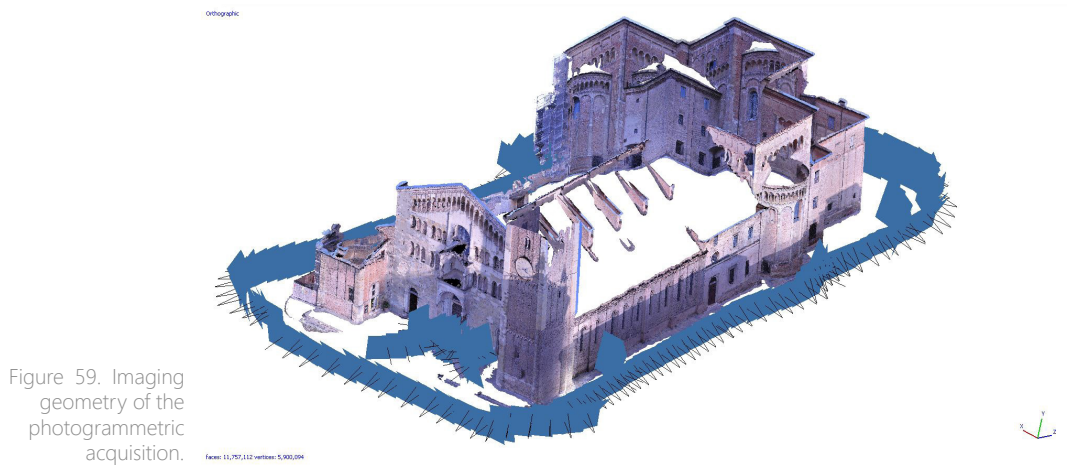


Figure 59. Imaging geometry of the photogrammetric acquisition.

day and the shadows on the façades are evident.

The camera sensor along with the optics used were previously calibrated through an analytical procedure: using a calibrated pattern a bundle block adjustment is performed, computing the parameters of the Brown distortion model [119].

The image sequence consisted of 326 images that were oriented automatically using Agisoft Photoscan. High accuracy image orientation with a generic pair pre-selection modality has been chosen. To define the reference system of the restitution and orient absolutely the image block, 15 well-distributed Ground Control Points (GCP) were selected on natural features (e.g. edges, corner, surface discontinuities, etc.) since, for the moment, the Cathedral Fabbriera did not granted permission the installation of targets to the Cathedral walls.

The use of natural points makes collimation more difficult and point identification less precise. This is true despite a GSD of the order of 3 mm, as the edges of architectural elements are always worn and corroded. Moreover, their topographical identification is also complex due to the strong irregularity and deformation of the architectural edges, which makes the points not univocally recognizable. For this reason, in order to improve the accuracy of the photogrammetric survey, using targets is desirable. Therefore, in accordance with the drone survey campaign, the installation authorization will be requested again.

At the end of the structure from motion procedure, with the same software package, the DSM of the exterior side of the Cathedral was obtained. In addition, the high-resolution orthophoto (GSD 3 mm) were produced (Figure 60).



## 4.2.4. Survey validation

### Laser scanner survey validation

As at the time of survey no targets could be fixed to the Cathedral walls, the TLS survey validation via total station independent measurements was not feasible.

However, targets were installed on the tripods set up over the points of the topographic network that were also used as scan stations. As explained before (§ 4.2.1), these targets have been detected both with Total Station and Laser Scanner and have been used as reference for point cloud registration (§ 4.2.2).

As far as the registration is concerned 146 constraints have been automatically detected by the software used (Cyclone), pairing up all target tie-points.

The table below (Table 9) shows the stats of the residuals of the scans registration.

	XYZ Error [mm]	X error [mm]	Y error [mm]	Z error [mm]
RMS	2.6	1.2	1.5	1.8
Mean	2.3	0.2	0.0	0.0
Std. dev.	1.0	1.2	1.5	1.8
Max	5.0	3.0	4.0	4.0
Min	0.0	-2.0	-4.0	-4.0

N. of constraints: 146

Table 9. Residuals of the scan registration on the basis of the topographical network.

These results are affected by topographical network initial adjustment, scan station registration and laser scanner accuracy on target acquisition. Considering that the topographic network adjustment provided station points coordinates with mean accuracy of ca. 2.1 mm (§ 4.2.1) and that the C10 accuracy on target acquisition is 2 mm standard deviation (Appendix B.1), the registration residuals are in accordance with what expected.

In addition to this validation, an internal measure of consistency of the registration has been obtained by comparing the distance between the point clouds of each scan after registration. Some registered pairs of clouds were selected and the deviation between them was evaluated in order to measure the displacement over the whole point cloud. In particular, the mesh surface of one of the two clouds was created and the point-to-mesh distance was calculated. It was decided to use a mesh as a reference instead of the point cloud in order to have a continuous reference surface, avoiding effects due

Figure 60. Orthophoto of the Cathedral main façade overlapped to the drawings of the photogrammetric survey made by FOART in 1989. (In the previous page).

to the different resolution of the scans that generally affect cloud-to-cloud comparison. Since the point cloud and the mesh were oriented in the same reference system, for the comparison there were no needs to use ICP (Iterative closest point) algorithm. The results, therefore, show the repeatability of the measurement acquired from different scan stations. Considering the residuals on the clouds registration and the instrument precision (2 mm - Appendix B.1), the expected deviation between the two compared clouds is of the order of  $0.4 \pm 0.5$  cm.

Figure 61 shows the false colour displacement map between two point clouds of the south façade. It can be seen that there are no systematic registration errors ; moreover, 75 % of the points distances are lower than 2.57 mm ( $1\sigma$ ) and 94 % of the whole dataset is under 5.4 mm ( $2\sigma$ ) of displacement (Table 10).

It is worth noting that the higher discrepancies between the two point clouds are in the areas richer in details such as upper cornice or window embellishment. This can be determined by mesh surface approximations in the definition of these areas.

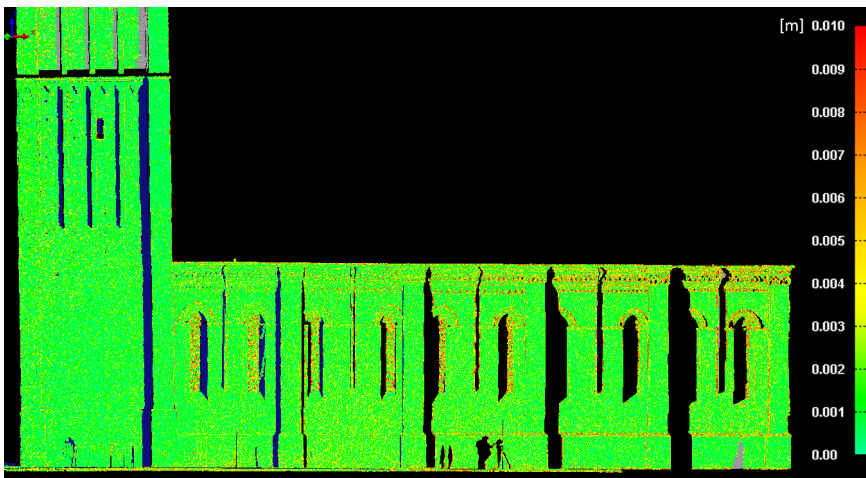


Figure 61. Map of displacement between two registered point clouds.

Table 10. Stats on the deviation between two registered point clouds.

Mean [mm]	Std. dev. [mm]	RMS error [mm]	Points < $1\sigma$ [%]	Points < $2\sigma$ [%]	Points < $3\sigma$ [%]
0.04	2.57	2.57	75.74	94.04	98.23

### Photogrammetric survey validation

Also for the validation of the photogrammetric survey, the lack of targets on the walls of the Cathedral caused greater difficulties. Two different procedures have been applied: the analysis of the residuals on some check points located on natural features and a comparison between the photogrammetric DSM and the laser scanner point cloud.

### Check points validation

Analysis of check points residuals allows a point-wise evaluation of the survey accuracy on the three X, Y, Z coordinates.

To this aim, natural points have been acquired by topographical measurements and monographed. Overall, 48 points were determined: 15 were used as CGP and the remaining 33 as check points. Figure 62 shows the position of GCPs and check points on the south façade.

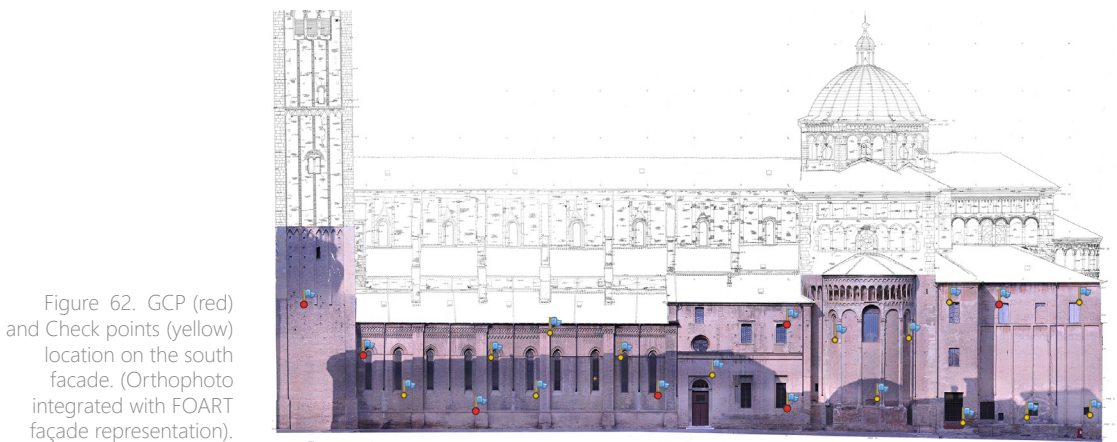


Figure 62. GCP (red) and Check points (yellow) location on the south façade. (Orthophoto integrated with FOART façade representation).

As can be seen from Figure 62 the distribution of GCP is not always optimal. For example, in the south façade, the ideal configuration would consist in pairs of points (one at the top and one at the bottom) every 15 metres. Nevertheless, it was not possible to use this distribution because of the difficulty of collimation of some points which made them unreliable.

Orientation tests were also carried out with a greater number of GCPs, but the estimated solution did not significantly improve the residuals.

Figure 63 provides a graphical representation of the estimated error on GCP (dots) and Check Points (crossings). The error along the nadir direction is represented by ellipse

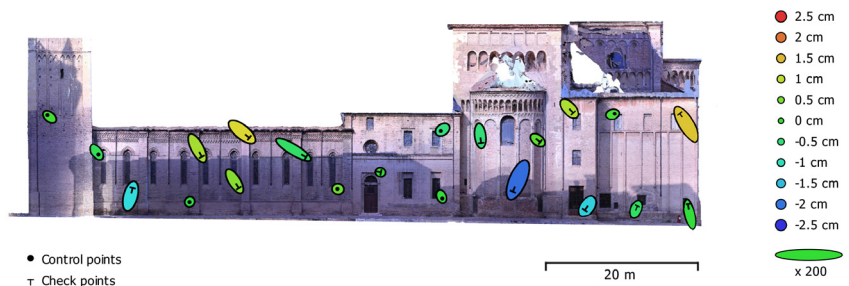


Figure 63. Photoscan report on GCP locations and error estimates.

colour as illustrated in the legend while the front plane errors are represented by the ellipse size and shape. Systematic error components are visible on the left and right areas of the façade, as will be noticed also in the Figure 64.

The stats of the whole check points dataset are reported in Table 11.

	XYZ Error [mm]	X error [mm]	Y error [mm]	Z error [mm]
RMS	16.1	9.2	9.7	9.0
Mean	14.9	2.0	0.8	2.3
Std. dev.	6.2	8.9	9.7	8.7
Max val	26.8	17.4	23.9	16.4
Min val	0.7	-14.6	-15.6	-20.9

N. of check points: 33

Table 11. Check points residuals.

Mean residual errors, that could highlight possible systematic shifts, are actually small and statistically not significant, considering population standard deviation and sample size.

However, from this stats, it is possible to note that the solution is apparently a little worse than the accuracy estimated in the block design phase (1 cm), with an RMS of 16.1 mm. On the contrary, the maximum error values are rather high. Given the difficulties of collimation mentioned above, it is possible that these high values are due to errors of collimation, either during the topographical survey or the image point identification.

### DSM comparison

The second validation procedure concerns the comparison between the DSM obtained from the photogrammetric survey and the laser scanner point cloud and therefore applies to the whole surface and not only to some distinct points. However, only the distance between the two surfaces can be highlighted, as there are no common points between the two datasets.

The mesh was imported without polygon decimation while the laser scanner point clouds was reduced to the 1/16th of points, in order to reduce computing times, ensuring, in any case, a reliable comparison (more than 500.000 points were used).

The outcomes of this comparison are shown in Figure 64.

The analysis of the discrepancies histogram shows that 71 % of the points distances are lower than 16 mm ( $1\sigma$ ) and 94 % of the whole dataset is under 32 mm ( $2\sigma$ ) of displacement. The results tend to confirm the pointwise indication gathered by the check point analysis.

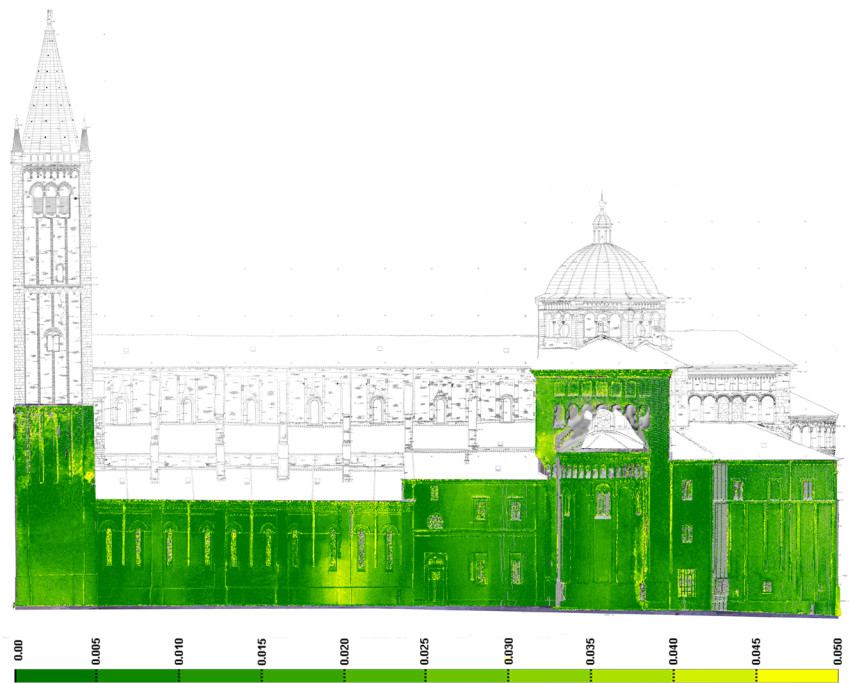


Figure 64. Map of displacement [m] between DSM and laser scanner point cloud.

Table 12. Stats on the deviation between DSM and laser scanner point cloud.

# Points	Mean [mm]	Std. dev. [mm]	RMS error [mm]
469013	-0.08	16.4	16.4

It is worth noting that, in the lower-central part of the south façade (Figure 64) higher discrepancies between LS point cloud and photogrammetric DSM are clearly visible. In particular, a very high deviation (ca 45 mm) at the fourth lesene highlights strong (most likely image block) deformations, probably due to an incorrect control of the orientation solution. At the moment, just few ground control points identified on rather irregular natural features being available, the problem cannot be solved: the use of artificial target, on the contrary, should solve the issue. For this area, the photogrammetric solution was discarded and, in the modelling stage, only the LS point cloud was considered.

Other areas where the deviation between laser scanners and photogrammetry is most evident are the upper parts of the transept. This behaviour was expected due to the lower quality of both laser scanner and photogrammetric surveys in these areas. In fact, the measurement accuracy of the laser is lower because the laser beam affects these areas with a very high incidence angle and the photogrammetric precision quadratically decreases with the distance, reaching values of ca  $\sigma_z = 2.4$  cm.

To mitigate this drastic reduction in accuracy, during the photogrammetric block design

phase, other longer-focal optics have been evaluated to detect the top end parts of the facades in order to have a more homogeneous GSD. However, by providing for a future integration with drone survey, it was considered superfluous, postponing the accurate survey of these areas to the UAV acquisitions.

In order to test the effect of the lower precision of the survey on the comparison between the photogrammetric DSM and the laser scanner point cloud, the comparison was run again reducing the area of investigation first to the lateral chapels only, where the general displacement map showed the best results, and to the upper part of the transept then, where, on the contrary, the results were worse.

The stats of the two comparison are reported below (Table 12).

Area	Mean [mm]	Std. dev. [mm]	RMS error [mm]
Side Chapels	2.5	12.1	12.4
Transept	-7.2	20.2	21.5

Table 13. Stats on the deviation between DSM and laser scanner point cloud, focusing on the side chapels area and on the upper part of the transept.

#### 4.2.5. Photogrammetric survey of details

The survey of the Parma Cathedral has provided a representation scale of 1:50, adequate for supporting the identification of materials and their degradation by the appointed technicians (Superintendents, restorers, maintenance professionals, etc.). If a higher representation scale is required (e.g. 1: 5 up to 1: 1), for instance to document ornamental details, embellishments or statues, it is possible anyway to proceed with photogrammetric survey.

On this topic, results are presented for the project "*Percorsi multimediali innovativi per la valorizzazione del Museo Archeologico di Parma*" (Innovative multimedia exhibitions itinerary for the promotion of the Archaeological Museum of Parma) [243] started in 2015, with the goal to document very small and medium size sculptures. In the box below, a summary of the adopted methodology is presented [100].

## Innovative multimedia exhibitions itinerary for the promotion of the Archaeological Museum of Parma [100]

The project addressed the promotion of the Archaeological Museum of Parma and in particular of the exhibits found in the archaeological site of Veleia (Piacenza, Italy), through new digital contents (reality-based 3D models of heritage sites and objects, AR applications). The main exhibits include: the Giulio-Claudio statuary, composed of twelve honorary marble sculptures symbolizing the imperial family members, and several antique bronzes.

Many problems must be evaluated when museum assets have to be surveyed. Immovable objects can generate problems for data acquisition: objects dimension and position are not always adequate for an easy survey. Surface complexity, high and rapid depth changing, material reflectance and lighting conditions can cause problems in the acquisition and 3D models production and can lead to erroneous surface reconstruction.

Although nowadays terrestrial laser scanning systems are very popular for cultural heritage documentation and 3D modelling, photogrammetry still remains an optimal solution for achieving accurate results and complete products in all possible operational frameworks.

Specifically addressing the Veleia heritage exhibits in the Archaeological Museum of Parma, several problems, made the data acquisition difficult. As it is shown in Figure 65, the important marble statuary symbolizing the Giulio-Claudio family, which represents the hearth of the remaining Veleia cultural and artistic heritage, is exhibited in a specific room where the sculptures are placed sequentially and, unfortunately, adjacent to the wall perimeter. Taking into account the very small space between the sculptures body and the back wall, and the impossibility of moving the artefacts, the data acquisition has just been possible by using a digital camera with wide-angle optics.

The sculptures draperies complexity offers an undeniable aesthetic beauty play, but the sudden depth changes that characterize the dresses require a high-accurate and detailed photogrammetric survey. A high-coverage between digital images, as well as a good design of the image block, must be guaranteed in order to model the finer details of the objects body and drapery. Materials reflectance and lighting conditions can cause difficulties. For avoiding shadows areas on the investigated artefact, artificial light sources, moved and placed around the object, must be used. The use of directional light source, together with the reflecting power of marble and, in particular, bronze materials (see for instance Figure 66), are



Figure 65. The Giulio-Claudio statuary exhibited in the Archaeological Museum of Parma.



Figure 66. The antique decorated bronze exhibited in the Museum of Parma.

key issues that must be taken into account for obtaining a successful, complete and accurate survey and 3D modelling.

All the photogrammetric surveys have been performed using a full-format Nikon D3X (6048x4032 pixels resolution and 6 micrometres pixel size) digital camera, with 105, 35 and 18 mm calibrated lens.

Most of the photogrammetric operations were performed with the commercial software Agisoft Photoscan (Agisoft Photoscan, 2016), which provides a very simple and automated workflow, through the following flow-chart: (i) image orientation; (ii) high-resolution dense image matching; (iii) 3D reconstruction and model texturing. A geometry or network design has been firstly studied to ensure that the number and location of the images to be used were appropriate to produce accurate results. To check the consistency of image orientation, all the image blocks were exported in Photomodeler and analysed more in detail.

Two different general image blocks design and workflows has been designed and tested for allowing the optimal 3D reconstruction of, respectively, the twelve sculptures that constitute the Giulio-Claudio marble statuary and the antique bronzes ("Ercole ebbro", "Vittoria alata" and "Dioniso" statuette).

### **The Giulio-Claudio statuary**

The photogrammetric survey has been characterized, for each case study, by an initial image acquisition step performed on a circular geometry with a 35 mm focal length optic. Generally, three image sequences (two for modelling the body and one for the head), taken with this geometry, have been necessary for accurate modelling all the sculpture, avoiding occlusion problems. After that, closer and shorter image sequence has been acquired for capturing sculptures particulars, such as draperies and dresses details. Finally, for acquiring images of the sculpture back side (wall adjacent) the 18 mm lens has been used. An example of a performed image network is shown in Figure 67.

All the assets surveys were computed with the support of two artificial light sources one of which has closely followed the images acquisition geometry, generating a diffused ambient lighting in the camera acquisition direction, while the second one was used as a sidelong light source for avoiding as much as possible shadows and reflections problems. With regard to the objects back-side, since it was difficult finding an easy location for the artificial illumination (because of the reduced space between the wall and the sculpture, and the reflection problems caused by the use of too much close light sources), the lights has been kept fixed in the wall directions, in order to generate a diffuse reflected ambient illumination on the sculptures back. The collected image sequence has been processed in Photoscan for achieving the final high-resolution three-dimensional models. The already discussed sculptures complexities, highlighted by the presence of high depth changes, reflections and discontinuity areas on the images, has made necessary the manual operator intervention for increasing the robustness of the more complex images orientation solutions.

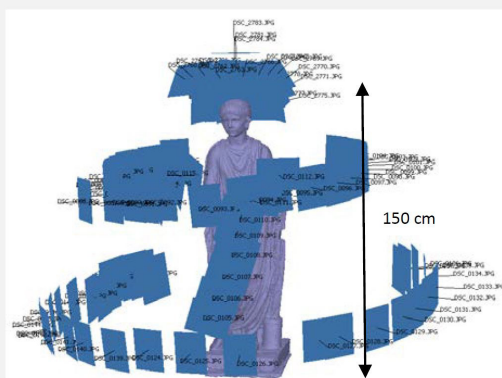


Figure 67. Typical camera network characterizing the sculptures photogrammetric surveys.

Finally, in order to obtain control data for scaling and orient the photogrammetric reconstructed 3D model, and to provide a general check of reconstruction correctness, a terrestrial laser scanner Leica C10 has been used for computing an overview scan of the room where the statuary is exhibited. The Scanner has a nominal precision of 2 mm (Appendix B.1), which is not indicated for precise assessment of DSM accuracies at this scale. The GSD was of 0.2 mm and so the GCP precision should be ca 0.1 mm. Therefore, a close-range Triangulation-based Laser Scanner would be more appropriate for those tasks, but strong time-limits requirements for data acquisition (the hall must be closed to the public during the survey), discouraged its use. However, since the photogrammetric block was high redundant and rigid it was decided to use the Leica C10 point cloud only as reference to scale the model.



Figure 68. Bare 3D models of the statuary.

### **The antique bronzes**

A different workflow characterized the antique bronzes survey. In all these cases the relics are much smaller, ranging from 20 cm to 40 cm in height. In this case, the high-reflectance material and the small objects details required a more careful and complex image acquisition procedure. Here is presented the Ercole Ebro survey (Figure 69a).

Besides the pose, shape and dimension of the relics, also a detail analysis of their surfaces, identifying matching scratches and defects for instance, can provide invaluable hints on the ordeals the statues endured during the last two thousand years.

Previous survey campaign using Triangulation Laser Scanning techniques did not lead to conclusive results, being the surface highly reflective, which, consequently, produced very noisy results in the final DSM. Also a photogrammetric approach, where highly reflective surfaces are considered, is a risky methodology, the most common matching algorithms relying on the same radiometric response of homologous points for identification. However, in this context, a careful design of the surveying environment, trying to limit specular highlights using cold lamps and diffuse illumination systems and polarized filters, can overcome many of (if not all) the problems.

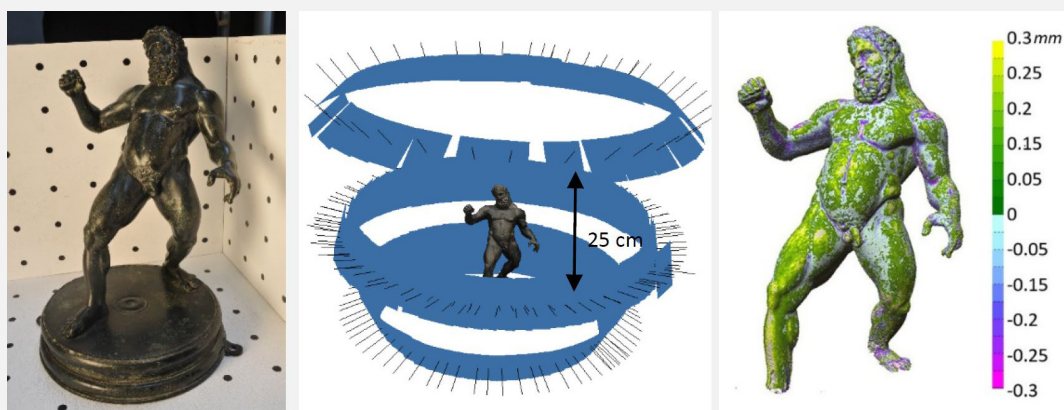


Figure 69. A: the Drunken Hercules ("Ercolo Ebro") statuette. B: Image block geometry for the bronzes surveys. C: Comparison map [mm] between two different reconstructions of the object.

Other imaging problems should be considered in order to provide an optimal acquisition environment: above all, with this object sizes, depth of field issues should always be expected. The use of high f-numbers is not possible unless stronger illumination (which increase specular and reflection issues) is provided. Long-time exposures, on the contrary, increase image noise problems. To obtain a good GSD (Ground Sampling Distance) and be able to capture the finest scratches on the statuette surface, requires the user to adopt macro long focal-length optics, staying as close as possible to the object. Finally, the shape of the object, makes the depth range of some poses (think, for instance acquiring the image from the right or left hand of the Hercules) very wide.

Other considerations, involving more specific photogrammetric issues, should be taken into account as well: the most important, in author's opinion, regards the camera model calibration. Enabling the autofocus of the camera is the easiest way to provide (hopefully) good quality images, but changes in every frames all the camera's interior and distortion parameters. The use of a self-calibration procedure assuming different parameters set for each frame, can make the Bundle Block Adjustment (BBA) unstable. On the other hand, the use of a fixed focal distance ensures the stability of the camera model parameters, but requires much longer acquisition time and efforts: it's worth noting, in fact, that the dark surface of the bronze statuette makes really hard, for the human operator, to understand if the object is focused correctly; being the focal distance fixed, the operator have to move toward/farther from the object to obtain the correct focus.

In this case a mixed approach was preferred: the object was collocated in an "acquisition box" with circular calibrated targets of known position, which was placed on a rotating tray (see Figure 69a). Centring approximately the statuette on the rotation axis of the tray and fixing the camera on its tripod, makes the object-camera distance almost constant for subsequent frame acquisition. The operator starts fixing the camera focus and acquires a set of subsequent images, rotating the calibration box. Every frame is checked and, if some defocusing is detected, auto-focus is enable and the frame acquired again. Then the auto-focus is deactivated and the acquisition goes on. During the image block orientation stage, at first an on-the-job calibration considering the same camera model for all the images acquired is performed. Analysing the BBA results, it's possible to identify if some subsets of images are not consistent with the solution and should be assigned to them a different camera model: in most of the cases, considering that the change

in focus is very limited and interior orientation parameters are strongly correlated with the exterior ones, especially when using long focal lengths, the split of camera models was not required.

All image blocks acquired consist of three circular strips all around the statuette, at three different heights (as shown in Figure 69b). For some details, where occlusions are more relevant, (for instance the upper parts of the legs and the lower part of the torso) other images have to be acquired for allowing a complete reconstruction of the model.

The software Photoscan was used to extract tie points, that were consequently reduced in number, exported in Photomodeler where the BBA was performed. The final orientation solution was exported back in Photoscan for Dense Matching and DSM reconstruction. comparison with an independent technique was not possible: triangulation laser scanners does not provide good enough reference data. For this reason, a repeatability analysis was performed, comparing two different reconstructions of the object using independent subset of images. The comparison is reported in Figure 69c: the results are good and show a standard deviation value of the differences of 0.11 mm, which is about two times the value of the calculated GSD.



## 5.1. Methodology and technical choices

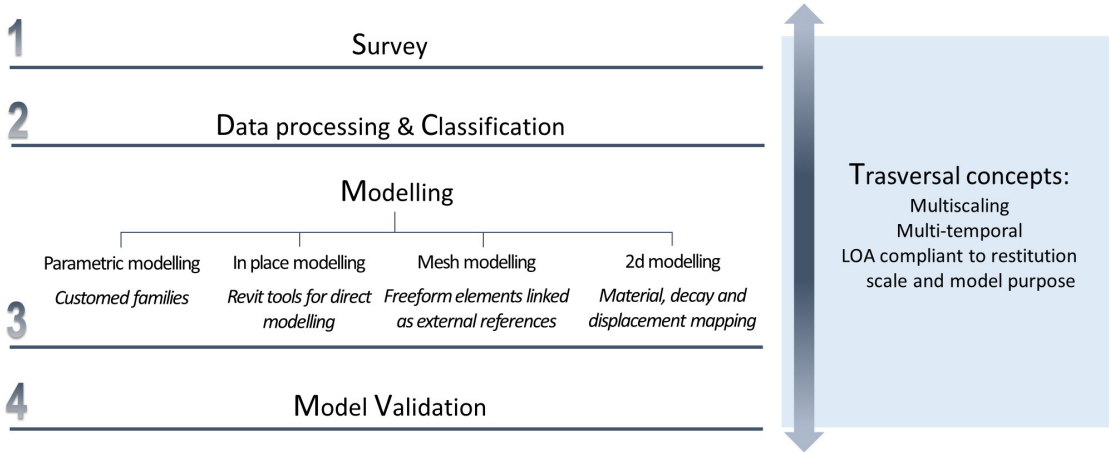
---

In the cultural heritage field, as far as 3D modelling is concerned, there are two main tasks to take into account (see Chapter 2): the choice of the modelling technique and the required accuracy and the reliability of the model.

With respect to the first issue, despite the already mentioned limitations of parametric modelling of Cultural Heritage, in this case study modelling has been carried out in BIM environment to take advantage of the management of the topological and relational component between the objects, of the editing capabilities and finally to test the latest modelling capabilities of BIM with Cultural Heritage.

Among the various software available, Autodesk Revit was chosen. It allows easy import and management of point clouds without the need for additional plug-ins and, compared to other BIM software, it has more advanced direct modelling tools. Today Revit is the most used BIM software [142], has many open plugins to implement its features and allows customization, as discussed in Chapter 6.

The modelling outcome should be a model suitable for representation at 1:50 scale, and to preserve the difference between similar architectural elements without excessive standardization. Thus, according to the scale of representation, the tolerance is of 2 cm and the model has to be compliant with the LOA 20 (15mm-50mm of displacement compared to the surveyed data).



The adopted modelling strategies are summarized in Figure 70.

Parametric modelling with the system families already present in the software libraries was possible only in a few cases. Normally, it was necessary to create custom parameter families (columns, window, decorative elements), with parameters that can be edited on the model (see paragraph 5.4), or use in-place modelling through traditional modelling functions (extrudes, merge, merge on path, revolution) as discussed in paragraph 5.5. However, this strategy does not allow handling freeform elements and deviations from regular shapes, since for freeform objects parametric modelling is totally a nonsense and only a mesh model can correctly return the object shape. With complex and irregular shapes, the modelling effort becomes inconsistent with the actual purpose of the work. In these cases, it was decided to simplify the shape of the elements and to represent them with equal volume objects, using external links for proper documentation. In particular, since it is not possible to import mesh surfaces into Revit, complex elements (such as capitals or decorative elements) were associated to the model via external file links. As far as the excessive deformation is concerned, deformation maps have been linked to the elements to indicate their actual form and emphasize existing damages. In this way, all the information requested for building knowledge is contained in the model and the user accesses the various data. The BIM model therefore acts as a data collector and, as far as possible, a faithful representation of reality. In addition, external links keep the model size manageable.

At the same time, the documentary value and the information content of the model is not affected. On the contrary it is increased since the models linked as external references are compliant to a representation scale higher than 1:50. Thus, the graphic

Figure 70. Diagram of the implemented methodology.

details are higher and the information more accurate.

As demonstrated from the association of maps of displacement to the BIM elements, in some cases an integration with two-dimensional representation (2D modelling) has been performed. In fact, a *model* of a building does not necessarily mean a 3D model, but *model* is an abstraction and simplification of reality, regardless of the medium adopted. Thus, in cases where a 2D representation was more effective and capable of modelling the phenomenon involved, this type of modelling has been used. This is the case of maps of displacement and material and decay mapping performed starting from the orthophoto (see paragraph 5.6).

Level of accuracy (LOA), level of reliability (LOR) and time management are also key elements of the implemented methodology.

As illustrated in paragraph 3.1 the correctness of the model and its compliance to the real object are affected by the survey and modelling quality. Metadata reporting the LOA and LOR are mandatory to certify the model quality, as they let the user to estimate *a priori* the correctness of the data process or data analysis. Thus, to ensure the maximum transparency, considering the different modelling techniques adopted, metadata on LOA and LOR are associated to each element of the model.

With regard to model validation, only the displacement between the global 3D model and the raw point cloud has been addressed.

With respect to the time management, considering the complex stratigraphy of the cathedral and the uncertainties about the constructive and reconstructive phases, it was decided to model the present state as the current state or time 0 of the BIM model. This does not prevent that, in light of future investigations, the BIM model can be enriched with several historic layers.

Previous restoration interventions or historical works in general on the Cathedral are entered into the database as textual information or as linked files. Future works, instead, will be uploaded directly in the system and, if architectural changes occurred, the 3D model will be updated with new constructive phases.

In this way, at present, diachronic analyses can be performed only on the textual and semantic data stored in the database, while it is not possible the graphic visualization of the construction history.

## 5.2. Semantic classification

Semantic classification regards at the same time the graphical representation of the building, identifying its constitutive parts, and the organization of the associated semantic information. With regard to the historical building, semantic classification represents still open research field. A building is indeed an organism and every strict classification is completely arbitrary and involves limitations and difficulties.

From a conceptual point of view, the building can be decomposed in different ways (functional, structural, stratigraphic, technological, etc.) and at different levels (building, macro-areas, areas, technological systems, architectural elements and so on), according to the purpose of the classification.

In order to describe completely a building a classification with increasing levels of detail is desirable. Therefore, the classification criterion followed in the thesis saw the identification of four semantic levels, as shown in Figure 71: the entire building, functional areas, architectural elements identified as subclasses of technological elements and architectural sub elements, i.e. elements components.

Each of these semantic entities has a graphical representation and, at each entry level, can be seen as the decomposition of the upper level or the grouping of the lower elements.

The Building level concerns the whole building and addresses data referred to the building in its entirety.

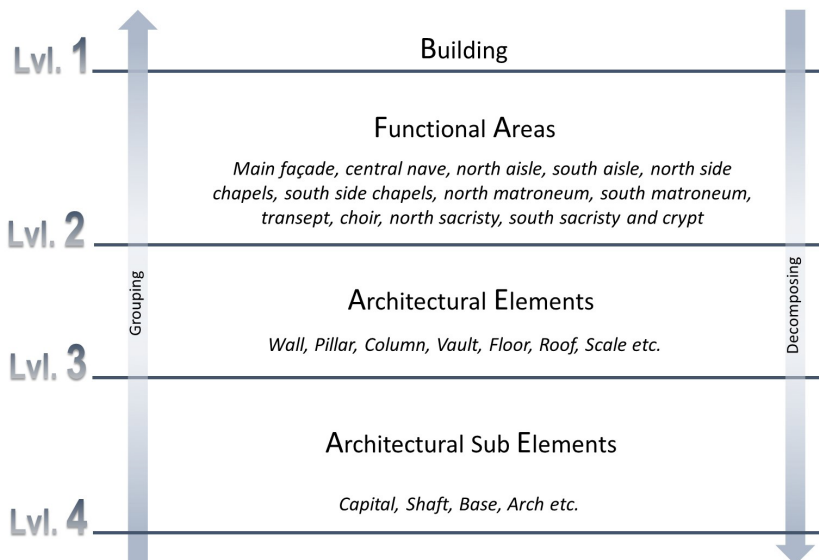


Figure 71. Semantic level classification.

The functional areas breakdown reflects the spatial organization of religious buildings and was chosen since it was the most suitable for structuring the available descriptive data and allows the Cathedral decomposition also from a volumetric point of view.

The identified areas consist of main façade, central nave, north aisle, south aisle, north side chapels, south side chapels, north matroneum, south matroneum, transept, choir, north sacristy, south sacristy and crypt (as shown in Figure 72).

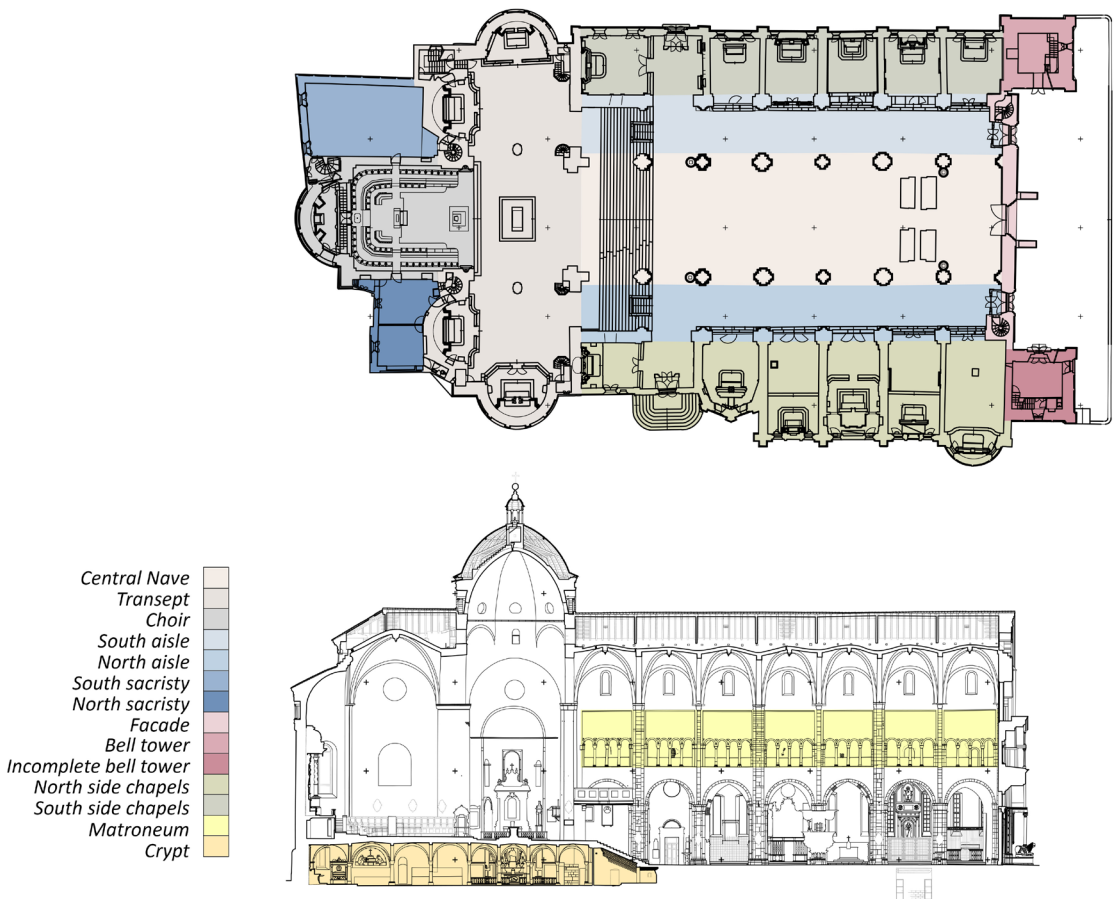


Figure 72. Functional areas schema.

The main façade has been considered as a functional area like the others, although strictly it is not. This choice was made because of the importance that the façade has in each cathedral and therefore deserves to be considered unique and not divided between the various aisles. Especially in a construction such as the Parma Cathedral, where the façade is architecturally independent from the naves and forms a unique element: it has pitched roof and does not follow the height of the aisles. In addition,

there are many descriptive data or documents that relates only to the façade, such as restoration works specific of the whole façade surface. This classification implies problems related to intersections between the areas (e.g. the attribution to the nave or to the aisle of the pillars that divide them). The problem was dealt with considering the

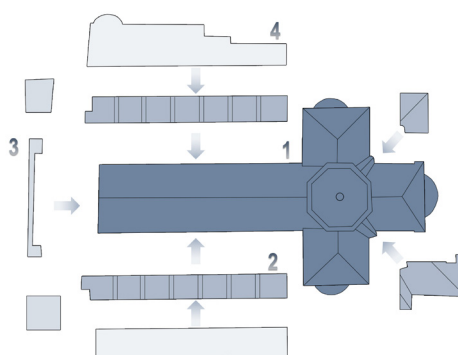


Figure 73. Hierarchical aggregation schema.

cathedral as a building composed of subsequent aggregation of parts, starting from the central Latin cross (central nave, transept and choir) (Figure 73). Then a hierarchy of aggregations has been identified: 1. Aisles, transepts and sacristies, 2. Façade, bell tower and incomplete bell tower, 3. Side chapels. According to this hierarchy, the elements at the boundary between two areas have been assigned to the top level area. Thus, for example, the lateral walls and pillars between the central nave and the aisles were attributed to the central nave.

The third level refers to architectural elements considered as technological elements. This classification derives from the requirement-performance approach, typical of building technology. It was adopted since it is the most widespread methodology when the maintenance plan drafting is concerned, as in this case study.

Rather than focus on the properties of the built object (physical, chemical, technological, morphological, dimensional, etc.) it examines the behaviour in relation to a number of functions that the object has to fulfil. Thus, the object quality is not expressed descriptively but in relation to the compliance with a set of requirements [251].

This method is described in UNI 10838:1999 and UNI 8290:1981 and is adopted in the guidelines of the Lombardy Region [251]. They are the first and most exhaustive ones for scheduled maintenance on historic buildings and have been adopted in this thesis as reference regulation. According to these guidelines, the building is divided into classes of technological elements (foundations, vertical structures, horizontal structures, etc.) and subclasses (plinth, beam, masonry, etc.).

Therefore, the Cathedral was decomposed, both from a graphical and descriptive point of view, according to technological elements subclasses, as described in detail in Appendix B. Starting from this level, the classification according to classes and subclasses has been extended to all the other semantic levels. For each level, proper classes have

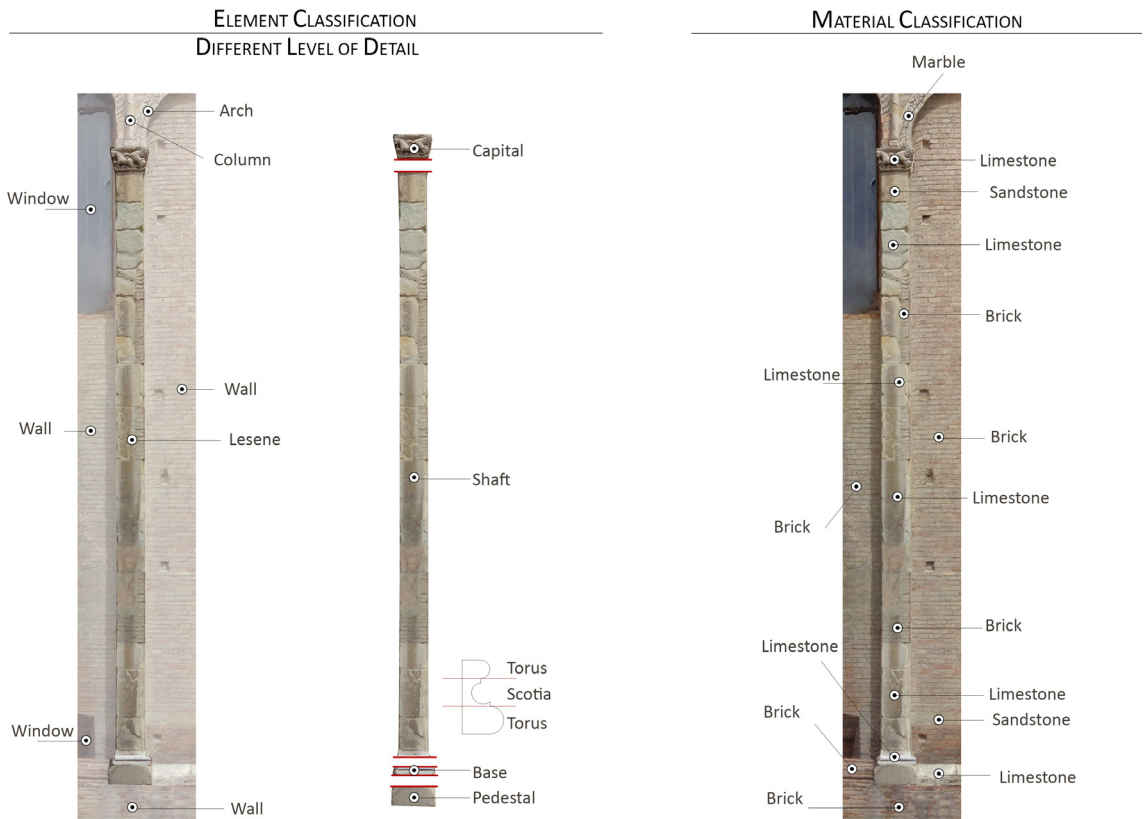
been defined based on the Parma Cathedral characteristics. In this way, each element in the database is identified by its proper semantic level, related class and (eventually) subclass. A summary of this hierarchical organization and of the main classes defined is proposed in Appendix C.1.

In addition to this third level of classification, a further sub level has been defined in order to describe the single components of each element. This level can be seen as a further specification and as an increasing level of detail both of the graphical representation (higher representation scale) and of the descriptive enrichment (see Figure 74).

It was decided to create a multi-resolution model based on the architectural elements:

- Architectural Elements (Lvl. 3): low detail level (comparable with a representation scale of 1:100 – 1:50) representing the entire architectural element. For instance, the column, the wall, the roof and so on.
- Architectural Sub Elements (Lvl. 4): High detail level (comparable with a representation scale of 1:20) referring to sub-parts of the architectural element,

Figure 74. Semantic classification: Level 3, Level 4 and material classification.



such as the base, the shaft and the capital of a column. This level was useful for representing high detailed and free form elements, which cannot be described well with parametric modelling. These elements are visible as external link of the model, since they are principally mesh surfaces and thus cannot be insert into Revit environment.

As far as the material description is concerned, in order to overcome the problem of the non-perfect accordance between geometric, semantic and material description (see paragraph 2.2.3), an approach similar to the “point of view approach” defined by De Luca et al. [103] has been adopted and the material classification was handled in two-dimensions.

The choice of working in 2D was made primarily considering the material characteristics of the Cathedral. The masonry is mostly composed by bricks but has numerous stone inserts (especially in the corners and in some reinforcement areas). Modelling, for instance, a 3D wall by distinguishing the various materials was impossible and a contradiction, since the architectural element is always the same and is simply made of different materials.

Moreover, from the survey data, it was possible to know only the surface layer of the Cathedral. No invasive surveys were made to know the internal structure of the masonry, so the thickness of the visible elements is unknown. Therefore, considering also the common practice in restoration projects to perform 2D mapping of materials, it was decided to document only the surface and to work in two dimensions (e.g. on orthophotos). A specific tool was created for associating orthophotos with elements of the model (see paragraph 5.6).

In general, the semantic classification was helpful for the point cloud segmentation, 3D modelling phases and database enrichment.

As far as modelling is concerned, only the lower level elements (architectonical elements) have been modelled, while higher levels have been created grouping them (“create group” Revit function) without further modelling efforts. Cloud segmentation and 3D modelling phases took advantages from the functional areas classification since the total point cloud has been decomposed in these areas, allowing importing into the modelling software and visualizing only the area under investigation, switching off the others, leaning computational operations.

Finally, the database organization has been affected by semantic classification having to discretise what information have to been associated to each semantic level.

## 5.3. Data processing

The point cloud has to be manageable and in .rcp format, the Autodesk proprietary indexed format, for import in Revit. The TLS raw data format (.txt, .e57, .pts, .ptx file, etc.) was therefore converted in .rcp with Autodesk® ReCap.

For this reason, after the point cloud registration performed with Cyclone, it was decided to import directly the total cloud in Autodesk® ReCap and here convert the format and make all reduction and filtering operations, thanks to its tools for filtering and segmenting.

Nevertheless, despite the multi-resolution approach appointed during the survey phase, the output raw data were a large point cloud of over 320 million points. This made impossible to work with Autodesk® ReCap: each operation was very time consuming. Point loading, 3D navigation and point deletion were so slow that it was impossible to have the certainty of the reliability and correctness of the final result.

On the basis of the various tests carried out, it is author's opinion that the point cloud was unmanageable in Autodesk® ReCap for two main reasons: the decision of not applying the decimation filter made available by the software before data import and a software data loading process less efficient.

So many strategies to work on complete data (reducing and filtering them a posteriori and in a more selective way) have been tried:

- working on individual scans making only one scan at a time visible
- dividing the cloud into regions and working on a single region at a time
- deleting a great number of points and using the optimizing data tool.

All these attempts failed. In fact, the software loads always all points and not just those displayed. For this reason, with very heavy files like this, computing times for any operation are huge. Reducing the number of points displayed turning off scans or regions was ineffective: time for loading and displaying points were identical to time for visualizing the whole point cloud.

For these reasons, after many efforts, it was decided to make all post-processing works in Cyclone, using Autodesk® ReCap only for format conversion.

The registered TLS point cloud has been processed in order to eliminate non relevant or noising elements and outliers. In particular, in each scan the areas furthest from the scan station have been deleted, in order to avoid inconsistencies with overlapping scans. Data have been filtered for noise reduction, the outliers have been removed and all

elements not involved in the modelling, such as non-architectonical elements, furniture and obstacles in general have been eliminated.

In addition, to be sure that the clouds imported in Revit were manageable, the total cloud was segmented into different areas corresponding to the various functional areas of the cathedral, such as north sacristy, south sacristy, choir and apse, transept south bay, transept north bay, crossing, and so on. Each of these parts was then imported in Autodesk® ReCap, indexed and imported in Revit.

A clarification on this regard is advisable: no point cloud segmentation has been performed, as commonly intended. The cloud has been decomposed into areas that have been imported individually into Revit to facilitate modelling operations and reduce the software calculation time.

In fact, in case of historical buildings, it is not possible to operate a true segmentation of the point cloud, as the segmentation methods presented in Chapter 2 are able to operate with rather simple or regular geometries, approximated with graphic primitives and characterized by repeated elements.

For this reason, in the field of cultural asset, subdivision is useful for point cloud management: it reduces the portion to be displayed (lowering calculation time), shows hidden elements, allows the modelling phases. Nevertheless, it remains a manual, not standardized operation. In historical buildings there are hardly identical elements, each item is a *unicum* and the operator experience is very important for correct element detection.

In addition, an excessive subdivision, aimed at identifying and isolating the single elements (as for modern buildings) is counterproductive. In fact, a building is an organism in which the elements are related to each other and, often, it is impossible to clearly distinguish one element from the other. Especially in historical architecture, because of the ancient construction techniques, distinguishing the architectural elements from the context is complex, or even senseless. In fact, to know (and model consequently) a historical building properly, it is necessary to refer always to the context and not to analyse the individual elements.

For these reasons, only a semantic segmentation of the point cloud into functional areas has been made. The area segmentation was also useful in the modelling phase. It was indeed possible to visualize only the area under investigation and, since the various areas had the same reference system, to import them in Revit, being sure to preserve their topological relationships and consistency.

## 5.4. Parametric modelling of repeated objects: examples

---

The purpose of this paragraph is not to find basic standard objects or create shared libraries of parametric architectural elements, such as made in some researches on this task (see paragraph 2.3.3). For Parma Cathedral, the attempt of creating common libraries on the basis of treatises would not have any sense since it is Romanesque architecture, so it is not possible to trace the proportional and compositional matrices of classical rule [245].

The attempt to create an ad hoc library of Romanesque elements can find diverging opinions. On the one hand, collecting parametric libraries of architectural orders could be an important tool for new studies on architectural proportion [245], making it possible to discover, for instance, still unknown rules and constraints. On the other hand, Romanesque architectures were affected by a great influence of the local workers and buildings differ from one region to another, thus making a shared and wide applicable library of Romanesque elements could be not particularly efficient. In addition, architectural elements are now deformed and consumed by time, thus trying to retrace their original geometry and conformation could be questionable for restoration purposes, since every original geometrical representation could be different from the actual conformation.

Based on these consideration, in the present case study it was decided to use parametric families only as an aid for modelling repetitive elements. The purpose of this paragraph is to show how, through some examples, it was possible to identify repetitive elements in the Cathedral and model them through the parametric families, adapting the parameters so that they could be edited even in place, in order to fit as much as possible to the real conformation of the object.

### **Example 1. Tapered arch window**

Tapered windows, especially with arch profile, are a recurring motif in Romanesque architecture and the Parma Cathedral is no exception on this point. The tapering can be either external (see Figure 75) or internal or both.

Revit allows importing point clouds only in the project interface and not in the family editor. The PointSense [133] plug-in allows management and processing of point clouds even in the family editor by segmenting the point cloud, extracting 2D sections and

producing orthographic projections. In order to properly model the window as a family, it was necessary to work on the point cloud directly in the family editor.

To create the tapering, it was necessary to work with Boolean operations (difference). The wall was subtracted with a solid having the upper face corresponding to the maximum (outer) width of the tapering and the lower face corresponding to the inner tapering shape.

Parameters have been set in order to adjust independently the interior and exterior width and height and the depth. Nevertheless, to make the window really parametric, it was necessary to model the arch as a perfect semicircle, with a radius equal to  $\frac{1}{2}$  of the window width.

Parameters have been applied to family type and different types have been created according to the window specific dimensions.

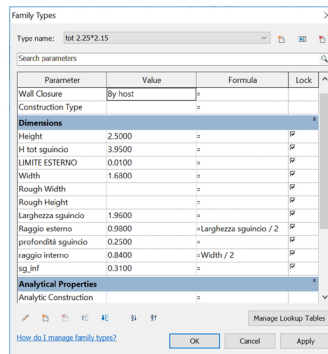
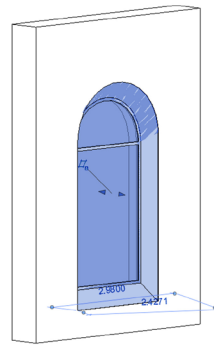
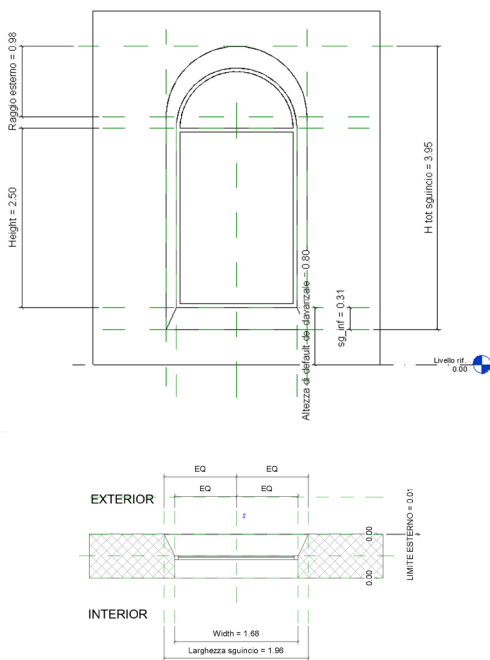


Figure 75. Parametric model of the tapered arch window.

### Example 2. Tapered window with cornice

The basic for creating this window was the same as for the previous arch window. Here, simply, the tapering profile was not arch but linear. In addition, the external cornice was created throughout the perimeter of the window. *Ad hoc* parameters were set to define the cornice size and distance between the cornice and the window opening.

Also in this case, parameters have been applied to family type and different types have been created according to the window specific dimensions.

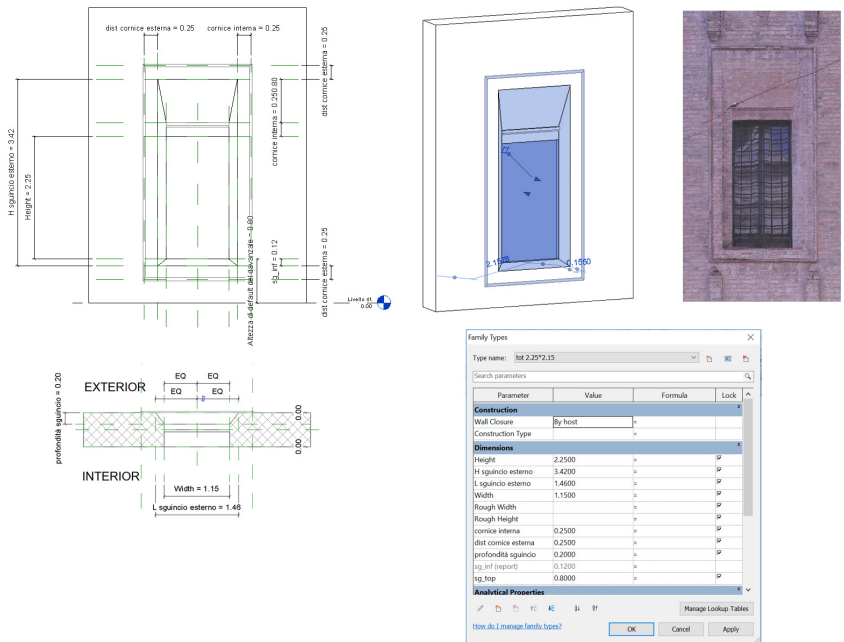


Figure 76. Parametric model of the tapered window with cornice.

### Example 3. Column

The column is a widespread decorative element, repeated above all in the aisles loggias. It is composed of a base with mouldings that can be traced back to the attic base, a cylindrical shaft tapered upwards and capitals (all different) with naturalistic features. These capitals are atypical, since they are parallelepipeds in order to support the barrel vaults of the loggia (see Figure 78a).

In the work methodology description (see paragraph 5.1), it was stated to approximate elements with high level of detail or free forms with simplified parametric models and to use the linked mesh models for their documentation in detail.

In this case, the capital had too complex shapes to be modelled by a parametric family, and the base, despite its original conformation based on the attic base, is now worn after centuries in most cases.

Then it was decided to model these columns through a geometric and simplified parametric model.

In particular, for management needs, three parametric families were created:

- The attic base profile, as generative profile for extrusion along a path

- The column with the base and the shaft
- The capital.

As far as the base is concerned, being the actual bases too damaged for retrace geometric rules, it was decided to adopt the classical rules for its generation, considering classical proportions and the sequence of torus, scotia and torus (Figure 77).

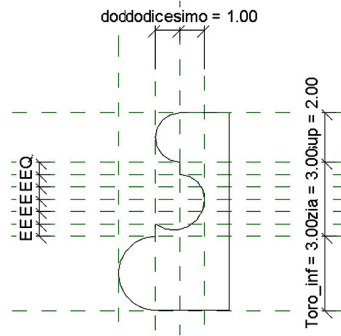
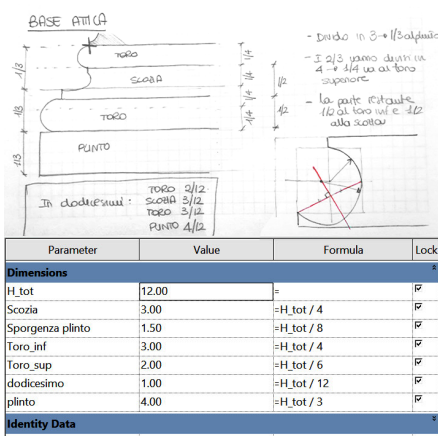


Figure 77. Parametric profile of the attic base.

All parameters are proportional and follow the classical rules. In this way the user has to insert only the total height value (in most cases the unique dimension really measurable in the Parma Cathedral columns) and the dimensions of the single mouldings are automatically updated.

As far as the column is concerned, the parameters refers to the top and bottom radius, to the height of the base, of the shaft and of the astragal. The different types of columns were created simply changing the value of those parameters.

Finally, the model of the capital: as premised, the capital acts as both the capital of the column and the architrave for the barrel vaults of the loggia. In the parametric model, its conformation has been simplified, leaving the possibility to edit the parameters related

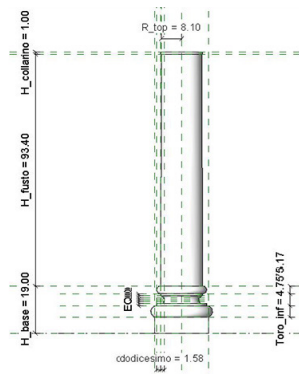


Figure 78. a: Columns of the apse loggia. b: parametric model of the loggia's columns.

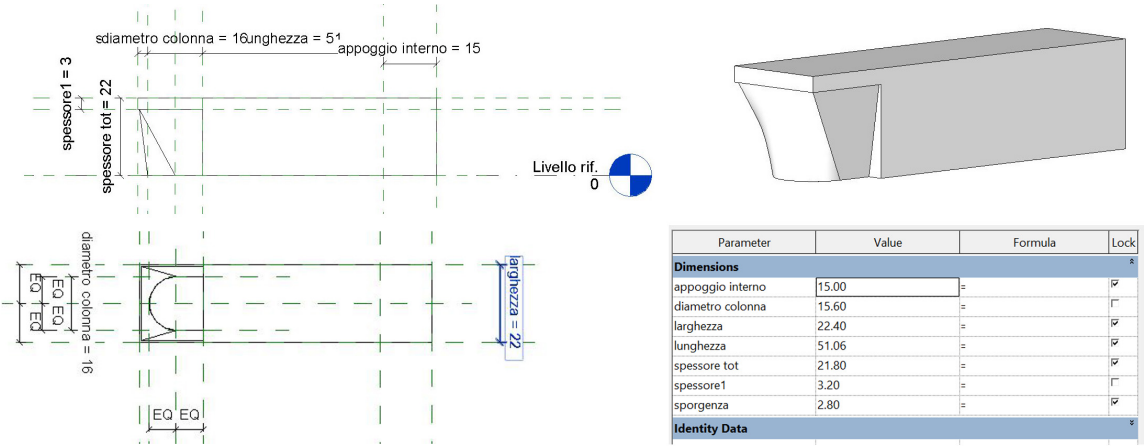


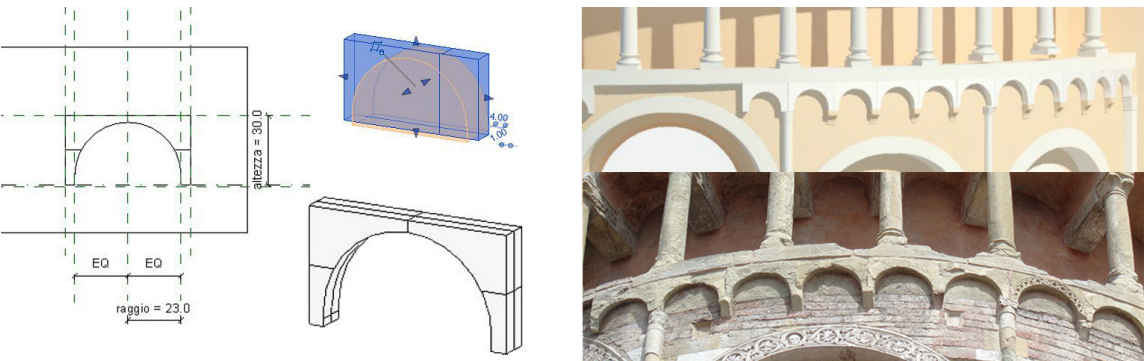
Figure 79. Parametric model of the capital. to: column diameter on which it rests, width, length and thickness.

**Example 4. Decorative element**

Another element that has been parameterized is the semi-circular decorative forms located below and above the loggia of the apses. This element is rather simple. It is composed by two solids, a parallelepiped and a semi-cylinder, and is obtained through a difference between them.

The peculiarity of this element is that, differently from the previous cases, the most variable parameters (in this case width and radius) have been attributed not to the family type, but to the project instance, i.e. the single element inserted in the model. In this way, the user does not have to create different family types, depending on the element size, and import them into the model, but can insert the same family into the model and edit the parameters directly, to make it better fit to the point cloud.

Figure 80. Parametric model of the decorative element.



## 5.5. Strategies for irregular shape modelling: examples

As mentioned before, in most cases it was necessary to resort to in-place modelling. The numerous irregularities and singularities have made parameterization not applicable. For example, the parametric model of the tapered arch windows (described in the previous paragraph) could not be used on curved walls such as apses. In fact, because of the curvature, the window did not properly cut the wall. In this case it was necessary to model the window directly subtracting void solids to the wall.

Figure 81 shows the entire modelling process.

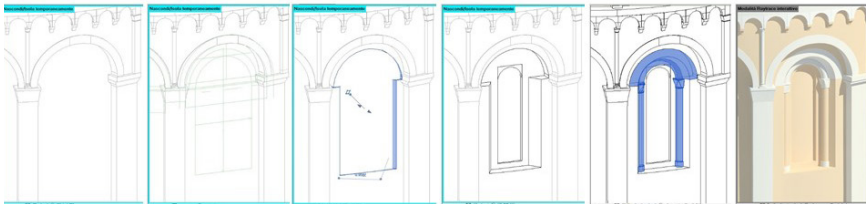


Figure 81. In place direct modelling of the apse close window.

This sample is a very complex case, due to the presence of additional decorative elements such as columns, arches, and different levels of openings. Nevertheless, wanting to outline a general workflow, the main actions are:

- Creating views and sections of the points cloud useful to individuate geometric generators
- Creating reference planes on which draw every two-dimensional reference line
- Drawing the reference lines
- Modelling the elements starting from the reference lines using traditional modelling tools (extrusion, blend, revolve, sweep, swept blend)
- Converting the solid created into void form if it is necessary to subtract it from another element to create an opening.

This procedure was adopted in the most modelling cases.

In addition, different modelling strategies have been tested, in order to reach the higher level of accuracy, trying to preserve the parametric feature of the objects (as far as possible). In the following an application of this test will be presented, and the results obtained with three different workflows will be compared. The sample described below refers to the modelling of an irregular wall, but can be extended, with little adjustment, to other elements such as vaults, semi-domes covering the apses or floors, etc.

The test purpose was to model a deformed wall, considering non-linear development, out of plumb, deformations along the vertical development, and so on.

The first tested mythology (A) refers entirely to in-place modelling using only direct modelling tools. The point cloud representing the wall was sectioned with a horizontal plane at the base and at the top (Figure 82a). The two closed profiles that define these two sections were then drawn (Figure 82b). A blending operation allowed to create the wall starting from the base and top profiles (Figure 82c).

This methodology allows representing a wall starting from any planimetric conformation, managing the out of plumb and, possibly, a variable thickness from the base to the top. The wall is a single element and does not affect the curvature changes of the profiles. However, it is a unique object and is not parametric, since, to edit it, it is necessary

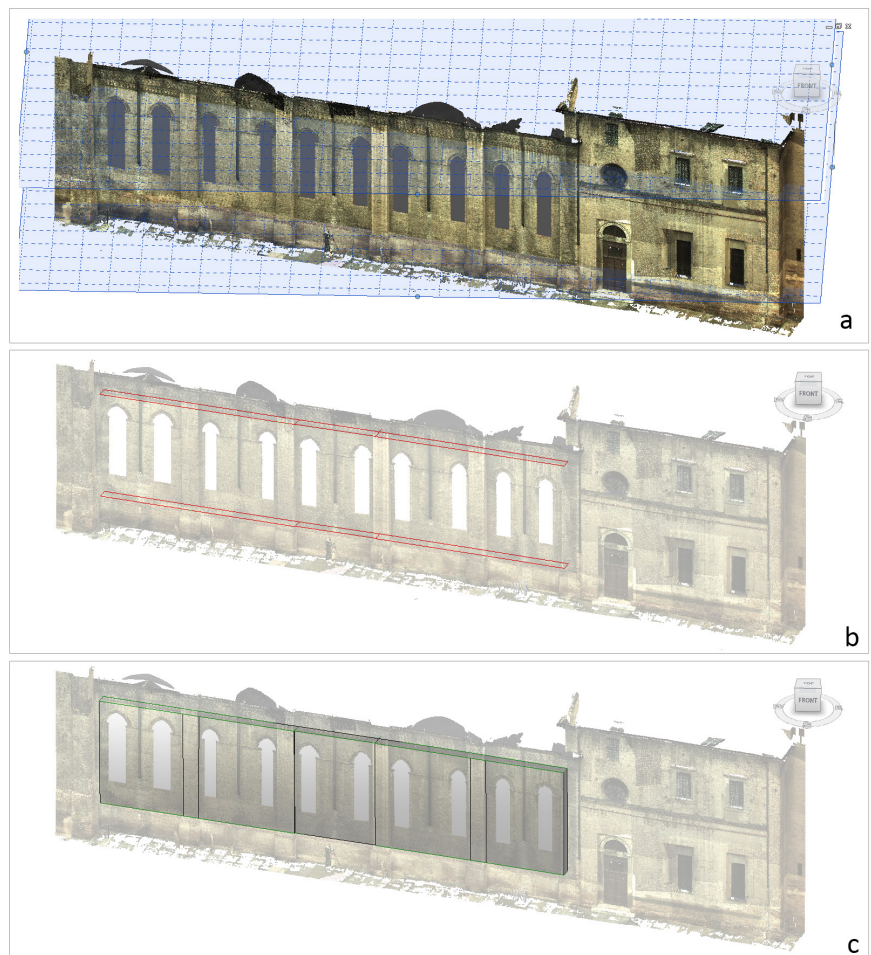


Figure 82. Blending operation for wall modelling.

to modify the blending profiles. Moreover, this strategy does not allow handling deformation along the vertical.

The second implemented methodology was to create a wall by face. Conversely from the previous case, here it is necessary to section the wall at different levels to reproduce more faithfully its conformation (Figure 83 a, b). Moreover, only one side of the wall (e.g. internal) is sectioned while the other will be modelled consequently. Based on the sections made, a surface or solid mass is created (Figure 83c). On this surface then the parametric wall by face will be created (Figure 83d).

This methodology makes it possible to model out of plumb and very deformed surfaces. Nevertheless, it allows reproducing faithfully only the shape of the wall that has been sectioned, while the other surface may be not perfectly adherent to the point cloud. In fact, the wall is parametric and wall has a constant thickness. In the case of irregular or variable thickness, it does not reproduce faithfully the shape of the real wall. In addition, to have a continuous wall, the curve that define its section has to be continuous. In other words, if the section is made with polylines or a sequence of curves non-tangent to one another, the software creates several walls (one for each polyline segment) in place of a unique wall, fragmenting excessively the architectural element.

Summarizing, this method, despite of a longer modelling time due to extracting sections, allows creating a wall that fits very well the original shape and with a parametric model. The wall is a parametric object, so editable at any time by changing the stratigraphy or editing the surface to which it refers.

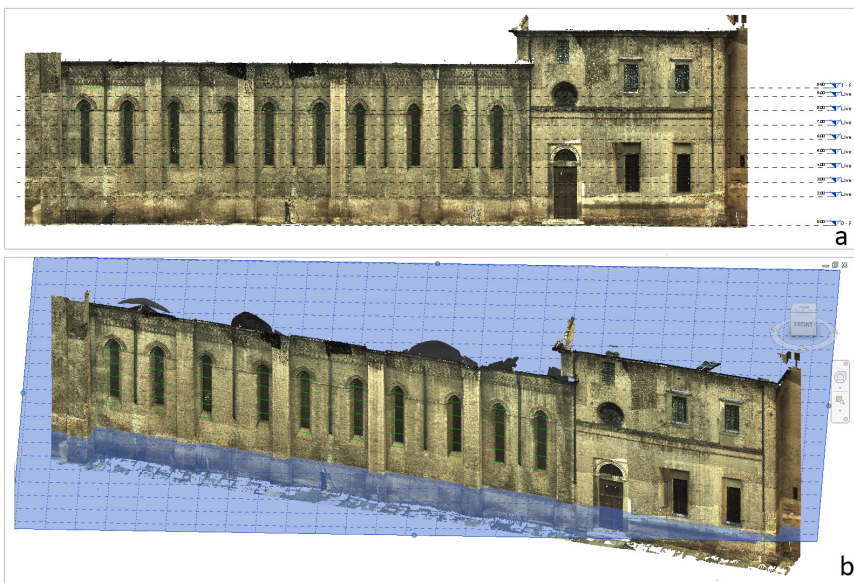
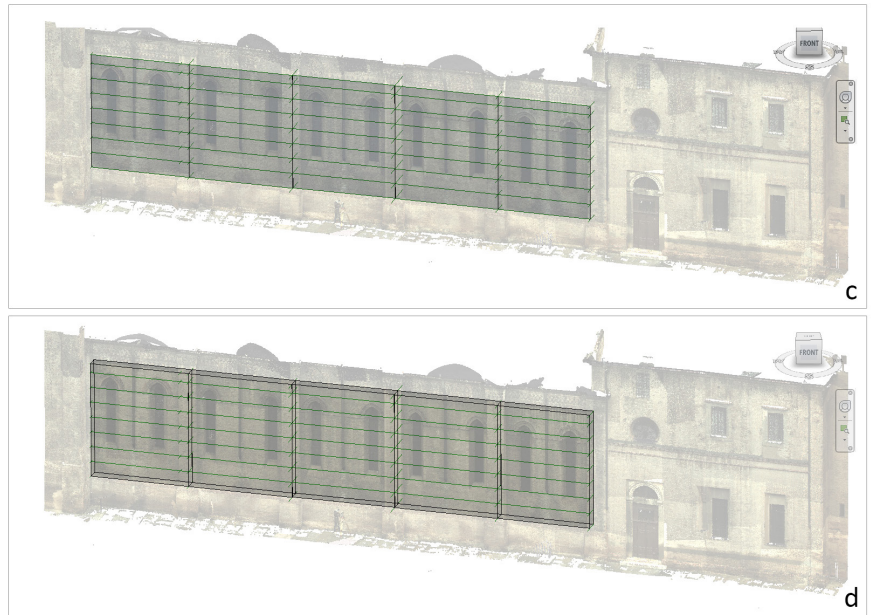


Figure 83. Wall by face (mass element) workflow. (It continues on the next page).



The third approach (Figure 84) is similar to the second one, but it differs in the first step. In fact, this workflow leads to the creation of a wall by face, as in the previous case, but starts from a NURBS surface. Creating a NURBS surface from the point cloud, using modelling software such as Rhinoceros (Figure 84b), could ensure a higher accuracy and a better adherence to reality. Nevertheless, it requires the use of software different from Revit and could cause interoperability problems.

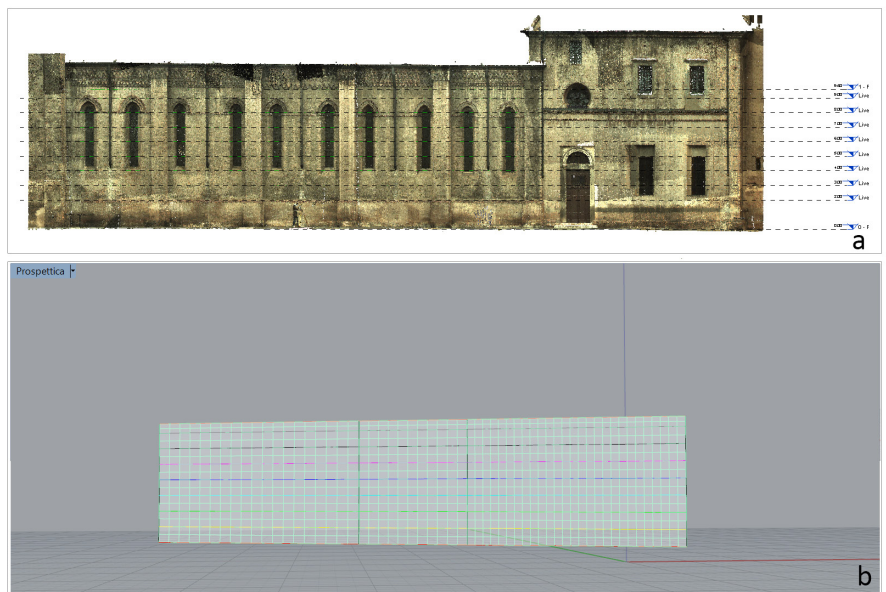


Figure 84. Wall by face (NURBS surface). Workflow. (It continues on the next page).

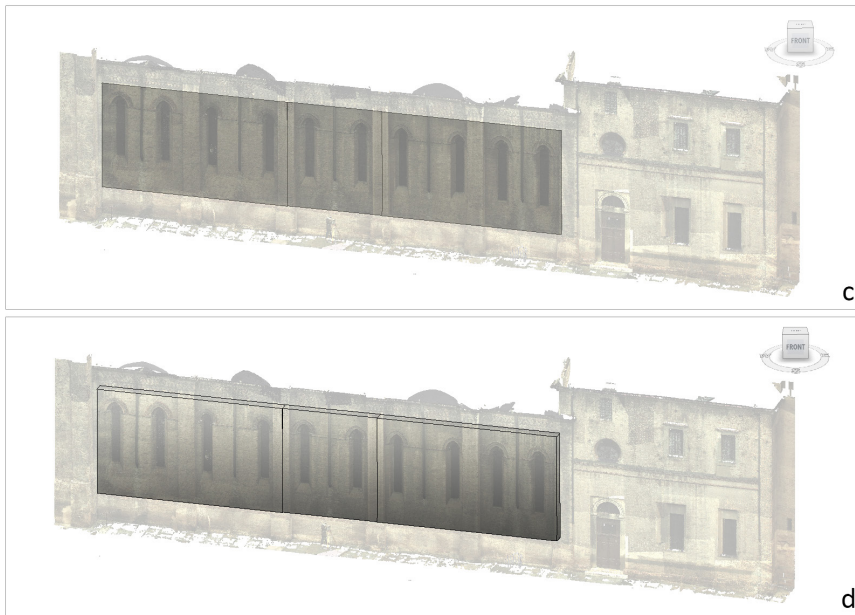


Figure 85 summarizes the tree tested workflows and compares the results. The comparison has been made only on the wall around the windows, wanting to test the methodology on a bare wall without considering lesenes and decoration. The aim was indeed to show the behaviour of the tested workload in the deformation modelling. The comparison shows that the three approach are comparable and, wanting to make a ranking, in this application the most accurate is the in-place modelling, followed by the model by Revit mass and the model by NURBS. On the other hand, all the three methodology has many pros and cons and it is author's opinion that the preference for one or another should depend on the peculiar feature of the object to model.

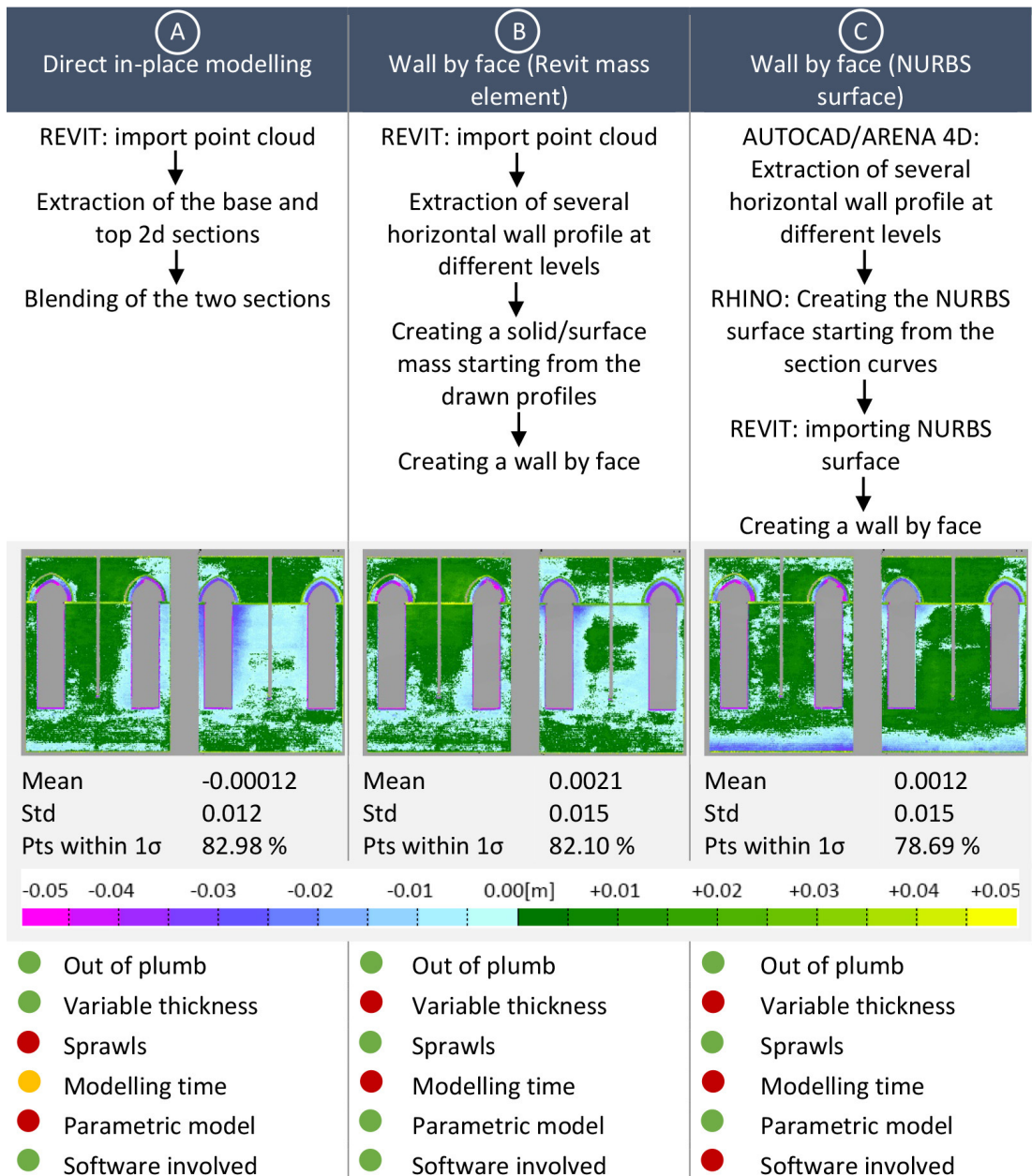
As far as free form elements are concerned, mesh modelling techniques have been foreseen. At present, no mesh models of the embellishment and sculptures of the Parma Cathedral have yet been made, because of the impossibility of high resolution surveys of these elements, mainly located in the top parts of the Cathedral. Nevertheless, the methodology has been tested on the exhibits of the Archaeological Museum of Parma (already mentioned in paragraph 4.2.5) and the developed workflow can also be applied to the detailed elements of the Parma Cathedral, creating the mesh models and link them as external references to the BIM model.

The followed workload is described below and concerned the realization of mesh models

starting from close range photogrammetric surveys. As will be explained, the models were designed for two different purposes: to provide a tool to assist archaeological analyses on the exhibits and for dissemination purposes through on line publication on the models.

Therefore, starting from the surveyed data, two different approaches were followed. The former aimed at guaranteeing maximum accuracy and definition of the mesh models and the latter pointed to creating manageable and online viewable models.

Figure 85. Summary of the three tested methodologies.



## Innovative multimedia exhibitions itinerary for the promotion of the Archaeological Museum of Parma [100]

The project addressed the promotion of the Archaeological Museum of Parma and in particular of the exhibits found in the archaeological site of Veleia (Piacenza, Italy), through new digital contents (reality-based 3D models of heritage sites and objects, AR applications). The main exhibits include: the Giulio-Claudio statuary, composed of twelve honorary marble sculptures symbolizing the imperial family members, and several antique bronzes.

Many problems must be evaluated when museum assets have to be surveyed. Immovable objects can generate problems for data acquisition: objects dimension and position are not always adequate for an easy survey. Surface complexity, high and rapid depth changing, material reflectance and lighting conditions can cause problems in the acquisition and 3D models production and can lead to erroneous surface reconstruction.

### **The Drunken Hercules ("Ercole Ebbro")**

The survey and the obtained model of this bronze (about 25 cm high) had to be at very high resolution (0.05 mm) for research and archaeological analysis. In particular, an identical (as far as a visual comparison allows to infer) statuette, is conserved at the Civic Medieval museum of Bologna (Italy). The researchers and scholars that work on this statuettes, are still trying to assess if one of the two is an actual replica of the other, and are trying to reconstruct the history and circumstances of the two relics over the centuries. An accurate survey and 3D reconstruction of both the bronze statues was considered, at this point, strategic to evaluate actual similarity and to highlight and scientifically quantify possible discrepancies. Besides the pose, shape and dimension of the relics, also a detail analysis of their surfaces, identifying matching scratches and defects for instance, can provide invaluable hints on the ordeals the statues endured during the last two thousand years.

The 3d model has been obtained with Photoscan, as explained in Chapter 4. The most interesting outcomes of the comparison between the two statuettes (the Veleia and Bologna Hercules) are reported in Figure 86 where it can be easily verified that the legs and arms poses of the two relics are quite different (with distances up to 5÷7 mm).

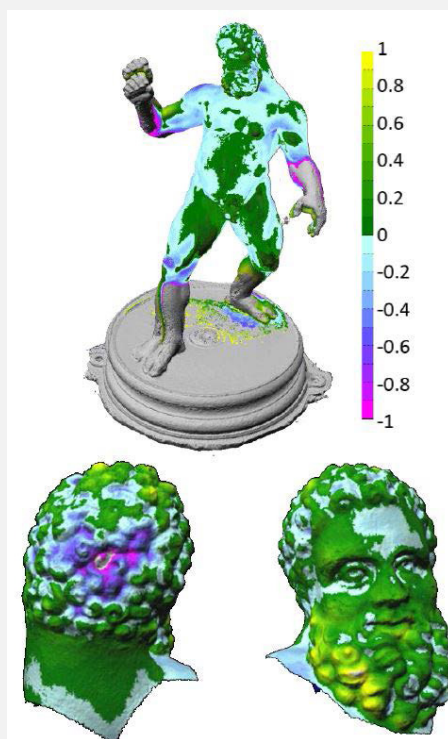


Figure 86. Comparison maps [mm] between the Veleia and Boulogne Hercules.

From the close-up images it's also quite evident that the Bologna Hercules presents lower level of details in the beard and in the hairs. Nonetheless, a comparison of the torso of the two bronzes shows very small discrepancies (lower than 0.3 mm), and some of the scratches and defects on the Veleia statue are present also on the Bologna exemplar.

### **The Giulio-Claudio statuary**

Once the 3D models has been generated in Agisoft Photoscan, a post-processing pipeline has been performed in the 3D modelling software Blender [60]. However, high-resolution DSMs are not suitable for on-line consultation activities, Augmented Reality and web/smartphone applications. Moreover, interesting studies about the sculpture level of damage and the original colour of the draperies have encouraged and motivated the data processing and manipulation in a 3D modelling environment.

The first processing level performed in Blender has been the sculpture 3D model resampling for achieving a low-resolution triangulated model characterized by ca. 200'000+300'000 faces. Hole-filling and noise-reduction post-processing procedure has been performed, as well, documenting carefully where the original surveyed model has been modified. Finally, high quality texture mapping of the sculptures has been generated for creating realistic 3D models.

Although many acquisition systems (e.g. laser scanner) as well as photogrammetric data processing software are able to capture the DSM vertex colour and perform model texturing (i.e. the texture is acquired from the images used for object surface reconstruction), several disadvantages can affect the final texture output. Images can show illumination and contrast problems, in particular if artificial light are used, and over/under saturated areas can hide object details. Moreover, being known historical information about the sculpture drapery decoration and original colours, it has been possible adapting and combining such information on the models shape. Nevertheless, texturing algorithms produce indented and patchy textures that are difficult to adjust and modify according to the available historical information. Thus, in order to have a comprehensible and editable texture, manual texture mapping should be advisable.

Therefore, the following post-processing pipeline for texture optimization has been followed in Blender for each sculpture digital model:

1. Due to the high-resolution of the 3D models (i.e. the high number of mesh vertices), the DSM has been firstly sectioned identifying suitable "seams" on the mesh. This has allowed to isolate portions of the model which can be easily unwrapped and projected on the texture plane;
2. The different sections of the mesh have been unwrapped following the defined seams, obtaining separated UV-maps (describing the whole model), that have been inserted into the image texture (see Figure 87);
3. Being obtained a unique texture map, where all the UV-map portions has been combined,

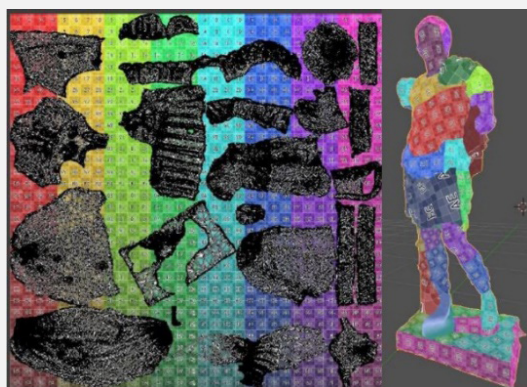


Figure 87. Blender UV-texture mapping process: on the right the 3D model and the identified seams used for subdividing the mesh; on the left the unwrapped UV-maps of each parts.

the 3D models has been re-imported in .obj format in Photoscan where, maintaining the new UV-map atlas, the texture was generated again;

4. Finally, the achieved texture has been adjusted in Photoshop: in some cases just homogenizing the radiometric property and in others (where historical information about the original colour of the sculpture were available), modifying directly the drapery data on the image texture according to the research studies.



Figure 88. Textured 3D models of the statuary.

## 5.6. 2D and 3D mapping

In historic buildings documentation, the surface mappings (referring at the same time to material, decay or damages) are an important requirement. They enrich the geometrical survey and give thematic information about the asset. Mappings are the basis for any restoration or conservation interventions that affect the façades of a building and are, therefore, one of the documents required by the superintendents when approving the projects. For this reason, considering a progressive use of the BIM for building conservation, it is mandatory to edit these documents directly into BIM. Usually, mappings are 2D elaborations of façades in which materials and decays are highlighted by hatched areas. Hatches are different according to the specific decay represented and are compliant to regulations, so, for their correct interpretation, the user refers to a specific legend. Producing mappings in BIM environment is difficult. In fact, BIM does not allow associating information to two-dimensional elements, such as polygons. However, it is not possible to model through BIM elements each ashlar in a wall or the areas of decay.

For this reason, mapping in BIM presents still many problems. A first response to this need is presented by Chiabrando et al. [89]. They produce 3D mapping directly on the building façade through specific adaptive components that can be associated both with flat and curved surfaces. To these components, they associate additional parameters to describe the material, the state of conservation and the needed interventions. They work directly on the 3D model, gathering information from the point cloud.

However, from author's point of view, in the decay/material mapping generation and, in general, in the documentation of a building aiming at restoration, it is not possible to exclude the orthophotos. Orthophotos are, in fact, a correct metric product and the most complete survey output for thematic representations, from which the user can extract dimensional data or material and pathological information. In addition, orthophotos can be used as a monitoring tool, since comparing images taken at different epochs allows observing the evolution of degradation over time.

For these reasons, in order to document correctly a historical building, the inclusion of orthophotos is crucial. In Revit images can be associated with elements and displayed as links. However, the orthophoto cannot be queried from a metric point of view, nor mapped onto the object surface.

Hence the idea of implementing a plug-in (see paragraph 6.3.4 for the technical plug-in description) for inserting the orthophotos in BIM environment and utilizing them as a basic tool for mapping both on the 2D orthophotos and, automatically, even on the 3D model.

Based on these considerations, a plug-in function was implemented, which allows:

- Associating the orthophoto to the element and displaying it in a floating window in Revit
- 2d polygons mapping on the orthophoto
- Automatic 3D modelling of the ashlar starting from the 2D polygons.

These tools have been designed to facilitate the tasks of restorers, who usually work with two-dimensional mapping of materials, degradation or interventions to do/already done. With the tool presented here, the aim was to provide a new way of working on 2D drawings but directly in the BIM environment, with additional potentials that can be assimilated to GIS. In fact, the approach does not differ much from CAD, but polygons are not simple hatched areas but vector polygons with attributes.

Moreover, each orthophoto is spatially related to the element to which it is attached. In this way, by using the "Create Parts" function of Revit, which divides the wall surface into delimited portions, the wall is automatically divided into parts corresponding to the

2D polygons drawn on the orthophoto. This also allows the user to get mappings in the three dimensions.

The technical analysis of the code structure and its interaction with the user will be described in paragraph 6.3.4, while here only the modelling functions will be addressed. The user can access these functionalities by clicking the "Create parts" button in the plug-in interface. The user has to select the orthophoto to associate with the 3D element and a floating window will appear showing the orthophoto (as it can be seen in Figure 89). The orthophoto opens in a floating window and not on the 3D model. 2D visualization is, in fact, easier and facilitates all subsequent editing operations, which would be more difficult in three dimensions. In addition, 2D visualization is much leaner and faster, requires less computational resources and allows the easy management of different viewing scales by image pyramids.

The ribbon panel of this window hosts three sets of command: visualize orthophoto, draw polygons and query polygons. The visualize function allows the user to move the image, to zoom in and out and to take measures directly on the image. The editing function lets the user to draw 2D polygons on the orthophoto, using the appropriate tools: draw, move, rotate, and delete. The query function shows information about polygons.

However, a clarification must be made in this regard. Mapping generally involves the creation of polygons corresponding to homogeneous areas of material and decay features, which are separate entities belonging to separate layers (see Figure 90).

Therefore, to properly document both the materials and the decays (for example), it would be necessary to proceed by information layer as in a GIS. Such layers intersect to

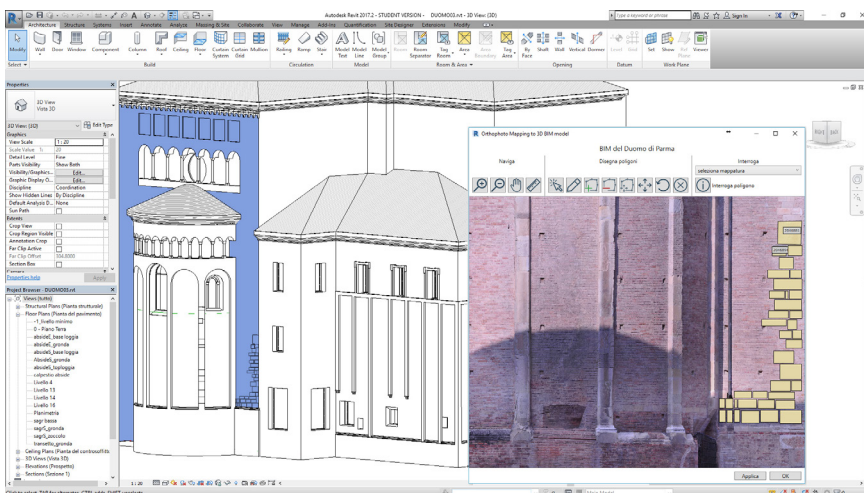


Figure 89. Example of 2d mapping on orthophoto.

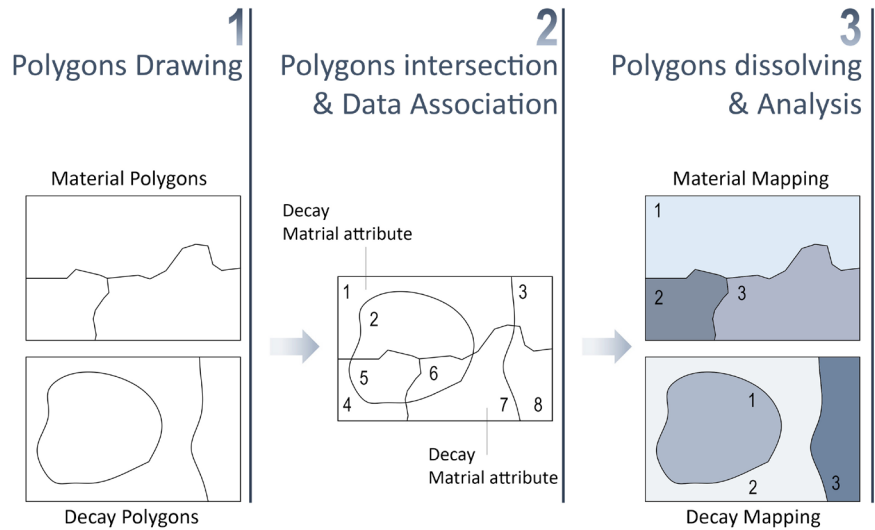


Figure 90. GIS mapping process.

define the minimum entity to which associate information (material attribute and decay attribute) and dissolve for thematic representation (Figure 90).

This structure, which incorporates typical GIS functions within the BIM, however, requires a further development of both the database organization and the plug-in coding. For the moment, in order to test principally the methodology, the implementation has been limited to the realization of 2D polygons corresponding to the ashlar in the wall and to the implementation of the automatic 3D modelling of these ashlar into the BIM model. To each of these polygons/3d elements it is possible to associate the data stored in the database as well as all the other elements of the model (BIM elements).

A future development will involve the implementation of the mapping function. Tests have already been made about the spatial extensions provided by SQL Server (RDBMS used for this research as described in Chapter 6).

## 5.7. Model validation and Level of Accuracy

The parametric modelling of a complex building like the Cathedral, has highlighted many problems and difficulties.

As shown in Chapter 2, proposals on modelling irregular geometries are being implemented. Nevertheless, it is possible to force some parametric modelling to

follow the deformations only in rather simple context, for example a linear wall without decorations. In more complex cases, such as the apses of the Parma Cathedral, these methodologies are inapplicable. In fact, apses have irregular curved walls, consistent out of plumb and many decorations, such as protruding elements, columns, lesenes, galleries and so on that lean on the wall and are constrained to it.

With the parametric software available today (2017) it is possible (with some efforts) to model an irregular wall, even with deformation in two directions, but, then it is a *unicum*, it is of course not parametric and, above all, produces modelling errors (such as holes, intersections) and cannot host decorative elements on its surface.

So the question is how can the model deviate from the real object shape? Moreover, do the benefits of such accurate model compensate for modelling efforts? There are no regulations in this regard and the only reliable and shared reference is the tolerance given by the scale of representation which, for historic buildings, is very demanding and equal to 2 cm. The deformations that a historic building is subject to are often ten times greater than this value.

Moreover, elements are often eroded by time and with obvious gaps. Their current conformation not only is different from any current geometric elements, but it does neither correspond to the original one. Therefore, conceptually, in order to be adherent to the present state, such objects have to be modelled as free form objects because each geometric approximation is arbitrary. But when does that make sense?

Another element of uncertainty is the lack of knowledge of the internal structure of the objects. For works on historical building that impose the absolute protection of the asset and non-invasive investigations, the knowledge of internal structures is near zero. It is possible to acquire information from historical treatise, ancient drawings, thermographic observations but there is no certainty about the real internal conformation.

From the restoration's point of view, it would be great to have a 3D model correct in all its parts, reliable and compliant to the tolerance of 2 cm, from which to extract all the required elaborations. However, to date, with parametric modelling this is often not possible. Integration with modelling techniques using mesh surfaces that are much more adherent to real object shape, on the other hand, cause interoperability problems, since mesh surfaces cannot be imported in BIM. The research in this field is still open.

In the case study presented here, it has been attempted to overcome the problem by proposing a hybrid solution that combines parametric models, direct modelling into BIM environment, meshes and two-dimensional modelling, in order to achieve the best accuracy in each case. The interoperability problem has been bypassed using links to

external references. In this way, the HBIM is conceived as an archive, an information collector and a unique access point to different data.

In the light of these considerations, it is author's opinion that the model validation, in order to certify its reliability and correctness, is mandatory. 3D model accuracy depends both on the quality of the survey and on the modelling operations performed and, usually, the modelling phase causes a drop in the accuracy compared to the survey.

Consequently, it is author's opinion that having metadata on survey and modelling techniques, on the accuracy and on the correspondence of the model to reality, is the first data quality control tool and the basis for a rigorous and scientific analysis of the asset.

In this specific case, such metadata have entered into the database of the information system (as shown in paragraph 6.3.2.5) in order to make the user aware about the quality of data.

From the comparisons made between the model and the surveyed point cloud, it was found that the average deviation is -7.4 mm with a standard deviation of 32.2 mm.

For the comparison a displacement range of  $\pm 10$  cm it has been adopted. As it can be seen in the false colour map in Figure 91, the grey parts are out of this range and have not been computed into the statistical reports. These areas refer to elements that still have to be modelled or refined (top part of the transept, embellishment, etc.) or that do not appear into the point cloud (roof of the apse, bottom part of the inside wall covered by an altar, etc.).

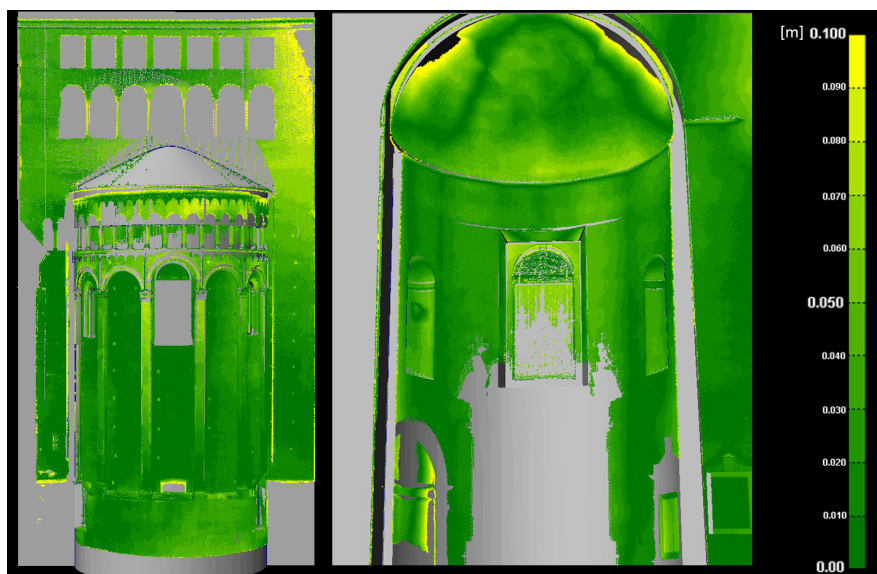


Figure 91. False colour map of displacement between Revit model and laser scanner point cloud.



## Chapter VI

# The HBIM application

As seen before, it is clear that a BIM process applied to Cultural Heritage must respect the peculiarities of historical assets, both in terms of its geometric description (Chapter 5) and association of information. This involves considerable problems and difficulties that are still open research topics [136][114]. As far as the management of the semantic data and the model enrichment are concerned, at the time being, there are no commercial tools capable of fulfilling all the specific functions required by Cultural Heritage documentation.

This chapter will deal with the implementation of the BIM oriented application at the base of this thesis, which tries to be a concrete solution to the lack of suitable instruments for Cultural Heritage maintenance, conservation and restoration. The application is an information system at the architectural scale and has been designed in order to be as flexible and customizable as CH specific needs require.

It is based on a BIM 3D model of the building (Chapter 5) and, thanks to the interaction with an external database specifically structured, allows users to properly archive and query the data required to describe the building. The application is standalone and has been structured to be integrated with major BIM software and with web applications as well.

Additional features have also been developed that allow easy data consultation and simple system usage: data entry, editing, query interface, thematic mapping, ad hoc elaborations such as mapping of degradation, etc., in order to support restoration and maintenance activities.

The chapter presents all the steps that, starting from data collection and requirements

analysis, brought to the development of the information system. In particular, paragraph 6.1 deals with the database design phase analysing the motivations that address the choice of creating an ad hoc database, the issues emerged and the resolving strategies. Paragraph 6.2 focuses on the adopted technologies in order to grant the system usability. In fact, especially for users scarcely acquainted with relational databases (such as restorers and maintainers for which this system is designed), working directly through RDBMS is difficult and lets to prefer the use of traditional and consolidated methodologies. Finally, paragraphs 6.3 and 6.4 address the integration of the database with BIM software (in this case Autodesk Revit) and with web applications, in order to assure data sharing and information spread.

## 6.1. Database design

---

In the Cultural Heritage field, beside the geometrical representation of the building, it is also important to consider and “model” all the associated information. To accurately describe an historical asset, its history, material composition, constructive phases, decays, structural information, technological feature and so on have to be taken into account.

To better organize all these data and make them useful for restoration and conservation interventions, associating a well-structured database with the three-dimensional model becomes crucial. For this reason, database design is the core element of the entire information system of the building. It gives information to the 3D model, allows archiving information, making temporal and semantic analyses, performing specific thematic queries for restoration and so on.

Literature references addressing database structuring in BIM are scarce. In general, the focus is on modelling and monitoring phases, while it is author’s opinion that, in particular for historical buildings, the correct organization of data in a database is a key point.

Thus, the BIM application developed in this thesis is focused on the database design. The database organizes the data, manages the interaction with the BIM model and interfaces with different applications ranging from desktop to web and mobile apps.

Structuring a relational database that interfaces with spatial data via BIM applications is non-trivial; moreover, historical data are, by nature, very complex to organize in a

relational structure as they follow, in fact, hierarchical relationships that hardly fit to relational databases.

All these topics will be addressed in the following paragraphs. There, the database design will be presented according to the well-known ANSI-SPARC<sup>1</sup> architecture, proposed in 1975 for Data Base Management System (DBMS) design [17]. In particular, paragraph 6.1.1 will deal with the external level of database, analysing the reasons for database implementation, database requirements, expectancies of customers and required functions. Paragraphs 6.1.2 and 6.1.3 will present the conceptual level, which, on the basis of the effective regulations and of data sources, defines how information is arranged within the database. In these paragraphs, the available data will be analysed, describing how they are inter-related and going to the definition of the data relationship model (DRM) and the logical data model (LDM).

Finally, the technical choices for database implementation will be addressed.

### 6.1.1. Reasons for an ad-hoc database for Cultural Heritage

To structure an information system on a historic building, there are two main aspects to take into account: the data necessary to describe it correctly and exhaustively (so the input data available) and the documents required by Superintendence to approve works on the asset (so the output that the information system has to produce).

This preliminary analysis is fundamental, on the one hand, to properly structure the system on the basis of the available data and, on the other hand, to provide queries and possible uses so that the system can be really used.

To document a cultural asset, the available data sources are many. Survey data (geometric, material, decay, structural or monitoring data) are principally used, in addition to which, photographic images, archival data, historical documents, reports etc. can be exploited. Generally, these data have a complex structure, complicated and multiple relationships, and are fuzzy in their description, thus their consultation through an information system has to take into account all these features and cannot ignore their relational structure.

Moreover, when an intervention on historical building occurs, in addition to the

---

1. ANSI-SPARC stands for *American National Standards Institute, Standards Planning And Requirements Committee*.

documentation required for obtaining the construction license, additional documents are essential to obtain approval by the Superintendence. These documents are usually photographic documentation, historical-artistic reports, estimate, geometric survey of plans, elevations and cross sections in scale 1:50, material survey, static damages survey, material conservation project, structural consolidation project, reuse project, comparative plates and stratigraphic plates. In particular, great importance has the description of materials and decays, generally made with façade mapping [281].

As seen in Chapter 2, Historic BIM has different characteristics and peculiarities w.r.t. BIM for new constructions; database organization assumes a central role and the main function are the following:

- Integrating different and heterogeneous data;
- Organizing historical data in a relational database;
- Managing time, not only w.r.t. constructive phases, but also to data that can be associated with an element. For instance, the user may want to associate the same element with several restoration works, carried out at different ages, and filter them by date. For example, the wall is always the same, its 3D model does not change over time, but the data associated with it change;
- Providing the required outputs. As far as the BIM environment is concerned, the most difficult output to produce is material and decay mappings. Mappings are not directly feasible on the 3D model: it is possible just to select an orthogonal view and process the mapping on it, drawing the polygons representing the decay areas. In this way, it remains as information linked only to that specific view and it does not appear in the other views. In addition, commercial BIM software do not allow associating attributes to 2D polygons.

In order to fulfil all these functions, simply recording the data and retrieving them in schedules about the elements is not enough, but it is necessary to structure data in a relational database, which allows breaking down and re-aggregating the data into tables connected by relationships with different degrees of cardinality (1: 1, 1: n, n:1, n: n). To the best of the author's knowledge, in the major BIM software, such data organization is not possible. In particular, Revit considers as elements only the model elements (walls, roofs, door, furniture etc.), the datum elements (grids, levels and reference planes) and the view-specific elements (annotation elements and details) [4], to which it is possible to associate attributes through the creation of parameters. They are all elements that have a graphic representation (two-dimensional or three-dimensional) and the attributes can be referred only to these elements. Thus, it is not possible to create hierarchical



problems for a HBIM aimed at restoration.

For this reason, an external standalone database has been designed and specific functionality has been implemented for its connection to BIM software (specifically Revit) and for its independent use, also via the web.

## 6.1.2. Database requirements and data analysis for Parma Cathedral

As seen in the paragraph about the semantic classification (§ 5.2), four different semantic levels have been identified: building, functional areas, technological elements and architectural sub-elements. Accordingly, several regulations and guidelines have been taken into account:

- DPCM 9 February 2011, *Council of Ministers Directive for Evaluation and reduction of the seismic risk of Cultural Heritage with reference to standards construction techniques (DM 14/01/2008)* [118]
- DPR 207/2010, *Implementing Regulations of the Public Contracts Code*, which for activities in Cultural Heritage and protected properties is still in force
- Lombardy region guidelines for the drafting of conservation plans [251]
- Italian Standard UNI 11257/2007 *Criteria for drafting plan and maintenance program for building assets. Guidelines.*
- Italian Standard UNI 10584/1997. *Maintenance - Systems Of Information Of Maintenance.*
- *Code of Cultural Heritage and Landscape (D.lgs 42/2004).*

At the building level, according to the DPCM 9 February 2011 and the Code of Cultural Heritage and Landscape, the building is identified uniquely through three fundamental parameters: denomination, toponymastics and cadastral data (see Table 14 for specifications).

Since the primary goal of the implemented HBIM was to archive and manage all data about the building, document the interventions occurred and assist maintenance and conservation planning, the database implementation focused on information and data required for scheduled conservation. As explained in paragraph 5.2, the requirement-performance analysis and the methodology proposed by Lombardy Region Guidelines [251] have been adopted.

<b>Building identification</b>	
<i>Data about owners</i>	Legal qualification of the possessor and other data
<i>Data about the asset</i>	Asset name, Asset address, Geographic coordinates of the asset location, Cadastral data, Neighbours, Epoch of construction, Actual use
<i>Photographic documentation</i>	
<i>Planimetry</i>	
<i>Description</i>	Morphologic description, Presence of decorative elements
<i>Other documents</i>	
<i>Evaluation of cultural interest</i>	
<b>Awareness factors - It refers the data needed to determine the relationship between the asset and the territorial context</b>	
Dimensional features	Covered area, eave height, number of stories
Location	Territorial context, geographic environmental features, anthropic environmental features
Soil and foundations	Orographic features, geomorphological features, soil changes
Asset analysis	Description of the architectural complex, accessibility, state of use

Table 14. Principal data required by BPCM 9 February 2011. Personal elaboration.

According to this approach, the quality of the built objects is not expressed descriptively but in relation to a number of functions (requirements) that the object has to fulfil. Nevertheless, working on historical buildings, rather than requirements, it is better to talk about “performance” and/or conservative “problems”. In fact, the bare requirements analysis is not appropriate for historic buildings, since it is not possible to require a priori performance level for elements already in place. Thus, it is preferable to evaluate the level of performance that the element can provide, adapting it to the needs of use. For this reason, the Lombardy Region Guidelines adopted the term “problem”, which, summarizing both the “requirement” for use and the “risk” for conservation, was more suitable for describing historical elements behaviour [251].

Therefore, to each technological element, identified by a proper class and subclass, as reported in Appendix C.1 the guidelines provide for:

- the identification of four general categories of problems: reliability, durability, adaptability to use variations and maintenance (see Appendix C.2),
- the evaluation of damages that affect the object
- the program of preventive actions
- the consequent inspections.

All this information contributes to the drafting of the technical manual and maintenance program of the conservation plan: the technical manual is, in fact, the document for gathering the data and information necessary for drafting the conservation program and for the subsequent checking of the performed and programmed operations; the maintenance program contains description about methods and scheduling of inspections, to ensure that repairs take place promptly to minimize damage.

The main forms provided by the plan, which will be used as a reference for thesis database design, are listed below.

### Problem evaluation form

Edificio – Comune – Provincia							
MANUALE TECNICO – SCHEDA DI ANALISI DELLE PROBLEMATICHE							
Elemento (classe e sottoclasse dell'elemento tecnologico)							
Identificativo elemento	Materiali e tecniche	Problematiche da valutare anche in futuro	Anomalie attese	Zone a rischio	Interazione con altri elementi	Azioni preventive	Metodi di verifica
		Problematiche da valutare in fase preliminare	Criticità connesse	Punti critici	Interazione con altri elementi	Provvedimenti	
Per un esempio di scheda compilata si veda la Scheda 1.							

Figure 93. "Problem Form". Form for problem evaluation according to [251].

This form belongs to the technical manual. Here, information and problems about each technological element is entered. For each problem, the anomalies are identified with regard to the risk areas, the interactions between the various construction elements and the methods of inspection.

### Damage evaluation form

Edificio – Comune – Provincia					
MANUALE TECNICO – SCHEDA GUASTI					
Elemento (classe e sottoclasse dell'elemento tecnologico)					
Identificativo elemento	Degrado in atto	Commento	Gravità	Diffusione (%)	Grado di urgenza
Per un esempio di scheda compilata si veda la Scheda 2.					

Figure 94. "Damage Form". Form for damage evaluation according to [251].

This form belongs to the technical manual. It contains all the information about the damage found in each technological item, specifying the type of alteration analysed. Data are both qualitative and quantitative and must be completed before restoration/maintenance works.

### Intervention program form

Edificio – Comune – Provincia							
PROGRAMMA DI CONSERVAZIONE – SCHEDA DI PROGRAMMAZIONE							
Elemento (classe e sottoclasse dell'elemento tecnologico)							
Identificativo elemento							
Problematiche	Anomalie attese	Zone a rischio	Azioni preventive	Metodi di verifica	Norme di riferimento	Tempi di monitoraggio	Procedure operative specifiche
Voce importata dalla Scheda di analisi delle problematiche	Voce importata dalla Scheda di analisi delle problematiche	Voce importata dalla Scheda di analisi delle problematiche	Voce importata dalla Scheda di analisi delle problematiche	Voce importata dalla Scheda di analisi delle problematiche			
Per un esempio di scheda compilata si veda la Scheda 3.							

Figure 95. "Program Form". Form for intervention program according to [251].

This form belongs to the maintenance/conservation program. For each technological element, all the indications on methods and timing of inspections are listed.

### Inspection form

Edificio – Comune – Provincia							
PROGRAMMA DI CONSERVAZIONE – SCHEDA DI ISPEZIONE							
Data				Compilatore			
Elemento (classe e sottoclasse dell'elemento tecnologico)							
Identificativo elemento	Anomalie attese	Zone a rischio	Metodi di verifica	Norme di riferimento	Esito/Valori riscontrati	Tendenza	Provvedimenti
Voce importata dalla Scheda di programmazione	Voce importata dalla Scheda di programmazione	Voce importata dalla Scheda di programmazione	Voce importata dalla Scheda di programmazione	Voce importata dalla Scheda di programmazione			

Figure 96. "Inspection Form". Form for collecting data during the inspections, according to [251].

This form belongs to the maintenance/conservation program. It is the instrument where the data collected during the inspections indicated in the programming form are reported and has to be compiled during the inspections.

In addition to the descriptive and textual data reported in the sheets described before, the maintenance program considers the entry of geometric and graphical data, as support for restoration analyses. In particular, the guidelines emphasize that representation must be, on the one hand, the basis for mapping damage, risk areas and expected

anomalies, and, on the other, the support scheme for references to other drawings and photographic images. Therefore, it is noted the need to create an information system that allows simultaneous textual and geometric data management.

Thus, in the context of information system, the graphic "layer" (i.e. the 3D model in a BIM) assumes particular importance. The geometric model is itself informative: it brings information about dimensions, deformation, interaction between elements, etc. and is the basis for referencing all thematic data. Therefore, the accuracy of the 3D model is crucial for the correct description of the asset.

For this reason, although no regulation refers to this topic, as discussed in Chapter 5, metadata about model validation and survey accuracy have to be entered into the information system in order to make the user aware about the quality of data.

As far as the Parma Cathedral is concerned, in addition to survey and modelling metadata and to the data required by regulations/guidelines for the correct draft of the maintenance plan, there are several document and requirements specific to the Cathedral.

To describe the actual state of the Cathedral, the Fabbriceria administration required data entry to document the degradation of external façades (resulting in decay and material mapping) and structural monitoring. In addition, the main documents concern:

- Data about previous surveys (as listed in Chapter 3), both textual and graphic data
- Archival data, previously digitized or transcribed
- Photographical images, current and historical
- Historical analyses
- Publications about the Cathedral.

### 6.1.3. Database design: conceptual and logical models

According to the analysis of the available/required data, described in the previous paragraph (6.1.2) and of the semantic classification (paragraph 5.2), a unique atomic database entity was identified corresponding to a general BIM Element. This entity is the link between the database data and the three-dimensional model.

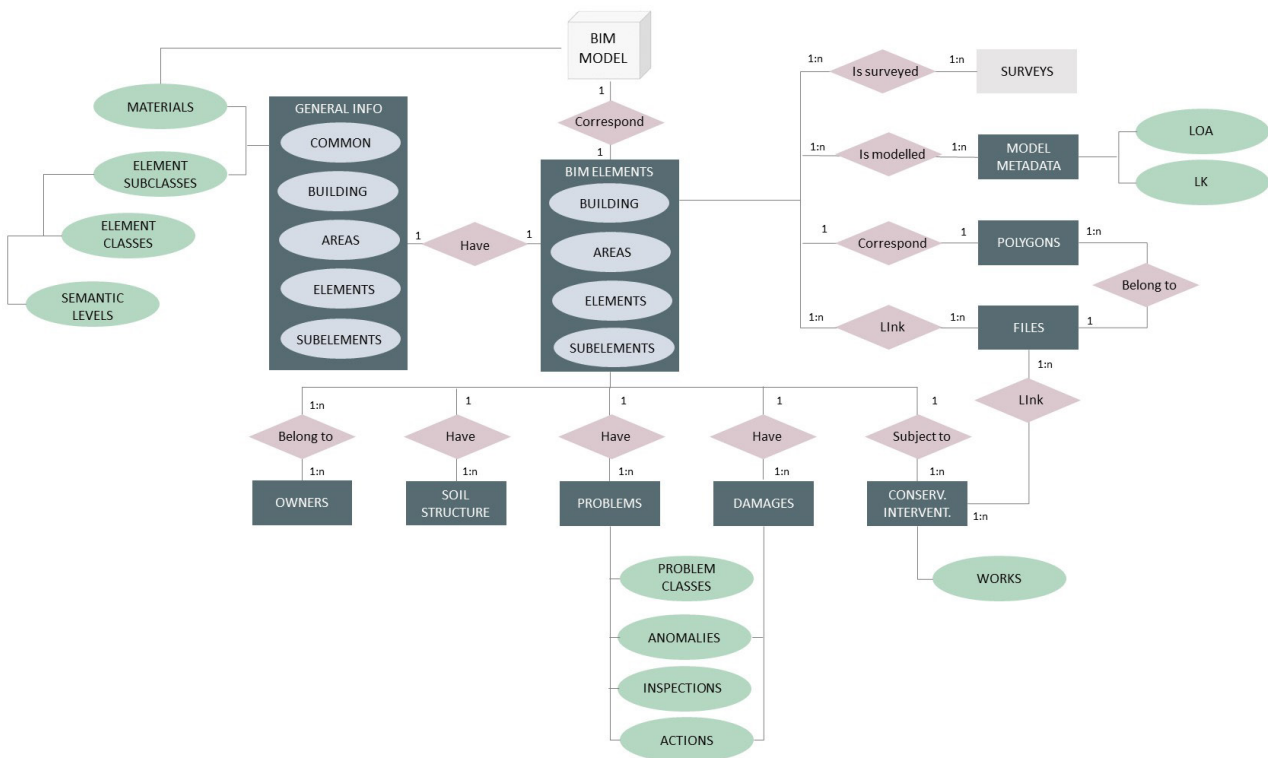
Despite the presence of four different semantic levels (building, areas, technological elements and sub architectural elements), it was decided to create a single database table as, conceptually, the four levels are the same. In fact, they all correspond to a

graphic element and are BIM elements, even if with different levels of hierarchical grouping.

From the data association point of view, the structure has been designed in order to be as flexible as possible and implementable over time with different data. However, the choice of using a single basic entity led to additional difficulties, since each semantic level has proper data (for example, building has the owner unlike an architectural element) and data in common with the others (for example, the description).

Thus, it was decided to organize the data into independent database tables. These tables can be associated to the element according to the needs. In this way, the user decides which data to associate with the element, making the system flexible. Additionally, it is always possible to add a new entity and associate it with the elements. The identified entities are represented in the conceptual diagram in the Figure 97 and are: BimElements, General information, Owners, Soil structures, Problems, Damages, Conservation interventions, Polygons, Files, Surveys and Modelling metadata. In the following, each entity will be described in detail.

Figure 97. Entity-Relationship schema.



## BimElements Entity

Id	RevitId	RevitDescription	InsertionDate
<i>Integer</i>	<i>Integer</i>	<i>String</i>	<i>Datetime</i>

Table 15. BIM Element Entity.

As said before, this table represent the database main entity which refers to the elements in the model independently from the semantic classification level. This entity groups the common data among all the semantic levels and contains the reference (RevitId) to the geometric element in the model (Table 15).

## General Infos Entity

Id	BimElementId	Description	SubClassId
<i>Integer</i>	<i>Integer</i>	<i>String</i>	<i>Integer</i>

Technique	Interior	Exterior	Inspectability
<i>String</i>	<i>Bool</i>	<i>Bool</i>	<i>Enum</i>

Name	Coordinates	Address	CadastralData	Neighbour	Epoch
<i>String</i>	<i>String</i>	<i>String</i>	<i>String</i>	<i>String</i>	<i>String</i>

Use	Area	EaveHeight	NStories	Accessibility	MorphDescription
<i>String</i>	<i>Real</i>	<i>Real</i>	<i>Integer</i>	<i>String</i>	<i>String</i>

Decorative Elements	Territorial Context	Environmental Features	Anthropic Features	CulturalInterestEvaluation
<i>String</i>	<i>String</i>	<i>String</i>	<i>String</i>	<i>String</i>

Table 16. General Info Entity. Grey data are common for all semantic levels, orange data refer to architectural element, green data refer to building.

This table contains general information about BIM Elements. Since the data referring to an architectural element are different from those relating to the entire building, the specific information of each semantic level has been grouped into subclasses and recalled according to the value of the discriminator that allows to switch from one subclass to the other. Table 16 shows all the data: the common data are represented in grey, the data relating to the architectural element in orange and those referred to the building in green.

These data have been identified on the basis of regulations. In particular, building data are indicated by the DPCM 9 February 2011 [118] as necessary to identify uniquely the building, while element data are gathered from Lombardy Region Guidelines [251] recommendations.

To each architectural element it is possible to associate one or more material. Materials are listed in a specific table and are linked to the General Information Entity through a many-to-many relationship.

**Materials Entity**

<b>Id</b>	<b>Name</b>	<b>Resistance</b>
<i>Integer</i>	<i>String</i>	<i>Real</i>

Table 17. Material Entity

The material list is retrieved from the Revit material library. In this way there is compliance between the materials used in the 3D models and the one indicated into the database. In addition, the user can access all material properties provided by Revit.

**Owner Entity**

<b>Id</b>	<b>FirstName</b>	<b>FamilyName</b>	<b>LegalSubject</b>	<b>Address</b>
<i>Integer</i>	<i>String</i>	<i>String</i>	<i>Enum</i>	<i>String</i>

Table 18. Owner Entity.

This table refers to data about the owner. The owner is generally referred to the entire building, but in the case of the Parma Cathedral it can also be referred to functional areas, as in the case of private chapels.

**SemanticLevels Entity**

<b>Id</b>	<b>Name</b>	<b>Initials</b>
<i>Integer</i>	<i>String</i>	<i>String</i>

Table 19. Semantic Levels Entity.

**ElementClasses Entity**

<b>Id</b>	<b>Name</b>	<b>Initials</b>	<b>SemanticLevelId</b>
<i>Integer</i>	<i>String</i>	<i>String</i>	<i>Integer</i>

Table 20. Element Class Entity.

**ElementSubClasses Entity**

<b>Id</b>	<b>Name</b>	<b>Initials</b>	<b>ElementClassId</b>
<i>Integer</i>	<i>String</i>	<i>String</i>	<i>Integer</i>

Table 21. Element SubClass Entity.

As discussed according to the semantic classification, each BIM element corresponds to a semantic level (Building, Functional Area, Technological element or Architectural Sub Element) and for each semantic level specific classes and sub classes have been defined, as fully reported in Appendix C.1.

As far as database structure is concerned, three different tables (levels, classes and subclasses) have been arranged. Since the relationship between levels, classes and subclasses is hierarchical (there are different classes for each semantic level and different subclasses for each class), a tree structure has been implemented and the BIM

element has been associated with only the corresponding subclass, as class and level are associated accordingly (Figure 98).

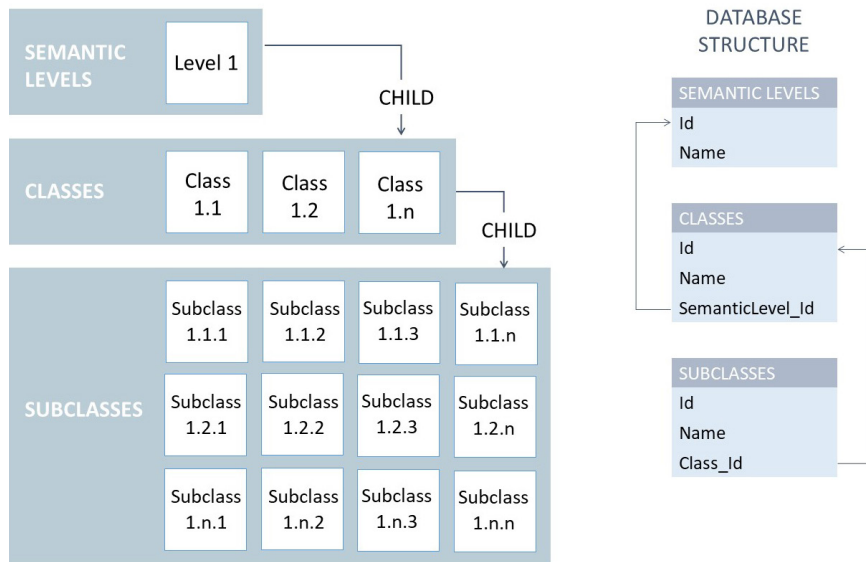


Figure 98. Database structure according to semantic classification.

### SoilStructure Entity

Id	AnalysisDate	OrographicFeatures	Geomorphological Features	SoilChanges	DocumentLink
Integer	Datetime	String	String	String	FK files

Table 22. Soil Structure Entity.

Data on soil characteristics are required by the DPCM 9 February 2011 [118] as a parameter for assessing possible risk factors for the asset. In addition to the decree requirements, the database provides the link to external files, such as diagnostic analyses or technical reports, and the date of such tests execution, in order to document any change in time.

### Problems Entity

Id	RiskZone	MonitoringTime	BimElementId	ProblemClassId	Note
Integer	String	String	Integer	Integer	String

Table 23. Problem Entity.

This table has to be intended as a Problem Form. It refers to what recommended by [251], as far as the "Problem Form" (Figure 93) of the maintenance *Technical Manual* is concerned (see paragraph 6.1.2). According to the *Technical Manual*, one or more

problems can be associated with a technological element. Each of these problems have associated data (such as risk areas, preventive actions, inspections, etc.) and may cause different anomalies. For example, a wall may be subject to mechanical stress and possible anomalies such as deformations or cracks have to be evaluated.

The database retraces this structure: one or more *Problems* (Table 23) can be associated to the BIM element and each *Problem* relates to a specific *ProblemClass* (Table 24) which define the nature of the problem, possible *Anomalies* (Table 25), *Inspections* (Table 26) and preventive *Actions* (Table 27).

*ProblemClasses*, *Anomalies*, *Inspections* and preventive *Actions* have all been organized in specific tables in order to add definitions and additional attributes.

In particular the list and the description of the *Problem Classes* is gathered from [251] and is presented in Appendix C.2. A clarification is desirable and concerns the field "To Evaluate in Future". This field considers the variability of the problem over time. There are indeed problems (such as stability, thermal insulation, etc.) that changes over time, thus periodic checks are required to verify the status of the architectural element. On the contrary, other problems such as ease of intervention or cleanliness are constant over time and so no inspection is required.

*Anomalies* are gathered from UNI standards. In particular, as far as natural and artificial stones are concerned it was adopted the UNI 11182/2006, for wood elements the reference standards were the UNI 11035-1/2010 and UNI 8662-3.

With regard to *Inspections* and *Action* no predefined records have been entered into the database, letting the user able to set its predefined values.

**ProblemClasses Entity**

<b>Id</b>	<b>Name</b>	<b>Description</b>	<b>ToEvaluateInFuture</b>
<i>Integer</i>	<i>String</i>	<i>String</i>	<i>Bool</i>

Table 24. Problem Class Entity.

**Anomalies Entity**

<b>Id</b>	<b>Name</b>	<b>Description</b>
<i>Integer</i>	<i>String</i>	<i>String</i>

Table 25. Anomaly Entity.

**Inspections Entity**

<b>Id</b>	<b>Name</b>	<b>Description</b>
<i>Integer</i>	<i>String</i>	<i>String</i>

Table 26. Inspection Entity.

### Actions Entity

Id	Name	Description
<i>Integer</i>	<i>String</i>	<i>String</i>

Table 27. Action Entity.

### Damages Entity

Id	Description	Diffusion%	Trend	InspectionDate
<i>Integer</i>	<i>String</i>	<i>Float</i>	<i>String</i>	<i>Datetime</i>

Seriousness	Urgency	Values	AnomalyId	BimElemId
<i>Enum</i>	<i>Enum</i>	<i>String</i>	<i>Integer</i>	<i>Integer</i>

Table 28. Damage Entity.

The conceptual structure of data related to *Damages* retrace the Problem organization. *Damage Class* too is intended as a form. It refers to the "Damage Form" (Figure 94) of the *Technical Manual* and the "Inspection Form" (Figure 96) of the *Conservation Program* analysed in paragraph 6.1.2.

Each *BIM Element* may be associated with one or more *Damages* that, indeed, correspond to the *Anomalies* suffered by the element and verified during the inspections. Thus, each *Damage* relates to one *Anomaly* (Table 25). In addition, fields about inspections have been inserted and the connection to the *Action* class (Table 27) has been set up, in order to foreseen future intervention already during the inspection phase.

### ConservationInterventions Entity

Id	Name	Description	Done	TotalCost	Executor
<i>Integer</i>	<i>String</i>	<i>String</i>	<i>Bool</i>	<i>Float</i>	<i>String</i>

Annotation	Source	StartDate	EndDate	BimElementId
<i>String</i>	<i>String</i>	<i>Datetime</i>	<i>Datetime</i>	<i>Integer</i>

Table 29. Conservation Intervention Entity.

This table has been created to keep track of all the actions that the asset was subject to. On the basis of the recurrent data on restoration interventions, the structure was organized as shown in Table 29. To each *Conservation Intervention* all the specific *Works* performed are associated. These *Works* are listed in the *Works* table (Table 30) with relative unit prices, as in terms of the contract. All the interventions are catalogued by date, allowing diachronic queries.

In addition to the list of works, it is possible to link as external references all files (*File Class*) related to that intervention, from simple images to design drawings, reports etc.

#### Works Entity

<b>Id</b>	<b>Name</b>	<b>Description</b>	<b>Cost</b>	<b>Units</b>
<i>Integer</i>	<i>String</i>	<i>String</i>	<i>Float</i>	<i>Enum</i>

Table 30. Work Entity.

#### File Entity

<b>Id</b>	<b>Alias</b>	<b>Description</b>	<b>FileName</b>	<b>Date</b>
<i>Integer</i>	<i>String</i>	<i>String</i>	<i>String</i>	<i>Datetime</i>
<b>PixelWidth</b>	<b>PixelHeight</b>	<b>PixelSize</b>	<b>Discriminator</b>	<b>SurveyData_Id</b>
<i>Integer</i>	<i>Integer</i>	<i>Double</i>		<i>Integer</i>

Table 31. File Entity. In Grey common data, in Orange data referred to raster files and in Green data about files that are survey data.

This table refers to all external files of any format that are linked to the database (raster images, vector files, text files, documents, etc.). *Files* can be associated with different object classes, architectural elements, functional areas or the entire building and are also linked to restoration work and to Survey Data to keep track of the attached documentation.

As said in Chapter 5, previous restoration interventions or historical work in general on the Cathedral are entered into the database as textual information or as linked files and are not modelled as different phases of the BIM model. In this context, the database acts as a general archive of the information and document related to the building.

Even in this table, a sub classification was necessary. Raster images have been separated from the other documents in general, in order to add attributes about the pixel size and the image resolution in pixel. This data are essential to define the image reference system, e.g. useful for mapping the orthophotos on the elements of the model, as will be described in paragraph 6.3.4.

#### Polygons Entity

<b>Id</b>	<b>RasterId</b>	<b>Geometry</b>	<b>BimElementId</b>
<i>Integer</i>	<i>Integer</i>	<i>Geom</i>	<i>Integer</i>

Table 32. Polygon Entity.

As discussed in paragraph 5.6, a plug-in function has been implemented for inserting

the orthophoto in BIM environment and utilizing them as a basic tool for mapping both on the 2D orthophotos and, automatically, even on the 3D model. The user can map by drawing two-dimensional polygons directly on the orthophoto and each polygon is stored into the database and can be associated with semantic data.

The table reported above contains all these 2D polygons. In particular, each polygon is stored in the database with the coordinates of its vertices, referred to the orthophoto image reference system. Thus each polygon belongs only to one raster (the orthophoto), since the raster reference system defines the polygon geometry. In addition, since the implemented tool (see paragraphs 6.3.4 and 5.6) allows for the creation of 3D elements subdividing the wall into different areas starting from the 2D polygon drawn, there is a 1:1 relationship with the polygon and the part of the wall, that is a BimElement object. Given this correspondence, all the data associated to the BimElement Entity are, consequently, related to the corresponding polygon.

### **ModelMetadata Entity**

<b>Id</b>	<b>Loald</b>	<b>Lkgld</b>	<b>Lksld</b>	<b>Lkmld</b>	<b>ScaleMax</b>
<i>Integer</i>	<i>Integer</i>	<i>Integer</i>	<i>Integer</i>	<i>Integer</i>	<i>String</i>

<b>ModellingTechniques</b>	<b>ModellingTools</b>	<b>Note</b>	<b>Author</b>	<b>InsertionDate</b>
<i>String</i>	<i>String</i>	<i>String</i>	<i>String</i>	<i>Datetime</i>

Table 33. Model Metadata Entity.

This table is particularly important to certify the correctness of the realized 3D model. The main purpose was to make the user able to reconstruct the modelling phases and access parameters that give indications about the quality of the model. This information is associated to each single object modelled, since the global quality of the model could be, and is in the most cases, different from the local quality of the single items.

The arranged fields to this aim are shown in Table 33. In particular:

**LOA** refers to the five Levels of Accuracy (LOA10, LOA20, LOA30, LOA40, LOA50) as defined by the US Institute of Building Documentation (USIBD) and described in paragraph 1.5.4.

#### **LK: Level of Knowledge**

There is not a proper reference standard that defines this parameter, in particular with reference to the BIM model. However, it is author's opinion that before modelling an object it is mandatory to have a thorough and accurate knowledge of the object.

This knowledge must concern all its main aspects: geometry, structure and materials. Knowing these aspects makes the model more reliable and, especially in the BIM context, where it is required to describe each feature of the element, these three parameters are fundamental.

This concept can be compared with the *Level of Knowledge (Livello di Conoscenza LC)* that results into the *Confidence Level (Fattore di Confidenza FC)*, provided by the Italian “Technical Standards for Construction” [91].

On the basis of the Technical Standard requirements, a classification of the level of knowledge was developed in this thesis. Compared to the Technical Standard, the proposed classification introduces three main changes:

- introduction of the Level of Knowledge 0
- introduction of different degree of knowledge about the geometry
- introduction of three different types of knowledge considering independently Geometry, Structure and Materials.

LK0 refers to the lack of knowledge. In the common practice, especially for historical building that present difficulty of access, some information is not available and are hypothesized on the basis of analogies, images or empirical evaluations.

As shown in Figure 99, the Technical Standard provides a unique degree of knowledge for geometry defined as “The geometry of the structure is known based on a survey

Livello di Conoscenza	Geometria (carpenterie)	Dettagli strutturali	Proprietà dei materiali	Metodi di analisi	FC
LC1		Progetto simulato in accordo alle norme dell'epoca e <i>limitate</i> verifiche in-situ	Valori usuali per la pratica costruttiva dell'epoca e <i>limitate</i> prove in-situ	Analisi lineare statica o dinamica	1.35
LC2	Da disegni di carpenteria originali con rilievo visivo a campione oppure rilievo ex-novo completo	Disegni costruttivi incompleti con <i>limitate</i> verifiche in situ oppure estese verifiche in-situ	Dalle specifiche originali di progetto o dai certificati di prova originali con <i>limitate</i> prove in-situ oppure estese prove in-situ	Tutti	1.20
LC3		Disegni costruttivi completi con <i>limitate</i> verifiche in situ oppure esauritive verifiche in-situ	Dai certificati di prova originali o dalle specifiche originali di progetto con estese prove in situ oppure esauritive prove in-situ	Tutti	1.00

Figure 99. Level of Knowledge according to available information. Table C8A.1.2 [91]

or original designs". It is author's opinion that simply referring to "survey" is reductive for the complexity that stands behind a survey. The results obtained from a survey can be so different in terms of reliability, accuracy and level of detail. Thus, without defining with this parameter the accuracy of the survey (for which a proper part of the database structure is set apart), with the Level of Knowledge several degrees of completeness of the survey have been defined.

Moreover, the Technical Standard defines three levels of knowledge (LC1, LC2 and LC3) based on the simultaneous contributions of all three factors considered (Geometry, Structure and Materials). However, it is author's opinion that, for a more rigorous description, it is more effective to keep the three parameters independent. For example, in some cases, it is possible to perform a very accurate geometric survey (therefore ascribable to the highest level of knowledge) but no information on the materials is available, or vice versa.

Thus, in the classification proposed, the three parameters have been separated and the following levels have been defined (Table 34):

- Level of Knowledge – Geometry (LKG): LKG0, LKG1, LKG2, LKG3
- Level of Knowledge – Structure (LKS): LKS0, LKS1, LKS2, LKS3
- Level of Knowledge – Material (LKM): LKM0, LKM1, LKM2, LKM3

Levels of Accuracy and Levels of Knowledge are stored into the database in specific tables, reporting their description. These tables are linked to the *Model Metadata* Entity.

The other fields in the Model Metadata Entity refer to:

- **Maximum scale of representation**, which is set on the basis of accuracy of survey data and of the level of detail (GRADE), implemented during the modelling phase
- **Modelling Techniques**, such as, direct modelling, generative modelling, parametric modelling etc.
- **Modelling Tools**, which refers to the software used for modelling operations
- **Insertion date**, useful in order to update the model in case of changes and make diachronic analyses.

Table 34. Personal elaboration of the Level Of Knowledge (LC) classification according to [91].

Level of Knowledge	Geometry (LKG)	Structure (LKS)	Material (LKM)
LK 0 Supposed	The geometry of the structure is not known and is supposed from analogies or images.	The structure and the construction technique of the element is not known and supposed from analogies.	Materials are not known and supposed from images or from view.
LK 1 Limited	The geometry of the structure is known from 2D surveys or original drawings.	Construction details are based on a simulated design carried out according to the construction practice.	Materials are known but their properties are not available neither from constructive designs nor from test certificates.
LK 2 Appropriate	The geometry of the structure is known from 3D incomplete survey integrated with other data.	Construction details are known from an in-situ analysis or are partially available from constructive designs.	Information on the mechanical properties of the materials is available on the basis of either the original design drawings or original test certificates, or appropriate in-situ tests.
LK 3 Accurate	The geometry of the structure is known from 3D complete and certified survey, with adequate accuracy to the representation scale.	Construction details are known from an accurate in-situ analysis or are available from original constructive designs.	Information on the mechanical properties of the materials is available on the basis of the original design drawings or certificates, or by in-situ accurate tests.

## SurveyMetadata

It was decided to structure a database section specifically to host data and metadata related to the survey, which would allow its description and documentation, in order to provide the user with a tool to control and keep track of the operations carried out. As shown in Figure 100, the survey has been conceived as the sum of *Survey Data* and *Processes*. The data may be either the raw data or the processes output. Processes documents the type of elaborations, with the associated input and output data.

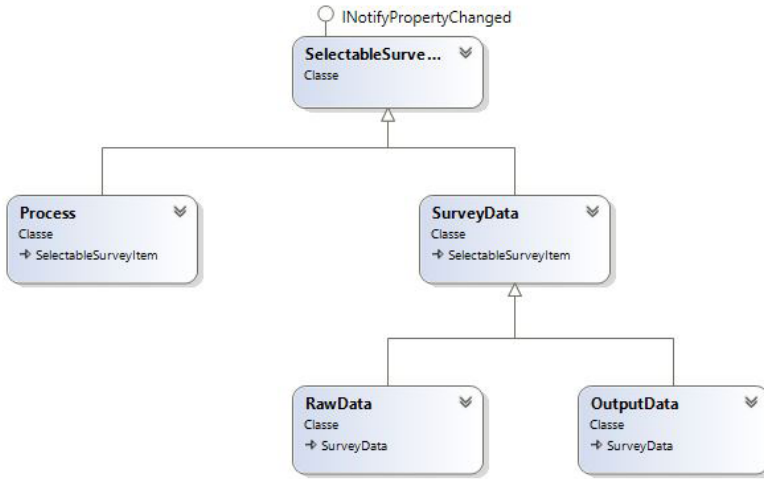


Figure 100. Class diagram which represents the survey database structure.

Each survey is a record in the *Surveys* table (Table 35) containing a general description and start and end date. The surveyed data and the processes are then associated with it. The structure of the database makes it possible to link data and processes in a sequential way, in order to reconstruct the entire sequence of raw data, processes and processed data, from the initial data produced by the instrument to the output data used for modelling (Figure 101).

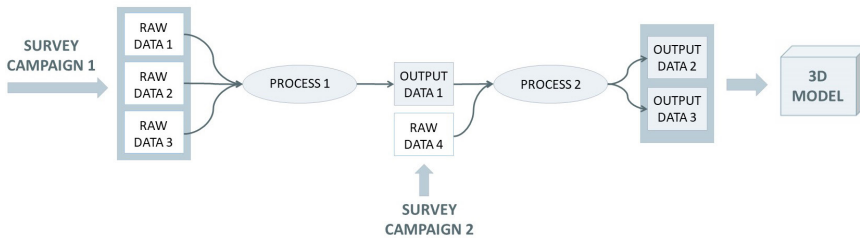


Figure 101. Schematic example of a survey process.

Both with regard to data and processes (Table 36 and Table 37), it is possible to associate descriptive metadata and the link to specific external reference files. These files are the instruments outputs and the working files, and are stored in the *File* table, to which both data and processes are linked.

Given the great heterogeneity of survey techniques and instruments, the description is currently intended as a free text field. In fact, defining specific descriptive fields would have been too binding. For example, the number of scans, the resolution, the type of laser used and the distribution of scans are important for a laser scanner survey. For a UAV survey, on the other hand, the flight altitude, image overlapping, resolution, sensor,

data about the camera etc. are important. It is then let to the user providing all the data necessary for the faithful documentation of the survey carried out.

The same goes for instruments that are entered into the database by name, brand and a description field, where the user can e.g. detail the technical specifications. For better documentation, the possibility to link the technical data sheet of the instrument has been foreseen. The structured tables are provided below.

**Surveys Entity**

<b>Id</b>	<b>StartDate</b>	<b>EndDate</b>	<b>Description</b>
<i>Integer</i>	<i>Datetime</i>	<i>Datetime</i>	<i>String</i>

Table 35. Survey Entity.

**SurveyData Entity**

<b>Id</b>	<b>Alias</b>	<b>Description</b>	<b>Discriminator</b>	<b>ProcessId</b>
<i>Integer</i>	<i>String</i>	<i>String</i>		<i>Integer</i>

<b>InstrumentId</b>	<b>Survey_Id</b>	<b>Process_Id1</b>	<b>Author</b>	<b>DateTime</b>
<i>Integer</i>	<i>Integer</i>	<i>Integer</i>	<i>String</i>	<i>Datetime</i>

Table 36. SurveyData Entity.

**Process Entity**

<b>Id</b>	<b>Alias</b>	<b>Description</b>	<b>SurveyId</b>	<b>Author</b>	<b>Datetime</b>
<i>Integer</i>	<i>String</i>	<i>String</i>	<i>Integer</i>	<i>String</i>	<i>Datetime</i>

Table 37. Process Entity.

**Instruments Entity**

<b>Id</b>	<b>Brand</b>	<b>Model</b>	<b>Alias</b>	<b>TechSpecFiles</b>	<b>Description</b>	<b>Discriminator</b>
<i>Integer</i>	<i>String</i>	<i>String</i>	<i>String</i>	<i>String</i>	<i>String</i>	

Table 38. Instrument Entity.

Based on the structure described in this paragraph, a template database was created, which includes the tables and the seeding of pre-compiled data (such as *Problems*, *Anomalies* etc.). This template can be applied to every new database related to BIM models for restoration and maintenance.

The relational model of the implemented database can be seen in the figure in the next page (Figure 102).

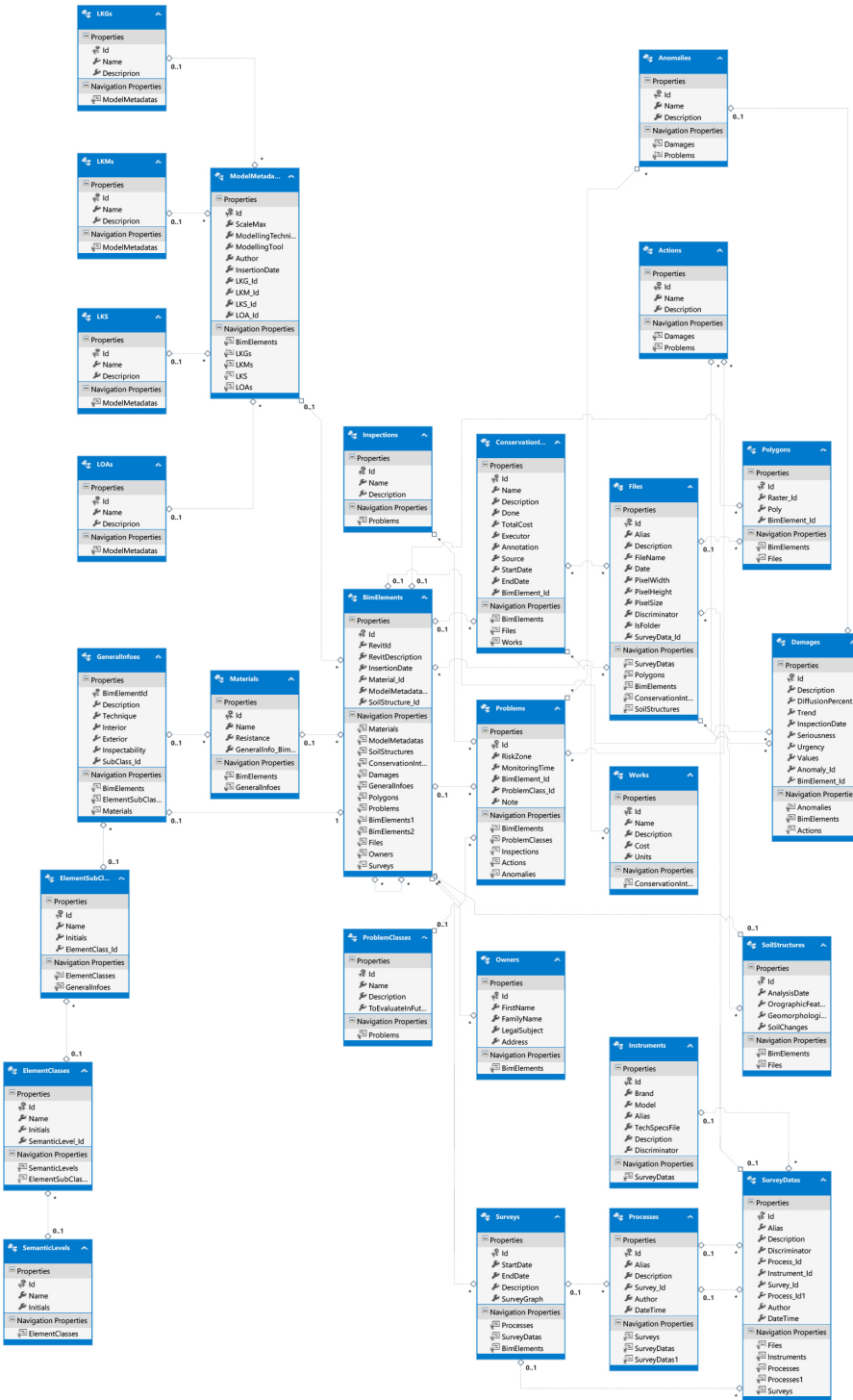


Figure 102. Relational model of the implemented database. (In the next page).

## 6.2. Technologies and software adopted

---

As already pointed out, the usability of applications is the key requirement for their effective success. Especially in the case of cultural assets, where HBIM oriented systems are used by non-AEC-experts, this condition is particularly important. The application implemented in this thesis is compliant to this requisite and has been developed to ensure usability and multi-platform implementation.

### 6.2.1. .NET Framework

The integration of the implemented application with other software is possible thanks to the use of .NET Framework. .NET applications are, in fact, targeted for Windows (actually, recent .Net Core Libraries allows to deploy applications also in Linux and Mac environments) and the web or mobile devices, so very suitable for the purposes of this thesis.

.NET Framework is a software framework developed by Microsoft® that enables programmers to interact with basic operative system features, create and/or extend software applications. It provides, indeed, underlying platform, libraries and services such as memory management, garbage collection, common type system, class libraries, etc., which make possible interoperability and integration [157].

As shown in Figure 104, .NET framework is based on the Framework Class Library (FCL) and the Common Language Runtime (CLR), which provide class libraries and language interoperability across several programming languages [2].

**Common Language Runtime (CLR)** is the foundation of the .NET Framework. It manages and executes the code, providing services such as memory management, type safety, exception handling, garbage collection, security and thread management. CLR improves code robustness by ensuring the executing code conforms to a common type system (CTS). The CTS ensures that all .NET (or managed) code – irrespective of the language – uses a similar set of object types and can work together in the same environment. This feature makes it possible to write applications in a chosen development language (C#, VB, Visual C++ or F#) and yet make use of components/

code written by programmers using other .NET languages [157].

**.NET Framework Class Library (FCL)**

is a library or collection of object types that can be used when developing .NET applications. It provides user interface, data access, database connectivity, cryptography, web application development, numeric algorithms, network communications and so on. In addition, the class library includes types that support a variety of specialized development scenarios, such as: Console apps, Windows Graphical User Interface (GUI), Windows Presentation Foundation (WPF) apps, Web Applications with ASP.NET, Windows services, Service-oriented apps using Windows Communication Foundation (WCF) and Workflow-enabled apps using Windows Workflow Foundation (WF) [1].

In this way, .NET Framework provides a consistent object-oriented programming environment, minimizes software deployment and versioning conflicts, promotes safe execution of code, eliminates the performance problems of scripted or interpreted environments and makes the developer experience consistent across widely varying types of apps [1].

In the present case study, the application has to be integrated with BIM software and, in particular, Autodesk Revit has been used to test this integration. Revit provides .NET

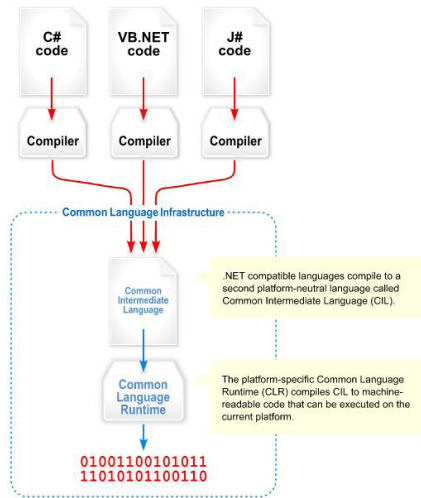


Figure 103. Visual overview of the Common Language Infrastructure (CLI). From: [2]

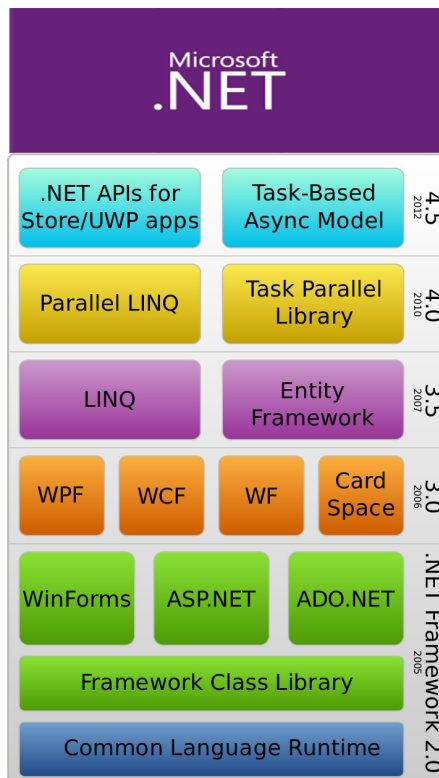


Figure 104. .NET Framework component stack. From: [2]

compliant API, thus, for the development of application, it was chosen to operate within the .NET Framework, using the available libraries for interfaces creation, database implementation, integration with other software and on-line extension, ensuring consistency and interoperability.

In particular, as explained in detail in the following paragraphs, the Entity Framework technology was used to support the development of the whole application enabling the easy interaction with the underlying relational database; Windows Presentation Foundation (WPF) was used to develop graphical interfaces and to build the desktop client application; finally, ASP.NET technology was used for creating the web extension of the application starting from the implemented data model.

### 6.2.2. SQL Server, Entity Framework Technology and Asp.NET

The principal aim of the project was to develop a data-oriented application based on the data model, consisting of entities, relationships, and logic, defined in paragraph 6.1.3. The starting point was therefore the data model, without considering the data engines used to store and retrieve the data. In addition, these data have to be accessed via several platforms, in order to increase the system usability.

The idea was thus to apply the same data model to different application usages (desktop and web interfaces), without changing the basic logical structure and preserving the same functions and rules (Figure 105).

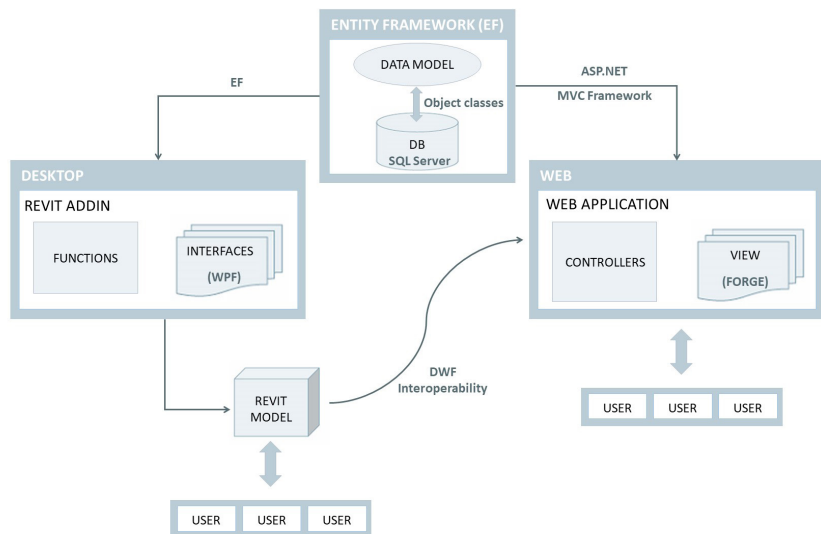


Figure 105. System architecture.

In this context, the **Entity Framework Technology (EF)** [125][126] was considered an optimal solution for the implementation of the desktop application.

Entity Framework is an object-relational mapper (ORM), i.e. a set of technologies that support the development of data-oriented software applications. It gives developers an automated mechanism for accessing and storing the data in the database, reducing the mismatch between the object-oriented world of .NET Framework developers and the world of relational databases.

The Entity Framework enables developers to work with data in the form of domain-specific objects and properties without having to concern themselves with the underlying database tables and columns where data are stored. Developers can work at a higher level of abstraction as Entity Framework translates the operations into relational database actions [126].

Entity Framework is useful in three scenarios (Figure 106):

- working on an existing database or designing the database ahead of other parts of the application (database-first approach)
- creating the database starting from defined domain classes (code-first approach)
- creating databases and classes starting from design of the database schema on the visual designer (model-first approach).

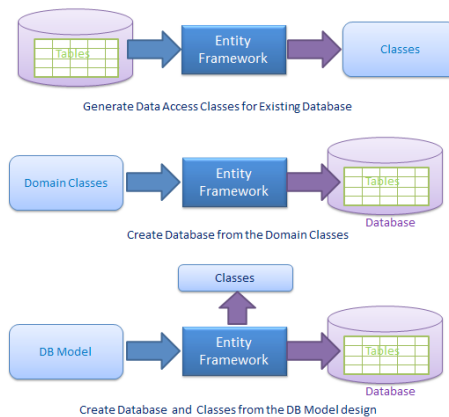


Figure 106. Entity Framework scenarios for database interaction. From [125]

In the implemented application, the code-first approach was adopted. Code First enables to describe the conceptual data model by using C# or Visual Basic .NET classes. In this way, it is possible to focus on the domain design and start by writing classes and context class according to domain requirement, before designing the database. The database is then created based on the entity classes and configuration defined in the code.

In the specific case of the application here presented, C# language was chosen and for each entity defined in the conceptual database schema (Figure 97) the correspondent class was created and the relationships with the other classes were defined (Figure 107).

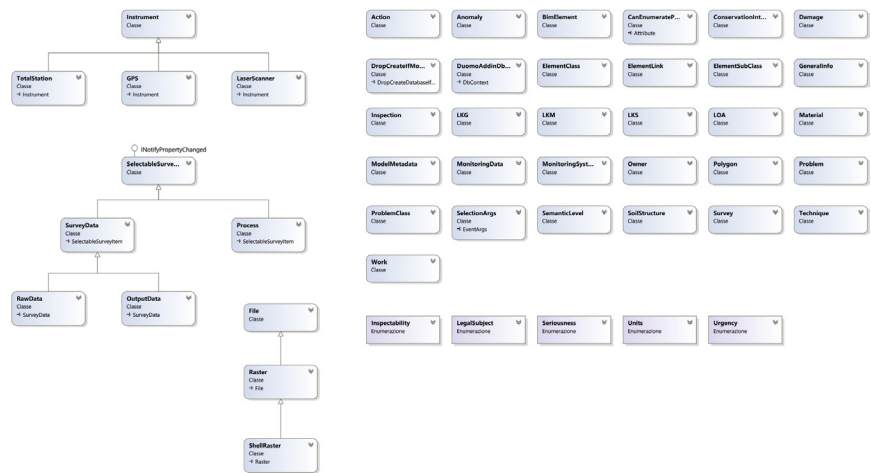


Figure 107. Implemented class diagram.

The classes that defines the data model, through the EF, represent both database entities and objects that can be consumed by programming languages. These objects enable to run queries against the conceptual model, bind objects to controls, track changes that were made to the objects and so on [126].

Based on the implemented class domain, the corresponding database was created, defining tables and relationships (Figure 102). As far as the choice of the RDBMS is concerned, EF does not tie to one specific RDBMS. Initially it was decided to use PostgreSQL [240], an open source database manager that ensures the easy management of spatial data thanks to the PostGIS spatial extension. However, the use of PostgreSQL had some limitations in the use of EF. For this reason, it was decided to use Microsoft SQL Server [191], which can be perfectly integrated with the EF structure.

In parallel with the development of the desktop application, its web extension has also been implemented. Also in this case, the objective was to exploit the same data model and on the basis of this develop the graphical interface and controllers. To this aim, the implemented architecture was based on the **ASP.NET MVC (Model-View-Controller) framework** [23].

ASP.NET technology [22] is a web development platform that provides a programming model and a comprehensive software infrastructure, making possible to develop web applications for PC and mobile devices. ASP.NET is a part of Microsoft .NET Framework and can use the entire hierarchy of classes in .Net framework, as made in the present case study.

In particular, the MVC (Model-View-Controller) framework [23] was particularly suitable

since it allows implementing the internal representations of information independently of the visual presentation to the user and make the application development more flexible and scalable.

MVC, in fact, separates an application into three main groups of components: Models, Views, and Controllers. The model represents the state of the application and any business logic or operations that should be performed by it [23]. It directly manages the data, logic

and rules of the application. Views presents content through the user interface and generates new output to the user based on changes in the model. The controller handles and responds to user input and interaction, accepts input and converts it to commands for the model or view [193].

In this way, it was possible to base the application on the same data model implemented for the desktop application and build and test the model without considering the user interface.

In addition, ASP.NET allows creating easily mobile apps and sites, using responsive design frameworks. This was particularly useful to reach the multiplatform usability of the application.

### 6.2.3. WPF controls

To make the system use easier and more intuitive, graphical interfaces and data forms have been developed to help with the consultation and implementation of the database. In addition, a multi-platform usability, which includes desktop, web and mobile integration, was advisable. To this aim, the HBIM application has been developed starting from the same class domain defined in Figure 107, implementing different solutions of usability.

The solution has been developed in Visual Studio 2017 [192]: WPF class library was used for creating graphical user-friendly interfaces that ensure desktop integration.

**WPF (Windows Presentation Foundation)** [166] is a user interface (UI) framework that

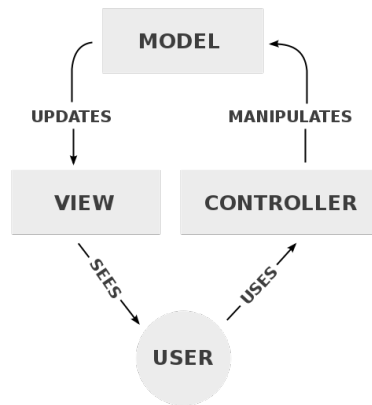


Figure 108. Diagram of interactions within the MVC pattern. From [193]

creates desktop client applications. The WPF development platform supports a wide range of application development features, including an application model, resources, controls, graphics, layout, data association, documents, and security.

WPF is able to handle all issues related to interaction between technologies such as document management, 3D graphics and multimedia components, and provides a unique platform for implementing applications, eliminating the need to use of external technologies and/or components.

Under WPF the interface and the functionality of the application can be implemented separately. The interface is generally a graphic task, implemented by a graphical designer, using the XAML language while the management of application functions, related to computer programming is implemented in .NET code.

XAML (Extensible Application Markup Language) is a XML-based markup language developed by Microsoft. XAML is the language behind the visual presentation of an application developed in Microsoft Expression Blend, as well as HTML is the language behind the visual presentation of a web page. It is based on objects in the Common Language Runtime and their properties or events [83].

XAML allows creating user interface documents by defining elements such as controls, text, images, forms, animation, and so on. XAML language is declarative: it is necessary to add code in order to add runtime logic to the application. The application, in other words, will not be able to run or respond to calculations, nor to create new user interface spontaneously without the addition of code. The code for an XAML application (e.g. a C# code) is stored in a separate file from the XAML document (file-code behind).

Separating the user interface structure from the code behind allows developers and designers to work together with the same project without interfering each other [86].

To implement the interface, WPF works on a grid that ensure the correct layout of the controllers and allows using the common UI components that are used in almost every Windows application. It is possible to add controls to an application by using either XAML or code. For this specific application, the layouts were created using XAML, while the C# code was used for subscribing to events or manage application functions.

The main controllers are [303]:

- **Button:** an event occurs when the button is clicked, hovered, pressed or released
- **TextBlock:** allows visualization of small dynamic contents. It is not editable
- **Label:** represents the text label for a control and provides support for access keys. It is not editable
- **TextBox:** is generally used to display or edit unformatted text

- **CheckBox:** allows the user to toggle an option on or off, usually reflecting a Boolean value
- **List:** is a container of selectable items
- **ComboBox:** is a list of selectable and non-editable items. Unlike the list, the entire content of the combo box are hidden when it is not used and occupies less space in the interface. It is like a drop-down menu with selectable values
- **TabPanel:** handles the layout organizing the contents in tabs
- **DatePicker:** gets or sets the currently selected date
- **Menu:** is a classical Windows menu control. It enables hierarchically organization of elements associated with commands and event handlers.

The layout is useful for arranging the items and managing dimensions, position and style of the elements.

Another important functionality of WPF is Data Binding [304]. Data Binding allows applications to present and interact with data and was the basic requested function in the development of this application in order to dialogue with database.

Data binding is the process that permits data synchronization with the application that has to use these data. In other words, when the data change value, the element bound to the data reflect changes automatically, or, on the contrary, whenever the user inserts or modifies a data value within an application (for instance editing the value in a TextBox element), the corresponding variable is updated.

It is possible to bind data from a variety of data sources and collect or stylize them into ContentControls such as Button and ItemsControls such as ListBox and ListView.

Regardless the specific element bound and the data source typology, the general binding schema is the following:

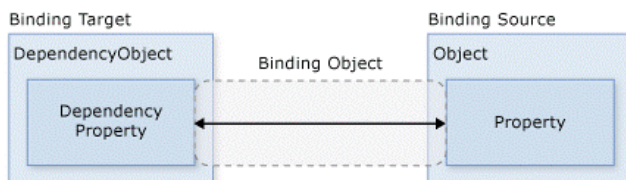


Figure 109. Data binding schema [304].

Data binding is a bridge between the binding target (the element in the application) and the binding source (storage data source). As said before, data value can change in a direction or in the other: from the binding target to the binding source (so the source value changes when a user edits the value in the application) and/or from the binding source to the binding target (changing the value in the data source, the value visible in the application will change). This two way direction of the data flow can be enabled or

limited to only one way mode, according to the specific requirements of the application [304] as illustrated in Figure 110.

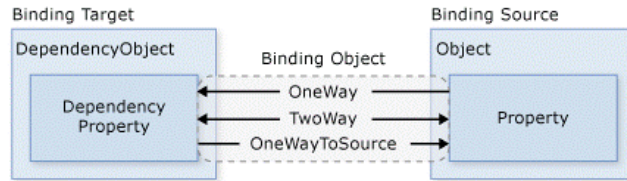


Figure 110. Direction of the data flow [304].

- **OneWay** binding is useful for read-only applications, where changes to the source automatically update the value in the application, but the user cannot modify directly the value.
- **TwoWay** binding is suitable for editable forms or other fully-interactive UI scenarios, where it is requested to modify either the source property or the target property to automatically update the other.
- **OneWayToSource** is the reverse of OneWay binding and is used in scenarios where the user has to re-evaluate the source value from the UI.

The interfaces developed for the HBIM application enable to interact dynamically with the database via WPF. In fact, data visualization, editing, entry and query have been implemented.

The developed application can be used also standalone. In this case, not having a graphical viewer to rely on, the user accesses the complete list of BimElements and can select which element to query. However, use with BIM software is much simpler. In this case, Autodesk Revit has been used to test this integration and has been exploited both as a 3D modeller and graphical model viewer.

The following paragraphs will show in detail the individual GUI implemented, analysing the relationship with the database and the specific features.

Paragraph 6.3 will analyse the interaction of the developed application with Autodesk Revit and paragraph 6.4 data sharing on the web.

### 6.3. Integration with Autodesk Revit

Among the BIM software, only the interoperability with Revit have been developed and tested so far. Revit is, in fact, the software used to build the 3D model and is currently the most used software for BIM applications. It also provides powerful APIs

(Application Programming Interfaces) and SDKs (Software Development Kits) [28] that make its programming easier. The API, in fact, can be used to create tailored plug-ins that improve Revit efficiency and extend its functionality. The user can automate repetitive, time-consuming tasks, customize the product's existing features or adding new ones. In addition, the Revit SDK contains documentation, samples and tools that are useful for using the API. When these additional modules contain codes that makes use of the Revit API, they are also called Add-ins.

To make use of the Revit API, the two *RevitAPI.dll* and *RevitAPIUI.dll* were added to the project references [28]:

- *RevitAPI.dll* deals with core product functionality and contains the APIs to access the Revit application, documents, elements, parameters, etc.
- *RevitAPIUI.dll* deals with the product's user interface and contains the APIs related to manipulation and customization of the Revit user interface, including command, selections and dialogs.

Revit API are .NET API which means the user can use any of the .NET compliant programming languages (C#, VB.NET, F#, etc.) to develop a plug-in. The custom code works with Revit as a plug-in and is loaded as a DLL (Dynamic-Link Library).

The dll compiled from the implemented solution, is loaded automatically at Revit opening. It contains all the additional implemented features that are accessible through custom icons in the ribbon panel, as shown in Figure 111.

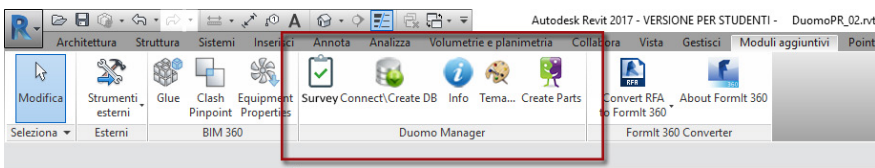


Figure 111. DuomoAddin in Revit ribbon panel.

The individual features implemented will be illustrated in the following paragraphs and can be summarized as follows:

- Connect/create the database (paragraph 6.3.1)
- Display data about an item through the graphical interfaces (paragraph 6.3.2)
- Query the database and thematic mapping the 3d model (paragraph 6.3.3)
- Associate orthophoto to elements, perform 2d mapping and 3D automatic modelling from 2D elements (paragraph 6.3.4)
- Enter survey and model metadata (paragraph 6.3.5).

### 6.3.1. Database connection

Each Revit project has to be associated to only one database and vice versa, and this database has to be accessed every time the project is opened without creating additional databases.

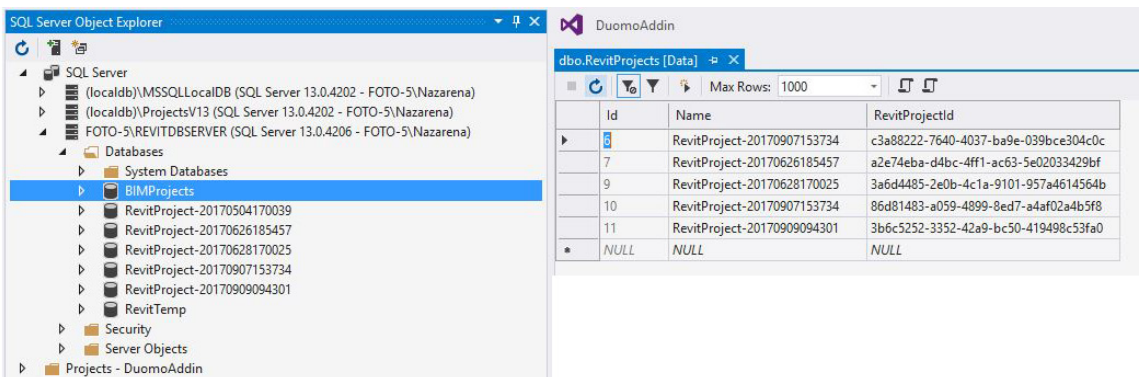
To do this, the project and the database have to be uniquely identified and the system has to control their correct associations. Therefore, each Revit project has been associated with a unique ID. This ID is a string automatically generated by the software and is used as a shared parameter (thus accessible also from external applications). The unique database identifier, instead, is created by code and is a DateTime string, formatted as the follows:

RevitProject-yyyyMMddHHmmss
RevitProject-20170922174132

To ensure the unique association between the Revit project and the database, an additional database, the *BIMProjects* database, has been created. It contains all Revit projects and the associated database ID (Figure 112). At Revit opening, the dll launches automatically the connection to this database, in order to check if the project already exists and what the associated database is.

Summarizing, there are two different types of databases: the *BIMProjects* database that is unique and contains the list of Revit projects and the associated database, and several databases (*RevitProject-yyyyMMddHHmmss*), one for each Revit project, containing all the data about the elements in the BIM model. This second type of database is created starting from the template defined in paragraph 6.1.3 and stores all the information about the building.

Figure 112. Database List in RevitDBServer.



The user can create/connect to the specific database associated to the Revit project, by clicking the “Connect / Create DB” button in the ribbon panel. This function allows Revit to connect to the database, if it already exists, or to create a new one if it does not exist. When the user executes the “Connect/create DB” command, the system works as follows (Figure 113):

- Connect to the *BIMProjects* database containing Revit projects
- Check if the project exists in the *BIMProjects* database:
  - if so, the system finds the associated database and connects to it
  - If not, the system creates a new database based on the *RevitTemp* template database, creates a record in the *BIMProjects* database to save this association and connects to the new database.

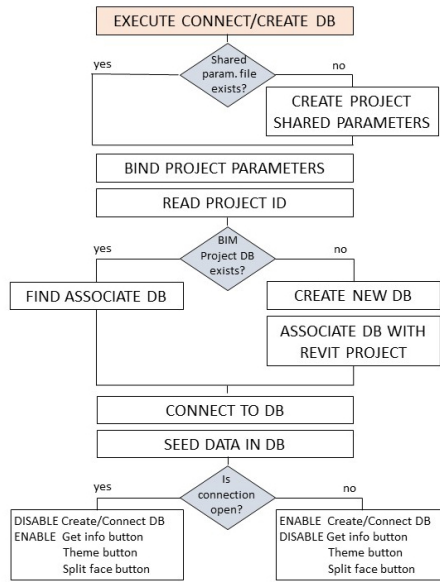


Figure 113. Connect DB workflow.

From the graphical point of view, the user understands whether or not the database is connected from the colour of the icons in the ribbon panel. When it connects, the database icon becomes grey and the icons of additional features are enabled (Figure 114).

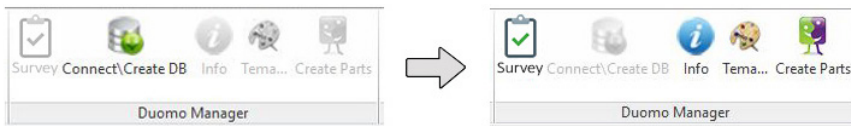


Figure 114. Database connection, ribbon panel action.

### 6.3.2. Get element information and data entry

The second implemented function (“Info” button) allows the user to get/set all the information about the elements of the model and access directly the database. In order to simplify the interaction with the database, graphical interfaces have been implemented that make operation as data entry, data retrieve, modify and delete, user-friendly and

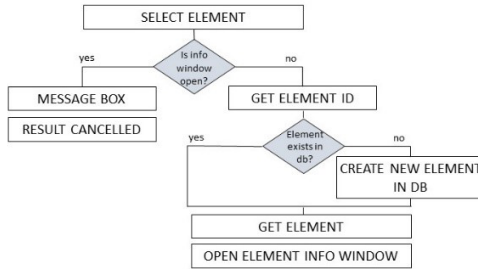


Figure 115. Get element information workflow.

immediately comprehensible to the user.

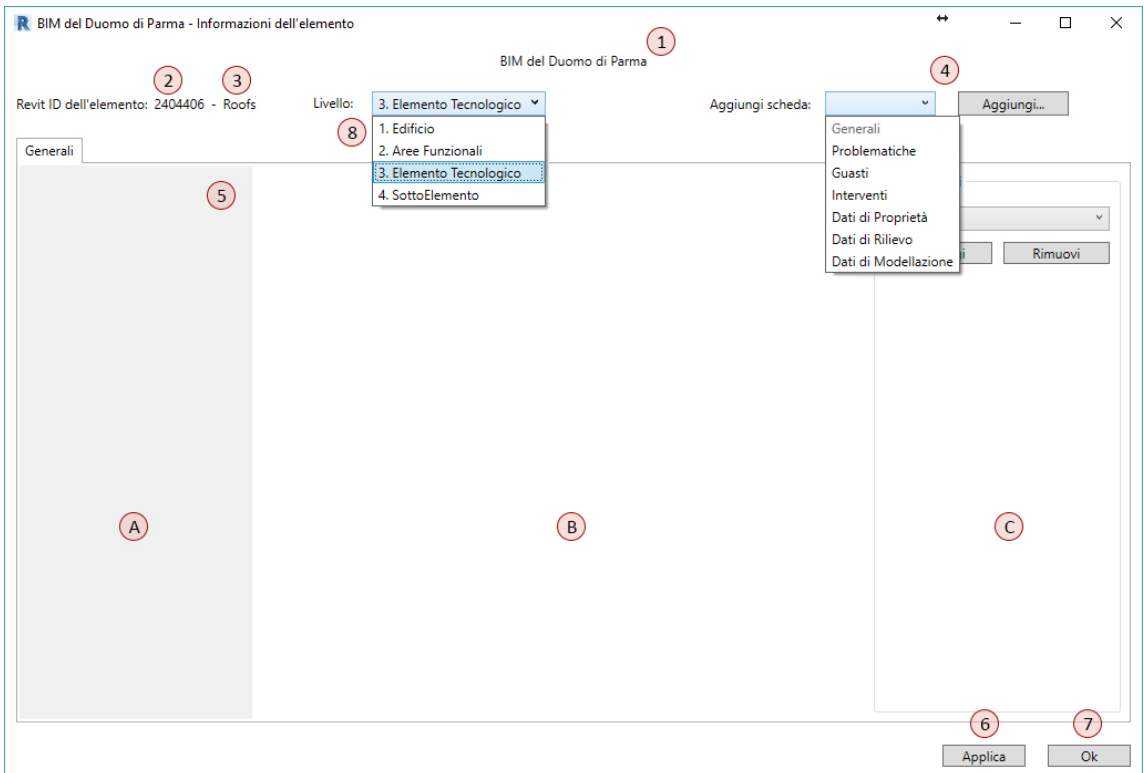
The flow chart (Figure 115) shows in detail the command execution.

As can be seen from the flow chart, the user is requested to select an item. The system gets the Id of the selected item and, if it has been

already stored in the database, its information is displayed; on the contrary, a new element is created. In this way, the tool allows the user not only to look at and edit the data in the database but also to enter new entities.

A dialog box with information opens when the user selects the item. To avoid errors, a check was inserted that notifies the user when he is requesting information about many items at the same time. The simultaneous opening of two dialog boxes is then prevented and the user can work on only one item at a time to avoid errors in data entry.

Figure 116. Element information window WPF layout.



The User Interface is quite simple and is organized as shown in Figure 116.

The data visible in this window are the title of the application (1), the identification code (ID) (2) of the selected item and the type of item according to the Revit classification (for example, a wall) (3).

To prevent accidental changes to the database, no automatic updating of the edited information in the interface is applied, until the user confirm these changes using the Apply button (6). This button actually handles the event to apply changes to the database and save them.

The Ok button closes the window. It checks the presence of unsaved changes: if there are any changes, a dialog opens where the user can decide whether to apply them and save ("Yes"), do not apply them and close ("No"), return to the edit interface ("Cancel"). If there are no changes, it closes the dialog box.

The central part of the GUI is dedicated to a tab panel, which shows the information about the selected item (5) according to the item semantic level, selected from the combo box (8).

As described before (paragraph 6.1.3), the information is stored in the database in different tables according to its category: general building information, general element information, problems, damages and so on, and can be related to the BIM element according to the specific needs. In the graphical interface, therefore, the information is grouped into tabs and each form generally corresponds to a database table. For example, the data for the General Information table are retrieved in the General Information form, and so on. Only the tabs containing data associated to the element are visible, while the others are hidden.

At opening, the system checks and loads the data associated to the element and shows the corresponding tab. The user can thus select from the combo box in the upper right corner (4) the tab (so the data) that he wants to associate to the element.

To each tab, a graphic form is associated, arranged in order to show the information required. The graphic layout (Figure 116) of these GUI is the same for all the forms, for a simpler usability. It is based on a grid and is divided into three main sections (A, B, C). The left section (A) is used to contain and organize by date the list of problems, damages, or interventions that are already associated with the item. The central section (B) hosts the controls to entry and display the data and is therefore different for each tab. It follows a grid organization where each row represents an attribute of the element, so one or more values in the database. The right section (C) gathers the associated files or additional descriptions/specifications, for instance retrieved from regulations.

Through these GUI, the user can enter, edit or simply retrieve all data. The available forms allow to:

- Access to all the general and morphological data about the element,
- View the problems that the element presents and the related anomalies,
- See the current and past damages in order to plan the restoration and maintenance operations,
- Access the information about restoration/maintenance/survey works, including photos, textual and technical documents,
- View the original survey data and metadata about methodology, accuracy and execution techniques of the survey
- View and enter metadata about the model execution process.

The individual user controls for the tab creation will be described in detail in the next paragraphs.

#### 6.3.2.1. General information form

This interface refers to all the general and morphological data about the element. According to the element semantic classification level (Building, Functional area or Architectural element, see paragraph 5.2), the information shown changes. The interface presented in the following refers to the information about the technological element level (see Figure 71).

As show in Figure 117, the database tables that are accessed through this interface are *BimElements*, *General information-element*, *Materials* and *Files*, giving information such as Element class and subclass (1, In Figure 118), description (2), constructive technique (3), placement (4), inspectability (5), material (6) and interaction with other elements (7). Interaction between elements is useful to understand whether contiguity, interaction, or adjoining between distinct elements can lead to structural or material damages. So, it is possible to select directly on the model the elements the item is related with (7) and to save the Id in the database.

File association (8) is also very important. For item documentation, associating non-textual data and documents gives added value. So it is possible to associate images, PDF files, CAD files or text documents (stored in the server), which can be previewed directly in the interface and can be opened by double clicking on the preview.

Starting from the top of the section B, there is a text block for the tab title, translate in English "General information – Element morphology".



Figure 118. General information interface.

The second row indicates the class and the subclass to which the element belongs according to the technological elements classification introduced in paragraph 6.1.2 and detailed in Appendix C.1. Thanks to two combo boxes (1), the user can select the class and subclass of the element.

To do this, a two-ways binding was made between these controllers and the database *ElementClasses* and *ElementSubclasses* tables. In this way, if the record is already stored in the database, the combo box will return the value, but if this information is void, the user can select the correct value in the combo box and this value will be recorded into the database and associated with the element. In the same way the user can change the value (for example, from “outside decorative elements” to “internal decorative elements”), and then update the value in the database.

Further descriptive data about the element regard the Description (2) and the Constructive Technique attribute (3). The description is contained in a text box that binds the *Description* column in *BimElements* table, which is a string value. The same goes for the Constructive Technique attribute (3), which is displayed in a text box and binds the *Technique* column in *BimElements* table.

The Location attribute is different. It is described either by the exposition of the element (interior or exterior) (4) and by its inspectability (5). Interior and Exterior are both Boolean values, so two check boxes are used to describe them. The two check boxes replicate the table structure where two distinct fields have been maintained since an element can be both internal and external at the same time. Inspectability is instead an enumerable value, so its predefined values are displayed in a combo box. This combo box binds *Inspectability* field in *BimElements* table, recording the selected enumerated value.

The sixth row of the grid refers to the element materials (6). In the database, materials are collected in an ad hoc table and linked by many-to-many relationships (n:n) with *BimElements*. As it is well-known, n:n relationship makes it possible to associate multiple attributes with the same entity and, at the same time, associate the same attribute to multiple entities. This solves the problem of having a field for each possible attribute (e.g. material1, material2, material3 and so on) without knowing with certainty how many attributes are possible. In order to manage the many-to-many relationship in the interface, a stack panel is used which allows to organize:

- a list box in which to display attribute values assigned to the element
- a combo box where the user can view all available values for that field
- "Add" and "Remove" action buttons to manage the attribute association to the element

The combo box binds a collection of all possible material stored in the *Materials* table and the list box binds the *Materials* table, displaying only the values assigned to the selected item thanks to the navigation properties. It should be noted that the list of materials in the table is not random, but is directly linked to the materials in the Revit project. So when a new material is created in Revit, the list of materials is automatically updated.

As for materials, the interaction between the elements is a n:n relationship too. Also in this case a list box displays the IDs of the related elements (7). On the contrary the combo box, being uncomfortable to select the item through its ID from a list, lets the user select the items directly on the 3D model with a "Select on the model" button and get the corresponding ID.

The section C is occupied by a Group Box (8) and relates to the external files linked to the database. These files (images, texts, pdf, dwg etc.) are stored in the project server and the corresponding path is recorded into the database. The group box contains a combo box with the list of associated files, two action buttons and the file preview.

Click on the "Add" button a Window search browser opens to associate files with the

element. The user can select the file and add metadata (such as name, description, insertion date) in a dedicated dialog box (Figure 119). All these data are directly inserted into the database *Files* table. Once the user has added the file, he can select it from the drop-down menu of the combo box, preview it in the bottom part of the group box, or open it by double-clicking on the preview.

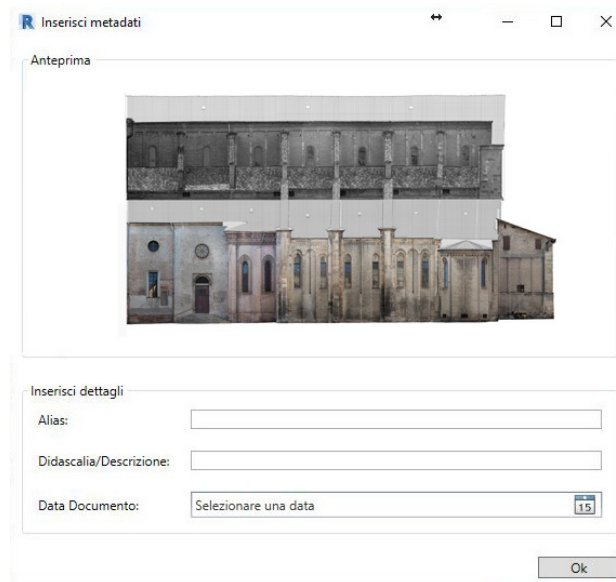


Figure 119. Dialog window for metadata association.

The actions performed by the different functions of the form can be summarized as follows:

- Loading the list of materials: this function may be generalized in uploading a data collection and its code will be reused, changing only the arguments, in all subsequent interfaces that will recall this function.
- “Add” and “Remove” button events: these buttons subscribe to an event when clicked. In particular, “Add” associates BimElement with the selected material (or file, etc.) in the combo box, “Remove” deletes the association between BimElement and the selected item in the list box. Also in this case, their code will be reused in the following tabs.
- Selection of 3D elements directly on the Revit model (Figure 120): when the button “Select on the model” is clicked, an event is subscribed which asks for a selection in Revit. The user selects the desired item and its RevitId returns to the subject that subscribed to the event and then stored it in the database.
- External file linking. The “Add file” button performs five functions (Figure 121):

1. Open a Window dialog box and allows the user to select files with different extensions
2. Check if the user-selected file is already in the database: if it is already stored, associate it with the BimElement, otherwise
3. Open an additional dialog box where the user can insert the metadata (Figure 119)
4. Insert the file information into the *File* table
5. Associate the file with the BimElement.

The added file is so visible in the combo box. From the drop-down menu of the combo box, the user can select the various files. For each file, a preview is shown that can be an image, for raster files, or the file extension icon for other files (Figure 122).

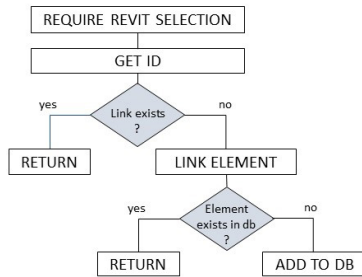


Figure 120. "Link element on the model" function workflow.

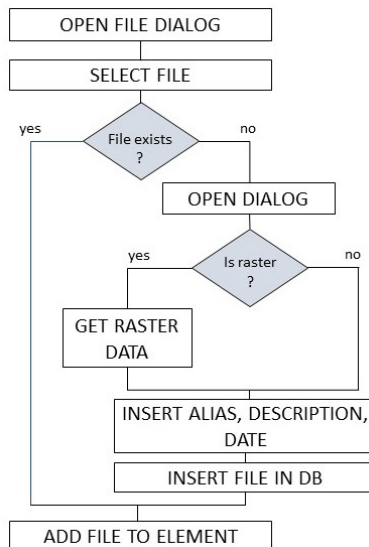


Figure 121. "Add file to element" function workflow.

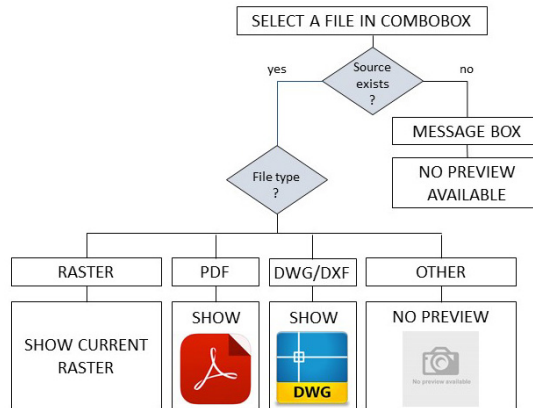


Figure 122. "Show file preview" function workflow.

### 6.3.2.2. Problem form

The problem analysis tab lists all the information related to each technological element, according to DPR n. 554/1999, from which the identification of requirements and levels of performance follow [251]. This tab shows the list of problems, which each item can be subject to, associating consequent damages, actions to be performed in order to prevent additional issues, frequencies of controls and so on, to plan maintenance work. The database tables that are accessed through this interface are: *Problems*, *ProblemClasses*, *Anomalies*, *Inspections* and *Actions*. Compared to the *General Information Form* described before, this tab has additional difficulties, due to the more complex structure of the data. In fact, as visible in Figure 123, the data displayed in this form (anomalies, precautionary actions, risk areas etc.) are not directly linked to *BimElements*, but are related to a problem (*Problems* table), which is linked to *BimElements*. Thus, for each *BimElement* there may be multiple problem forms with related data.

This structure, already extensively illustrated in the database design paragraph (§ 6.1.3), makes the information very dynamic but complicates the relationship between the elements and the data binding.

From the layout point of view (Figure 124), the tab follows general the setting common to all forms. The section A, this time, presents a *ListView* containing the list of issues associated with the *BimElement*. In other words, the *ListView* shows the index of the *Problems* table records (sorted by problem name) that refer to the *BimElement* queried. When the user selects the various items in the index, all the data related to the problem

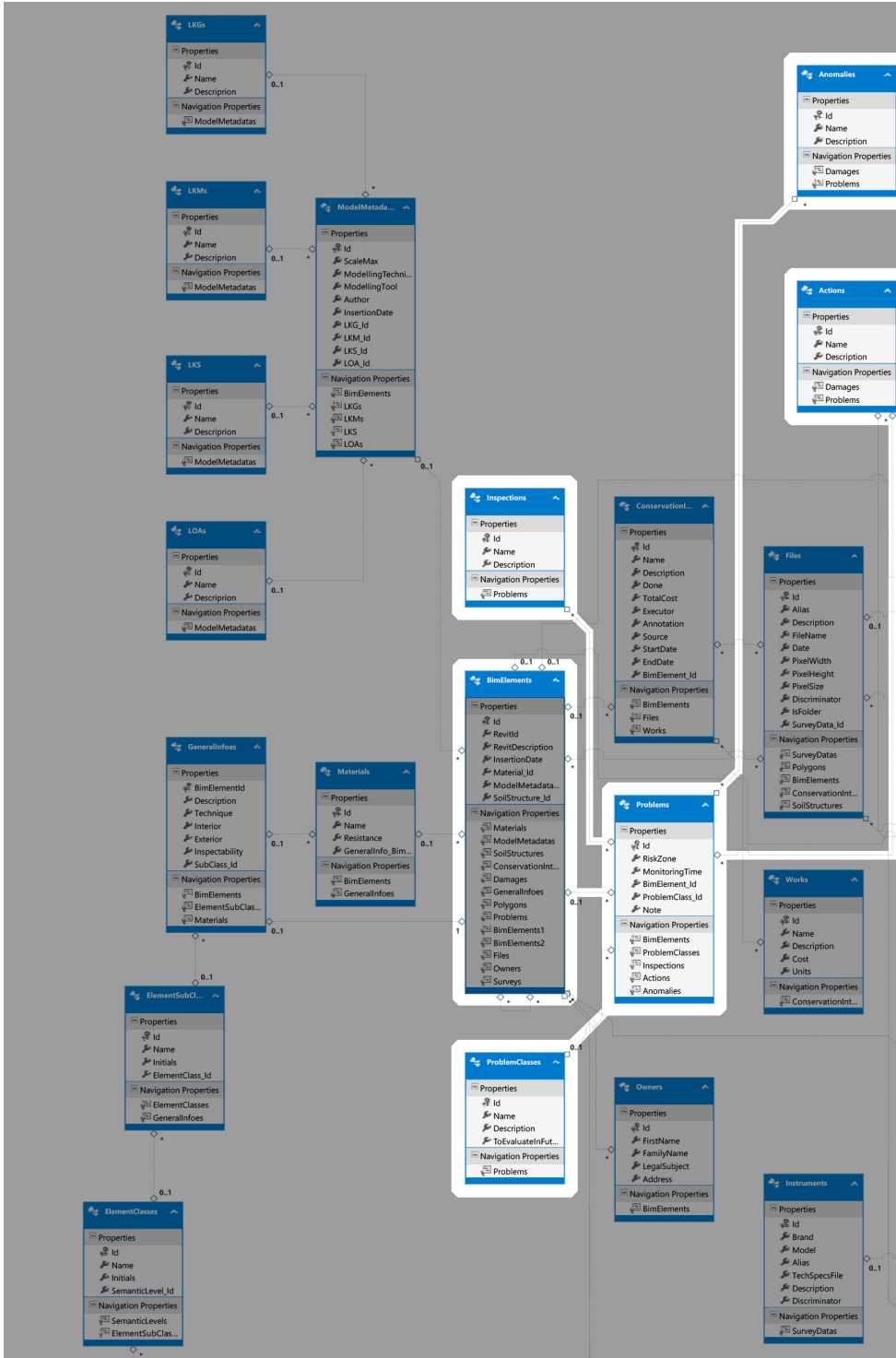


Figure 123. tabase graphical model. The table to which problem form refers are highlighted.

appears in section B. With the “Add” button, the user can add a new problem to the item by selecting it from a list defined on the basis of the reference guidelines (Appendix C.2). Adding a problem means, actually, creating a new record in the *Problems* table, related to the query *BimElement*.

As far as the section B is concerned, the technical details of the controls used will not be illustrated, since they have been already described for the previous form. In particular, the controls used can be summarized as follow:

- a ComboBox from which the user can select the problem name from the list of issues contained in the *ProblemClasses* table (1)
- combinations of *ListBoxes* and Comboboxes to handle many-to-many relationships with regard to damages (2) that an element can have, preventative actions (4), and inspections (5) that can be performed
- TextBoxes to directly edit the data with regard to the zones at risk (3), the frequency of inspections (6) and any notes (7), for which the binding is done directly with the *Problem* table.

Figure 124. Problem Form interface.

Section C instead has a GroupBox containing the regulatory description of the problem

The screenshot shows the 'Problem Form' interface for 'BIM del Duomo di Parma'. The window title is 'BIM del Duomo di Parma - Informazioni dell'elemento'. The Revit ID is '1556533 - Muri' and the level is '3. Elemento Tecnologico'. The form is divided into several sections:

- Generali** (selected): Contains a list of problem types (A) such as 'Vulnerabilità all'azione degli agent', 'Esposizione agli attacchi biologici', 'Facilità di intervento', 'Pulibilità', and 'Sostituibilità'.
- Analisi delle problematiche**: The main section, titled 'ANALISI DELLE PROBLEMATICHE'.
  - ProblematICA** (1): A dropdown menu showing 'Vulnerabilità all'azione degli agenti atmosferici'.
  - Anomalie riscontrabili** (2): A list box containing 'Alterazione cromatica', 'Alveolizzazione', and 'Erosione fisica'. To the right, there is a dropdown for 'Erosione fisica' and 'Aggiungi'/'Rimuovi' buttons.
  - Zone a rischio** (3): A text box containing 'Intero elemento'.
  - Azioni preventive** (4): A list box (empty) and a dropdown menu. To the right, there are 'Aggiungi'/'Rimuovi' buttons.
  - Controlli eseguibili** (5): A list box containing 'A vista - Rilievo alterazione superfici'. To the right, there is a dropdown for 'A vista - Rilievo alterazione supe' and 'Aggiungi'/'Rimuovi' buttons.
  - Periodicità controlli** (6): A text box containing 'Ogni anno'.
  - Note** (7): A large text box (B) for entering notes.
- Descrizione della problematica** (C): A text area containing a detailed description: 'Predisposizione all'insorgenza di alterazioni e/o degradazioni legate alle azioni chimiche e fisiche degli agenti atmosferici. Tale analisi è da compiersi in relazione alle caratteristiche materiche dell'elemento tecnologico, alle condizioni ambientali, alle tecnologie utilizzate e alle condizioni d'uso. (Regione Lombardia, La conservazione programmata del patrimonio storico architettonico)'. There is a checked checkbox 'Da valutare in futuro'.

Buttons for 'Aggiungi' and 'Rimuovi' are present at the bottom of the main form area and at the bottom right of the window.

analysed and whether it is to be evaluated in future or not, in order to properly draft the maintenance plan.

From the code point of view, the functions for loading data collections (anomalies, inspections, problem classes, precautionary actions) and for "Add" and "Remove" buttons have been used, as outlined in the previous paragraph.

In addition, a new function has been implemented to change data displayed in Section B, according to the problem selected in the section A index. This function, summarizing, changes the context of the data whenever the problem is changed.

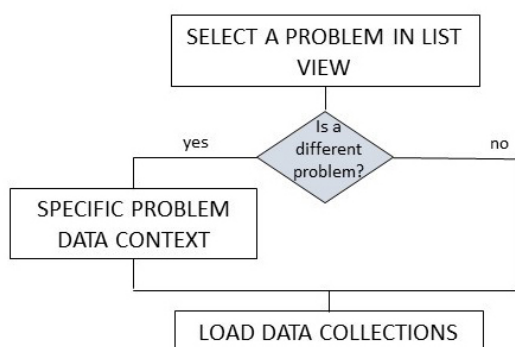


Figure 125. "Change problem db context" workflow.

### 6.3.2.3. Damage form

The damage form contains the information about the damage found in each technological element, specifying the type of alteration analysed. The data entered on the tab are both qualitative, expressed through a free text comment, and quantitative, referring to vulnerability data [251].

This form is generally compiled after the inspections. For this reason, in addition to the data provided by DPR n. 554/1999, additional data on the inspection, in which the damage was found, was also included.

Thus, the information contained can be summarized as follows: the name of the observed anomaly (1), its description or comments (2), the seriousness (3), the percentage of diffusion (4), the urgency of intervention (5), the tendency to increase or not (6), the date of the survey (7), the measured values (8) and the planned interventions (9). All these data are stored in the *Damages*, *Actions* and *Anomalies* database tables.



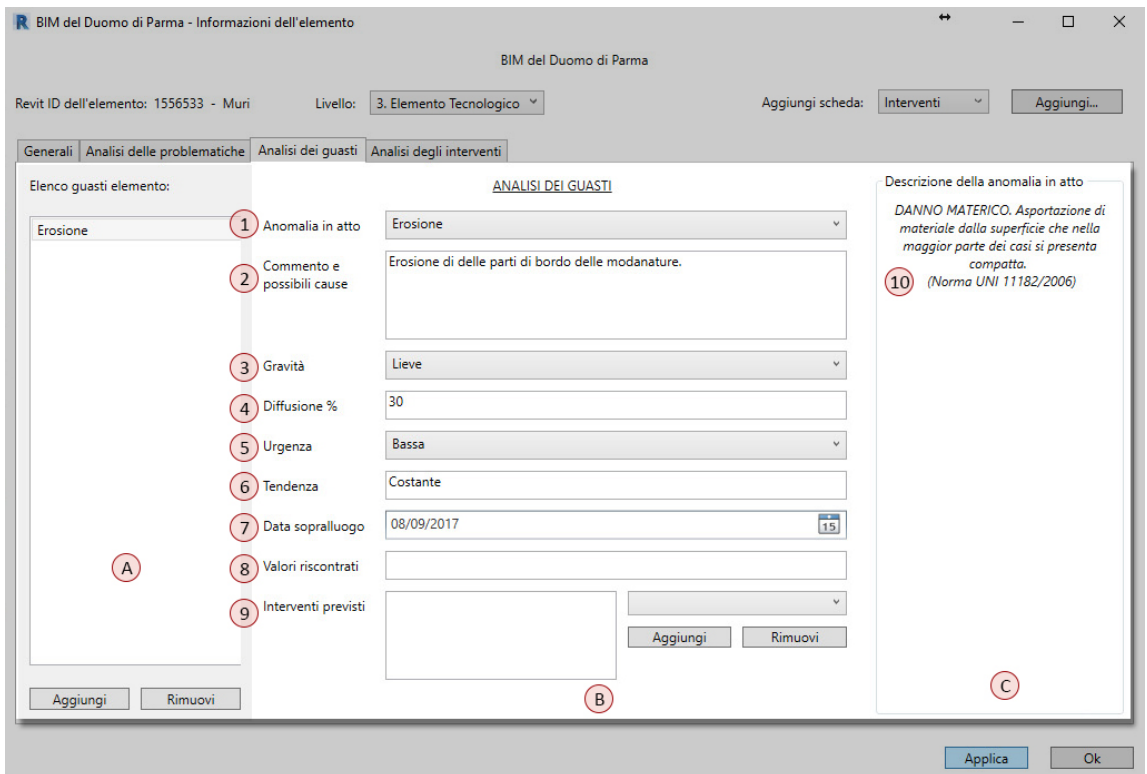
As well as for the *Problem Form*, data displayed in this form are not directly linked to *BimElements*, but are related to a damage (*Damages* table), which is linked to *BimElements*. Thus, for each *BimElement* there can be multiple damages forms with related data (Figure 126).

For this reason, the structure of the tab is the same of the *Problem Form*: the section A with the ListView containing the list of damages associated with the *BimElement*, the section B with all the data related to the specific damage selected in the ListView index and the section C containing the regulatory description of the anomaly observed (Figure 127).

Obviously, with respect to the previous tab, the information and the structure of the data in section B is different.

The first control is a ComboBox (1) from which the user can select the anomaly name from the list of failures contained in the *Anomalies* table. The description of the selected anomaly will appear automatically in the GroupBox in the section C (10), while the user can insert a description of the anomaly, of its possible causes or a general comment in the TextBox (2) under the anomaly name. This text is free and should be useful for

Figure 127. Damage form interface.



describing the situation better.

In addition to free comment textbox, quantitative data should be provided:

- Seriousness is expressed by an enumerable value (mild, medium, high) that can be recalled via a ComboBox (3)
- Diffusion is a percentage value and is manually entered in a TextBox. A check ensures that the value matches the required data type (4)
- Urgency of intervention is also expressed through an enumerable value reported in a ComboBox, variable from low, medium or high (5)
- Trend is a free text field (6)
- the Date of the inspection is entered by the user by typing it directly or selecting day, month and year from a DatePicker (7)
- the measured values are a free text field (8)
- Planned actions are described through many-to-many relationship handled, as seen in the previous tabs, by the combinations of ListBox and Combobox (9)

All these data are editable by the user and are directly bound to the *Damages* table in the database.

#### 6.3.2.4. Intervention form

The intervention tab has been structured to handle all the survey, restoration and maintenance works carried out on a cultural asset, giving access to the data contained in *ConservationInterventions*, *Files* and *Works* tables (Figure 128). It acts as an archive, as a single collector of data on the history of the building.

All information relating to a work are given in this sheet: name (2), description (3), list of specific works (as in technical documents) (4), the cost of the intervention (5), the work executor (6), any notes (9). A source field (10) specifies the origin of the intervention.

Particularly important in this form is time management. In fact, the start and end dates of each intervention should always be entered. In addition, future interventions can be scheduled (leaving the “done” field unchecked). Time management allows the system to, act as a backup archive and a tool for scheduling and organizing future actions.

The layout structure retrace the previous tabs (Figure 129). Even in this case, the data displayed in section B are related to the single intervention (*ConservationInterventions* table) and not to the *BimElement*, thus the user need to select from the index of section A the desired action.

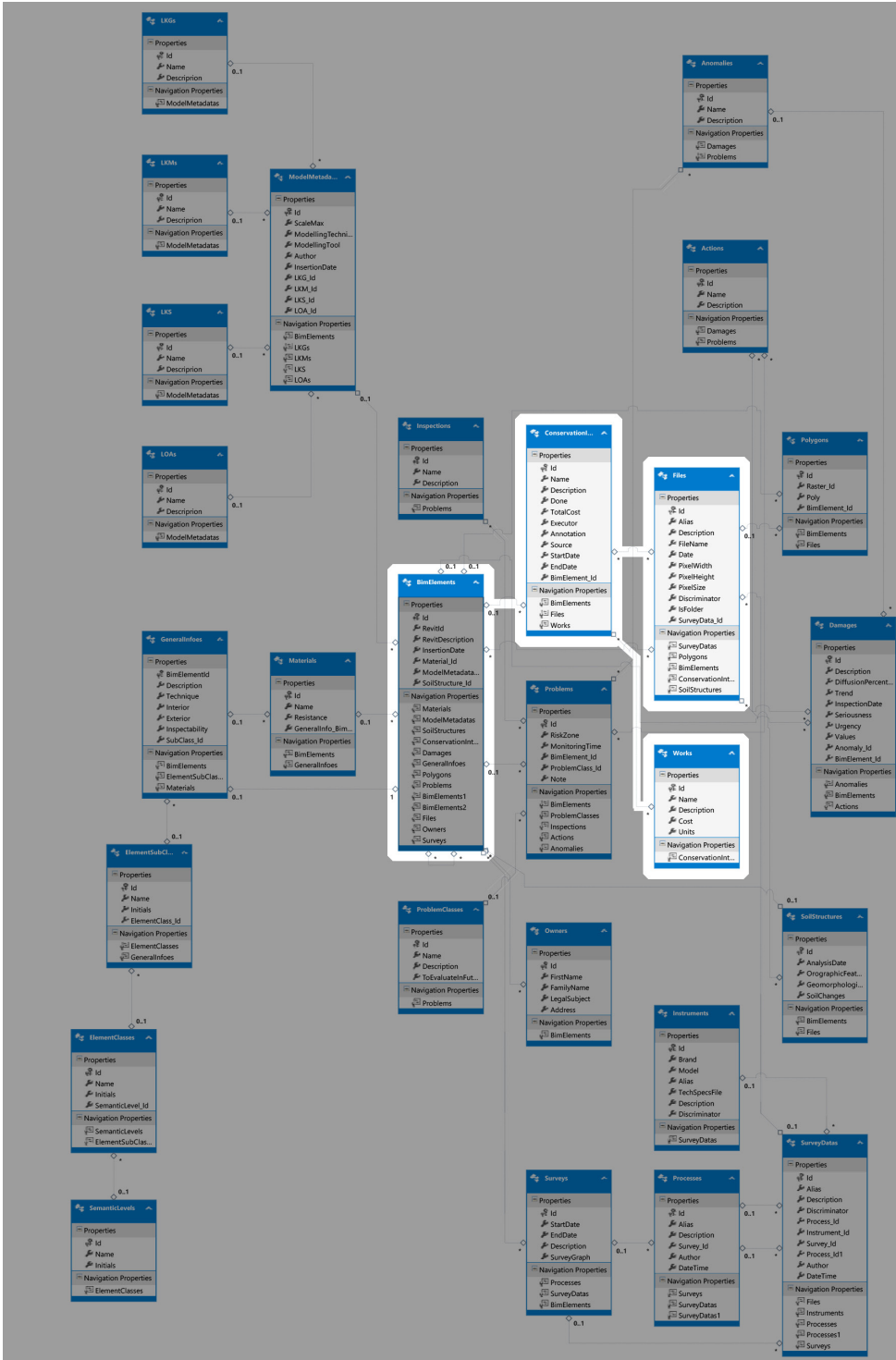


Figure 128. Database graphical model. The table to which intervention form refers are highlighted.

To facilitate research, interventions in the ListView (1) can be filtered and searched by data. A RangeSlider displaying the start and end dates can be used for limiting and refining the search.

Section C is structured as in the general form and allows the association of files that document the intervention. In fact, for each intervention, there are usually many documents (drawings, reports, photographs) that need to be traced, to properly document the building.

Coming now to the detailed description of section B, the data are almost completely bound to the *ConservationIntervention* table. Therefore, free TextBoxes were used principally (2,3,6,9,10), except for the cost that have to be a number (5).

The attributes related to the works, dates, and field "made" were not inserted through the TextBox. The latter, in fact, is a Boolean and has been managed via CheckBox (7). For the dates, a DatePicker (8) was used, while ComboBox and ListBox (4) were used to handle many-to-many relationships between Works and *ConservationInterventions*.

As far as the code is concerned, code writing has been almost limited to uploading data collections (Works), changing the data context in section B whenever the selected

Figure 129. Conservation Intervention form interface.

The screenshot shows the 'BIM del Duomo di Parma - Informazioni dell'elemento' window. The main form is titled 'ANALISI DEGLI INTERVENTI'. On the left, there is a 'Seleziona l'intervento' section with a 'Filtra per data' range slider (1) and a list of interventions (2). The main form contains the following fields and controls:

- Intervento:** Text box (2) containing 'Indagini diagnostiche'.
- Descrizione:** Text box (3) containing 'Esecuzione di indagini diagnostiche e definizione del progetto esecutivo sia delle opere di restauro del paramento lapideo e laterizio dei fronti esterni. Per quanto riguarda la definizione delle metodiche e la tipologia delle opere di restauro da adottare nel recupero del paramento lapideo esterno e laterizio del fronte nord dell'edificio, appare prioritaria l'esecuzione di alcune'.
- Opere:** List box (4) containing 'Rilievo fotogrammetrico', 'Mappatura litologia', and 'Mappatura degrado'. A dropdown menu 'Mappatura degrado' is also present.
- Costo [Euro]:** Text box (5) containing '2000'.
- Esecutore:** Text box (6) containing 'FOART e Archè Restauri'.
- Realizzato:** Checked checkbox (7).
- Data inizio:** Date picker (8) set to '01/04/2013'.
- Data fine:** Date picker (8) set to '01/06/2013'.
- Note:** Text box (9) containing 'Indagini diagnostiche 01/1 01'.
- Fonte:** Text box (10) containing 'Relazione di Restauro Archè Restauri'.

On the right side, there is a 'Files associati' section with a file list (3) containing 'Prospetto SUD zona presbiterio', 'AbS\_nicchia3\_ghiera arco', and 'Prospetto SUD zona presbiterio'. Below the list is a thumbnail image of a building facade (3). At the bottom right, there are 'Applica' and 'Ok' buttons.

intervention in section A changes and to handle the “Add” and “Remove” buttons functions. In addition, the time management function was added. Each intervention is associated with the corresponding date and it is possible to filter the interventions by date through the sidebar in the interface.

### 6.3.2.5. Survey and model metadata forms

This interface is related to the insertion of all survey and model metadata. The final accuracy of the BIM model is affected by both the accuracy of the surveyed data and the accuracy of the modelling activities. Thus, in order to certify and validate the quality of the BIM model, both survey and modelling phases must be certified.

Right now, the general adopted reference relates the tolerance with the representation scale. Through this interface the user can insert all data about the modelling and survey phases, as shown in paragraph 6.1.3 and summarized in Figure 130.

As far as the modelling is concerned the entered data are (Figure 131):

- **Modelling Techniques** (1), such as, direct modelling, generative modelling, parametric modelling etc.
- **Modelling Tools** (2), which refers to the software used for modelling operations
- Author (3) of the model
- **Insertion date** (4), useful in order to update the model in case of changes and make diachronic analyses.
- **Level of Accuracy** (7) obtained comparing the model with the surveyed point cloud
- **Level of Knowledge** (8) calculated on the basis of the Table 34 (paragraph 6.1.3)
- **Maximum scale of representation** (5), which is set on the basis of accuracy of survey data and of the level of detail (GRADE), implemented during the modelling phase
- Eventual **Notes** (6) about the model.

For levels of knowledge (LK) and accuracy (LOA), a legend is given below each combo box with the description of the specific values for each level (7) (8).

Survey metadata relative to a modelled object are entered with the form shown in Figure 132. On the left side of the interface, the list of the all surveys associated to the Revit Model is provided (3). Once the user selects from this list, the chosen survey (2), is associated to the BIM element and appears in the upper ListView (1).

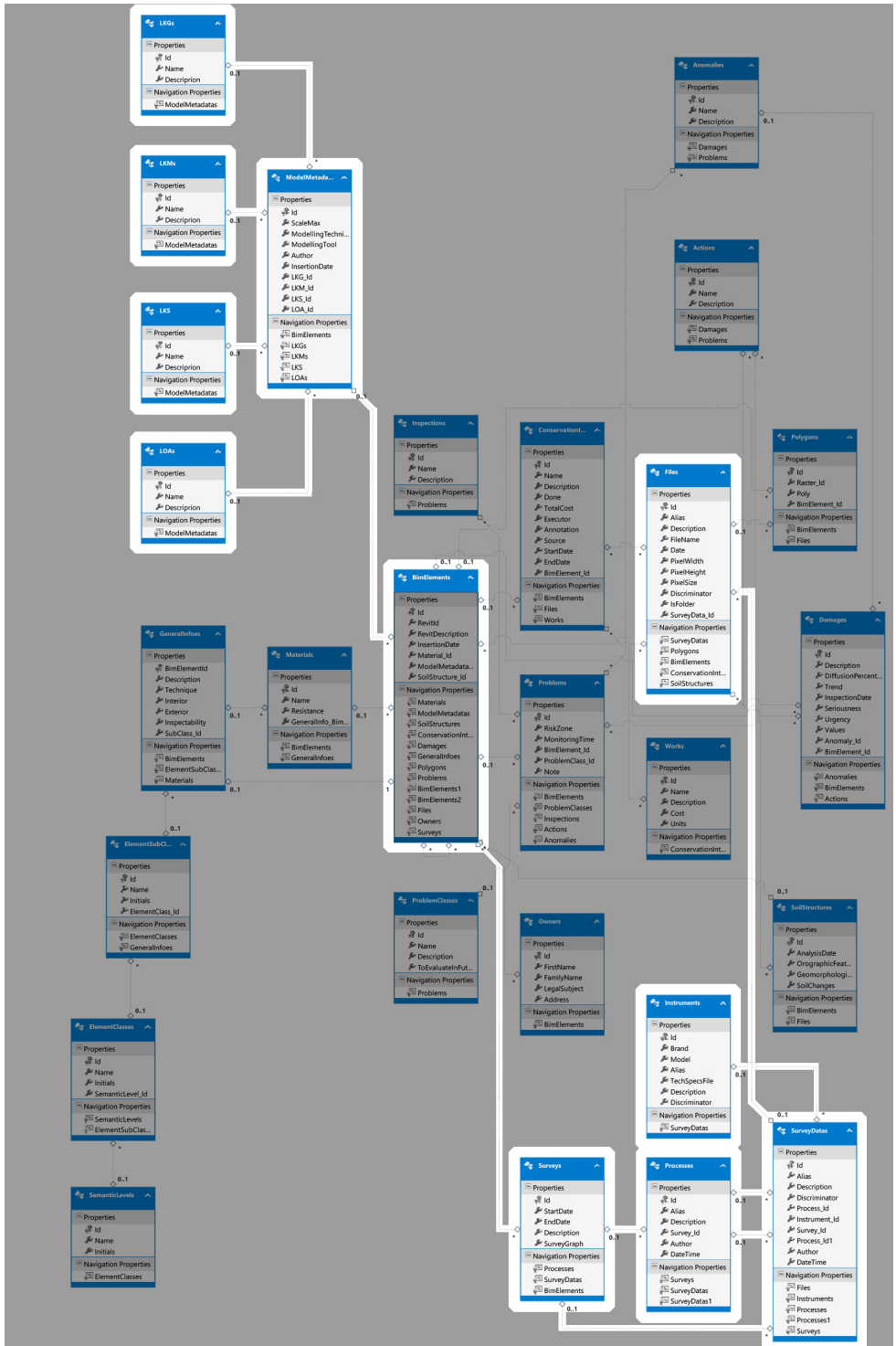
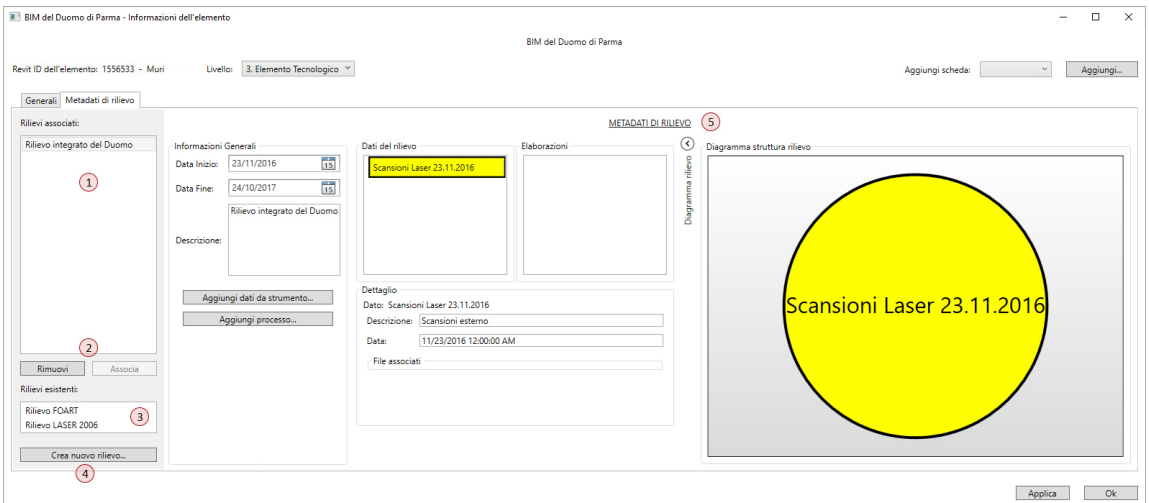
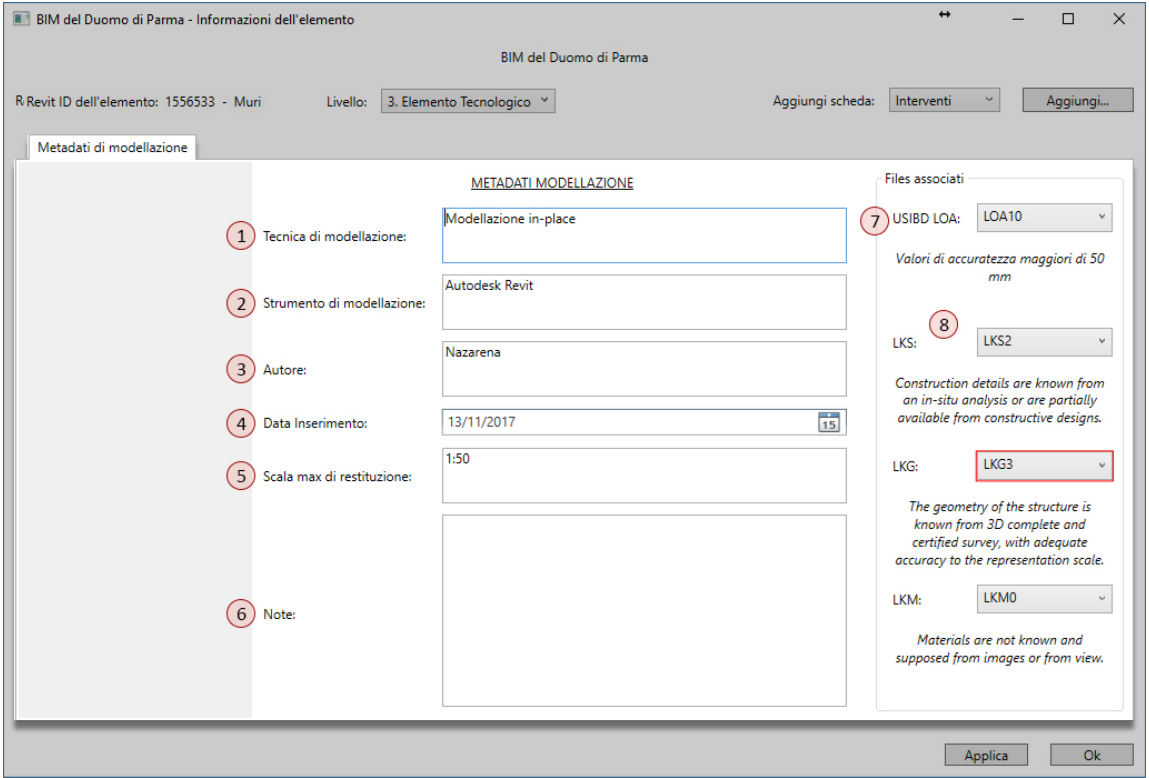


Figure 130. Database graphical model. The table to which Metadata refers are highlighted.



Each of these surveys has proper parameters associated, which can be visualized and edited in the right part of the interface. In fact, by clicking on the survey name in the ListView (1), its specific data are shown in the right part of the GUI (5). Here general

Figure 131. Model Metadata Form. (In the previous page).

information about the survey and specific data such as raw data, outputs and processing actions are reported, as visible in Figure 132.

In this regard, a clarification should be made: since survey is a general entity that does not refer only to a single element of the model, but, rather, it can be associated with the whole model of the building, it is possible to access the interface of the survey metadata both from the dialogue window containing the information of the single element (Figure 132), and through the "Survey" function of the Ribbon Panel, as will be shown in paragraph 6.3.5.

Therefore, since the survey should be considered as an attribute of the general model, please refer to the following paragraph (§ 6.3.5) for a description of the interface.

### 6.3.3. Queries and thematic visualization

In addition to the data entry function, in a database the query function is very important too. Directly querying a relational database implies the writing of queries (usually through SQL syntax) with different degrees of complexity, depending on analysis to perform. However, this way of interacting with the database is not easy to use and therefore does not fit the usability required by non IT specialists.

Thus, to match the user's needs, there were two different options:

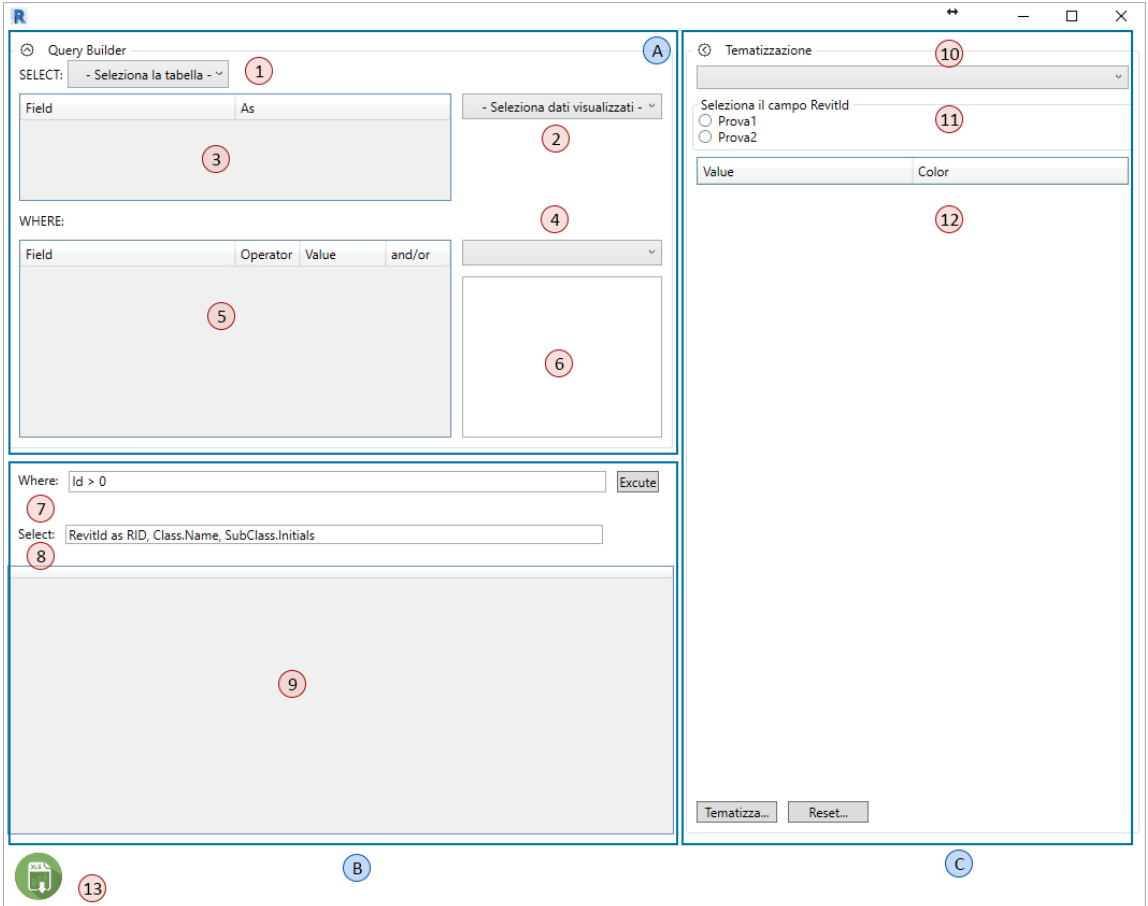
- Create pre-compiled queries or visibility filtering
- Create a graphic query builder, more difficult to use but definitely more versatile to respond to user requests.

After some thoughts, the second hypothesis was preferred since:

- It is impossible to define a priori all possible queries on a database
- This thesis has a mainly methodological approach, so, in this research context, limiting the capability to query the database would be a primary drawback,
- it was more interesting to elaborate a tool that gives the user the capability to work autonomously, rather than to think of possible queries, that should be better defined by restoration specialists.

For these reasons, a graphical interface (Figure 133) was implemented that allows querying the database both through text queries and a query builder, theming the Revit 3d model according to the attributes stored in the database and exporting the search results in Excel.

Figure 132. Survey metadata form. (In the previous page).



### The query function

The user can write the query directly by filling the “Select” (number 8 in Figure 133) and “Where” (7) text fields and display the result in a table at the bottom of the interface (9). To simplify query writing, the graphical query builder (A) has been developed. It is contained in a GroupBox that can be shown or hidden if needed.

The query can be done in few steps as explained below:

#### 1. Elements to query selection

The first step is the selection of the element to query among the entire database (Figure 134). The combo box at the top of the interface (1) lists all the database tables and the user can select the table to query from this list. Selecting the table to query, in the combo box (2) the list of the selectable fields appears. The user can thus select from

Figure 133. Query and theme interface.

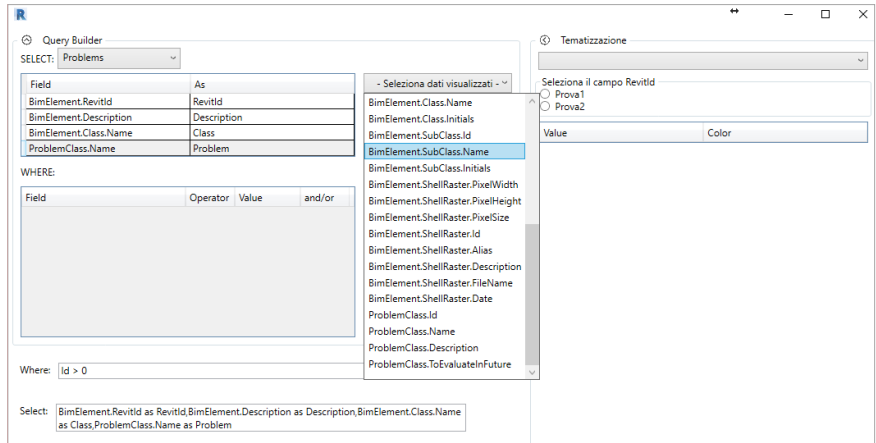


Figure 134. The use of query builder for selecting the elements to query.

the combo box several fields, which will appear in the left column of the DataGrid (3). The right column instead is an editable field in which the user can specify the field name to visualize in the answer (for example BimElement.Description as Description).

2. Definition of the query conditions (WHERE) (Figure 135)

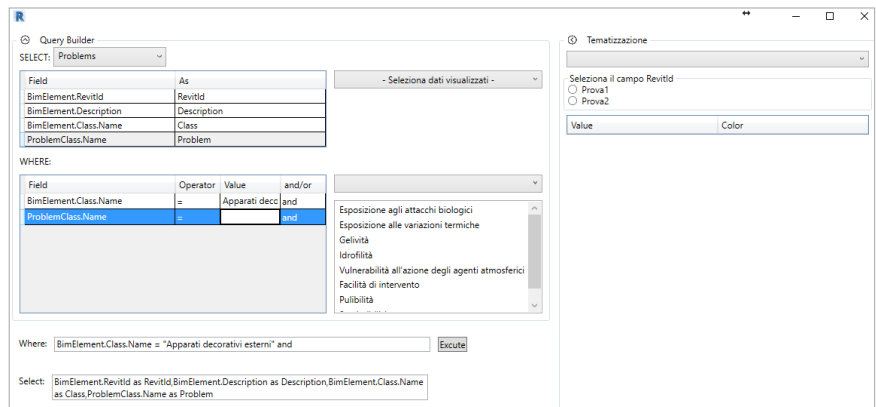


Figure 135. The use of query builder for defining the conditions of the query.

The next step is to define the conditions of the query. By default, the `Id > 0` condition is entered, so that the query will list all the items available, but the user can customize this field using the user controls at the bottom of section A. Specifically, the user can select the various fields to use as a query condition. The ComboBox indicated by the number (4) in Figure 133 will be populated automatically with the list of selectable fields depending on the choices made in the first step. The ComboBox will show, in fact, both the field of the table to query and fields of tables related to it.

The selected fields will be listed in the DataGrid indicated by the number (5). As shown in Figure 135, the DataGrid has 4 columns: field name, relational operator (<, >, =, <=,

>=, !=), condition value and logical operator (and, or, not). The operators are selectable via drop down menu, while the values can be typed directly by the user or, if they can be enumerated, they can be selected by a double click from the ListView indicated with number (6).

### 3. Execution of the query.

Pressing “Execute” the query result appears in the DataGrid (9) at the bottom of the interface. This DataGrid is dynamic: the number of rows and columns, and the displayed values change according to the query.

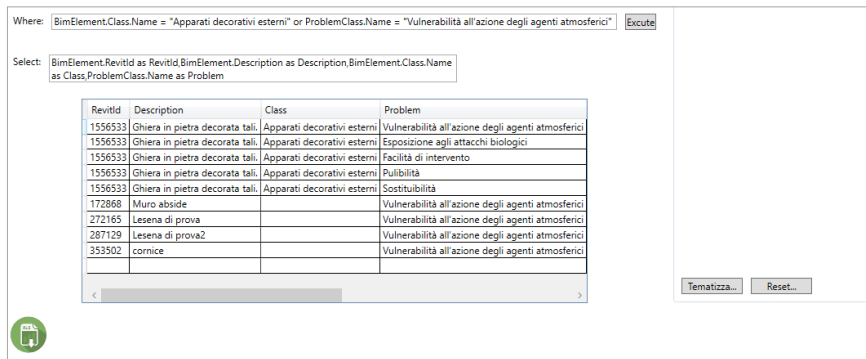


Figure 136. The answer to the query in the DataGrid.

### The theme function

A second GroupBox of the interface (indicated by C), handles the theme of the 3D model in Revit, according to one of the fields selected in the query. A ComboBox (10) lets the user select the field to be themed (for instance “Problem”, as in Figure 137).

To allow Revit to change element colours appropriately based on their DB attribute, the user has to indicate which of the fields that appear in the query is the RevitId (11). The RevitId is, in fact, the key to link the database data to the Revit 3d model elements.

On the basis of these two user inputs (field to be themed and RevitId), all the possible values are parsed in the DataGrid indicated as (12). To each value, a colour is associated, which the user can customize.

Clicking the “Theme” button, the user can see the 3D model coloured according to this colour range and surf the model (Figure 137).

From a technical point of view, the code sends an input to Revit for overriding the graphic settings. The theming acts only on the visibility/graphic settings, specifying for each element (according to its id) what colour should be displayed. When the theming dialog window is closed or reset, the override is deleted.

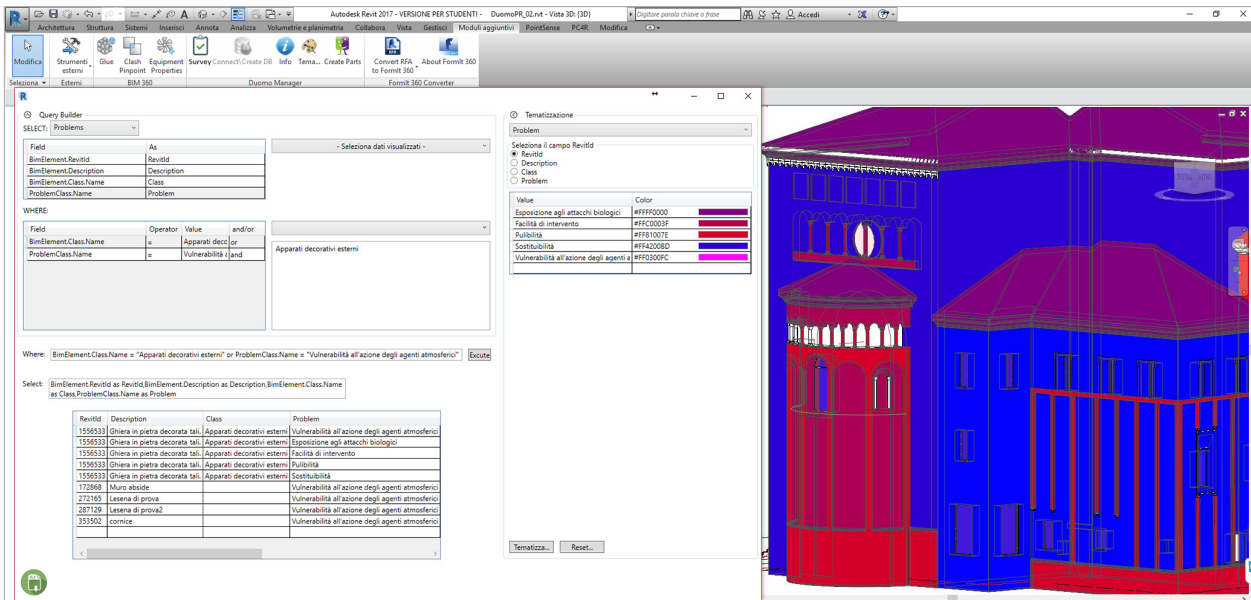


Figure 137. Theme interface and an example of model thematic mapping.

### The export to Excel function

A further feature implemented for this interface is the ability to export the query results to an Excel file in a simple and easy way. Clicking the “Export to Excel” button (13) the system allows exporting a comma-separated text file and then to format it into an Excel table.

Exporting data in traditional formats, such as CAD, .xls, .pdf, is useful for the dialogue among all professionals, even the ones who are used to working with the traditional method rather than with the BIM software. In this way, a tool like the one developed in this thesis becomes usable on a larger scale.

Analysing the literature, many authors talk about interoperability (paragraph 1.6), understood as horizontal interoperability, i.e. data exchange between BIM software, or between BIM software and modelling or analysis tools. This is still a current and ongoing research field, given all the issues related to the preservation of the integrity of the data. However, it is of particular interest, especially in the field of cultural assets, to speak also of vertical interoperability, i.e. the interchange of data with the, so-called, traditional software. In fact, the user community and administrations are accustomed to work with and still require such formats.

### 6.3.4. 3D mapping starting from 2D orthophotos

As highlighted into paragraph 5.6, surface mapping is an important requirement for each restoration work. It is a specific document required by Superintendence in order to approve restoration projects.

To this aim a function for the Revit plug-in to associate each element in the 3D model with the corresponding orthophoto has been implemented. The orthophoto is displayed in a dialog box and here, thanks to the special tools implemented, the user can make mappings by drawing two-dimensional polygons directly on the orthophoto. At each polygon can be associated semantic data, working as in a GIS environment. In addition, every orthophoto is spatially related to the element to which it is attached. In this way, the wall is automatically divided into parts corresponding to the 2D polygons drawn on the orthophoto. This also allows the user to get mappings on the 3D model.

The technical analysis of the code structure and its interaction with the user will be described below with reference to the workflow shown in Figure 139. However, before proceeding with the description of the code, it is necessary to open a parenthesis to describe the Revit "Create parts" and "Divide parts" tools, which represent the functions used to programmatically create 3D elements.

"Create Parts" tool allows dividing an element into parts (slices corresponding to element's layers or components) and "Divide Parts" function subdivide each of these slices into smaller parts, either by drawing division lines or by selecting reference elements that intersect the part [30] (Figure 138).

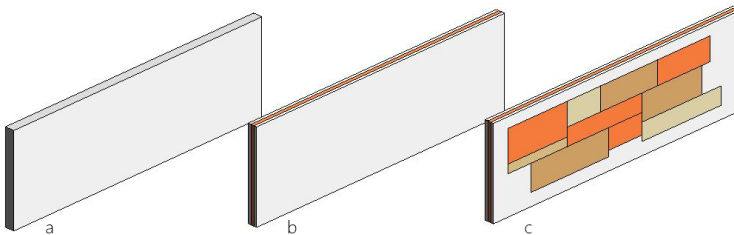


Figure 138. "Create Parts" and "Divide Parts" Revit tools example. a. Original wall, b. Wall divided into parts after "create Parts" command, c. Wall with a part divided into sub parts after "Divide Parts" command.

The "Divide Parts" command, which in the implemented system is used to create individual ashlars, therefore needs:

- a starting wall
- a stratigraphy
- a sketch plane on which drawing the lines that will cut the wall

- a closed polygon, drawn on this plane, which will be used as a cutting element.

Coming back to the implemented code and workflow, to apply the command, the user has to select the element to which associate the orthophoto. This element has to be a wall or a part (if the wall the parts belongs to has been already parted). As shown below (Figure 139), if the selected item is a wall, the system, calling the Revit tool "Create Parts", makes a first layer subdivision (internal, external and centre) to allow different mapping of internal and external shells. The user is then required to select the side to which refer the orthophoto.

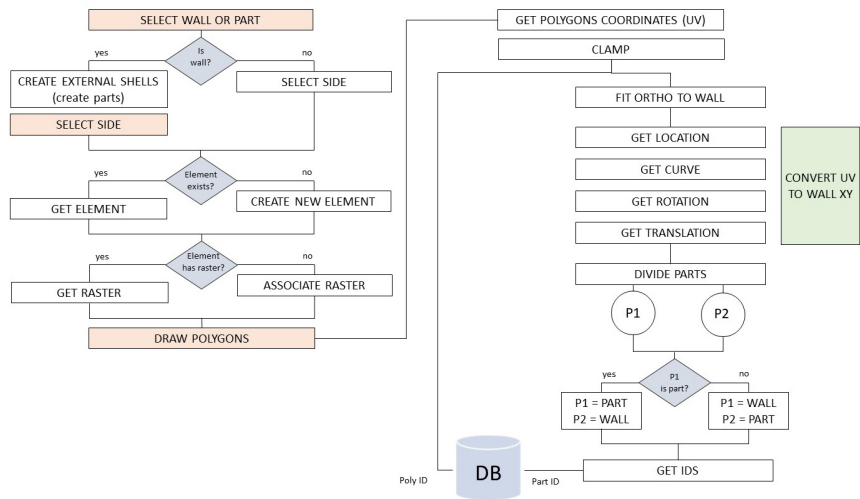


Figure 139. "Create parts" function workflow. Orange text boxes refer to the actions performed by the user.

The system checks if an orthophoto has been already associated with the element. If not, the user can browse to associate a new orthophoto.

After that, a floating window will appear showing the orthophoto and the user, using the implemented tools, is able to draw 2D polygons on the orthophoto. These polygons are stored in the database in the *Polygons* table as a sequence of vertices of known coordinates. These coordinates are referred to the orthophoto reference system (RS) and are so image coordinates. The RS is defined with the origin in the upper left corner of the image, the horizontal x-axis from left to right, and the vertical y-axis from top to bottom (Figure 139).

Each polygon is related to the 3D element (BimElement) to which it belongs and with the raster image (orthophoto) on which it was drawn. For each polygon, it is possible to indicate a material, one or more anomalies and one or more interventions.

Starting from these polygons it is possible to obtain the 3D mappings. In order to create 3D ashlar corresponding to the polygons, it is necessary to draw the polygons on a sketch plane parallel to the wall and use them as division lines.

The first step is to fit the orthophoto to the wall. A wall in Revit is defined by the Location Curve (a curve that describes the planimetric development of the wall) and by a parameter that defines the height. Knowing the size of the wall (length of the Location Curves and height parameter) and of the orthophoto (number of

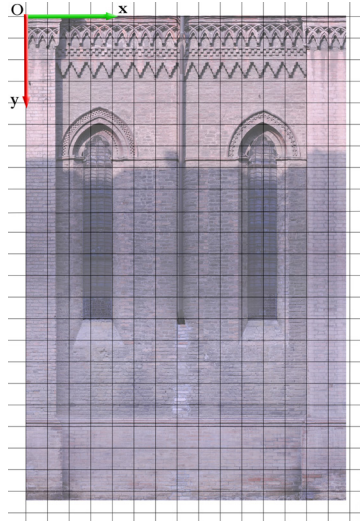


Figure 140. Image Reference System.

pixels \* resolution), it is possible to scale the orthophoto so that it matches perfectly with the wall. This operation is acceptable if the discrepancies between wall and orthophoto sizes is lower than the admissible error according to the representation scale. In this case, the representation scale is 1:50 and then the tolerance allowed is 2 cm.

Since the orthophoto and the model are both extract from survey data and have an accuracy appropriate to the representation scale, there should be no need of scaling and the two data should coincide. However, it is well known that modelling is a degrading process of data quality. A 3D model has always a lower accuracy than the surveyed data. In the modelling phase, it is necessary to approximate some deformations or irregularities, mainly because of the limitations that the modelling tools still impose, especially the parametric ones (see paragraph 5.4). Therefore, when the difference between the wall and the orthophoto is greater than the tolerance allowed, a message box appears and asks the user whether proceed with the orthophoto scaling, specifying its position w.r.t. the wall, or not execute the command, allowing the user to remodel the wall.

The second step is then to align the RS of the orthophoto to RS of the wall, converting the uv coordinates of the image into the XY coordinates of the wall. The starting points are the orthophoto RS and the Location Curve that determines the position of a wall in space. The implemented code gets the location of the wall and the curve (in this case a line) by the coordinates of its start and end points. Then, the perpendicular vector to the curve is extracted and, by this vector and the Location Curve, the sketch plane is defined. The orthophoto plane, thus all the polygons that are drawn on that plane, must

be roto-translated to coincide with the new sketch plane. In particular, a rotation of 90 degrees around the x-axis is imposed, to make the plane coincident with a XZ plane. Another rotation makes the plane of the orthophoto tangent to the wall face and a translation equal to the origin coordinates of the Location Curve makes, finally, the two planes corresponding.

The third step is the creation of the parts. Having aligned the two reference systems, polygons can be used as division lines. Creating a new part, the original wall is no longer a wall but becomes a part and its RevitId changes. So it is necessary to recognize which of the two parts that have been created is the ashlar and which is the original wall. To this aim, the code compares their geometric width: the longer is the parent wall, the shorter is the new part. Therefore, the system gets the two RevitIds and update the database. The parent wall RevitId is changed, while the part is entered as a new item. Parts are entered as new elements in the *BimElements* table, and are linked to their generative polygon and their attributes. In addition, each part is related to the parent wall from which it was generated and to which it belongs. Parts are detail elements of the model and according to the display filters, the user can choose whether to interrogate the entire wall or the individual ashlars.

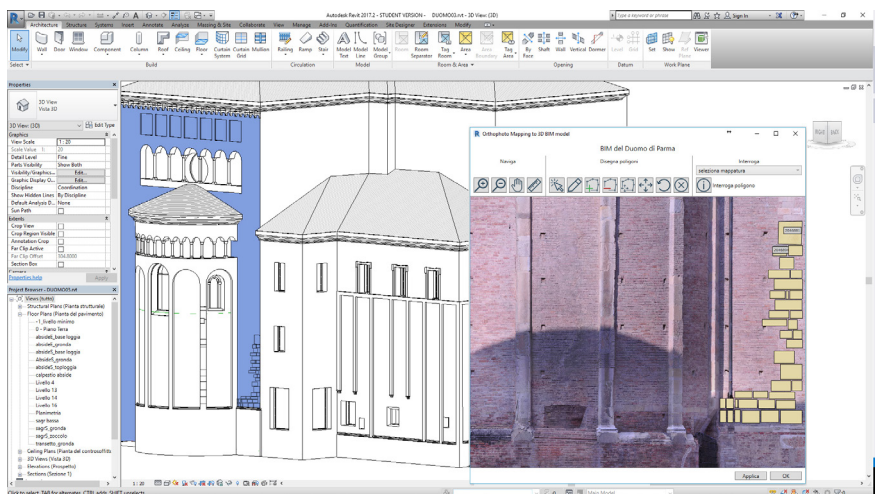


Figure 141. Example of 3D mapping created.

The function of the 3D mapping through 3D modelling of the parts has been implemented so far only for vertical walls based on a line segment. Extending such function to cylindrical walls, only the part of the code concerning the conversion of the uv image coordinates in the XY coordinates of the wall has to be modified. The other nodes of the workflow remain valid at any time.

Specifically, two main issues will have to be addressed:

- an information technology problem related to how to programmatically design the parts on Revit on curve areas
- a photogrammetric problem linked to the realization of the orthophoto. The orthophoto is in fact an orthogonal projection; working with cylinders a cylindrical projection might be preferable.

### 6.3.5. Survey metadata entry

The thesis offers a contribution to the validation of the BIM model by prototyping a tool that allows inserting all the metadata and data related to the survey. To each modelled element it is possible to associate the survey outputs on the basis of which it has been modelled and trace backwards the survey chain, up to the initial raw data, to certify the correctness and quality of the operations carried out.

The user accesses the interface via the “Survey” function in the Revit Ribbon Panel.

In particular, it is possible to associate one or more surveys with the BIM project. As explained in § 6.1.3, the survey is assumed as the sum of *Data* and *Processes*. The data may be either the raw data surveyed or the data provided as output by the processes performed. Processes are instead data elaborations, which therefore have associated input and output data.

In order to enter the survey information, the user can first fill in section A of the interface, inserting general information such as the start and end dates (1) and a general description (2). User can then add data and processes using the “Add survey data” and “Add process” buttons (3).

Figure 142. Survey metadata entry implemented interface.



Figure 143. Add survey data interface.

Clicking on the “Add survey data” button, another interface opens (Figure 143). Here the user enters the relative data: the name of the data (1), the date (3), a general description (2) and the authors (4).

In addition, it is possible to insert data about the instrument adopted (5) and link external references to files and folders so that it is possible to have direct access to this information and, if necessary, validate the data (7).

Figure 144. Add instrument interface.

The instrument can be selected from a list of available instruments (5), or added creating a new record in the database (6). A dialog opens to let the user enter data about the instrument (Figure 144). In that interface, the user can insert instrument name, brand, model, description and link the technical description provided by the vendor.

Process information can also be entered in the same way. An interface (Figure 145) is opened by clicking the button “Add process” and, in this case, the user must enter the process name (1), date (3), description (2), author (4) and related input data (4) and output data (7). The input data are selected from the list of already entered data (6) while the output data are entered as additional data. By clicking the “Add data” button (8) the interface shown in Figure 143 is recalled with the

Figure 145. Add process interface.

difference that the "Instrument" field is not enabled, since those data are not acquired by instrument but produced by a process of elaboration.

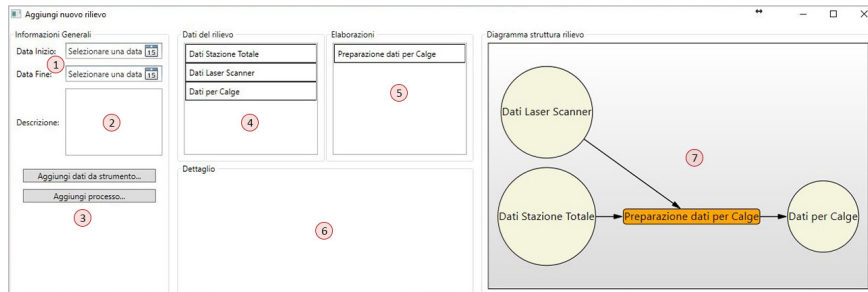


Figure 146. Data entered into the interface.

In this sense, guidelines could be implemented that specify which information to include in relation to a survey so as to document correctly all the steps and provide the metadata necessary for its accurate validation.

Once inserted, the processes and data are listed in the respective boxes marked in the image with the numbers (4) and (5) and are graphically represented in section (7) of the interface as shown in Figure 146. Graphical visualization helps to trace the chain of processes carried out in the presence of complex elaborations for which, from the simple list of processes and data, it would not be possible to understand the general organization.

By clicking either on the list of data/processes or on the corresponding graphical representation, the user can see in the box (6) all the associated information and any external files loaded (Figure 147). In addition, by double-clicking on a node of the graphic representation (date or process) all the other nodes connected to it will be highlighted in order to trace more easily the chain of processes carried out and allow an immediate understanding (Figure 147).

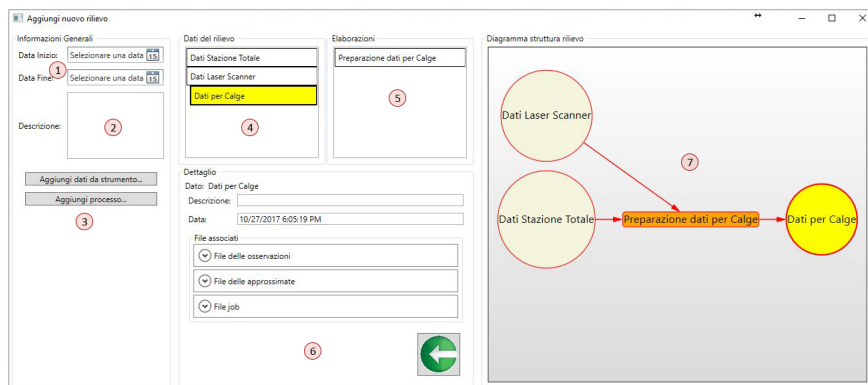


Figure 147. The Figure shows the information associated to the selected item (in this case the Process "Dati per Calge" and the highlighted nodes connected to it.

## 6.4. Data sharing and application usability

---

As seen in chapter 2, the web is getting more and more attention in the field of cultural heritage. The web allows, on the one hand, overcoming some interoperability restrictions between commercial software and, on the other hand, providing an easy and unique point of access to data.

In fact, for access the data it is sufficient to have a web browser and connect to the web server containing the data. In addition, users need not to use any specific commercial software, avoiding personnel training and licensing, which can limit the actual use of the system.

In addition, the visualization of the model directly on the web allows the portability of the project. Only with the help of an internet connection, the user can view the model anywhere, on a PC, tablet or smartphone. This can be very useful for on-site maintenance operations where the worker can view the model directly on the tablet and enter data directly, reducing working time and transcription errors.

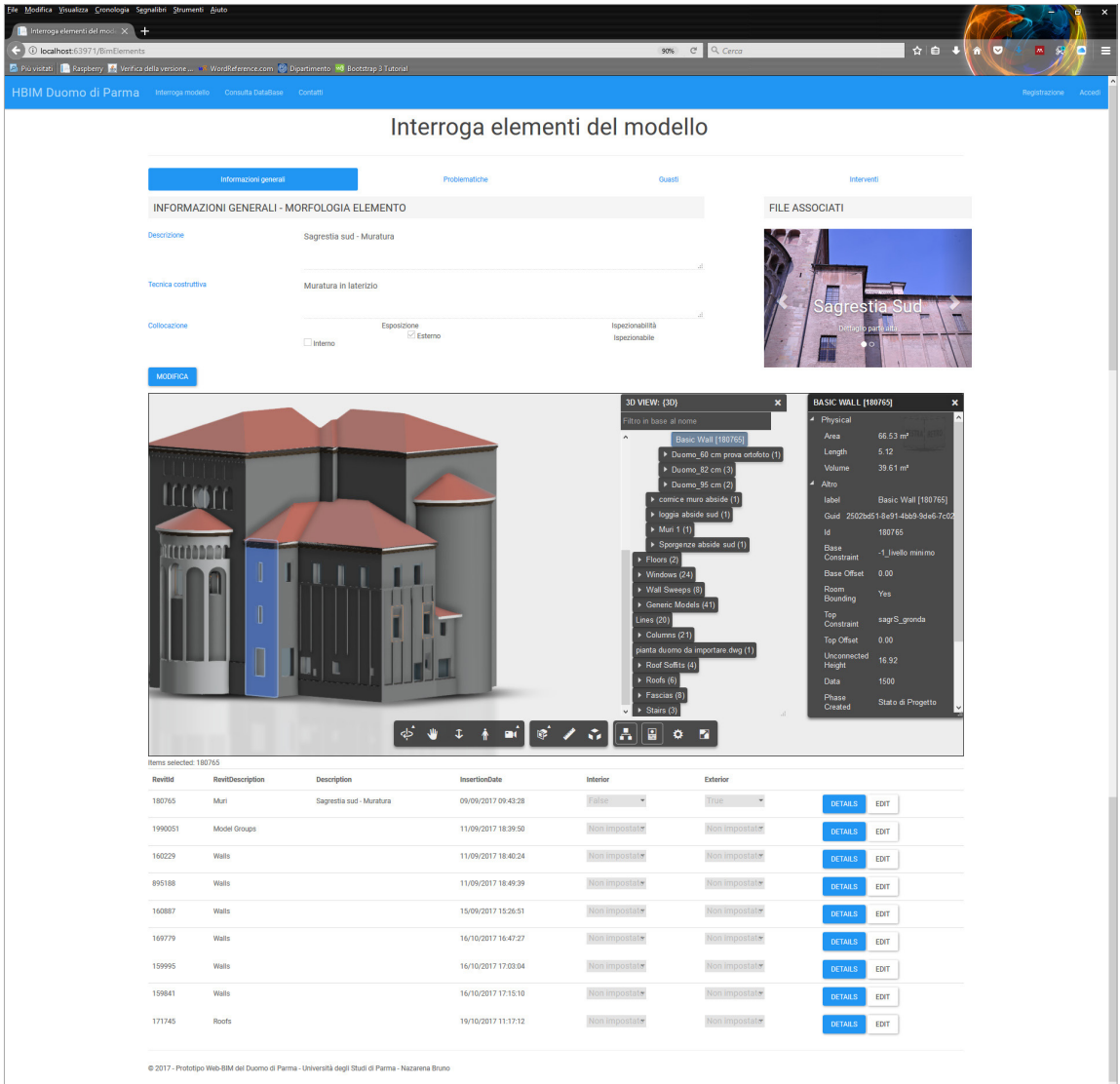
For these reasons, the following paragraphs show the first results of an experimentation carried out in order to display the BIM of Parma Cathedral via web.

### 6.4.1. Web application characteristics and functionalities

In order to allow a wider sharing of the developed application, its use via web has also been implemented. With Autodesk 3d Forge viewer [29], it is possible to upload and view the Revit model and its parameters directly via the web. The Viewer supports a wide variety of 2D and 3D model file formats and natively communicates with the Derivatives Model API to retrieve model data, respecting its authorization and security requirements.

The Viewer implements graphic UI for 3D navigation that makes possible to easily handle the model: a tool bar with the main 3D viewing function and the ViewCube, a tool that helps orienting the camera view on the model, are provided.

In addition, Forge allows accessing Revit model parameters and visualizing them by clicking on the 3D elements in the model, as it can be seen in Figure 148.



In the Figure, the central part of the web interface is constituted by the 3D model viewer and is provided directly by Forge. Figure 148. Implemented web interface.

On the contrary, the other parts of the web page have been expressly implemented. In particular, it has been organized by replicating the scheme developed for the graphical interfaces implemented for the desktop application and accessible through Revit. The upper part is occupied by tabs that give access to information organized in sheets. The user can view them by clicking on the model element. The information is organized as in the desktop interfaces and for this reason it will not

be described here, referring to the in-depth analysis made in the paragraph 6.3.2. In addition, the data displayed are the same. In fact, the Asp. NET libraries (see paragraph 6.2.2) make possible to connect the database and access the data directly online. The user can then retrieve data, edit and insert them, operating directly on the database.

In this way, being the database shared between all the applications (desktop, web and mobile), all data are consistent and it is possible to access the information about the model everywhere and from any device.

Different levels of users (visitor, developer, fabricator, restorer) have been considered, everyone with different limits and privileges in terms of data access and editing. The user, after an authentication procedure, can visit sections and edit information, according to his role.

## 6.4.2. Mobile application implementation

Two different targets of mobile application have been implemented to meet different user needs. On the one hand, there are the stakeholders involved in the conservation of the cathedral and, on the other hand, the citizens, interested in discovering Parma Cathedral.

For the former, the main requirement is to have as complete as possible access to all data and to be able to navigate the model also on site, as it is handy in inspection or maintenance operations: the database and the model can be accessed directly and updated in real time, reducing time and errors. In addition, the extreme portability of a device such as a smartphone or tablet allows access to all the data available for the building in a very simple way.

In order to meet this need, the implemented web site (described in the previous paragraph) has been created with a responsive layout, in order to be viewed on smartphones and tablets. The software used for the web site implementation provides this possibility, without the need of writing additional code. In this way, from mobile devices, it is possible to access the web page described in the previous paragraph and view the 3D model of the Cathedral and the implemented descriptive sheets.

The second type of application, has instead been developed for knowledge dissemination. In the Cultural Heritage context, dissemination and promotion are indeed very important for the assets enhancement and safeguarding. The asset knowledge should be available to the entire population and not just to the people responsible for its preservation. In

the recent years, projects aiming at this purpose are increasing and, in particular, as seen in chapter 2, BIM model integrations with applications for smartphones or tablets are becoming more and more widespread, coming to the realization of mobile applications that involve the use of Augmented and Virtual Reality environments based on 3D BIM models.

In this context, mainly for dissemination purposes, the BIM model of the Parma Cathedral has been integrated with a mobile application (*AMA 3D – Arte Museo Archeologia*) [12] previously developed during the project “*Innovative multimedia itineraries for the valuation of the Archaeological Museum of Parma*” [100], that will be described in the bracket in the next page.

The Parma Cathedral has been inserted in the virtual tour described in the next page, inserting descriptive textual data and historical images.

Additional sections of the app relating to the Cathedral have also been created.

The first section presents an interactive plan of the Cathedral. It is possible to click on the various areas identified (central nave, side aisles, dome, side chapels etc.) and see the relative panoramic image, which can also be displayed in Virtual Reality. In addition, for each functional area, a descriptive tab containing the relative data stored in the BIM database has been inserted and can be viewed by the user.

The second section, entitled “*La Cattedrale si racconta*” (The cathedral illustrate itself), allows to theme a AR 3D model on the basis of the restoration work carried out and to see a brief description of the intervention. In this way, the community is made aware of the interventions that are periodically carried out to preserve the cathedral.

Finally, the mesh detailed models created during the modelling phase of the decorative elements were loaded into the app and made viewable with the tool prepared for the archaeological museum exhibits.



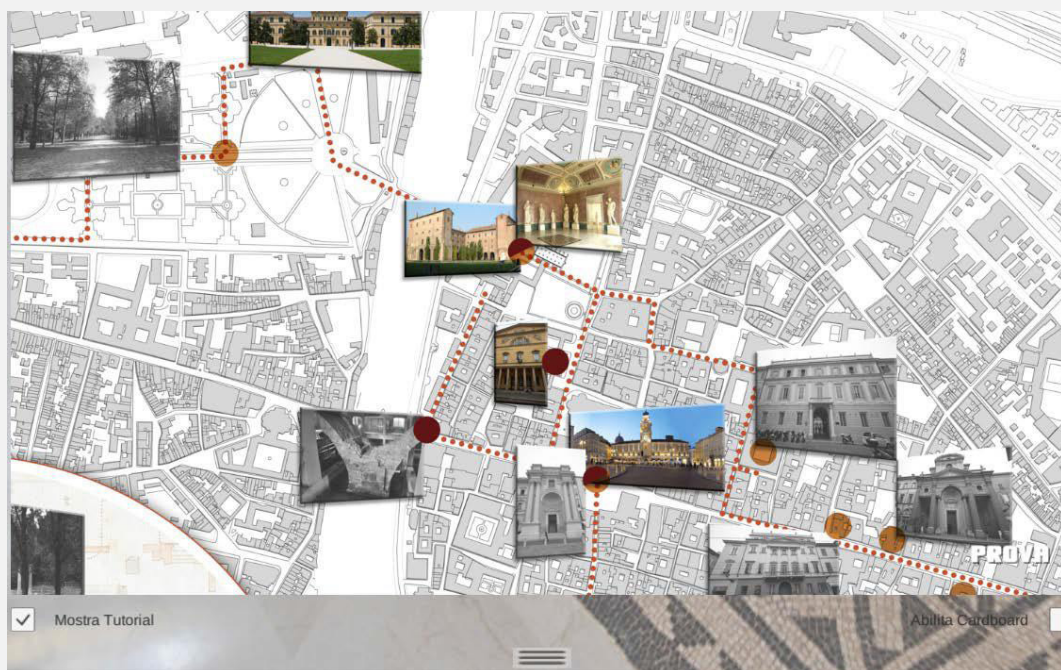


Figure 150. Interactive map for the virtual tour of Parma.

In addition, in order to create a connection between the Archaeological Museum and other sites of interest in the city of Parma, the app presents a section dedicated to the virtual tour of Parma. An interactive map of the city highlights the various cultural heritage and connects them in a virtual itinerary.

The points of interest are related to two itineraries: Ancient Rome Parma and Parma eighteenth-century. The former, identified since the Museum houses exhibits dating back to Roman times, connects the Museum with the remains of the ancient Roman age. The latter, identified as the Museum was founded in the mid-eighteenth century, links the Museum with the main palaces of XVIII century.

Each point of interest is visible on an interactive map within the app and associated with it are descriptive/informative data that allow the use of the App in two ways:



- Visits on site: the inclusion of textual descriptions and images of places of interest are a guide for tourists wishing to visit Parma along these thematic itineraries.
- Virtual visit: 360° panoramic views of the places of interest have been created so that they can be visited virtually as well, both in standard display mode on the device and in virtual reality through viewers such as Google Cardboards.

The creation of navigable 3D digital contents has been realized in the UNITY development environment [296]. UNITY is a cross-platform game engine, which is primarily used to develop video games and simulations for computers, consoles and mobile devices. It supports 2D and 3D graphics, scripting through C# and built-in system which allows creating user interfaces fast and intuitively.

However, one of the main feature that makes UNITY very performant tool is its multiplatform support. More than 25 platforms are supported (Android, IOS, Windows, Xbox One, Play Station and so on) across mobile, desktop, console, TV, VR, AR and the Web. In this way, it is possible to build the application once and deploy it to different platform.

The present application has been implemented for Android systems, but could be easily deployed for IOS or Windows Phone.

As far as the augmented reality is concerned, Vuforia platform has been used. It is an Augmented Reality Software Development Kit (SDK) for mobile devices that enables the creation of Augmented Reality applications. It tracks in real-time planar images (that operates as targets) and simple 3D objects, such as boxes, using Computer Vision technology. In this way, it is possible to position and orient virtual objects (in this case the 3D models of the archaeological exhibits) in relation to real-world images when they are displayed through the camera of a mobile device. The position and the orientation of the target image are tracked in real time: in this way, the perspective on the virtual object and on the target is the same and the observer has the impression that the virtual object belongs to the scene of the real world.

Vuforia can be used in UNITY, making possible to work in the same development environment.

Figure 151. Panoramic view examples.





---

# Conclusions

In this work, the implementation of a BIM system aimed at maintenance, conservation and restoration of Cultural Heritage was presented. Its main goal was to give a concrete answer to the lack of specific tools required by Cultural Heritage documentation: organized and coordinated storage and management of historical data, easy analysis and query, time management, 3D modelling of irregular shapes, flexibility, user-friendliness, etc.

In the author's opinion, BIM methodology, providing an information system at architectural scale and making it possible to manage semantically enriched three-dimensional models, represents an effective solution, on condition that suited tools and functions are made available. On a general level, for instance, technological implementations must be developed to model more easily complex elements, to automate operations, to improve data sharing and interoperability and to provide easy-to-use tools (also for non-BIM-specialists) for data enquiry and analysis.

The application developed in this thesis started from a BIM system and enriched it with functions to address these goals. In particular, a specifically designed database was implemented, where all data about the historical building can be stored. A tailored database is necessary to organize historical data that generally are not standardized, have a complex structure and are fuzzy in their description. The database is compliant to the currently in-force Italian regulations and allows storing and retrieving information useful for maintenance purposes.

The application was implemented with the specific aim of providing tools also for non-AEC experts: it gives user-friendly graphical interfaces to access the data and makes

available tools for data entry, element modelling, attribute query and thematic mapping. It works standalone or can be integrated into the main commercial BIM software (at the moment the experimentation has been limited to Revit) or accessed via web. One of the main goals was not to be bounded to a specific software and to make the system usable on a larger scale, by developing a flexible and customizable methodology that can be applied to a wide range of historical assets.

To address all these topics, the experience typical of geomatics in design and implementation of relational databases integrated into GIS software has been essential. In the HBIM the approach is comparable and only the scale of investigation changes, from the territorial to the architectural one.

In any BIM process applied to existing building, the validation of the model is fundamental: geometric and semantic data have to be reliable and accurate enough to fulfil specific requirements and their reliability and accuracy should be properly documented by BIM authors. The model accuracy is affected by both the survey accuracy and the modelling accuracy, so survey and modelling phases should be certified. The thesis offered a contribution on this topic, by proposing prototype tools that allow inserting survey metadata. The system allows each modelled element to be associated to the survey products used for its modelling and also to trace backwards all the survey chain processes (up to the raw data), in order to evaluate the correctness and quality of the operations carried out.

The BIM methodology requires an interdisciplinary and collaborative approach: surveying, modelling, historical analyses, database design, system usability, user-friendliness, etc. are all aspects to be addressed and refer to different disciplines and specific expertise. In the field of Cultural Heritage this matter is more relevant, since figures such as historians, art historians, restorers and professionals, external to the AEC industry, are involved.

This thesis, addressing BIM from a geomatics perspective, aimed on the one hand at giving a contribution especially to survey and database implementation, and, on the other hand, at interfacing with other disciplines actors, in order to collaborate and share objectives and strategies.

---

The relationships between Cultural Heritage and technological innovation are potentially quite fruitful. However, for new approaches to Cultural Heritage to gain acceptance will take time, also to find out, on a case-by-case analysis, what are true improvement from technical and economical aspects. The direction is the right one, but many questions are still open and common efforts are needed to create a general awareness about the importance of BIM methodology application in the Cultural Heritage field. Public and private investment in this area, education, proper regulations and shared objectives should be undertaken to spread the HBIM use.





# APPENDIX A

---

The use of BIM worldwide



## A.1. Scandinavian countries: Norway, Denmark, Sweden and Finland

---

The Scandinavian countries (Finland, Norway and Sweden) were the first countries in which public administrations promoted and mandated the use of BIM in public projects. The first national mandate was adopted by the Oslo government in 2005, while the Finnish and Danish governments made the use of the BIM mandatory from 2007 for all national public projects [183]. Conversely, in Sweden, despite the existence of guidelines and regulations, BIM projects have not been yet required.

The transition from CAD to BIM was determined by several factors including:

- National significant investments in innovative technologies, including advanced technologies, tools and services for buildings
- Importance of the BIM for building performances increase and energy costs reduction
- National interest in becoming a world leader in the construction industry, being able to export these skills to other countries.

Finnish and Norwegian policies are generally more prescriptive and have focused in particular on the development of the Industry Foundation Class (IFC), exchange format that enables collaboration between professionals, secure archiving and data transfer between software. Denmark, on the other hand, has not given a very strict definition of standards; it has specified general objectives for the use of BIM data but has delegated the individual sectors to determine the guidelines for their full implementation.

In general, Scandinavian countries have invested in university and professional training, education, dissemination of case studies, drafting of guidelines, manuals and recommendations, in order to create a culture in the use of BIM that goes beyond the legal obligation.

At present, national governments continue to support research in the BIM area, in order to use the BIM in an innovative way and throughout the building life cycle [183].

**Finland** is the most avant-garde country. The government company in charge of state-owned real estate management (Senate Properties) has set up pilot projects to test the use of new technologies since 2001, and has made the BIM use mandatory and compliant with IFC standards since 2007.

The current *Common BIM Requirements 2012 (COBIM)* guidelines have been drawn up

according to the results of one of these pilot projects, the ProIT (Product Model Data in the Construction Process) project [222].

The guidelines aim to coordinate all disciplines involved in modelling, by defining precise modelling procedures. The latest update, which revises the first publication of 2007 (Series 1-9) implementing it with the 10-13 Series, dates back to 2012 and is structured as follows [72].

- Series 1 – General part – v1.0 2012
- Series 2 – Modeling of the starting situation – v1.0 2012
- Series 3 – Architectural design – v1.0 2012
- Series 4 – MEP design – v1.0 2012
- Series 5 – Structural design – v1.0 2012
- Series 6 – Quality assurance – v1.0 2012
- Series 7 – Quantity take-off – v1.0 2012
- Series 8 – Use of models for visualization – v1.0 2012
- Series 9 – Use of models in MEP analyses – v1.0 2012
- Series 10 – Energy analysis – v1.0 2012
- Series 11 – Management of a BIM project – v1.0 2012
- Series 12 – Use of models in facility management – v1.0 2012
- Series 13 – Use of models in construction – v1.0 2012
- Series 14: Use of models in Building Supervision – v1.0 2014

In **Norway** [222] the BIM adoption has been promoted by the Norwegian Directorate of Public Construction and Property (Statsbygg) [211][222], a public body that refers to the Ministry of Local Government and Regional Development. It oversees building construction and management in the public sector, provides business support and achieves socio-political objectives based on architectural development, planning and conservation of environmental heritage [51].

Since 2010, Norway has required BIM projects in IFC format and has promoted BIM adoption for the entire building life cycle. The reference standard is the *Statsbygg BIM Manual* (latest version 1.2.1 – 2013) which is the national mandate currently in use. The purpose of this manual is to provide general requirements for the BIM adoption in design and building management and to improve the use of the IFC format. The main target audiences are design teams, facility managers and, in general, all professionals involved in the construction process, but it can also be used as a guide for software developers [283].

Other reference guidelines are the *BIM User Manual* (v. 2.0 - 2012) [222] defined by the Norwegian Home Builders' Association. This manual is based on *Norwegian CAD standards* (NS8353 CAD) and has been developed in coordination with the National BIM Standard (NBIMS) of the United States. It intended to be a practical aid for the design of residential buildings, summarising the general modelling methodology (independently from the software used) and referring in particular to the benefits of the transition from CAD to BIM [212].

**Denmark** began the BIM experimentation in 2001 with the *Danish Digital Building Initiative* (DIBS), which aimed at increasing productivity and competitiveness in the construction sector through a better use of *Information & Communication Technologies (ICT)* [169].

In 2003, the Government launched the *Digital Construction Project* (*Det Digitale Byggeri* in Danese), a three-year programme focused on the use of three-dimensional models, digital and collaborative working methods, digital public tenders and digital delivery of projects [207]. At the end of the project, in 2006, four guidelines for the use of 3D CAD and BIM applications were issued [87]:

- 3D CAD Manual 2006,
- 3D Working Method 2006,
- 3D CAD Project Agreement 2006,
- Layer and Object Structures 2006.

Since 2007, Denmark has required digital delivery of all public funded projects, whereas for private funded projects it was considered optional. The period from 2007 to 2014 saw a considerable increase in digital projects, partly due to the progressive definition of legislation and projects such as Cuneco. This project (supported by Bips between 2011 and 2015) focused on the transition from digital to BIM, considering the structure of information and the exchange processes between professionals involved [207].

In 2013 with the issue of the *Executive Order No. 118* (also known as *Danish BIM Mandate*), the Danish government has made the use of ICT mandatory for public procurement above € 700,000 and for public participation/financing projects above € 2,700,000 [261]. Denmark is now projected towards the development of the BIM at level 3 and represents one of the most advanced countries on the BIM theme.

In **Sweden**, the government does not require the mandatory use of BIM in public projects, but many companies have been using it for a long time and are investing in

the large-scale application of this new technology at national level. This is the case of the Swedish Transportation Administration (STA) which has used BIM for the design of complex works such as Stockholm Bypass and Röfors Bridge. STA has launched the *BIM Implementation Project* in order to standardize internal processes and allow for more extensive collaboration [87].

With regard to the development of standards and guidelines, the Swedish Standards Institute (SIS) has published from 1991 to 2013 the series of *Bygghandlingar 90* guides consisting of 8 documents that define how to produce the project documents, both in terms of drawing, information content and information exchange between all the different actors involved [280].

With regard to BIM, SIS developed the practical guide *BIM för Byggmästare* in 2010, with the aim of helping small and medium-sized companies to adopt the BIM [52].

Additional guidelines (*BIM – Standardiseringsbehov*), which direct the transition from CAD to BIM, was produced in 2013 by the OpenBIM organization, which since 2014 has been part of the new BIM Alliance Sweden organization [52].

## A.2. The United Kingdom

---

The UK is one of the most advanced European countries in the BIM adoption and is considered the benchmark for standards and regulations. In fact, since 2011, the Government has provided for a plan for the progressive BIM adoption, for all national public projects, aimed at the complete conversion to the BIM starting from 2016. The plan, drawn up by the Cabinet Office and contained in the Government Construction Strategy, has been recognised as the most ambitious and far-sighted mandate in the AEC industry to date. It requires that all government-funded public projects (both construction and infrastructure) provide BIM data for the entire life cycle of the building, thus reaching what has been defined as Maturity Level 2 [183].

The BIM adoption is considered fundamental for the future of the entire sector and is seen as a prerequisite for its future development, since it leads to modernisation of the construction industry, efficiency increment and cost reduction. The UK Government estimates that the widespread adoption of the BIM will lead to a 20% reduction in the building life-cycle costs and carbon consumption [71].

*Part of the UK's overall construction strategy is "to drive a more competitive construction sector that's effective, efficient, productive, and can export design and engineering services to other parts of the world. BIM fluency is part of the needed skill set".*

Adam Matthews – Autodesk executive and BIM Task Force member [183].

The entire process has been coordinated by the Cabinet Office with the involvement of industry groups, professional bodies, public sector, standardisation bodies, institutions and universities [222]. From this collaboration the BIM Task Group [71] was born. It is a working group that brings together the various competences involved in order to achieve and comply with the established objectives.

In this regard, the BIM Task Group has invested on three main areas to guide the country in the transition to the BIM: creation of shared standards and regulations, training of professionals and modernization of public administrations.

As far as the regulatory framework and the production of standards are concerned, Britain is certainly at the forefront and is also playing a key role in the definition of standards and protocols at European level.

### **CAD and BIM Protocols**

The adoption of shared standards has in fact proved to be essential to guide the correct transition from CAD to BIM, in order to adopt the new technology in a coherent way, sharing work and projects and exploiting the potential of the collaborative work offered by BIM.

In this context, the protocols drawn up by the **AEC (UK) Committee** [8], both with regard to CAD and BIM, aim at improving project processes and information management and exchange [222].

Documents related to the CAD system have been produced since 2000 and concern file management and the naming of drawings and layers. They can be summarized as follow:

- *AEC (UK) CAD Standard for drawing management;*
- *AEC (UK) CAD Standard for model file naming;*
- *AEC (UK) CAD Standard for layer naming (Latest version v4.0.2 – January 2016);*

Since 2009, in accordance with the previous CAD standards, standards for the BIM system have been produced. These are both general protocols for BIM implementation and specific protocols related to the commercial software with which the BIM is realized:

- *AEC (UK) BIM Technology Protocol* (Latest version v2.1.1 – June 2015) updated document referring to current protocols, specifications and documents of the construction sector
- *AEC (UK) BIM Protocol – BIM Execution Plan* (Latest version v2.0 – September 2012) that is compliant to PAS1192-2 and defines how the modelling aspect of the project is to be carried out and how the model and data are formatted.
- *AEC (UK) BIM Protocol – Model Matrix* (Latest version v2.0 – September 2012) representing a template for project sharing
- *AEC (UK) BIM Protocol For Autodesk Revit* (Latest version v2.0 – September 2012)
- *AEC (UK) BIM Protocol For Autodesk Revit – Model Validation Checklist* (Latest version v2.0 – September 2012)
- *AEC (UK) BIM Protocol For Bentley ABD* (Latest version v2.0 – September 2012)
- *AEC (UK) BIM Protocol For Bentley ABD – Model Validation Checklist* (Latest version v2.0 – September 2012)
- *AEC (UK) BIM Technology Protocol For ARCHICAD* (Latest version v2.0 – January 2016)
- *AEC (UK) BIM Technology Protocol For ARCHICAD – Template Checklist* (Latest version v2.0 – January 2016)
- *AEC (UK) BIM Technology Protocol For ARCHICAD – Model Validation Checklist For Import* (Latest version v2.0 – January 2016)
- *AEC (UK) BIM Technology Protocol For ARCHICAD – Model Validation Checklist For Export* (Latest version v2.0 – January 2016)
- *AEC (UK) BIM Protocol For Nemetschek Vectorworks* (Latest version v1.2 – October 2014)

### **BIM standards**

They have been published by the BSI B/555 committee (Construction design, modelling and data exchange) of the **British Standards Institution (BSI)** [67], British Standardisation Body and one of the leading global standardisation and certification bodies.

#### British Standards (BS):

- BS 1192:2007: *Collaborative production of architectural, engineering and construction information*; It includes BIM maturity levels from level 0 to level 2. It is a Code of Practice which defines, at a general level, the collaborative production of information

in the field of architecture, engineering and construction [260].

- BS 7000-4:2013: *Design management systems. Guide to managing design in construction*;
- BS 8541-1:2012: *Library objects for Architecture, Engineering and Construction – Identification and classification* (actually under review);
- BS 8541-2:2011: *Library objects for Architecture, Engineering and Construction – Recommended 2D symbols of building elements for use in Building Information Modelling*;
- BS 8541-3:2012: *Library objects for Architecture, Engineering and Construction – Shape and measurement* (actually under review);
- BS 8541-4:2012: *Library objects for Architecture, Engineering and Construction – Attributes for specification and assessment*;
- BS 8541-5:2015: *Library objects for architecture, engineering and construction. Assemblies. Code of practice*;
- BS 8541-6:2015: *Library objects for architecture, engineering and construction. Product and facility declarations. Code of practice*;
- BS 1192-4:2014: *Collaborative production of information – Fulfilling employers information exchange requirements using COBie – Code of practice*.

#### Publically Available Specifications (PAS)

- PAS 1192-2:2013: *Specification for information management for the capital/delivery phase of construction projects using Building Information Modelling*; This standard specifies the requirements necessary to achieve BIM level 2.
- PAS 1192-3:2014: *Specification for information management for the operational phase of assets using building information modelling*;
- PAS 1192-5:2015: *Specification for security-minded building information modelling, digital built environments and smart asset management*.

#### **Common Libraries**

UK is active also in the development of common libraries. In 2011, the **National Building Specification (NBS)** [201] developed the **National BIM (Building Information Modelling) Library** for the UK construction industry. The library is available free of charge online [215] and constitutes a database in accordance with the NBS BIM Object Standard. They refer to information content, geometry, behaviour and visualization, guaranteeing quality, consistency and allowing greater collaboration with the entire

construction industry.

The library contains all categories of objects and is the primary source of standard and proprietary BIM objects [222]. Each object has metadata and descriptive sheet and can be downloaded in IFC and Autodesk Revit format, while only for some objects ArchiCAD, Bentley, Tekla and Vectorworks formats are also available.

In addition to the library, NBS made available the **BIM Toolkit** [205] and the **NBS Create** [206]. The BIM Toolkit contains a detailed guide to define, manage and verify information at every stage of the building life cycle, so that projects compliant to Development Level 2 required by the standard can be implemented. The NBS Create is designed to facilitate the collection of data needed to produce the necessary project specifications.

### Manuals and guidelines

The **Royal Institution of Chartered Surveyors (RICS)** [264] published in 2014 the *International BIM Implementation Guide* which highlights the principles for the use of BIM in the design, construction and management of the built environment for any company that uses BIM or is planning to use it [257].

The **Chartered Institute of Building (CIOB)** [85], a UK-based corporation with subsidiaries around the world representing professionals working within the built environment, periodically publishes the *Code of practice for Project Management for construction and development*. The latest version (fifth edition 2014) refers to the implementation of the BIM in all design phases, with particular emphasis on preliminary design and sustainability [49].

## A.3. Other European Countries

In **Netherlands** the Rijkswaterstaat (RWS, the Dutch Directorate General for Public Works and Water Management), part of the Dutch Ministry of Infrastructure and Environment, established a BIM development programme between 2012 and 2014 involving research institutes and stakeholders, in order to promote the use of BIM in the country.

In 2011, the Government Building Agency (Rijksgebouwendienst, Rgd) regulated the use of the BIM for projects over 7,000,000 square metres [87].

The legislation currently in force is the *Rijksgebouwendienst BIM Standard (Rgd BIM Norm* in Dutch) Version 1.1, published in 2013 which regulates the BIM use, especially

w.r.t. Facility Management, and considers it mandatory for DBFMO contracts (Design-Build-Finance-Maintain-Operate). Nevertheless, a plan for BIM mandate in public procurement is still in progress [261].

In **Germany**, BIM is not yet mandatory. Although in 2012 the Federal Ministry of Transport, Construction and Urbanism (BMVBS) commissioned a one-year research project entitled *ZukunftBAU (Future Building)* from which the *BIM-Guide for Germany* [261] was produced in 2012, only since mid-2014 a concrete plan for the BIM adoption has been started.

In February 2015, the main institutions and associations of design and construction formed the Planenbauen 4.0 society for the digitalisation of building projects. The aim of this initiative is to make digital design shared and accessible to all actors in the construction sector. The objective of the plan, which came into effect in December 2015, is to develop universally applicable processes and solutions for different types of projects and to progressively introduce the BIM into design from 2017 [228].

The BIM will then be introduced in three successive stages:

- Preparatory phase until 2017
- Pilot phase up to 2020
- Final phase requiring the use of the BIM for all new public infrastructure projects from 2020.

In addition, in 2015, collateral initiatives were launched, such as the digital platform for construction (*Plattform Digitales Bauen*), with the aim of gathering experiences and contributions, in order to outline a national strategy for the BIM adoption starting from case studies [261]. Another important action towards BIM development has been the establishment by the German Standardisation Institute (DIN) of a special committee for the implementation of BIM standards (NA005-01-39AA) [228].

Since 2014, **France** has invested in personnel training, in order to create the skills needed to move towards BIM conversion. Examples include the BIM Master Class set up by Paris Tech - Institute of Science and Technology in Paris -, the BIM Manager Course promoted by GEPA (i.e. the official training organisation for architects), the opening of a BIM school by the Architects' Union (UNSFA) and the French national research project MINnd (financed by the Ministry of Industry). This project aimed at connecting and training contractors, engineers, software manufacturers and exponents of the universities [228]. The French Government considers the housing sector as the most suitable for BIM

adoption. By the end of 2017, the Government has established the objective of constructing around 500,000 dwellings using the BIM methodology and of defining appropriate regulations [261].

## A.4. The United States

As mentioned above, the United States [87][183][222] are one of the most advanced countries in BIM adoption: US are among the pioneers in the development of this technology and are also experiencing a very high effective use. However, the use of BIM has been introduced, standardized and made mandatory by agencies and proprietary guidelines have been developed for each federal commissioning or administration that requested its use. Even at the regulatory level, there is no federal legislation, but the regulation of the BIM is left to the individual states (see e. g. the *Wisconsin State Guidelines and Standards Design or Ohio BIM Protocols*), while at the federal level, standards protocols produced by various national agencies are available [259].

The first agency that required the use of the BIM was the **United State General Services Administration (GSA)**, an independent agency of the United States Government. In 2003, through the Public Building Service (PSBS) Office of Chief Architect (OCA) established the *National 3D-4D-BIM Programme* [293] with the following objectives:

- Define a policy that requires the adoption of the BIM for all major GSA projects and investment lines
- Provide support and qualified resources for projects that incorporate 3D, 4D and BIM technologies
- Provide guidance for the use of BIM data in building management and facility management
- Assessing development
- Develop contractual requirements and languages for 3D-4D-BIM services (for internal GSA use only)
- Partnerships with BIM suppliers, other federal agencies, professional associations, open standards organisations and academic and research institutions
- Creating a community of Champions BIM within the GSA

In this context, more than 200 BIM projects have been implemented, which have led

to the definition of 8 BIM Guides (which will be analysed later), the identification of some reference case studies, the encouragement of collaborations between teams that exploit BIM and the sharing of best practices and information within the industry [183]. In 2007, the GSA requested the production of projects in IFC format, representing along with the Scandinavian countries, one of the first cases worldwide.

In 2006, the **United States Army Corps of Engineers (USACE)** also introduced the use of BIM, publishing the *Road Map for Implementation To Support MILCON Transformation and Civil Works Projects within the United States Army Corps of Engineers*, in which it announced its intention to be the leader in the use of BIM.

In 2012, the Roadmap was updated (*Roadmap for Lifecycle BIM*) and extended to the use of the BIM in projects for the construction of military and civil works [183].

GSA and USACE were the first agencies to introduce the use of BIM, but many other agencies or public bodies at different levels (national, state, city and public university) have introduced their own reference standards. Based on the findings of Cheng & Lu's research in 2015 [87], there are 47 BIM standards publicly available (in 2015) in the United States, most of which refer to the Project Execution Plan, modelling methodology, graphical representation and data organization.

Below, only the national public standards/guidelines, subdivided according to the issuing body, will be referred to:

#### (1) **The United State General Services Administration (GSA)**

The published series are [293]:

- BIM Guide 01 – 3D-4D-BIM Overview (2007)
- BIM Guide 02 – Spatial Program Validation (2015)
- BIM Guide 03 - 3D Laser Scanning (2009)
- BIM Guide 04 - 4D Phasing (2009)
- BIM Guide 05 - Energy Performances (2015)
- BIM Guide 06 - Circulation and Security Validation (N/A)
- BIM Guide 07 - Building Elements (2016)
- BIM Guide 08 - Facility Management (2012)

#### (2) **The United States National Institute of Building Sciences (NIBS)**

The National Institute of Building Sciences (NIBS) [295] is a non-profit non-governmental

organisation that brings together representatives of government, professions, industry, workers and regulatory agencies to focus on identifying and resolving problems in the construction industry. It consists of multiple councils including the *BuildingSMART Alliance*, which provides leadership and support at the industrial, public and private levels for the development, standardisation and integration of ICT to provide complete automation of the entire building lifecycle.

*BuildingSMART Alliance* supports the *National BIM Standard - United States* [200], a national project aimed at providing standards to foster innovation processes, improve planning, design, construction and management processes using a standardized BIM model and creating the conditions for effective collaborative work.

Since 2007, the publication of the standards has begun.

- 2007: *National Building Information Modeling Standard (NBIMS-USTM) Version 1.0 - Part 1: Overview, Principles, and Methodologies*
- 2012: *National Building Information Modeling Standard (NBIMS-USTM) Version 2.0*
- 2015: *National Building Information Modeling Standard (NBIMS-USTM) Version 3.0 Information Exchange Standards; Construction Operation Building information exchange (COBie) – Version 2.4*

### (3) American Institute of Architects (AIA)

AIA [14] has published its first standards already in 2007, in order to standardise the digital transition, setting out the procedures that professionals should have to follow in digital data exchange [87].

- AIA documento E201™ – *2007 Digital Data Protocol Exhibit*
- C106™ – *2007 Digital Data Licensing Agreement*

In 2008, following the growing diffusion of BIM, AIA released document E202™ – *2008 Building Information Modeling Protocol Exhibit*, in which it established the five levels of development (LOD) in BIM applications.

In 2013, a further implementation produced new documents related to the use of BIM:

- AIA Document E203™–2013, *Building Information Modeling and Digital Data Exhibit*
- AIA Document G201™–2013, *Project Digital Data Protocol Form*
- AIA Document G202™–2013, *Project Building Information Modeling Protocol Form*
- *Guide, Instructions and Commentary to the 2013 AIA Digital Practice Documents*

### (4) Department of Veterans Affairs (VA)

The *VA BIM Guide v1.0* published in 2010 is a project-oriented BIM guide. It defines the

management of information during the building life cycle and introduces a management plan and modelling methodologies [87].

**(5) National Institute of Standards and Technology (NIST)**

In 2007, NIST released the *General Buildings Information Handover Guide: Principles, Methodology and Case Studies*. This guide, starting with the presentation of six case studies, focuses on technological concepts, definitions and modelling methodology and provides a guide to the exchange of information between stakeholders [87].

**(6) Association of General Contractor (AGC)**

AGC provides guidelines for contractors in order to guide them in the BIM adoption. The first published guide is *Contractor's Guide to BIM Edition 1*, updated to version 2 in 2010.

AGC has also made available a forum (*BIMForum*) that focuses on the use of virtual design and construction and, in agreement with AIA, has published annually since 2013 onwards standards for LOD (Level of Development Specification - latest Version 2016) [87].

## A.5. Canada

---

In Canada [50] there are two reference bodies for the BIM adoption and for the development of standards and guidelines.

The **Institute for BIM in Canada (IBC)** mission is "To lead and facilitate the coordinated use of BIM in the design, construction, and management of the Canadian built environment" [165]. In 2011, the IBC published the *Environmental Scan of BIM Tools and Standards*, a report listing 79 commercially available software (divided according to the life cycle phase of the building in which they are used: planning & design, implementation and management) and providing a general overview of the software tools that can be used in the BIM environment [222].

Another body is the **Canada BIM Council (CanBIM)** [78] which aims to promote a collaborative and open communication environment among all stakeholders in the AEC industry, providing learning opportunities and best practices to spread the use of BIM in Canada. In 2011, CanBIM started a collaboration with AEC (UK) to develop a parallel

protocol based on the English one. The protocols issued to date are the following:

- *AEC (Can) BIM Protocol (2014)*
- *AEC (Can) BIM Protocol - Revit V2 (2014)*

These protocols focus mainly on the correct use of BIM in the design phase, in order to maximize production efficiency and project quality through the coordinated and consistent use of BIM technology [50].

## A.6. Australia

---

The objectives for the BIM adoption in Australia were expressed in the National BIM Initiative Report, published by BuildingSmart Australasia [75] in 2012 on behalf of the Built Environment Industry Innovation Council (BEIIC), a government advisory body. The report makes three main recommendations:

- Mandate of using BIM for all Australian public procurement contracts, starting from 1 July 2016
- Encouragement of Australian states to require the use of open BIM formats
- Implementation of a national plan for the BIM adoption [87].

The development of BIM in Australia is followed by the Built Environment Digital Modelling Working Group – a joint initiative of BEIIC and the Information Technology Industry Innovation Council (ITIIC) – which aims to develop an Australian built environment industry capable of adopting integrated digital modelling technologies, in order to improve efficiency, environmental sustainability, manage the entire life cycle of buildings and increase international competitiveness. The working group brings together companies from industry, researchers, policy makers, industry associations in the building sectors and recently the Air Conditioning & Mechanical Contractors' Association (AMCA), which has been active in the BIM sector since 2010 [55].

As far as the production of standards and guidelines are concerned, the reference organisations are the National Specification System (NATSPEC), the Australia Cooperative Research Centre (CRC) for Construction Innovation and the Air Conditioning & Mechanical Contractors' Association (AMCA).

NATSPEC [203] is a non-profit organisation that brings together designers, builders

and real estate owners to improve the quality of construction in Australia by providing information, tools, products and services [222]. NATSPEC published:

- *NATSPEC National BIM Guide* – v. 1.0 September 2011 reconfirmed in March 2016
- *NATSPEC BIM Management Plan Template (BMP)* – v. 2.0 March 2016

The guide is not technical and prescriptive, but it is intended to be a general guidance tool to help designers in establishing shared BIM requirements, in order to avoid problems and conflicts and create a common and shared operating framework. The guide also supports the use of open tools in order to ensure the free exchange of information between different platforms [184].

One of the key requirements of this guide is the preliminary drafting of the BIM Management Plan (BMP) to address the entire BIM process. The BMP template has the purpose of guiding the correct drafting of the document to ensure that the BIM process is managed in the best possible way and that the work can be really collaborative [222]. The guide is in accordance with the BIM Guide published by the Department of Veteran Affairs (USA) in 2010 [87] and the *National Guidelines for Digital Modelling* published by the CRC for Construction and Innovation in 2009.

The CRC for Construction and Innovation [25] is a research, development and implementation centre, founded in 2001, active on issues related to real estate, design, construction and Facility Management [222]. In 2009 it published the *National Guidelines for Digital Modelling*, guidelines accompanied by six case studies to address the use of BIM.

AMCA [10] endorse the BIM-MEPAUS initiative that aims at facilitating exchange of information and BIM use. It establishes a common and practical set of mechanical, electrical and plumbing (MEP) protocols that ensures consistency and integrity of the shared models [184]. AMCA asserts that in order to overcome barriers to the adoption of BIM it is necessary to invest in the production of standards and guidelines, in solving interoperability issues, in training and in exchanging information in a clear and secure way. This includes the publication in 2011 of the *Building Information Modelling and Integrated Project Delivery*.

## A.7. The BIM adoption in Asia

**Singapore** is one of the most advanced cases worldwide. In 1995, the e-Plan Check system was developed in the country, which represents “one of the largest projects ever undertaken by a government agency in support of IFCs and BIM technology” [222]. It is an internet-based system that allows professionals to submit directly via the web the drawings and documentation necessary for project approval and to verify their regulatory compliance. This brings considerable benefits, such as project digitisation, simplification of delivery procedures, reduction of response times and harmonisation of rules and forms.

This project was developed by the Construction Real Estate Network (CoRENet), which is the main organisation involved in the enhancement of BIM adoption in government projects, and was co-organised by the Construction Industry Development Board (CIDB), the National Computer Board (NCB), the Singapore Productivity and Standards Board (PSB) and the Singapore Chapter of the International Alliance of Interoperability, in order to jointly create a set of common standards to be adopted at national level [222].

Starting from these premises, the Building and Construction Authority (BCA) published in 2010 a Roadmap with the objective to adopt BIM and e-submission in 80% of new construction projects with an extension larger than 5000 square meters, by 2015. This is part of the general government’s strategy to improve productivity in the construction sector by 25% through the BIM use [87].

To achieve these goals, since 2011 the government has developed a strategy based on pilot projects, training of professionals and public administration personnel, incentives for interoperable exchange formats adoption and company competition, in order to encourage enterprises to innovate through BIM [87].

In *South Korea* [87] the use of BIM in the design of public works has increased significantly in recent years and the government started a programme for the progressive adoption of the BIM since 2012. In particular, the Ministry of Territory, Transport and Maritime Affairs (MLTM) used the BIM in some projects already in 2011 and envisaged the use of BIM in all major construction projects between 2012 and 2015, extending it to all public projects in 2016.

At the same time, the Public Procurement Service (PPS) has set up a BIM programme in 2011, with the objective of adopting BIM for all turnkey projects with a value of more


than 50 million dollars, between 2013 and 2015, making it mandatory for all public projects by 2016.

To achieve these goals, thanks to the joint efforts of state bodies, research institutions and universities, standards and guidelines have been drawn up, including the National Architectural BIM Guide (which contains a general guide to work through BIM, a technical guide and a management guide), the *PPS Guideline v1: Architectural BIM Guide 2010* and the *PPS Guideline v2: BIM based Cost Management Guide 2011*.

In **Japan** [87] the government's interest in BIM started in 2010 thanks to a pilot project launched by the Ministry of Territory, Transport and Maritime Affairs (MLTM). Since then, the Japan Federation of Construction Contractors (JFCC) has established a special BIM section, dependent on its Building Construction Committee, with the aim of standardizing its requirements and find methods to increase the positive impact of the use of BIM in the construction phase.

**China** [87] is also moving towards the use of BIM. In 2012, the Government launched a five-year national plan to support the BIM adoption and many local authorities are also encouraging the implementation of BIM projects, training programs and guides.

The Chinese government through the China Institute of Building Standard Design & Research (CIBSDR) published in 2014 two national standards for the use of BIM: *Deliver Standard of Building Design – Information Modeling and Standard for Classification and Coding of Building Constructions Design Information Model*. In addition to these standards, there are also standards produced by local governments, such as those published by the Beijing Government in 2013 (*Building Information Modeling Design Standard for Civil Building*) and Shanghai in 2015 (*BIM Application Standard*).



“*Les architectes [...] ne doivent jamais perdre de vue que le but de leurs efforts est la conservation de ces édifices, et que le moyen d'atteindre ce but est l'attention apportée à leur entretien. Quelque habile que soit la restauration d'un édifice, c'est toujours une nécessité fâcheuse; un entretien intelligent doit toujours la prévenir.*

Architects [...] must never forget that the aim of their efforts is the conservation of these buildings, and that the way to achieve this goal is to pay attention to their maintenance. No matter how skillful the restoration of a building may be, it is always an unwelcome necessity; intelligent maintenance must always prevent it. ”

[Falloux, The Minister of Education and Religious Affairs, *Instructions pour la conservation, l'entretien et la restauration des édifices diocésains, et particulièrement des cathédrales*, 1849]



# APPENDIX B



Survey instruments technical references



## B.1. Leica C10 Scan Station

### Leica ScanStation C10 The All-in-One Laser Scanner for Any Application



[http://www.leica-geosystems.it/it/Leica-ScanStation-C10\\_79411.htm](http://www.leica-geosystems.it/it/Leica-ScanStation-C10_79411.htm)

#### General

Instrument type	Compact, pulsed, dual-axis compensated, very high speed laser scanner, with survey-grade accuracy, range, and field-of-view; integrated camera and laser plummet.
User interface	Onboard control, notebook, tablet PC or remote controller
Data storage	Integrated solid-state drive (SSD), external PC or external USB device
Camera	Auto-adjusting, integrated high-resolution digital camera with zoom video

#### System Performance

Accuracy of single measurement	
Position*	6 mm
Distance*	4 mm
Angle (horizontal/vertical)	60 $\mu$ rad / 60 $\mu$ rad (12" / 12")
Modeled surface precision**/noise	2 mm
Target acquisition***	2 mm std. deviation
Dual-axis compensator	Selectable on/off, resolution 1", dynamic range +/- 5', accuracy 1.5"

#### Laser Scanning System

Type	Pulsed; proprietary microchip
Color	Green, wavelength = 532 nm visible
Laser Class	3R (IEC 60825-1)

Range	300 m @ 90%; 134 m @ 18% albedo (minimum range 0.1 m)
Scan rate	Up to 50,000 points/sec, maximum instantaneous rate
Scan resolution	
Spot size	From 0 – 50 m: 4.5 mm (FWHH-based); 7 mm (Gaussian-based)
Point spacing	Fully selectable horizontal and vertical; <1 mm minimum spacing, through full range; single point dwell capacity
Field-of-View	
Horizontal	360° (maximum)
Vertical	270° (maximum)
Aiming/Sighting	Parallax-free, integrated zoom video
Scanning Optics	Vertically rotating mirror on horizontally rotating base; Smart X-Mirror™ automatically spins or oscillates for minimum scan time
Data storage capacity	80 GB onboard solid-state drive (SSD) or external USB device
Communications	Dynamic Internet Protocol (IP) Address, Ethernet or wireless LAN (WLAN) with external adapter
Integrated color digital camera with zoom video	Single 17° x 17° image: 1920 x 1920 pixels (4 megapixels) Full 360° x 270° dome: 260 images; streaming video with zoom; auto-adjusts to ambient lighting
Onboard display	Touchscreen control with stylus, full color graphic display, QVGA (320 x 240 pixels)
Level indicator	External bubble, electronic bubble in onboard control and Cyclone software
Data transfer	Ethernet, WLAN or USB 2.0 device
Laser plummet	Laser class: 2 (IEC 60825-1) Centering accuracy: 1.5 mm @ 1.5 m Laser dot diameter: 2.5 mm @ 1.5 m Selectable ON/OFF

All specifications are subject to change without notice.

All ± accuracy specifications are one sigma unless otherwise noted.

\* At 1 m – 50 m range, one sigma

\*\* Subject to modelling methodology for modelled surface

## B.2. Topcon Image Station IS203



[http://www.topcon.co.jp/en/positioning/products/product/3dscanner/imaging\\_station.html](http://www.topcon.co.jp/en/positioning/products/product/3dscanner/imaging_station.html)

### Telescope

Length	165 mm
Objective lens	45 mm (EDM 50 mm)
Magnification	30x
Image	Erect
Field of view	1°30'
Resolving power	3"
Minimum focus	1.4 m
Reticle illumination	provided

### Image sensor

Wide		
	Pixel	1.3 Mpixel (1280x1024) SXGA
	Magnification	0.5 / 1.0 / 2.0 / 4.0 / 8.0
	Minimum focus	2.0 m
	Angle of field (diagonal)	33°
Telescope		
	Pixel	1.3 Mpixel (1280x1024) SXGA
	Magnification	0.5 / 1.0 / 2.0 / 4.0 / 8.0
	Minimum focus	2.0 m
	Angle of field (diagonal)	1°

### Electronic angle measurement

Method	Absolute reading
Directing system:	
Horizontal	2 sides
Vertical	2 sides
Minimum reading	5"/1" (1mgon/0.2mgon, 20mmil/5mmil) reading
Accuracy	3" (1.0mgon)
Diameter of circle	71mm

**Distance measurement**

---

Prism mode	Up to 1000 m or 65000 m according to atmospheric conditions and prism type
Non-prism mode	From 1.5 to 250 m
Non-prism long mode	Gray surface, A square wall with sides of 0.5 m → 5 to 700 m White surface, A square wall with sides of 1 m → 5 to 2000 m

## B.3. Leica GPS1200 - GX1230 GG



### Leica GPS1200 Series High performance GNSS System



<http://leica-geosystems.com/products/gnss-systems>

#### General

GNSS technology	SmartTrack+
Type	Dual frequency
Channels	72 Channels 14 L1 + 14 L2 GPS 2 SBAS 12 L1 + 12 L2 GLONASS
RTK	SmartCheck+
Status indicators	LED indicators: for power, tracking, memory

#### SmartTrack+

Advanced GNSS measurement technology	<p>Time needed to acquire all satellites after switching on: typically about 50 seconds. Re-acquisition of satellites after loss of lock (e.g. passing through tunnel): typically within 1 second.</p> <p>Very high sensitivity: acquires more than 99% of all possible observations above 10 degrees elevation.</p> <p>Very low noise. Robust tracking.</p> <p>Tracks weak signals to low elevations and in adverse conditions.</p> <p>Multipath mitigation. Jamming resistant.</p> <p>Measurement precision: Carrier phase on L1: 0.2 mm rms. On L2: 0.2 mm rms. Code (pseudorange) on L1 and L2: 20 mm rms.</p>
--------------------------------------	--

#### SmartCheck+

Advanced, long range RTK technology	<p>Initialization typically 8 seconds.</p> <p>Position update rate selectable up to 20 Hz.</p>
-------------------------------------	--

Accuracies	<p>Latency &lt; 0.03 secs.          Range 30 km or more in favorable conditions.          Self checking.          Kinematic          Horizontal: 10 mm + 1 ppm          Vertical: 20 mm + 1 ppm          Static (ISO 17123-8)          Horizontal: 5 mm + 0.5 ppm          Vertical: 10 mm + 0.5 ppm          Reliability: 99.99% for baselines up to 30 km.          Formats supported for transmission and reception:          Leica proprietary, CMR, CMR+,          RTCM V2.1/2.2/2.3/3.0/3.1.</p>
Reference station networks	<p>RTK rover fully compatible with Leica's Spider i-MAX &amp; MAX formats, VRS and Area Correction (FKP) reference station networks.</p>

### DGPS

GX1230 (GG)	<p>DGPS, includes support of WAAS and EGNOS.          RTCM V2.1/2.2/2.3/3.0/3.1. formats supported for transmission and reception.          Baseline rms: typically 25 cm rms with suitable reference station.</p>
-------------	--

### Position update rate and latency

NMEA output	<p>Applies to RTK, DGPS and navigation positions.          Update rate selectable from 0.05 sec (20 Hz) to 1 sec.          Latency less than 0.03 secs.          NMEA 0183 V3.00 and Leica proprietary.</p>
-------------	---

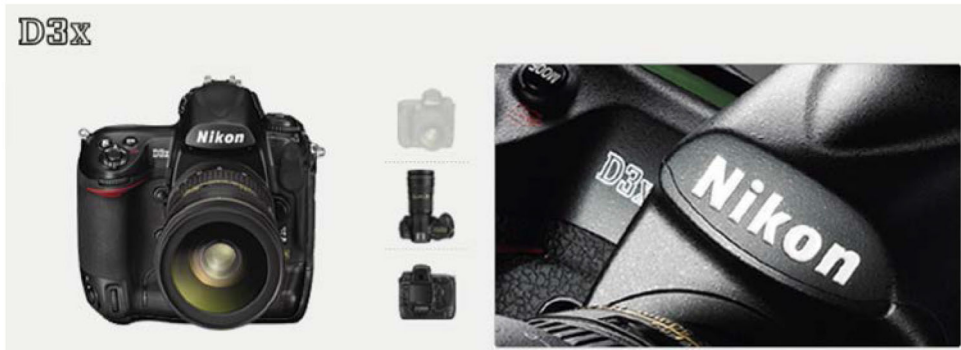
### Post-processing with Leica Geo Office software

All GPS1200 dual-frequency receivers	<p>Horizontal: 10 mm + 1 ppm, kinematic          Vertical: 20 mm + 1 ppm, kinematic          Horizontal: 5 mm + 0.5 ppm, static          Vertical: 10 mm + 0.5 ppm, static          For long lines with long observations          Horizontal: 3 mm + 0.5 ppm, static          Vertical: 6 mm + 0.5 ppm, static</p>
--------------------------------------	---

### Coordinate systems

Same for GNSS and TPS	<p>Ellipsoids, projections, geoidal models, coordinate, transformations, transformation parameters, country specific coordinate systems</p>
-----------------------	---

## B.4. Nikon D3x digital camera



<http://imaging.nikon.com/lineup/dslr/d3x/>

### General

- Nikon FX-format CMOS image sensor with 24.5 effective megapixels
- Exceptional noise control from ISO 100 to ISO 1600
- Fast 14-bit A/D conversion incorporated onto the image sensor for high signal-to-noise ratio and low power consumption
- Nikon's EXPEED image-processing system, utilizing a supremely powerful CPU with 16-bit image processing
- Near-instantaneous shutter release time lag of approx. 0.04 second (based on CIPA Guideline)\*
- 5-frames-per-second continuous shooting in FX format and 7 fps in DX crop mode (up to 130 frames)\*
- 51-point Multi-CAM3500FX autofocus system
- Scene Recognition System for more accurate AF, AE, and AWB results
- Active D-Lighting for complete control over highlight and shadow detail
- Picture Control: Standard, Vivid, Neutral and Monochrome (Landscape, Portrait and D2x Modes I, II and III are available free via download)
- Live View mode for shooting handheld and with a tripod
- High-resolution (approx. 920k dots), 3-inch VGA-size LCD monitor with tempered glass
- Durable, lightweight magnesium-alloy construction and comprehensive weather sealing against dust and moisture
- Intelligent power management that lets you shoot up to approx. 4,400 frames on a single battery charge (based on CIPA Standards)\*\*
- Compatibility with the Nikon Total Imaging System

\* In 12-bit A/D conversion mode

\*\* Using EN-EL4a lithium-ion battery at Single-frame [S] mode

## Specifications

Effective pixels	24.5 million
Image sensor	CMOS sensor, 35.9 x 24.0 mm; Nikon FX format; total pixels: 25.72 million
Image size (pixels)	FX format (36 x 24): 6,048 x 4,032 [L], 4,544 x 3,024 [M], 3,024 x 2,016 [S] DX format (24 x 16): 3,968 x 2,640 [L], 2,976 x 1,976 [M], 1,984 x 1,320 [S] 5:4 (30 x 24): 5,056 x 4,032 [L], 3,792 x 3,024 [M], 2,528 x 2,016 [S]
Sensitivity	ISO 100 to 1600 in steps of 1/3, 1/2, or 1 EV; can be set to approx. 0.3, 0.5, 0.7, or 1 EV (ISO 50 equivalent) below ISO 100, or to approx. 0.3, 0.5, 0.7, 1, or 2 EV (ISO 6400 equivalent) over ISO 1600
Storage media	CompactFlash (Type I/II, compliant with UDMA); Microdrives
LCD Monitor	3-in., approx. 920k-dot (VGA), 170-degree wide-viewing-angle, 100% frame coverage, low-temperature polysilicon TFT LCD with brightness adjustment
Exposure metering	TTL full-aperture exposure metering using 1,005-pixel RGB sensor <ol style="list-style-type: none"> <li>1. 3D Color Matrix Metering II (type G and D lenses); Color Matrix Metering II (other CPU lenses); Color Matrix Metering (non-CPU lenses if user provides lens data)</li> <li>2. Center-weighted: Weight of 75% given to 8-, 15- or 20-mm circle in center of frame, or weighting based on average of entire frame</li> <li>3. Spot: Meters 4-mm circle (about 1.5% of frame) centered on selected focus area (on center focus area when non-CPU lens is used)</li> </ol>
Exposure modes	A1. Programmed Auto (P) with flexible program, A2. Shutter-Priority Auto (S), A3. Aperture-Priority Auto (A), A4. Manual (M)
Interface	Hi-speed USB
Power sources	One Rechargeable Li-ion Battery EN-EL4a/EL4, Quick Charger MH-22/MH-21, AC Adapter EH-6 (optional)
Dimensions (WxHxD)	Approx. 159.5 x 157 x 87.5 mm (6.3 x 6.2 x 3.4 in.)
Weight	Approx. 1,220 g (2 lb. 11 oz.) without battery, memory card, body cap or accessory shoe cover

## B.5. SenseFly Albris drone



<https://www.sensefly.com/drones/albris.html>

### Flight modes

Types	Automatic Interactive ScreenFly Manual (RC)
Availability	Switch between modes at any time
Automatic	
Control interface	Mouse, keyboard or touchscreen
Mission planning	Drag-and-drop mission blocks
Types of mission blocks	Horizontal mapping Around point of interest Panorama Custom route
In-flight mission changes	Yes: manual waypoint changes and updates possible at any time
Interactive ScreenFly	
Primary control interface	Screen-based actions & USB controller
Flight assistance (depending on the flight phase)	Cruise control Distance lock Range sensing
Manual (RC)	
Primary control interface	RC (remote control)

### On-board computing

Type	4 on-board CPUs
Quad-core processor	Principal autopilot & artificial intelligence

Dual-core processor	Video co-processing
Single-core processor	Low-level autopilot (safety fallback) and motor control
Single-core processor	Communication link management

### Flight system

Type	V-shaped quadcopter
Dimensions (incl. shrouding)	56 x 80 x 17 cm (22 x 32 x 7 in)
Engines	4 electric brushless motors
Propellers	4
Take-off weight	1.8 kg (3.9 lb) incl. battery, payload & shrouding
Flight time (full system)	Up to 22 min
Max. climb rate	7 m/s (15 mph)
Max. airspeed	Automatic flight: 8 m/s (18 mph) Manual flight: 12 m/s (27 mph)
Wind resistance	Automatic: up to 8 m/s (18 mph) Manual: up to 10 m/s (22 mph)
Autopilot & control	IMU, magnetometer, barometer & GPS/GNSS
Materials	Composite body, moulded carbon fibre arms and legs, precision-molded magnesium frame, precision-molded injected plastic
Operating temperature	-10 to 40° C (14°-104° F)

### Integrated payloads: TripleView head

Main camera		
Still images		38 MP, mechanical shutter DNG (RAW image with correction metadata) Ground sampling distance (GSD): - 1 mm/pixel at 6 m - 1 cm/pixel at 60 m Recorded on board Geo-referenced (position & orientation)
Video		HD (1280 x 720 pixels) Recorded on board or streamed
Horizontal field of view		63 degrees
Digital zoom		6x
Thermal camera		
Still images/video		Thermal (80 x 60 pixels) overlaid on main camera stream
Horizontal field of view		50 degrees
Edge enhancement		Yes
Head navcam (visual sensor)		
Video		VGA (640 x 480 pixels)

Video live streaming range	Up to 2 km (1.24 miles)
Horizontal field of view	100 degrees
<b>Lights</b>	
Headlamp	Yes, used for video
Flash	Yes

### **Integrated payloads: Additional navcams (visual sensors)**

Number	4 navcams
Positions	Left, right, rear, bottom
Video	VGA (640 x 480 pixels)
Horizontal field of view	100 degrees
Availability	One navcam at a time
Operational use	Side views (w/o turning main camera) & parallel flight along objects Back-up safely & control in tight environments Landing & ground proximit

### **Situational awareness & assistance**

<b>Multidirectional video feed</b>	
Source	Navcams (visual sensor)
Number	5
Video	VGA (640 x 480 pixels)
Horizontal field of view	100 degrees
Availability	One navcam at a time
<b>Object &amp; range detection</b>	
Sensor	Ultrasonic
Number	5
Range	Up to 6 m (20 ft)
Feedback	Audio and visual object warning

### **Operational safety**

<b>Shrouding</b>	
Material	Carbon fibre
Function	Defines propeller rotation area Protects from damage at low speed
<b>Signalisation lights</b>	
Navigation lights	2 green on the right, 2 red on the left
Anti-collision lights	1 top strobe, 1 bottom strobe
<b>Ground proximity detection</b>	
Avoidance procedure	Automatic stop (can be deactivated)

Warning signals	Audio & visual
<b>Flight assistance features (Interactive mode)</b>	
Cruise control	Maintains (low) constant speed in a given direction
Distance lock	Keeps distance to frontal objects 3 - 5 m (9.8 – 16 ft)
Obstacle avoidance	Depending on flight phase
<b>Safety procedures</b>	
Automated failsafe behaviours	Geofencing, return home, emergency stop, emergency landing
Operator triggered	Hold position, return home, go land, land now, emergency motor cut-off
<b>Autopilot fallback</b>	
Type	Independent low-level autopilot (backup for main autopilot)
Manual RC control	Independent RC controller (take manual control at any time)







# APPENDIX C

---

Data entered in the database



## C.1. Semantic classification of the elements

The data presented here are reported into their original Italian version, since they are proper of Italian regulations and guidelines, thus a translation could not be sufficiently meaningful.

LIVELLO SEMANTICO 1: EDIFICIO (ED)			
Sigla	Classe	Sigla	Sottoclasse
ER	Edificio Religioso	Ch	Chiesa
		Ca	Cattedrale
		Pv	Pieve
		Bs	Basilica
		Ba	Battistero
		Cn	Canonica
		Cv	Convento
		Ab	Abbazia
		Mn	Monastero
ES	Edificio Scolastico	An	Asilo nido
		Sm	Scuola materna
		Se	Scuola elementare
		Sp	Scuola secondaria di primo grado
		Ss	Scuola secondaria secondo grado
		Un	Università
		Co	Collegio
ER	Edificio Residenziale	Vu	Villa unifamiliare
		Eu	Edificio unifamiliare aggregato
		El	Edificio plurifamiliare in linea
		Et	Edificio a torre
SR	Strutture ricettive	Al	Albergo
		Cs	Casa dello studente
		Cr	Casa di riposo
		Ra	Residenza per anziani
OS	Strutture ospedaliere	Os	Ospedale
		Cm	Centro Medico
		Am	Ambulatorio

EC	Edifici commerciali	Ne Su Mm	Negozi Supermercato Minimarket
CS	Centri sportivi	Pa Ps Cb	Palestra Palazzetto dello sport Centro benessere
ET	Edifici terziari	Pp Bb Mu Cc Ar Ci Te	Padiglione polifunzionale Biblioteca Museo Centro civico Archivio Cinema Teatro

#### LIVELLO SEMANTICO 2: AREE FUNZIONALI (AF)

Sigla	Classe	Sigla	Sottoclasse
FA	Facciata		
NC	Navata centrale		
NL	Navata laterale	No Su	Nord Sud
CL	Cappelle laterali	No Su	Nord Sud
MA	Matronei	No Su	Nord Sud
TR	Transetto		
CO	Coro		
SA	Sacrestia	No Su	Nord Sud
CR	Cripta		

#### LIVELLO SEMANTICO 3: ELEMENTI TECNOLOGICI (ET)

The technological classification of the building elements is described in UNI 10838:1999 and UNI 8290:1981 and is adopted in the guidelines of the Lombardy Region [251]. Here the classification is taken from these guidelines.

Classe	Elemento tecnologico	Sottoclasse	Elemento costruttivo
FN	Fondazioni	Pl Tr	Plinto Trave rovescia

		Mc Al	Muratura continua Altro
SV	Strutture verticali	Mp Md Pi Co Mt Pa Al	Muratura portante Muro divisorio Pilastro Colonna Muro di tamponamento Parasta Altro
SO	Strutture orizzontali	So Vo Cu Ba Bl Te	Solaio Volta Cupola Balcone Ballatoio Terrazzo
CP	Coperture	Mc St Gr	Manto di copertura Struttura Gronda
CV	Collegamenti verticali	Ra Sc	Rampa Scala
PVe	Pavimentazioni esterne		
PVi	Pavimenti interni		
RVi	Rivestimenti interni	In Zo Mp Md Mt Pi Co Pa Al Sc	Intonaco Zoccolatura Muratura portante Muro divisorio Muro di tamponamento Pilastro Colonna Parasta Altro Scala
Rve	Rivestimenti esterni	In Zo Mp Md Mt	Intonaco Zoccolatura Muratura portante Muro divisorio Muro di tamponamento

		Pi Co Pa Al Sc So Vo Pl Tr Mc Rv	Pilastro Colonna Parasta Altro Scala Solaio Volta Plinto Trave rovescia Muratura continua Rivestimento
ADi	Apparati decorativi interni	In  Af Sc Ca Le At St Ed Nc Co Al	Intonaco  Affresco Stucco Camino Lesena Altare Statua Edicola Nicchia Cornice Altro
ADe	Apparati decorativi esterni	In  Da Co Pr Ms Mo Af Zo Nc Ed St Al	Intonaco  Davanzale Cornice Portale Mosaico Modanatura Affresco Zoccolatura Nicchia Edicola Statua Altro

INe	Infissi esterni	Fi	Finestra
		Os	Oscuramento
		Po	Porta
		If	Inferriata
		Gr	Grata
		Al	Altro
INi	Infissi interni	Po	Porta
		Os	Oscuramento

The **SEMANTIC LEVEL 4** is defined by user according to specific needs.

## C.2. Problem list and description

The list of problems is retraced according to the guidelines of the Lombardy Region [251].

<b>Problematiche di affidabilità</b>	
<b>Benessere termoisometrico</b>	Insieme delle condizioni ambientali, quali la temperatura ambiente, la sua distribuzione, l'umidità dell'aria, le correnti d'aria e l'irraggiamento, che l'elemento, in conformità con le condizioni d'esercizio, deve poter controllare al fine di garantire i parametri idonei a un buono stato di conservazione, valutato in relazione all'uso dell'intero sistema.
<b>Funzionamento di finiture, organi meccanici e impianti</b>	Funzionamento delle finiture e degli organi meccanici dell'elemento, in corrispondenza delle condizioni d'uso e d'esercizio.
<b>Integrabilità degli elementi tecnici</b>	Attitudine dell'elemento a subire integrazioni funzionali, per adeguamenti normativi o malfunzionamenti, senza subire danneggiamenti e modificazioni.
<b>Isolamento acustico</b>	Capacità da parte dell'elemento di garantire un'adeguata resistenza al passaggio dei rumori. Tale aspetto è da considerarsi in relazione all'effettiva necessità, valutata rispetto alle condizioni d'uso e all'ambiente circostante.
<b>Isolamento termico</b>	Capacità da parte dell'elemento di garantire un'adeguata resistenza al passaggio di calore. Tale aspetto è da considerarsi in relazione all'effettiva necessità, valutata rispetto alle condizioni climatiche e alle condizioni d'esercizio.
<b>Sollecitazione meccanica</b>	Capacità a contrastare efficacemente le azioni statiche di progetto con sforzi compatibili con il legame costitutivo dei materiali, senza che si verifichino rotture e/o deformazioni eccessive. Sarà da specificare l'idoneità delle strutture, o i limiti delle azioni sopportabili, con riferimento alle soglie indicate dalle norme sulle azioni di progetto, in relazione alla necessità e all'uso.
<b>Stabilità</b>	Capacità degli elementi o dei sottosistemi costituenti l'elemento stesso di resistere sotto le azioni di carichi dinamici o ciclici probabili nelle condizioni d'uso. La presenza di elementi o sottosistemi sensibili si traduce in limitazioni d'uso.
<b>Tenuta all'acqua</b>	Capacità di impedire il passaggio di acqua e altri liquidi, in relazione alle condizioni d'esercizio, al materiale e a eventuali soluzioni tecnologiche e/o protettive adottate.

<b>Problematiche di durabilità</b>	
<b>Aderenza al supporto</b>	Attitudine a mantenere la coesione con il supporto. È necessario valutare l'insorgenza di fenomeni di degradazione legati all'insufficiente coesione con il supporto. Il problema si pone tipicamente per i rivestimenti.
<b>Esposizione agli attacchi biologici</b>	Attitudine a presentare le condizioni favorevoli per l'insediamento di organismi viventi con conseguenti degradi e caduta prestazionale dell'elemento, in conformità con le condizioni d'esercizio.
<b>Esposizione ai reagenti chimici</b>	Attitudine del materiale a subire trasformazioni se posto a contatto con prodotti chimicamente reattivi. Valutare se gli elementi soggetti al contatto con solventi (compresa l'acqua) e reagenti, nelle condizioni d'uso, risultano chimicamente stabili, mantenendo invariate nel tempo le proprie caratteristiche chimico-fisiche.
<b>Esposizione alle intrusioni</b>	Capacità dell'elemento tecnologico di impedire, con appositi accorgimenti, l'ingresso ad animali nocivi o a persone non desiderate.
<b>Esposizione alle variazioni termiche</b>	Idoneità a sopportare senza conseguenze gli sbalzi di temperatura, in relazione alle proprietà del materiale. Il fenomeno è da considerarsi in relazione alla ciclicità dell'evento.
<b>Gelività</b>	Attitudine del materiale a subire disaggregazioni e/o mutamenti di dimensioni e aspetto a causa dei cicli di gelo e disgelo. Il fenomeno è da valutare in relazione alla ciclicità dell'evento e all'effettivo stato di degrado del materiale; eventuali sovrapposizione di patologie possono, infatti, cambiare la struttura porosa di un materiale «non gelivo», rendendolo sensibile ai cicli di gelo e disgelo.
<b>Idrofilità</b>	Capacità di assorbire fluidi allo stato liquido. È necessario valutare l'attitudine di un elemento a essere penetrato da fluidi liquidi, ad esempio in relazione all'efficienza residua di eventuali trattamenti protettivi per rivestimenti esterni oppure per umidità di risalita capillare per strutture verticali.
<b>Igroscopicità</b>	Capacità del materiale di assorbire umidità dall'ambiente, senza che si verifichino cambiamenti di forma, dimensioni e/o aspetto. Tale assorbimento va valutato in relazione alle condizioni d'esercizio del sistema, inteso come l'interazione tra l'elemento tecnologico e l'ambiente.
<b>Irraggiamento</b>	Attitudine a subire mutamenti di aspetto e delle caratteristiche chimico-fisiche a causa dell'esposizione all'energia raggianti (ad esempio, le radiazioni solari).

<b>Sali solubili</b>	Attitudine a subire processi di degradazione e/o alterazione legati alla ricristallizzazione dei Sali solubili. La verifica sull'elemento tecnologico sensibile va fatta anche in relazione alle condizioni ambientali.
<b>Sporcabilità</b>	Attitudine ad amplificare gli effetti di sostanze imbrattanti, ristagni d'acqua, contatti accidentali e depositi di pulviscolo, valutando la tendenza dell'elemento tecnologico a fissare i depositi, ad esempio per conformazioni che ostacolano il dilavamento naturale.
<b>Traspirabilità</b>	Attitudine a permettere il passaggio di vapore acqueo dall'interno della struttura verso l'ambiente. Controllare la permeabilità al vapore dell'elemento tecnologico coerentemente al materiale utilizzato e alle condizioni ambientali, valutando in particolare l'eventuale impedimento del passaggio di vapore acqueo dall'interno della struttura verso l'ambiente, che è spesso causa di processi di degradazione.
<b>Usura</b>	Perdita di materia per attrito tra parti in movimento, o al contatto con oggetti. Si tratta di una tipica problematica «mista», nel senso che mette in luce un rischio di degrado dell'oggetto, legato a un requisito delle funzioni che l'oggetto svolge. Valutare tale idoneità coerentemente all'uso dell'elemento tecnologico soggetto a usura.
<b>Vulnerabilità all'azione degli agenti atmosferici</b>	Predisposizione all'insorgenza di alterazioni e/o degradazioni legate alle azioni chimiche e fisiche degli agenti atmosferici. Tale analisi è da compiersi in relazione alle caratteristiche materiche dell'elemento tecnologico, alle condizioni ambientali, alle tecnologie utilizzate e alle condizioni d'uso.

<b>Problematiche di adattabilità</b>	
<b>Asportabilità</b>	Attitudine a consentire la collocazione di elementi tecnici o componenti al posto di altri.
<b>Attitudine all'integrazione impiantistica</b>	Possibilità di completare funzionalmente oggetti edilizi non impiantistici con oggetti edilizi impiantistici accostati, fissati o incorporati.
<b>Attrezzabilità</b>	Attitudine a consentire l'installazione di attrezzature e arredi.
<b>Recuperabilità</b>	Attitudine degli elementi tecnici e delle loro componenti tecnologiche a essere riutilizzati. Tale aspetto deve essere verificato rispetto sia all'edificio antico, sia alle aggiunte funzionali; precisare se in caso di smontaggio per guasto possono essere recuperate e reimpiagate parti di materia antica o delle aggiunte odierne.

<b>Problematiche di manutenibilità</b>	
<b>Facilità di intervento</b>	Possibilità di operare ispezioni, manutenzione e ripristino in modo agevole. Tale facilità è da relazionare anche all'economicità e alla sicurezza e tutela della salute degli operatori.
<b>Pulibilità</b>	Attitudine a consentire la rimozione di sporcizia e sostanze indesiderate, valutando la facilità di asportazione dei depositi incoerenti, senza alterare e/o danneggiare la materia costituente l'elemento tecnologico.
<b>Regolabilità</b>	Attitudine a subire variazioni, indotte intenzionalmente da un operatore attraverso dispositivi tecnici, di un valore o di una funzione.
<b>Riparabilità</b>	Attitudine a ripristinare l'integrità, la funzionalità e l'efficienza di parti o di oggetti guasti. In senso proprio caratterizza gli impianti, ma può essere interessante valutarla anche rispetto ai rivestimenti (attitudine a essere reintegrati senza demolizione totale), ad alcuni tipi di strutture murarie e agli infissi.
<b>Sostituibilità</b>	Attitudine a consentire la collocazione di elementi tecnici al posto di altri. Nel caso di edifici storici la sostituzione deve essere limitata a casi estremi, e condotta con la consapevolezza che si supplisce la funzione, non l'identità dell'elemento. In altre parole, il piano di conservazione non deve diventare lo strumento per eseguire estese sostituzioni in assenza di meditate valutazioni progettuali. Pertanto l'analisi della problematica avrà senso e andrà eseguita soltanto rispetto a quelle parti, come i manti di copertura e gli impianti, in cui il guasto di un singolo componente deve essere riparato e soltanto un elemento con caratteristiche morfologiche simili può integrarsi con gli altri.



---

# Bibliography

- [1] .NET\_Framework <<https://docs.microsoft.com/en-us/dotnet/framework/get-started/overview>>, Last access 26/09/2017.
- [2] .NET\_Framework <[https://en.wikipedia.org/wiki/.NET\\_Framework](https://en.wikipedia.org/wiki/.NET_Framework)>. Last access 26/09/2017.
- [3] *A report for the Government Construction Client Group. Building Information Modelling (BIM) Working Party.* Strategy Paper. March 2011.
- [4] About Element Behavior in Revit < <https://knowledge.autodesk.com/support/revit-products/getting-started/caas/CloudHelp/cloudhelp/2016/ENU/Revit-GetStarted/files/GUID-5BFA499A-5ACA-4069-852C-9B60C9DE6708-htm.html>>. Last access 26/09/2017.
- [5] Achille, C., Brumana, R., Fassi, F. & Tuncer, H. (2007). Application of mixed technique for the 3d modelling of the noble floor of the Real Villa in Monza. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 36(5/C53).
- [6] Achille, C., Lombardini, N. & Tommasi, C. (2015). BIM & Cultural Heritage: compatibility tests in an archaeological site. In Mahdjoubi L., Brebbia C.A. & Laing R. (editors), *Building Information Modelling (BIM) in Design, Construction and Operations*, Witpress, pp. 593-604.
- [7] Adorni. B. (2006). *Le trasformazioni architettoniche cinquecentesche*, in Blasi, C. &

Coisson, E. (Editors), *La fabbrica del Duomo di Parma. Stabilità, rilievi e modifiche nel tempo*. Grafiche Step, Parma, pp. 111-123.

- [8] AEC (UK) CAD & BIM Standard Site <<https://aecuk.wordpress.com/>>. Last access 27/06/2017.
- [9] AIA Integrated Project Delivery: A Guide <https://www.aiacontracts.org/resources/64146-integrated-project-delivery-a-guide>. Last access 26/09/2017.
- [10] Air Conditioning & Mechanical Contractors' Association (AMCA) < <https://www.amca.com.au/>>. Last access 26/09/2017.
- [11] Albris – SenseFly. <<https://www.sensefly.com/drones/albris.html> >. Last access 26/09/2017.
- [12] AMA 3D – Arte Museo Archeologia <<https://play.google.com/store/apps/details?id=com.unipr.retidarte2016&hl=it>>. Last access 26/09/2017.
- [13] Amato, E. (2012). Case study 9. Software interoperability in the structural field with exportation to IFC standard. In Osello A., *The future of drawing with BIM for engineers and architects*, Dario Flaccovio Editore, Palermo, pp.159-163.
- [14] American Institute of Architects (AIA) < <https://www.aia.org/>>. Last access 26/09/2017.
- [15] Anafyo (2015), *Il BIM in Italia: un quadro della situazione. BIM Report 2015*.
- [16] Angulo Fornos, R. (2015). Digital models applied to the analysis, intervention and management of architectural heritage. In Mahdjoubi L., Brebbia C.A. & Laing R. (editors), *Building Information Modelling (BIM) in Design, Construction and Operations*, Witpress, pp. 407-418.
- [17] ANSI/X3/SPARC Study Group on Data Base Management Systems: (1975), Interim Report. FDT, ACM SIGMOD bulletin. Volume 7, No. 2
- [18] Apollonio, F., Gaiani, M. & Sun, Z. (2012). BIM-based modeling and data enrichment of classical architectural buildings. *Scires-It*, 2(2), pp. 41-62.
- [19] Arayici, Y. (2008). Towards building information modelling for existing structures. *Structural Survey*, 26(3), pp. 210–222.

- [20] Armeni, I., Sener, O., Zamir, A. R., Jiang, H., Brilakis, I., Fischer, M., & Savarese, S. (2016). 3D semantic parsing of large-scale indoor spaces. In Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition, pp. 1534-1543.
- [21] Arrivano le prime norme tecniche italiane sul BIM: UNI 11337 parti 1, 4 e 5. BibLus-net < <http://biblus.acca.it/arrivano-le-prime-norme-tecniche-italiane-sul-bim-uni-11337-parti-1-4-e-5/>>. Last access 26/09/2017.
- [22] ASPNET <<https://docs.microsoft.com/en-gb/aspnet/overview>>. Last access 26/09/2017.
- [23] ASPNET Core MVC framework <<https://docs.microsoft.com/en-us/aspnet/core/mvc/overview>>. Last access 26/09/2017.
- [24] Attar, R., Prabhu, V., Glueck, M. & Khan, A., (2010). 210 King Street: a dataset for integrated performance assessment. Proceedings of the 2010 Spring Simulation Multiconference (SpringSim '10), Society for Computer Simulation International, San Diego, CA, USA, Article 177.
- [25] Australia Cooperative Research Centre (CRC) for Construction Innovation <<http://www.construction-innovation.info/index-2.html>>. Last access 26/09/2017.
- [26] Autodesk 3D Studio Max <<https://www.autodesk.it/products/3ds-max/overview>>. Last access 26/09/2017.
- [27] Autodesk Maya < <https://www.autodesk.it/products/maya/overview>>. Last access 26/09/2017.
- [28] Autodesk – My first plug-in training <<http://usa.autodesk.com/adsk/servlet/index?siteID=123112&id=18162650>>. Last access 26/09/2017.
- [29] Autodesk Forge < <https://forge.autodesk.com/>>. Last access 26/09/2017.
- [30] Autodesk Revit – Parts < <https://knowledge.autodesk.com/support/revit-products/learn-explore/caas/CloudHelp/cloudhelp/2016/ENU/Revit-Model/files/GUID-22D24055-61A2-40BB-A2F7-A37990300B2B-htm.html>>. Last access 26/09/2017.
- [31] Autodesk Revit < <https://www.autodesk.it/products/revit-family/overview>>. Last access 26/09/2017.

- [32] Azhar, S. (2011). Building information modeling (BIM): trends, benefits, risks and challenges for the AEC industry. *ASCE Journal of Leadership and Management in Engineering*, 11(3), pp. 241–252.
- [33] Azhar, S., Khalfan, M. and Maqsood, T., (2012). Building information modeling (BIM): now and beyond. *Australasian Journal of Construction Economics and Building*, 12(4), pp. 15–28.
- [34] B/555 Roadmap (June 2013 Update). Design, Construction & Operational Data & Process Management for the Built Environment.
- [35] Baik, A., Alitany, A., Boehm, J. & Robson, S. (2014). Jeddah historical building information modelling “JHBIM” – object library. *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 2(5), pp. 41–47.
- [36] Baik, A., Yaagoubi, R. & Boehm, J. (2015). Integration of Jeddah historical BIM and 3D GIS for documentation and restoration of historical monument. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 40(5/W7), pp. 29–34.
- [37] Balletti, C., Guerra, F., Scocca, V. & Gottardi, C. (2015). 3D integrated methodologies for the documentation and the virtual reconstruction of an archaeological site. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 40(5/W4), pp. 215–222.
- [38] Barazzetti, L., Banfi, F., Brumana, R. & Previtali, M. (2015). Creation of parametric BIM objects from point clouds using NURBS. *The Photogrammetric Record*, 30(152), pp. 339–362.
- [39] Barazzetti, L., Banfi, F., Brumana, R., Gusmeroli, G., Oreni, D., Previtali, M., Roncoroni, F. & Schiantarelli, G. (2015). BIM from laser clouds and finite element analysis: combining structural analysis and geometric complexity. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 40(5/W4), pp. 345–350.
- [40] Barazzetti, L., Banfi, F., Brumana, R., Gusmeroli, G., Previtali, M., Schiantarelli, G. (2015). Cloud-to-BIM-to-FEM: Structural simulation with accurate historic BIM from laser scans. In *Simulation Modelling Practice and Theory*, 57, September

- 2015, pp. 71–87.
- [41] Barazzetti, L., Banfi, F., Brumana, R., Oreni, D., Previtali, M. & Roncoroni, F. (2015). HBIM and augmented information: towards a wider user community of image and range-based reconstructions. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 40(5/W7), pp. 35-42.
- [42] Bedford, J., Blake, B., Bryan, P., Andrews, D., Barber, D. & Mills, J. (2009). *Metric Survey Specifications for Cultural Heritage, English Heritage*.
- [43] Bianchi, G., Bruno, N., Dall'Asta, E., Forlani, G., Re, C., Roncella, R., Santise, M., Vernizzi, C., & Zerbi, A. (2016). Integrated survey for architectural restoration: a methodological comparison of two case studies, *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLI (B5), pp. 175-182.
- [44] Bianchini, C. (2016). Dal BIM all'H-BIM: un percorso tortuoso. Oral presentation at the *Brainstorming the BIM model* conference. 25 November 2016, Milan.
- [45] BIM Forum *Level of Development Specification 2016*
- [46] BIM Foundation <<http://www.bim.foundation/>>. Last access 7/06/2017.
- [47] BIM Group – BEP – BIM Execution Plan <<http://bimgroup.eu/bep-bim-execution-plan/>>. Last access 26/09/2017.
- [48] BIM Group – Documenti BIM <<http://bimgroup.eu/bim-documents/>>. Last access 26/09/2017.
- [49] BIM Group – Il BIM del Regno Unito. <<http://bimgroup.eu/2015/01/30/il-bim-del-regno-unito/>>. Last access 26/09/2017.
- [50] BIM Group – Il BIM in Canada <<http://bimgroup.eu/il-bim-in-canada/>>. Last access 26/09/2017.
- [51] BIM Group – Il BIM in Norvegia. <<http://bimgroup.eu/2015/02/13/il-bim-norvegia/>>. Last access 26/09/2017.
- [52] BIM Group – Il BIM in Svezia <<http://bimgroup.eu/2015/02/21/il-bim-in-svezia/>>. Last access 26/09/2017.

- [53] BIM Group – MIDP – Master Information Delivery Plan <<http://bimgroup.eu/midp-master-information-delivery-plan/>>. Last access 26/09/2017.
- [54] BIM Tools Matrix < [https://bimforum.org/wp-content/uploads/2011/02/BIM\\_Tools\\_Matrix.pdf](https://bimforum.org/wp-content/uploads/2011/02/BIM_Tools_Matrix.pdf)>. Last access 26/09/2017.
- [55] BIM-MEPAUS < <http://www.bimmepaus.com.au/>>. Last access 26/09/2017.
- [56] Bitelli, G., Dellapasqua, M., Girelli, V.A., Sanchini, E. & Tini, M.A. (2017). 3D geomatics techniques for an integrated approach to Cultural Heritage knowledge: the case of San Michele in Acrboli's Church in Santarcangelo di Romagna. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 42(5/W1), pp. 291-296.
- [57] Bitelli, G., Girelli, V.A., Tini, M.A. & Vittuari L. (2005). Integration of geomatic techniques for quick and rigorous surveying of Cultural Heritage. Proceedings of XX CIPA International Symposium, 26 September – 01 October, Torino, Italy.
- [58] Blasi, C. & Coisson, E. (Editors) (2006). *La fabbrica del Duomo di Parma. Stabilità, rilievi e modifiche nel tempo*. Grafiche Step, Parma.
- [59] Blaso, L., Dalmasso, D. & Pellegrino, A. (2012). Interoperability in the field of lighting. In Osello A., *The future of drawing with BIM for engineers and architects*, Dario Flaccovio Editore, Palermo, pp.217-235.
- [60] Blender. <<https://www.blender.org>>. Last accessed 13/04/2016.
- [61] Boeykens, S., Himpe, C. & Martens, B. (2012). A case study of using BIM in Historical Reconstruction - The Vinohrady synagogue in Prague. 30th International Conference on Education and research in Computing Aided Architectural Design in Europe, Prague, Czech Republic, 12-14 September.
- [62] Boguslawski, P, Mahdjoubi, L., Zverovich, V, Fadli, F. & Barki, H. (2015). BIM-GIS modelling in support of emergency response applications. In Mahdjoubi L., Brebbia C.A. & Laing R. (editors), *Building Information Modelling (BIM) in Design, Construction and Operations*, Witpress, pp. 381-392.
- [63] Bolpagni M., (2016). The Many Faces of 'LOD' <<http://www.bimthinkspace.com/2016/07/the-many-faces-of-lod.html>>. Last access 26/09/2017.

- [64] Boulaassal, H., Landes, T. & Grussenmeyer, P. (2009). Automatic extraction of planar clusters and their contours on building façades recorded by terrestrial laser scanner. Special issue of the *International Journal of Architectural Computing IJAC*, Issue 07, Vol. 01, pp. 1–20.
- [65] Boundary Representation <<https://pages.mtu.edu/~shene/COURSES/cs3621/NOTES/model/b-rep.html>>. Last access 26/09/2017.
- [66] B-Rep – Wikipedia <<https://it.wikipedia.org/wiki/B-Rep>>. Last access 26/09/2017.
- [67] British Standard Institution <https://www.bsigroup.com/>. Last access 27/06/2017.
- [68] Brumana, R., Oreni, D., Raimondi, A., Georgopoulos, A. & Breggiani, A. (2013). From survey to HBIM for documentation, dissemination and management of built heritage: the case study of St. Maria in Scaria d'Intelvi. Digital Heritage International Congress, Marseille, 2013, pp. 497–504.
- [69] Bruno, N., Bianchi, G., Zerbi, A. & Roncella R. (2015). An open-HGIS project for the city of Parma: database structure and map registration, In *Free and Open Source Software for Geospatial - Open Innovation for Europe*. GEOMATICS WORKBOOKS, vol. 12, p. 189-203, Como: Laboratorio di Geomatica - Politecnico di Milano - Polo Territoriale di Como, ISSN: 1591-092X, Como, 14-17 luglio 2015.
- [70] Bruno, N., Coisson, E. & Cotti, M. (2017). Laser-scanner survey of structural disorders: an instrument to inspect the history of Parma Cathedral's central nave. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, Vol. XLII (5/W1), pp. 167-174.
- [71] Building Information Modelling (BIM) Task Group <<http://www.bimtaskgroup.org/>>. Last access 28/06/2017.
- [72] Building Smart Finland – COBIM <<https://buildingsmart.fi/yleiset-tietomallivaatimukset-ytv/>>. Last access 29/06/2017.
- [73] BuildingSmart - Implementation <<http://www.buildingsmart-tech.org/implementation/implementations>>. Last access 26/09/2017.
- [74] BuildingSmart <<http://buildingsmart.org/>>. Last access 26/09/2017.
- [75] BuildingSmart Australasia <<http://buildingsmart.org.au/>>. Last access

26/09/2017.

- [76] BuildingSmart Italia < <http://www.buildingsmartitalia.org/> > . Last access 26/09/2017.
- [77] Butt, T.E., Francis, T.J., Greenwood, D., Jones, K.G. & Nasir, A.M. (2015). The role of BIM in tackling obsolescence, climate change, and sustainability. In Mahdjoubi, L., Brebbia, C.A. & Laing, R. (ediors), *Building Information Modelling (BIM) in Design, Construction and Operations*. WITPress, pp. 555-565.
- [78] Canada BIM Council (CanBIM) < <http://www.canbim.com/> >. Last access 26/09/2017.
- [79] Capra, A., Bertacchini, E., Castagnetti, C., Rivola, R. & Dubbini, M. (2015). Recent approaches in geodesy and geomatics for structures monitoring. *Rendiconti Lincei*, 26(1), pp. 53-61.
- [80] Carbonari, G., Stravoravdis, S. & Gausden, C. (2015). Building information model implementation for existing buildings for facilities management: a framework and two case studies. In Mahdjoubi, L., Brebbia, C.A. & Laing, R. (ediors), *Building Information Modelling (BIM) in Design, Construction and Operations*. WITPress, pp. 395-406.
- [81] Castagnetti, C., Dubbini, M., Ricci, P.C., Rivola, R., Giannini, M. & Capra, A. (2017). Critical issues and key points from the survey to the creation of the historical building information model: the case of Santo Stefano Basilica. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 42 (5/W1), pp. 467-474.
- [82] CEN/TC 442 - Building Information Modelling (BIM) <[https://standards.cen.eu/dyn/www/f?p=204:32:0::::FSP\\_ORG\\_ID,FSP\\_LANG\\_ID:1991542,25&cs=1085D2CA41E34A1C2DA860E5234AA5A97](https://standards.cen.eu/dyn/www/f?p=204:32:0::::FSP_ORG_ID,FSP_LANG_ID:1991542,25&cs=1085D2CA41E34A1C2DA860E5234AA5A97)>. Last access 26/09/2017.
- [83] Cenni preliminari su XAML (WPF) <[https://msdn.microsoft.com/it-it/library/ms752059\(v=vs.110\).aspx](https://msdn.microsoft.com/it-it/library/ms752059(v=vs.110).aspx)>. Last access 26/09/2017.
- [84] Centofanti, M., Continenza, R., Brusaporci, S. & Trizio I. (2011). The architectural information system SIArch3d-Univaq for analysis and preservation of architectural

- heritage. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 38 (5/W16), pp. 9-14.
- [85] Chartered Institute of Building (CIOB) < <http://www.ciob.org/>>. Last access 28/06/2017.
- [86] Che cos'è XAML? <<https://msdn.microsoft.com/it-it/library/cc295302.aspx>>. Last access 26/09/2017.
- [87] Cheng, J.C.P. and Lu, Q., (2015). A review of the efforts and roles of the public sector for BIM adoption worldwide. *ITcon - Journal of Information Technology in Construction*, vol. 20, pp. 442-478.
- [88] Chevrier, C., Charbonneau, N., Grussenmeyer, P.& Perrin, J.P. (2010). Parametric documenting of built heritage: 3D virtual reconstruction of architectural details. *International Journal of architectural Computing*, vol. 8, pp. 131-146.
- [89] Chiabrando, F., Io Turco, M. & Rinaudo, F. (2017). Modeling of the decay in a HBIM starting from the 3D point clouds. A followed approach for cultural heritage knowledge. The *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 42(2/W5), pp. 605-612.
- [90] Cipriani, L., Fantini, F. & Bertacchi, S. (2013). Criteri di indagine degli spazi voltati nell'ambito dell'architettura storica e in archeologia. *SCIRES-IT, SCientific RESearch and Information Technology*, Vol 3, Issue 2, pp. 101-134.
- [91] Circolare 2 febbraio 2009, n. 617 - Istruzioni per l'applicazione delle "Nuove norme tecniche per le costruzioni" di cui al D.M. 14 gennaio 2008 – Cap. 8, Costruzioni esistenti.
- [92] Ciribini A.L.C. (2017). La progettazione LOD(evole) dei Servizi. *INGENIO web* <[www.ingenio-web.it/Articolo/5099/La\\_Progettazione\\_LOD\(evole\)\\_dei\\_Servizi.html](http://www.ingenio-web.it/Articolo/5099/La_Progettazione_LOD(evole)_dei_Servizi.html)>
- [93] CodeBook < <http://www.codebookinternational.com/>>. Last access 26/09/2017.
- [94] CodeBook < <http://www.codebookinternational.com/>> . Last access 26/09/2017.
- [95] Constructive Solid Geometry – Wikipedia <[https://en.wikipedia.org/wiki/Constructive\\_solid\\_geometry](https://en.wikipedia.org/wiki/Constructive_solid_geometry)>. Last access 26/09/2017.

- [96] Crespi, P., Franchi, A., Ronca, P., Giordano, N., Scamardo, M., Gusmeroli, G. & Schiantarelli, G. (2015). From BIM to FEM: the analysis of an historical masonry building. In Mahdjoubi L., Brebbia C.A. & Laing R. (editors), *Building Information Modelling (BIM) in Design, Construction and Operations*, Witpress, pp. 581-592.
- [97] CULTURE Supporting Europe's cultural and creative sectors <<https://ec.europa.eu/culture/>>. Last access 26/09/2017.
- [98] CyArk Project. <<http://www.cyark.org>> . Last access 26/09/2017.
- [99] d.P.R. 5 ottobre 2010, n. 207. *Regolamento di esecuzione ed attuazione del decreto legislativo 12 aprile 2006, n. 163, recante «Codice dei contratti pubblici relativi a lavori, servizi e forniture in attuazione delle direttive 2004/17/CE e 2004/18/CE».*
- [100] Dall'Asta, E., Bruno, N., Bigliardi, G., Zerbi, A., & Roncella, R. (2016). Photogrammetric techniques for promotion of archaeological heritage: the archaeological museum of Parma (Italy), *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 41 (B5), pp. 243-250.
- [101] Davardoust, S. & Chiaia, B. (2015). L'interoperabilità per il calcolo strutturale. In Osello, A. (editor), *Building Information Modelling, Geographic Information System, Augmented Reality per il Facility Management*, Dario Flaccovio Editore, Palermo, pp. 101-115.
- [102] De Luca, L. (2013). 3D Modelling and Semantic Enrichment in Cultural Heritage. *Photogrammetric Week 2013*, Dieter Fritsch (Ed.), Wichmann/VDE Verlag, Belin & Offenbach, pp. 323-333.
- [103] De Luca, L., Busarayat, C., Stefani, C., Véron, P., Florenzano, M. (2007). An integrated framework to describe, analyze, document and share digital representations of architectural buildings. *VAST2007 – Future technologies to empower heritage professionals*, Brighton, UK.
- [104] De Luca, L., Bussayarat, C., Stefani, C., Véron, F. & Florenzano, M. (2011). A semantic-based platform for the digital analysis of architectural heritage *Computers & Graphics*. Volume 35, Issue 2, April 2011, Pages 227-241. Elsevier.
- [105] De Luca, L., Driscu, T., Peyrols, E., Labrosse, D. & Berthelot, M. (2014). A complete methodology for the virtual assembling of dismounted historic buildings.

- International Journal for Interactive Design and Manufacturing (IJIDeM)* 8(4), pp.265-276.
- [106] De Luca, L., Veron, P. & Florenzano, M. (2006). Reverse engineering of architectural buildings based on a hybrid modeling approach. *Computers & Graphics* 30 (2), pp. 160–176.
- [107] Decreto BIM, ci siamo: provvedimento in consultazione pubblica. Il testo. *INGENIO News* 20/06/2017 <[http://www.ingenio-web.it/Notizia/9732/Decreto\\_BIM\\_ci\\_siamo:\\_provvedimento\\_in\\_consultazione\\_pubblica.\\_Il\\_testo.html](http://www.ingenio-web.it/Notizia/9732/Decreto_BIM_ci_siamo:_provvedimento_in_consultazione_pubblica._Il_testo.html)>
- [108] Decreto legislativo 12 aprile 2006, n. 163. *Codice dei contratti pubblici relativi a lavori, servizi e forniture in attuazione delle direttive 2004/17/CE e 2004/18/CE*
- [109] Decreto legislativo 18 aprile 2016, n. 50 “Codice dei contratti pubblici”.
- [110] Di Benedetto, M., Ponchio, F., Malomo, L., Callieri, M., Dellepiane, M., Cignoni, P. & Scopigno, R. (2014). Web and mobile visualization for Cultural Heritage. In *Lecture Notes on Computer Science LNCS 8355*, Springer, pp. 18–35.
- [111] Díaz-Vilariño, L., Lagüela, S., Armesto, J. & Arias, P. (2012). As-Built BIM with shades modeling for energy analysis. Proceedings of International Conference on Virtual Systems and Multimedia (VSSM), pp. 353-359, NJ, USA, Milan, Italy, 2012.
- [112] DODGE Data & Analytics, *Measuring the Impact of BIM on Complex Buildings*. SmartMarket Report, 2015.
- [113] Dodge Data Analytic, *SmartMarket Brief: BIM Advancements No. 1*
- [114] Donato, V., Biagini, C., Bertini, G. & Marsugli, F. (2017). Challenges and opportunities for the implementation of H-BIM with regards to historical infrastructures: a case study of the Ponte Giorgini in Castiglione della Pescaia (Grosseto – Italy). *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 42 (5/W1), pp. 253-260.
- [115] Dore, C. & Murphy, M. (2012). Integration of HBIM and 3D GIS for Digital Heritage Modelling. Proceedings of Digital Documentation, 22-23 October, 2012 Edinburgh, Scotland.
- [116] Dore, C. & Murphy, M. (2014). Semi-automatic generation of as-built BIM façade

geometry from laser and image data. *Journal of Information Technology in Construction*, 19, pp. 20-46.

- [117] Dore, C., Murphy, M., McCarthy, S., Brechin, F., Casidy, C. & Dirix, E. (2015). Structural simulations and conservation analysis – historic building information model (HBIM). *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 40(5/W4), pp. 351–357.
- [118] DPCM 9 Febbraio 2011, *Direttiva del presidente del Consiglio dei Ministri per la valutazione e la riduzione del rischio sismico del patrimonio culturale con riferimento alle Norme tecniche per le costruzioni di cui al D.M. 14/01/2008*. (Pubblicata nella Gazzetta Ufficiale n. 47 del 16/02/2011 – suppl. ord. N. 54)
- [119] Duane, C. B. (1971). Close-range camera calibration. *Photogramm. Eng.*, 37(8), pp. 855-866.
- [120] Dynamo < <http://dynamobim.org/> > . Last access 26/09/2017.
- [121] Eastman, C. (1974). An Outline of the Building Description System. Issue 50 of Research report. Institute of Physical Planning, Carnegie-Mellon University, Pittsburgh.
- [122] Eastman, C., (1975). The Use of Computers Instead of Drawings, *AIA Journal*, March, Volume 63, Number 3, pp. 46–50.
- [123] Eastman, C., Teicholz, P., Sacks, R. & Liston, K. (2008). BIM Handbook – A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers, and Contractors, John Wiley & Sons, Inc.
- [124] Edelsbrunner, J., Havemann, S., Sourin, A. & Fellner, D. W. (2016). Procedural Modeling of Round Building Geometry. Conference Paper: 2016 International Conference on Cyberworlds (CW).
- [125] Entity Framework <<http://www.entityframeworktutorial.net/what-is-entityframework.aspx>> . Last access 26/09/2017.
- [126] Entity Framework <[https://msdn.microsoft.com/en-us/library/gg696172\(v=vs.103\).aspx](https://msdn.microsoft.com/en-us/library/gg696172(v=vs.103).aspx) > . Last access 26/09/2017.
- [127] Erba, D. (2012). Case study 10. Software interoperability in the energy field

- according to gbXML scheme. In Osello A., *The future of drawing with BIM for engineers and architects*, Dario Flaccovio Editore, Palermo, pp. 163-169.
- [128] EU BIM Task Group < <http://www.eubim.eu/>>. Last access 26/09/2017.
- [129] *European Union Public Procurement Directive (EUPPD2014/24)* < <http://eur-lex.europa.eu/legal-content/IT/TXT/?uri=celex%3A32014L0024>>. Last access 26/09/2017.
- [130] Fai, S. & Rafeiro, J. (2014). Establishing an appropriate level of detail (LOD) for a building information model (BIM) – west block, parliament hill, Ottawa, Canada. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 2(5), pp. 123-130.
- [131] Fai, S., Filippi, M. & Paliaga, S. (2013). Parametric modelling (BIM) for the documentation of vernacular construction methods: a BIM model for the commissariat building, Ottawa, Canada. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 2 (5/W1), pp. 115–120.
- [132] Fai, S., Graham, K., Duckworth, T., Wood, N. & Attar, R. (2011). Building Information Modelling and heritage documentation. Proceedings XXIIIrd International CIPA Symposium, Prague, Czech Republic, September 12 - 16, 2011.
- [133] Faro PointSense < <http://www.faro.com/en-gb/products/construction-bim-cim/faro-pointsense/>>. Last access 26/09/2017.
- [134] Fassi, F., Achille, C. & Fregonese, L. (2011). Surveying and modelling the main spire of Milan Cathedral using multiple data sources. *Photogrammetric Record*, 26(136), pp. 462–487.
- [135] Fassi, F., Achille, C., Fregonese, L. & Monti, C. (2010). Multiple data source for survey and modelling of very complex architecture. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 38(5), pp. 234–239.
- [136] Fassi, F., Achille, C., Mandelli, A., Rechichi, F. & Parri, S. (2015). A new idea of BIM system for visualization, web sharing and using huge complex 3D models for facility management. The *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 40(5/W4), pp. 359-366.

- [137] Fassi, F., Fregonese, L., Ackermann, S. & De Troia, V. (2013). Comparison between laser scanning and automated 3D modelling techniques to reconstruct complex and extensive Cultural Heritage areas. ISPRS Workshop 3D-ARCH: 3D virtual reconstruction and visualization of complex architectures, Trento, 25-26 February.
- [138] Fiorani, D. & Acierno, M. (2017). Conservation process model (CPM): a twofold scientific research scope in the information modelling for Cultural Heritage. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 42(5/W1), pp. 283-290.
- [139] Forlani G. & Mussio L., 1986. Test on Joint adjustment of geodetic and photogrammetric data. *International Archives of Photogrammetry and Remote Sensing*, vol. XXVI, part 3.1, Rovaniemi, 1986, 237-251. issn 0256-1840.
- [140] Fregonese, L., Barbieri, G., Biolzi, L., Bocciarelli, M., Frigeri, A. & Taffurelli, L. (2013). Surveying and monitoring for vulnerability assessment of an ancient building. *Sensors*, 13(8), pp. 9747-9773.
- [141] Garagnani, S. & Manferdini, A.M. (2013). Parametric accuracy: Building Information Modeling process applied to the cultural heritage preservation. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 40(5/W1), pp. 87-92.
- [142] Garagnani, S. (2014). Il processo costruttivo tra rappresentazione e conoscenza: la nascita del Building Information Modeling. *INGENIO* n. 27, 23/09/2014.
- [143] Garagnani, S. (2016), I Livelli di Sviluppo (LOD) nel progetto digitalizzato: La misura dell'informazione all'interno del percorso BIM. Building Smart Italia.
- [144] Garagnani, S., (2016). Il BIM nella progettazione di edifici NZEB: Team IES vincitori del concorso ASHRAE. *INGENIO* news 08/01/2016 < [http://www.ingenio-web.it/Notizia/5992/Il\\_BIM\\_nella\\_progettazione\\_di\\_edifici\\_NZEB:\\_Team\\_IES\\_vincitori\\_del\\_concorso\\_ASHRAE.html](http://www.ingenio-web.it/Notizia/5992/Il_BIM_nella_progettazione_di_edifici_NZEB:_Team_IES_vincitori_del_concorso_ASHRAE.html)>. Last access 26/09/2017.
- [145] gbXML <[http://www.gbxml.org/About\\_GreenBuildingXML\\_gbXML](http://www.gbxml.org/About_GreenBuildingXML_gbXML)>. Last access 26/09/2017.
- [146] Geomagic < <http://www.geomagic.com/it/>>. Last access 26/09/2017.

- [147] Geometria solida costruttiva – Wikipedia <[https://it.wikipedia.org/wiki/Geometria\\_solida\\_costruttiva](https://it.wikipedia.org/wiki/Geometria_solida_costruttiva)>. Last access 26/09/2017.
- [148] Gerges, M., Austin, S., Mayouf, M., Ahikwo, O., Jaeger, M., Saad, A. and Gohary, T.E., (2016). An investigation into the implementation of Building Information Modeling in the Middle East. *ITcon - Journal of Information Technology in Construction*, vol. 22, pp. 1-15.
- [149] Giandebiaggi, P., Ghiretti, A., Roncella, R., Vernizzi, C. & Zerbi, A. (2015). Integrated survey methodologies for the multi-scale knowledge of archaeology of architecture: the survey of the Amphitheatre in Durrës, *SCientific RESearch and Information Technology Ricerca Scientifica e Tecnologie dell'Informazione*, Vol 5, Issue 2, pp. 3-14.
- [150] Graphisoft Archicad < <https://www.graphisoft.com/it/soluzioni/> > . Last access 26/09/2017.
- [151] Grasshopper < <http://www.grasshopper3d.com/> > . Last access 26/09/2017.
- [152] Guarisco, G. (1992). *Il Duomo di Parma: materiali per un'altra storia*. Alinea, Firenze.
- [153] Guidi, G., Remondino, F., Russo, M., Menna, F., Rizzi, A. & Ercoli, S. (2009). A multi-resolution methodology for the 3D modeling of large and complex archaeological areas. *International Journal of Architectural Computing*, 7(1), pp. 39–55.
- [154] Günay, S. (2011). From data to information: methodology for a gis based historic building conservation project. *Proceedings of XXIII CIPA Symposium - Prague, Czech Republic - 12/16 September 2011*.
- [155] Havemann, S.& Fellher, D. (2004). Generative Parametric Design of Gothic Window Tracery. *Shape Modelling Application Proceedings*, June 7-8, Genova, Italy, pp. 350–353.
- [156] Hichri, N., Stefani, C., De Luca, L. & Veron, P. (2013). Review of the “as-built BIM” approaches. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 40(5/W1), pp. 107–112.

- [157] <<http://usa.autodesk.com/adsk/servlet/index?siteID=123112&id=18171347>>. Last access 26/09/2017.
- [158] Hyun, S. K., Marjanovic-Halburd, L. & Raslan, R. (2015). Investigation into informational compatibility of Building Information Modelling and Building Performance Analysis software solutions. In Mahdjoubi, L., Brebbia, C.A. & Laing, R. (ediors), *Building Information Modelling (BIM) in Design, Construction and Operations*. WITPress, pp. 543-553.
- [159] IBC Institute for BIM in Canada, (2011). *Environmental Scan of BIM Tools and Standards*. National Research Council of Canada
- [160] Ideate – BIMLink < <http://www.ideatebimlink.com/>>. Last access 26/09/2017.
- [161] Imprese Edili, Agenda digitale delle costruzioni | Analisi Anafyo – Tecniche Nuove. Italian BIM Report 2016 <[http://www.cng.it/CMSContent/Consiglio-Nazionale/Repository/files\\_news/Imprese%20Edili\\_28%20maggio%202017\(1\).pdf](http://www.cng.it/CMSContent/Consiglio-Nazionale/Repository/files_news/Imprese%20Edili_28%20maggio%202017(1).pdf)>. Last access 26/09/2017.
- [162] Industry Foundation Classes – Version 4 – Addendum 1. buildingSMART International. <<http://www.buildingsmart-tech.org/ifc/IFC4/Add1/html/>>. Last access 26/09/2017.
- [163] INNOVance < <http://test-innovance.dd.agoramed.it/default.aspx>>. Last access 26/09/2017.
- [164] INNOVance Web Portal <<http://test-innovance.dd.agoramed.it/>>. Last access 26/09/2017.
- [165] Institute for BIM in Canada (IBC) < <https://www.ibc-bim.ca/>>. Last access 26/09/2017.
- [166] Introduzione a Windows Presentation Foundation <<https://msdn.microsoft.com/it-it/library/cc185038.aspx>>. Last access 26/09/2017.
- [167] ISO Technical Committee 59 (ISO/TC 59) Buildings and civil engineering works <<https://committee.iso.org/home/tc59>>. Last access 26/09/2017.
- [168] ISTAT, I musei, le aree archeologiche e i monumenti in Italia <<https://www.istat.it/it/archivio/194402>>. Last access 26/09/2017.

- [169] Jensen, P.A. and Jóhannesson, E.I. (2013). Building information modelling in Denmark and Iceland, *Engineering, Construction and Architectural Management*, Vol. 20 Issue: 1, pp.99-110.
- [170] Knowles, A. K. (2002). *Past Time, Past Place: GIS for history. A collection of twelve case studies on the use of GIS in historical research and education*. ESRI press.
- [171] Laguela, S., Diaz-Vilarino, L., Armesto, J. & Martinez, J.L. (2013). Automatic thermographic and RGB texture of as-built BIM for energy rehabilitation purposes. *Automation in Construction*. 31, pp. 230–240.
- [172] Laing, R., Leon, M., Isaacs, J. & Georgiev, D. (2015). Scan to BIM: the development of a clear workflow for the incorporation of point clouds within a BIM environment. In Mahdjoubi L., Brebbia C.A. & Laing R. (editors), *Building Information Modelling (BIM) in Design, Construction and Operations*, Witpress, pp. 279-289.
- [173] Lassen, A. K. & Merschbrock, C. (2015). Investigating 'Green BIM' in a Norwegian construction project: an institutional theory perspective. In Mahdjoubi, L., Brebbia, C.A. & Laing, R. (editors), *Building Information Modelling (BIM) in Design, Construction and Operations*. WITPress, pp. 519-530.
- [174] Lee, Y.C., Eastman C.M., Solihin, W., & See, R. (2016). Modularized rule-based validation of a BIM model pertaining to model views. *Automation in Construction* 63, pp. 1–11.
- [175] Legge 11 febbraio 1994, n. 109. *La nuova legge quadro in materia di lavori pubblici*
- [176] Letellier, R. (2015). *Recording, Documentation and Information Management for the Conservation of Heritage Places*. Routledge, New York.
- [177] Logothetis, S., Delinasiou, A. & Stylianidis, E. (2015). Building Information Modelling for cultural heritage: a review. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 2(5/W3), pp.177-183.
- [178] Lucas, J., Bulbul, T. & Thabet, W. (2013). An object-oriented model to support healthcare facility information management, *Automation in Construction*, 31, pp. 281–291.
- [179] Luchterhandt, M. (2009). *Die Kathedrale von Parma. Architecture und Skulptur im*

*Zeitalter von Reichskirche und Kommunebildung*, Himer Verlag, Monaco.

- [180] Mandelli, A. (2016). *Surveying, modeling and management of Cultural Heritage. Definition of good practices through applications on monuments and artworks*. Doctoral Thesis. Politecnico di Milano, Department of civil and environmental engineering.
- [181] Mario Guttman (2013), *Advanced Techniques for Managing Building Data in Autodesk Revit*, Speaking at Autodesk University, Las Vegas, November 2013. Available at <<http://au.autodesk.com/au-online/classes-on-demand/class-catalog/2013/revit-for-architects/ab1796#chapter=0>>. Last access 26/09/2017.
- [182] McGraw Hill Construction, (2012). *Smart Market Report – The business value of BIM in North America: Multi-Year trend Analysis and User Rating (2007-2012)*. McGraw Hill, New York.
- [183] McGraw Hill Construction, (2014). *Smart Market Report – The business value of BIM for owners*. McGraw Hill, New York.
- [184] McGraw Hill Construction, (2014). *Smart Market Report – The business value of BIM In Australia and New Zealand: How Building Information Modeling is Transforming the design and Construction Industry*. McGraw Hill, New York.
- [185] McGraw Hill Construction, (2014). *Smart Market Report – The business value of BIM for construction in major global markets: How contractors around the world are driving innovation with building information modelling*. McGraw Hill, New York.
- [186] McPartland, R. (2017). BIM dimensions - 3D, 4D, 5D, 6D BIM explained, NBS.com – knowledge. 10 July 2017
- [187] McPartland, R. (2017). EU BIM Task Group launches handbook for the strategic implementation of BIM, NBS.com – knowledge. 06 July 2017
- [188] MeshLab < <http://www.meshlab.net/>>. Last access 26/09/2017.
- [189] MIBACT Ufficio di statistica <[http://www.statistica.beniculturali.it/Visitatori\\_e\\_introiti\\_musei\\_16.htm](http://www.statistica.beniculturali.it/Visitatori_e_introiti_musei_16.htm)>. Last access 26/09/2017.
- [190] Micalizzi, P., Magaudda, S., Buonora, P., & d’Elia, L. S. (2012). A GIS for the city of

- Rome: archives, architecture, archaeology. *e-Perimtron*, 7(1), 28-35.
- [191] Microsoft SQL <Server <https://www.microsoft.com/it-it/sql-server/sql-server-2016>> . Last access 26/09/2017.
- [192] Microsoft Visual Studio 2017 <<https://www.visualstudio.com/it/vs/whatsnew/?rr=https%3A%2F%2Fwww.google.it%2F>> . Last access 26/09/2017.
- [193] Model–view–controller <<https://en.wikipedia.org/wiki/Model%E2%80%93view%E2%80%93controller>> . Last access 26/09/2017.
- [194] Montorsi, W. (2000). *Alla scoperta del duomo di Parma*. Modena, Il Fiorino.
- [195] Moreno, A. (2016). BIM, Ance: "Italia in ritardo; necessaria una strategia nazionale", *iBIMI*, 2 may 2016. <<http://www.ibimi.it/bim-ance-italia-in-ritardo-necessaria-una-strategia-nazionale/>> . Last access 26/09/2017.
- [196] Müller, P., Zeng, G., Wonka, P. & Van Gool, L. (2007). Image-based Procedural Modeling of Façades, *ACM Transactions on Graphics*, In: *Proceedings of SIGGRAPH*, volume 26, number 3, article number 85, pp. 1–9.
- [197] Murphy M., McGovern E. & Pavia, S. (2011). Historic Building Information Modelling - Adding Intelligence to Laser and Image Based Surveys, *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 38(5/W16), pp. 1-7.
- [198] Murphy, M., McGovern, E. & Pavia, S. (2009). Historic Building Information Modelling (HBIM), *Structural Survey*, vol. 27, n. 4, pp. 311-327.
- [199] Murphy, M., McGovern, E. & Pavia, S. (2013). Historic building information modelling – adding intelligence to laser and image based surveys of European classical architecture. *ISPRS Journal of Photogrammetry and Remote Sensing*, 76, pp. 89–102.
- [200] *National BIM Standard - United States* < <https://www.nationalbimstandard.org/>> . Last access 26/09/2017.
- [201] *National Building Specification (NBS)* < <https://www.thenbs.com/>> . Last access 28/06/2017.

- [202] National Institute of Building Science, United States. *National Building Information Modeling Standard. Version 1 – Part 1: Overview, Principles, and Methodologies*.
- [203] NATSPEC Building Information Modeling Portal < <https://bim.natspec.org/>>. Last access 26/09/2017.
- [204] NBS – BIM Execution Plan. <https://www.thenbs.com/knowledge/what-is-a-bim-execution-plan-bep>. Last access 26/09/2017.
- [205] NBS BIM Toolkit < <https://toolkit.thenbs.com/>>. Last access 26/09/2017.
- [206] NBS Create < <https://www.thenbs.com/services/our-tools/nbs-create>>. Last access 26/09/2017.
- [207] NBS, *International BIM Report 2016*.
- [208] Nemtschek Allplan < <https://www.allplan.com/it/>>. Last access 26/09/2017.
- [209] Nicolle, C. & Cruz, C., (2011). Semantic Building Information Model and multimedia for facility management, Web Information Systems and Technologies, Lecture Notes in Business Information Processing 2011. S. 14–S. 29.
- [210] Nocerino, E., Menna, F. & Remondino, F. (2014). Accuracy of typical photogrammetric networks in Cultural Heritage 3D modeling projects. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XL(5), pp. 465–472.
- [211] Norwegian Directorate of Public Construction and Property (Statsbygg) <<http://www.statsbygg.no/>>. Last access 29/06/2017.
- [212] Norwegian Home Builders' Association, (2012). BIM User Manual. Vers. 2.0.
- [213] Nosyko dRofus < <http://drofus.com/en/>>. Last access 26/09/2017.
- [214] Nosyko dRofus < <http://drofus.com/en/>>. Last access 26/09/2017.
- [215] NSB National BIM Library < <https://www.nationalbimlibrary.com/>>. Last access 28/06/2017.
- [216] NSB, *National BIM Report 2013*
- [217] NSB, *National BIM Report 2015*

- [218] NSB, *National BIM Report 2016*
- [219] Onuma Planning System < <http://www.onuma.com/>> . Last access 26/09/2017.
- [220] Oreni, D., Brumana, R., Della Torre, S., Banfi, F., Bertola, L., Barazzetti, L., Cuca, B., Previtali, M., & Roncoroni, F. (2014). Survey turned into HBIM: the restoration and the work involved concerning the Basilica di Collemaggio after the earthquake (L'Aquila). *ISPRS Annals of the photogrammetry, Remote Sensing and Spatial Information Sciences*, Volume II-5, pp. 267-273.
- [221] Oreni, D., Brumana, R., Georgopoulos, A. & Cuca, B (2013). HBIM for conservation and management of built heritage: towards a library of vaults and wooden beam floors. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 2(5/W1), pp. 215-221.
- [222] Osello, A. (2012). *The future of drawing with BIM for Engineers and Architects*. Dario Flaccovio Editore, Palermo.
- [223] Osello, A. (a cura di), (2015). *Building Information Modelling, Geographic Information System, Augmented Reality per il Facility Management*. Dario Flaccovio Editore, Palermo.
- [224] Osello, A., Cangialosi, G., Dalmaso, D., Di Paolo, A., Lo Turco, M., Piumatti, P. & Vozzola, M. (2011). Architecture Data and Energy Efficiency Simulations: BIM and Interoperability Standards. *Proceedings of Building Simulation*.
- [225] Osello, A., Del Giudice, M., Rapetti, N. & Semeraro, F. (2016). Il BIM per la gestione dei dati alla scala edilizia e urbana. *Costruire in laterizio*, vol. 167, giugno 2016, pp.74-79.
- [226] Osello, A., Macii, E. (2012). A BIM interoperable process for energy efficiency control in existing buildings. *International Journal of Design Sciences and Technology*, 19(1), pp. 27-43.
- [227] Osello, A., Moglia, G., Del Giudice, M. & Boido, C. (2014). BIM e GIS per la metodologia DIMM(ER). In Giandebiaggi P., Vernizzi C. (a cura di), *Italian Survey & International Experience*, Atti del 36° Convegno Internazionale dei Docenti della Rappresentazione (Parma, 18-20 settembre 2014), Gangemi Editore, Roma 2014, pp. 975-982. ISBN: 9788849229158.

- [228] Panzeri, E. (2017). A che punto siamo con la progettazione digitale? BIM: adozione a livello internazionale. *Il Giornale dell'Ingegnere*, n1/2 2017, pp. 8-9.
- [229] PAS 1192-2:2013 *Specification for information management for the capital/delivery phase of construction projects using building information modelling*
- [230] Pauwels, P., Verstraeten, R., De Meyer, R. & Van Campenhout, J. (2008). Architectural Information Modelling for virtual heritage application, *Digital Heritage – Proceedings of the 14th International Conference on Virtual Systems and Multimedia*, pp.18-23.
- [231] Pauwels, P., Zhang, S. & Lee, Y.C. (2017). Semantic web technologies in AEC industry: A literature overview. *Automation in Construction* 73, pp. 145–165.
- [232] Pavan, A. & Mirarchi, C. (2016). La nuova norma UNI 11337, gestione digitale delle costruzioni. *Costruire in laterizio*, vol. 167, giugno 2016, pp.64-67.
- [233] Pavan, A. (2015). "Rivoluzione" BIM. Anche nella normazione tecnica. <[http://www.uni.com/index.php?option=com\\_content&view=article&id=3554%3Arivoluzione-bim-anche-nella-normazione-tecnica&catid=171&Itemid=2612](http://www.uni.com/index.php?option=com_content&view=article&id=3554%3Arivoluzione-bim-anche-nella-normazione-tecnica&catid=171&Itemid=2612)>. Last access 26/09/2017.
- [234] Pavan, A., Daniotti, B., Re Cecconi, F., Lupica Spagnolo, S., Pasini, D. & Chiozzi, M.A. (2016). INNOVance: la prima piattaforma nazionale BIM per le costruzioni. *Costruire in laterizio*, vol. 167, giugno 2016, pp.68-73.
- [235] Pavan, A., Re Cecconi, F., Maltese, S. & Caffi, V. (2013). INNOVance: il database italiano per l'edilizia. *INGENIO*, 17 < [http://www.ingenio-web.it/Articolo/1363/INNOVance\\_il\\_database\\_italiano\\_per\\_l\\_edilizia.html](http://www.ingenio-web.it/Articolo/1363/INNOVance_il_database_italiano_per_l_edilizia.html)>. Last access 26/09/2017.
- [236] Perego G. (2017). *Italian BIM report 2016* <<http://www.gisinfrastrutture.it/2017/06/italian-bim-report-2016/>>. Last access 26/09/2017.
- [237] Piazza Duomo Parma < <http://www.piazzaduomoparma.com/>>. Last access 26/09/2017.
- [238] Piumatti, P. & Savoyat, J. (2012). Interoperability in the thermal field. In Osello A., *The future of drawing with BIM for engineers and architects*, Dario Flaccovio Editore, Palermo, pp.235-243.

- [239] Polygon Mesh – Wikipedia < [https://en.wikipedia.org/wiki/Polygon\\_mesh](https://en.wikipedia.org/wiki/Polygon_mesh)>. Last access 26/09/2017.
- [240] PostgreSQL <<https://www.postgresql.org/>> . Last access 26/09/2017.
- [241] Practical BIM <<http://practicalbim.blogspot.it/2013/03/what-is-this-thing-called-lod.html>> . Last access 26/09/2017.
- [242] Previtali, M., Barazzetti, L., Brumana, R., Cuca, B., Oreni, D., Roncoroni, F. & Scaioni, M. (2013). Automatic façade segmentation for thermal retrofit. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 40(5/W1), pp. 197-204.
- [243] Project "Percorsi multimediali innovativi per la valorizzazione del Museo Archeologico di Parma" < <http://www.retidarte.unipr.it/>>. Last access 26/09/2017.
- [244] Pu S. & Vosselman G., (2006). Automatic extraction of building features from terrestrial laser scanning. IAPRS, vol. 36, part 5, Dresden, Germany, September 25–27, 5 p.
- [245] Quattrini, R., Malinverni, E.S., Clini, P., Nespeca, R. & Orlietti, E. (2015). From TLS to HBIM: high quality semantically-aware 3D modeling of complex architecture. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 40(5/W4), pp. 367–374.
- [246] Quattrini, R., Pierdicca, R., Morbidoni, C., & Malinverni, E. S. (2017). Conservation-oriented HBIM. the bimexplorer web tool. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 42(5/W1), pp. 275-281.
- [247] Quintavalle, A.C. (1974). *La Cattedrale di Parma e il romanico europeo*. Università, Istituto di storia dell'arte, Parma.
- [248] Quintavalle, A.C. (2005). *Basilica cattedrale di Parma: novecento anni di arte, storia, fede*. Cariparma & Piacenza; Grafiche Step, Parma.
- [249] Re, C., Robson, S., Roncella, R., & Hess, M. (2011). Metric Accuracy Evaluation of Dense Matching Algorithms in Archeological Applications. *Geoinformatics FCE CTU*, 6, pp. 275-282.

- [250] Rechichi F., Fassi F., Mandelli A., Achille C., 2016. A system for sharing high-resolution models and information on web: the analysis of the web module of bim3dsg system, *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 41(B5), pp. 703-710.
- [251] Regione Lombardia (2003), *La conservazione programmata del patrimonio storico architettonico, Linee guida per il piano di manutenzione e il consuntivo scientifico*, Edizioni Angelo Guerrini e Associati Spa, Milano.
- [252] Remondino, F. (2011). Heritage recording and 3D modeling with photogrammetry and 3D scanning. *Remote Sensing*, 3(6), pp. 1104-1138.
- [253] Remondino, F. (2011). Rilievo e modellazione 3D di siti e architetture complesse. *DisegnareCon*, 4(8), pp. 90-98.
- [254] Rhinoceros – NURBS < <https://www.rhino3d.com/nurbs>>. Last access 26/09/2017.
- [255] Rhinoceros < <https://www.rhino3d.com/it/>>. Last access 26/09/2017.
- [256] Richards, M., Churcher, D., Shillcock, P. & Throssell, D., (2013). *Post Construct-Award Building Information Modelling (BIM) Execution Plan (BEP)*. Building Information Modelling (BIM) Trask Group, Royal Institute of British Architects.
- [257] RICS, (2014). *International BIM implementation guide*.
- [258] Risk Map information system < <http://www.cartadelrischio.it/index.asp>>. Last access 26/09/2017.
- [259] Rizzarda C.C., (2015). Il COBie, questo sconosciuto: verso un BIM per il Facility Management? <<https://www.linkedin.com/pulse/il-cobie-questo-sconosciuto-verso-un-bim-per-facility-c-rizzarda>>. Last access 10/07/2017.
- [260] Rizzarda C.C., (2015). PAS 1192-2 e la "I" in Building Information Modeling. <<https://www.linkedin.com/pulse/pas-1192-2-la-i-building-information-modeling-chiara-c-rizzarda>>. Last access 28/06/2017.
- [261] Rizzarda C.C., (2016). BIM e normative in Europa: cerchiamo di essere lucidi. <<https://www.linkedin.com/pulse/bim-e-normative-europa-cerchiamo-di-essere-lucidi-chiara-c-rizzarda>>. Last access 29/06/2017.

- [262] Rogers, J., Chong, H.Y., Lim, C.C. and Jayasena, H.S., (2015). *BIM Development and Trends in Developing Countries: Case Studies*, Bentham Science Publishers, Sharja, Emirati Arabi Uniti.
- [263] Roncella, R., Re, C. & Forlani, G. (2011). Performance evaluation of a structure and motion strategy in architecture and Cultural Heritage. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 38(5/W16), pp. 285-292.
- [264] Royal Institution of Chartered Surveyors (RICS) Italia. <<http://www.rics.org/it/>>. Last access 28/06/2017.
- [265] Sabap, *Archivio Perizie*, b. Parma Storico 1988-1998 PRM26 Parma Cattedrale
- [266] Sabap, *Archivio Perizie*, Perizia 1269-29.06.1987
- [267] Sabap, *Archivio Perizie*, Perizia 1468-10.10.1988
- [268] Sabap, *Archivio Perizie*, Perizia 1533-10.04.1989
- [269] Sabap, *Archivio Perizie*, Perizia 1618-29.09.1989
- [270] Sabap, *Archivio Perizie*, Perizia 1782-02.11.1990
- [271] Sabap, *Archivio Perizie*, Perizia 533-16.06.1980
- [272] Sabap, *Archivio pratiche monumentali*, b. Archivio Storico 1970-1988 M26 III Duomo 2
- [273] Sabap, *Archivio pratiche monumentali*, b. PRM26 Duomo1989 Ril.Fotogramm 4
- [274] San José-Alonso, J.I., Finat, J., Pérez-Moneo, J.D., García, M., Fernández-Martín, J.J. & Martínez-Rubio J. (2009). Information and knowledge systems for integrated models in Cultural Heritage. *ISPRS Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 38(5/W1).
- [275] Santagati, C. & Lo Turco, M. (2017). From structure from motion to historical building information modeling: population a semantic-aware library of architectural elements. *Journal of Electronic Imaging*, 26(1), pp. 1-12.
- [276] Sawhney, A., and Singhal, P., (2013). Drivers and barriers to the use of building

information modelling in India. *International Journal of 3D Modelling Information*, 2/3, IGI Global, Hershey.

- [277] Saygi, G. & Remondino, F. (2013). Management of Architectural Heritage Information in BIM and GIS: State-of-the-art and Future Perspectives. *International Journal of Heritage in the Digital Era*. 2 (4), pp. 695-713.
- [278] SICaR < <http://www.sbap-pr.beniculturali.it/index.php?it/180/progetto-rearte-sicar>>
- [279] SICaRweb – Sistema Informativo per i Cantieri di Restauro <<http://sicar.beniculturali.it:8080/website/>>. Last access 26/09/2017.
- [280] SIS - *Bygghandlingar 90: byggsektorns rekommendationer för redovisning av byggprojekt* <<https://www.sis.se/konstruktionochillverkning/bygg/bygghandlingar90/>>. Last access 26/09/2017.
- [281] Soprintendenza Archeologia Belle Arti e Paesaggio per le province di Parma e Piacenza - Modulistica < <http://www.sbap-pr.beniculturali.it/index.php?it/128/modulistica-standardizzata>>. Last access 26/09/2017.
- [282] Soprintendenza per i beni ambientali e architettonici dell'Emilia (1991). *Duomo di Parma, recenti restauri*. Grafis, Casalecchio di Reno.
- [283] Statsbygg Building Information Modelling Manual Version 1.2.1 (SBM1.2.1) – 2013.
- [284] Steel, J., Drogemuller, R. & Toth, B. (2010). Model interoperability in Building Information Modelling. *Software & Systems Modeling*, 11(1), pp. 99–109.
- [285] Stefani, C., De Luca, L., Veron, P. & Florenzano, M. (2010). Time indeterminacy and spatio-temporal building transformations: an approach for architectural heritage understanding. *International Journal for Interactive Design and Manufacturing (IJIDeM)* 4(1), pp.61-74.
- [286] Tedeschi A., (2011). *Architettura Parametrica. Introduzione a Grasshopper*. Edizioni Le Pensur, Potenza, Italy.
- [287] Thomson, C. & Boehm, J. (2015). Automatic Geometry Generation from Point Clouds for BIM. *Remote Sensing*, 7, pp.11753-11775.

- [288] Tommasi, C., Achille, C. & Fassi, F. (2016). From point cloud to BIM: a modelling challenge in the Cultural Heritage field. The *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 41(B5), pp. 429-436.
- [289] Trelligence – Affinity <<http://www.trelligence.com/>> . Last access 26/09/2017.
- [290] UNESCO World Heritage List <<http://whc.unesco.org/en/list/>> . Last access 26/09/2017.
- [291] UNI 11337-1:2017 Standard < <http://store.uni.com/magento-1.4.0.1/index.php/uni-11337-1-2017.html>> . Last access 26/09/2017.
- [292] UNI 11337-5, la quinta parte della norma italiana sul BIM. BibLus-net <<http://biblus.acca.it/la-uni-11337-5-la-quinta-parte-della-normativa-tecnica-italiana-sul-bim/>>
- [293] United State General Services Administration (GSA) - 3D-4D Building Information Modeling < <https://www.gsa.gov/portal/content/105075>> . Last access 26/09/2017.
- [294] United States General Services Administration (GSA) (2009), BIM Guides Series 03: BIM Guide For 3D Imaging. < <https://www.gsa.gov/portal/content/102282>> . Last access 26/09/2017.
- [295] United States National Institute of Building Sciences (NIBS) < <https://www.nibs.org/>> . Last access 26/09/2017.
- [296] UNITY <<https://unity3d.com/>> . Last access 26/09/2017.
- [297] USIBD (2016). Level of Accuracy (LOA) Specification Guide.
- [298] Van Berlo, L. & De Laat, R. (2011). Integration of BIM and GIS: The development of the CityGML GeoBIM extension. In Kolbe, T. H.; König, G.; Nagel, C. (Eds.) 2011: *Advances in 3D Geo-Information Sciences*, ISBN 978-3-642-12669-7 Series Editors: Cartwright, W., Gartner, G., Meng, L., Peterson, M.P, ISSN: 1863-2246.
- [299] VectorWorks < <http://www.vectorworks.net/>> . Last access 26/09/2017.
- [300] Volk, R., Stengel, J. & Schultmann, (2014). Building Information Modeling

(BIM) for existing buildings – Literature review and future needs. *Automation in Construction* 38, pp. 109–127.

- [301] VUFORIA <<https://www.vuforia.com/>>. Last access 26/09/2017.
- [302] WhiteFeet Tools <<http://www.whitefeettools.com/>>. Last access 26/09/2017.
- [303] WPF Controls <[https://msdn.microsoft.com/en-us/library/bb613551\(v=vs.100\).aspx](https://msdn.microsoft.com/en-us/library/bb613551(v=vs.100).aspx)>. Last access 26/09/2017.
- [304] WPF Data Binding Overview <[https://msdn.microsoft.com/en-us/library/ms752347\(v=vs.100\).aspx](https://msdn.microsoft.com/en-us/library/ms752347(v=vs.100).aspx)>. Last access 26/09/2017.





---

# Ringraziamenti

Giunta al termine di un percorso così importante, vorrei ringraziare tutte le persone che mi hanno supportata, sia nel lavoro di tesi sia nei tre anni di dottorato.

Il primo ringraziamento va al mio relatore, il prof. Riccardo Roncella, per avermi accolta nel gruppo di geomatica e per aver reso possibile questa ricerca. Insieme al prof. Gianfranco Forlani, che ringrazio a sua volta, sono stati per me guida, supporto e incoraggiamento nel migliorarmi continuamente, arrivando a risultati che credevo irraggiungibili.

Grazie alla mia correlatrice, la prof.ssa Cristiana Achille che, con il suo entusiasmo, la sua passione e la sua disponibilità, mi ha portato ad amare e a concretizzare questo progetto.

Un ringraziamento particolare va al mio correlatore, il prof. Andrea Zerbi, presenza costante e punto di riferimento e sostegno in tutti questi anni.

Ringrazio la Fabbrica del Duomo di Parma, in particolare l'Ing. Gualtiero Savazzini e l'Arch. Sauro Rossi, per la disponibilità e la possibilità di lavorare sulla Cattedrale. Desidero esprimere inoltre la mia gratitudine al restauratore Stefano Volta per i preziosi consigli e la collaborazione.

Ringrazio tutto il 3D Survey Group, in particolare il prof. Francesco Fassi, Cinzia e Alessandro, per avermi accolta con grande disponibilità, e i docenti del DIA, Proff. Chiara Vernizzi, Eva Coisson e Carlo Mambriani, che a vario titolo hanno contribuito alla realizzazione di questo lavoro.

Un pensiero speciale va alle mie colleghe e amiche Elisa e Marina, per avermi sempre sostenuta nei momenti di difficoltà e per aver condiviso con me le gioie e i successi ottenuti insieme in questi anni.

Ringrazio infine la mia famiglia e tutte le persone con cui ho condiviso il lavoro e la vita privata, accompagnando con calore e sorrisi questi tre anni.

*Nazarena*



