Historic Building Information Modelling: performance assessment for diagnosis-aided information modelling and management

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Review

Gda Historic Building Information Modelling: performance assessment for diagnosis-aided information modelling and management

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Acronyms:
AEC
Architecture, Engineering and Construction
AIA
American Institute of Architects
API
Application Programming Interface
AR
Augmented Reality
BACnet
Building Automation and Control networks
BAS/BA
Building Automation System
BCVTB
Building Control Virtual Test Bed
BEMS/BEM
Building Energy Management Systems
BHIMM
Built Heritage Information Modelling and Management
BIM
Building Information Modelling
BrIM
Bridge Information Modelling
BT
breakage-triggered
CAD
Computer Aided-Design

ABSTRACT

Building Information Modelling, new paradigm of digital design and management, shows great potential for the refurbishment process, as it represents a possible way out of criticalities that occur in documentation and preservation of existing assets, if connected to cognitive automation. The combination of BIM with automation systems improves the quality control during diagnosis, design and work execution, and the labour savings, which is particularly relevant for rapid intervention in case of hazardous conditions.

Therefore, the paper is going to address a methodological discussion concerning complete "as-built" parametric models of historical buildings, supporting the design of refurbishment and conservation interventions. Although some reviews of the state of the art exist on the topic of Historic Building Information Modelling, the present research introduces a different perspective on HBIM modelling, with diagnosis and performance assessment as key-aspects, in terms of automating performance assessment.

Specifically, from the data collection of contributions regarding HBIM/BIM, diagnostics and monitoring on existing buildings and infrastructures, a critical review by selected criteria is developed. Nevertheless, general methods and tools for information management and exchange tasks in BIM are briefly described as well, since they are considered useful for future developments of HBIM approach. The core of the critical analysis is focused on the scientific and technical relations among HBIM models, diagnosis and performance assessment features. In addition, the review identifies specific activities and relative tools and methods for knowledge acquisition and semantic enrichment.

Finally, gaps in knowledge of the current literature are outlined and discussed, with specific focus on performance assessment in HBIM. In this regard, a new methodology toward Diagnosis-Aided Historic Building Information Modelling and Management (DA-HBIMM) is proposed as a framework to be developed in order to address smart knowledge acquisition, collection and notification of assessed performances and eventual risks, by cognitive automation and artificial intelligence, in the near future.

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CH
Cultural Heritage
CHIM
Cultural Heritage Information Management
CMMS
Computerised Maintenance Management System
COBie
Construction Operations Building information exchange
CPS
Cyber Physical Systems
DA-HBIMM
Diagnosis-Aided Historic Building Information Modelling and Management
DB
DataBase
DBMS
DataBase Management System
EDMS
Electronic Document Management System
FDD
Fault Diagnostic and Detection
FEM
Finite Elements Model
FM
Facility Management
GBI
Green Building Index
gbXML
Green Building extensible mark-up language
GPR
Ground Penetrating Radar
GPS
Global Positioning System
HBIM[1]/H-BIM
Historic Building Information Modelling
HBIM[2]
Heritage Building Information Modelling
HBIMM
Historic Building Information Modelling and Management
HBRP
Housing Building Refurbishment Plan
HVAC
Heating, Ventilation and Air Conditioning
ICP
Iterative Closest Point
IE
Information Exchange
IFC
Industry Foundation classes
IoT
Internet of Things
IR
Information Requirements
LCA
Life Cycle Assessment
LEED
Leadership in Energy and Environmental Design
LiDAR
Light Detection and Ranging
LoD
Level of Detail
LOD
Level Of Development
LVDT
Linear Variable Displacement Transducer
MCDM
Multiple Criteria Decision Making
mesh-OBIM
mesh to BIM objects
MVD
Model View Definition
NoSQL
Not Only SQL
NURBS

non-Uniform Rational Basis-Spline
ODBC
Open Database Connectivity
pointclouds-OBIM
point clouds to BIM objects
RANSAC
RANdom SAmple Consensus
RFID
Radio Frequency Identification
RGB-D sensors
RGB colours and Depth sensors
RPVs
Remotely Piloted Vehicles
SCADA
Supervisory Control and Data Acquisition
SfM
Structure for Motion
SHM
Structural Health Monitoring
SOA
service-oriented architecture
SQL
Structured Query Language
TMH
Traditional Malay House
UAVs
Unmanned Aerial Vehicles
VR
Virtual Reality
WSN
Wireless Sensors Networks
XML
Extensible Markup Language

1. Introduction

Building Information Modelling, new paradigm of digital design and management, shows great potential for the refurbishment process [1], as it represents a possible way out of criticalities that occur in documentation and preservation of existing assets, especially if connected to cognitive automation. For instance, BIM can be very attractive for the management of the comprehensive and incremental knowledge of the built heritage, fundamental activity for an accurate assessment of the residual building performances to be recovered by refurbishment and retrofit. The approach can also ensure the effective involvement of all the technicians with multidisciplinary skills and the successful information sharing. The integration of BIM with automation systems would positively support the quality control during diagnosis, design and work execution as well as the labour savings.

Therefore, Building Information Modelling can be a guide tool for work and information flows as long as it stands on the concept of integrated digital archive that collects geometric, semantic and topological data, in different formats and contents, within parametric objects [1]. BIM proprietary or customised tools can manage and analyse the multiplicity of variables due to query operations and specific programmed automation algorithms.

The application of BIM in the built heritage was initially identified as Historic Building Information Modelling (HBIM) [2]. However, according to the previous definition, the concept of information management - complementary to the modelling one - is excluded; thus, an evolution has occurred toward the approach of Built Heritage Information Modelling and Management (BHIMM) [3]. Reviews of the state-of-the-art exist on the topic of “Historic Building Information Modelling” for building refurbishment (both in general terms [4], and specifically related to existing buildings [5]). However, some guidelines are still needed to achieve a complete “as-built” model of historical buildings, especially featured with irregular and complex morphology, toward the design of refurbishment and conservation interventions [6].

A critical activity, which the authors are dealing with, is the integration of a variety of information through independent and structured methods. Such information comes from historically archived documentation, analytical investigations, surveys, diagnostics and monitoring and requires continuous updating during performance assessment, design and execution.

BIM tools are software programs (more or less interoperable) and databases that support the organisation and the collection of information, which is disconnected and sometimes unavailable, and reported in separate sources.

Ultimately, the scientific community must invest resources in the development of HBIMM methodology in order to improve its ability to contain both tangible and intangible information inherent to the existing buildings [7].

In this way, the information could be available to all the stakeholders for management of building operation and maintenance throughout the life cycle. Furthermore, real-time updates and notifications of centralised models are expected by installing integrated monitoring systems [8].

In this context, this revision of the state-of-the-art is drawn up for the following purposes: 1) analysing criticalities and potentialities of HBIMM, as emerged in refereed publications; 2) formalising the first attempts of HBIMM application; 3) proposing a methodological flow to be consolidated; 4) suggesting future developments toward a Diagnosis-Aided HBIMM (DA-HBIMM) within an automation-based framework.

2. Research methodology

The aim of this state of the art is to identify gaps in knowledge and to provide insights for future development on methods and tools of Historic Building Information Modelling for the refurbishment project, toward the automated diagnosis of the residual performances and design of coherent structural reinforcement and energy retrofitting. In addition, relevant issues, investigated within this work, concern knowledge acquisition and management of the diagnosis, with the future perspective of automatic performance assessment within the BIM approach, in order to achieve accurate and precise performance assessment in acceptable time, as well as in risk situations. Therefore, this article excludes the project phase - analysis and simulation of design trade-offs, graphs and documents, scheduling, cost estimation, etc. The originality of the state of the art, compared to the works by Volk et al., 2014 [5] and Ilter and Erger, 2015 [4], stands on the focused specific gaps and possible developments of BIM for diagnosis and performance assessment, also by integrating diagnostic tests and monitoring measurements.

The current literature review regards scientific and technical contributions from 2004 to 2017, following the research methodology illustrated in Fig. 1.

It begins with the *Data collection* of contributions by the listed keywords, successively analysed with a first *Bibliometric study about HBIM* (Section 3). The consultation and selection of the research works among scientific publications and pilot projects was carried out via Scopus, ScienceDirect, Google Scholar, ASCE library, "white papers" sections of construction companies and software houses. Among the selected sources, 120 contributions, 86 with international impact, and 1 project were analysed. Among them, 13 articles include the word HBIM in title, abstract, keywords or paper body.

The bibliometric study concerns the papers with keywords correspondent to BIM approach to existing buildings, investigating impact of different denominations over the years. The scope of Section 3 relies on analysing trends, from 2007 to 2017, of HBIM methodology and the distribution by typology of sources (journals, conference proceedings, books, etc.), in order to evaluate the international interest of the technical and scientific community.

Section 4 regards the *Critical analysis*, conducted after screening the papers by selected *Criteria*. These themes are reported in Fig. 1, and correspond to the structure of the paragraphs in Sections 4 and 5.

To expand, the first step of the critical analysis concerns principles and methods of understanding adequate approaches that are worthwhile in managing the performance assessment and the diagnosis by BIM logic. In this perspective, the exploration of information management and exchange tasks provides insights into information classification and representation, information management standards and protocols, and available BIM services for knowledge sharing and reuse.

Moreover, the second step of the critical analysis is the core of the review of the HBIM model, as well as diagnosis and performance assessment features. As starting point, the identification of such tasks in the traditional construction practices is carried out to delineate further development of the BIM approach in the building refurbishment. In addition, articles on innovative workflows in Facility Management (FM) for new buildings are considered a guide for extending the BIM vision to the existing buildings. For this reason, the selected papers regard the refurbishment workflows as traditional or BIM-compliant processes and applications of BIM for diagnostics and monitoring on infrastructure, where both academic articles and professional practice prove effective inclusion in BIM for rehabilitation. The objective is to extract the relevant aspects of traditional methods of planning and executing interventions and to identify possible answers to some revealed open issues in the HBIM specific domain.

The review of scientific and technical contributions of geometric survey, visual inspection and parametric modelling is an analysis of trends, methods and tools of parametric modelling from acquired point clouds in HBIM, as well as the level of automation from reverse engineering to HBIM. The paragraph on the implementation of diagnostics and monitoring data in BIM includes integrated applications of BIM with diagnostics and monitoring, firstly analysing literature on implementation of diagnosis and monitoring for energy retrofitting and structural reinforcement in traditional and HBIM-aided processes. The new approaches and tools are also investigated.

The critical analysis tracks the *Gaps-in-knowledge* from the current theories and practices to be solved with the proposal of *future developments*. Gaps and developments are herein discussed by the same selected criteria of diagnosis and performance assessment in Section 5.

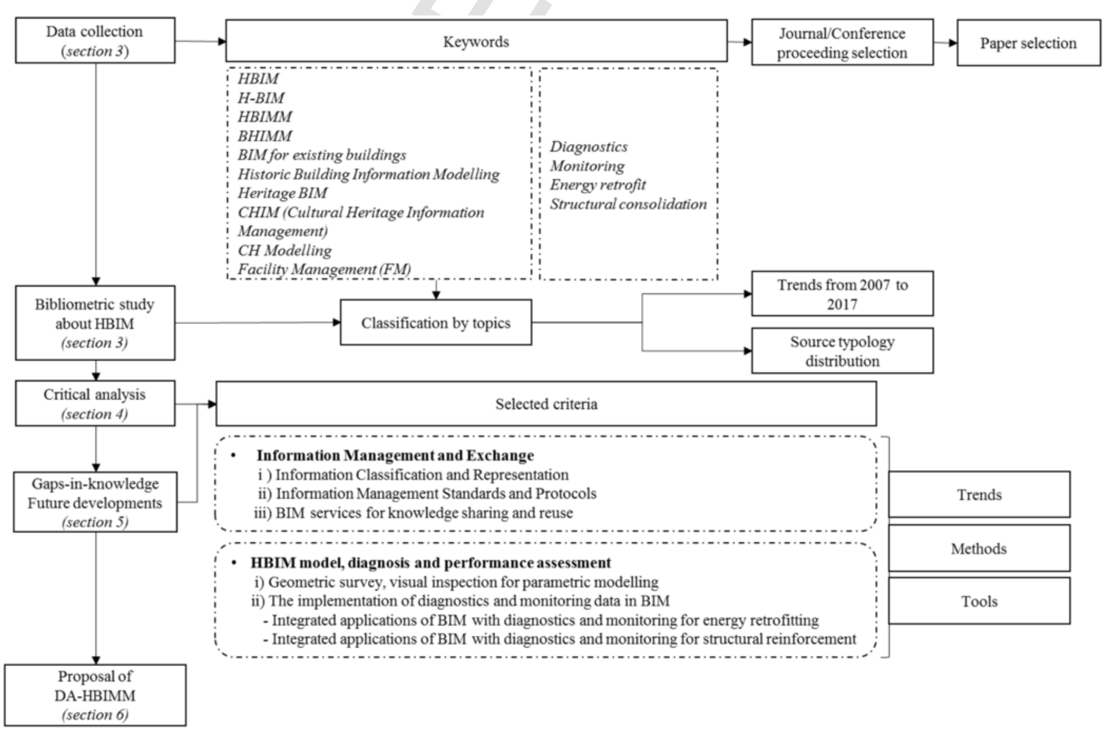


Fig. 1. Research methodology.

Following the discussion of the obtained results, a Diagnosis-Aided Historic Building Information Modelling and Management (DA-HBIMM) is proposed for data acquisition, processing, organisation and exchange techniques, focusing the attention on activities that deserve a role within the digital approach to the refurbishment process: diagnosis and performance assessment through geometric survey, traditional and augmented visual inspection, experimental diagnostics and monitoring.

3. Data collection and bibliometric approach about HBIM

According to the aforementioned methodology, the phase of *Data collection* of the scientific literature is primarily based on the research of published contributions by keywords. All the analysed projects (1) and research works (86) (concerning BIM, HBIM and diagnostics/monitoring) are then classified according to source type, namely journals, conference proceedings, white papers, regulations and books and the year, as shown in Table 1. Particularly, it was found that the papers, mostly written in 2015 (23), are mainly scientific contributions in journals (51), while the 23 works are reported in publications in conference proceedings. Moreover, a high number of papers were written in ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences (11) and in Automation in Construction journal (8).

The occurrence of the keywords HBIM, H-BIM, HBIMM, BHIMM, BIM for existing buildings, Historic Building Information Modelling, Heritage BIM, CHIM (Cultural Heritage Information Management), CH modelling and Facility Management (FM) is measured. The bibliometric approach (Fig. 2) has shown an increasing interest about the topic "BIM for existing buildings" in the last decade, mostly from 2013 to 2016. Obviously, the review about 2017 is incomplete, as papers have been written in half a year. Globally, the denomination "HBIM" emerged in 2009, is less employed in titles and keywords than "BIM for existing buildings, structures and facilities", revealing that Historic Building Information Modelling requires further development and investigations to result into a robust methodology, as concluded by Arayici et al., 2017 into their last work [9].

4. Critical analysis

Based on the selection of relevant papers, as reported in Section 3, specific methods and tools for HBIM model, diagnosis and performance analysis are illustrated in Sub-Sections 4.2. Nevertheless, a preliminary brief description of concepts, standards/protocols, methods and tools about BIM is reported in Sub-Section 4.1, in order to outline the general background and discuss some aspects in the specific field of existing buildings that will be beneficial to guide a new configuration of Diagnosis-Aided HBIMM via automating operations.

4.1. Information management and exchange tasks

The sector of FM (including refurbishment) is generally lacking adequate interoperable platforms and calls for a paradigm shift among the involved actors [4]. The problems increase when the team is involved in the refurbishment of existing/historic buildings because the effectiveness of the decisions depends on the accuracy of the knowledge of the building and its components. Traditionally, professionals use different organisational schemes and archives to handle information, with consequent difficulty and time consumption for consultation that might result in incomplete documentation.

The solution is offered by the immediate access to a centralised BIM model that integrates all information; data analysis can be graphically displayed and inserted within internal or independent databases, the latter connected to BIM instruments via ODBC or programming automated tasks [5,4].

4.1.1. Information classification and representation

The information requirements for "as-built" modelling of a historical building concern both technical information on building components and historical/analytical information [10]. The first set of information relates to materials, construction techniques, performance, conservation conditions, settlements, and maintenance instructions. The second type consists in intrinsic parametric relations between measurable data and intangible data about history, musical culture and traditions [7].

The use of BIM requires the identification of the Level of Development (LOD) and the Level of Detail (LoD) for the information in the model, with the purpose of limiting misunderstandings. The Level of Detail quantifies the details within building object, whereas the Level of Development is a degree of graphic and semantic information that can be reached for each defined objective, following the protocol of the minimum information content, its updating and the reliability of graphical content and information [11,12]. According to the American Institute of Architects (AIA) definition and protocols [1], the Level of Detail measures graphic accuracy and awareness of properties.

In refurbishment projects, the Level Of Development should not be lower than LOD 500, because BIM models must represent an "as-built" or "as-is" condition thus providing a higher degree of completeness by a geometric survey, finalised and updated with all the necessary information for management and maintenance, aiming at a certain level of automation in semantic enrichment and analysis. The graphical representation of historic buildings for refurbishment might not be smaller than scale 1:100 to reach a reliable and detailed "as-built" model with LOD G, as defined by UNI [13]. The data is collected within the database and the creation of relations among parameters allows connecting them when changed. However, when modelling architectural objects of existing buildings is the objective, understanding the level of accuracy of the geometrical parameterised objects is paramount, taking into account the complexity of the shapes. In addition, the project stage imposes fixing the information requirements of the specific LOD by defining simplifications or enrichments of the geometric models. The continuous digital flow in BIM requires the acceptance of a shared language for unique understanding and interoperability among the software products, which should classify tasks and information within a single team or networked companies. The language models used in BIM approach are exchange formats among applications, categorised in proprietary and open-source ones. Some researchers have conducted an analysis on Semantic Web technologies integrated with HBIM; the result is an ontological system for knowledge representation and management of decisions on interventions or functional activities of the architectural heritage [14,15].

4.1.2. Information management standards and protocols

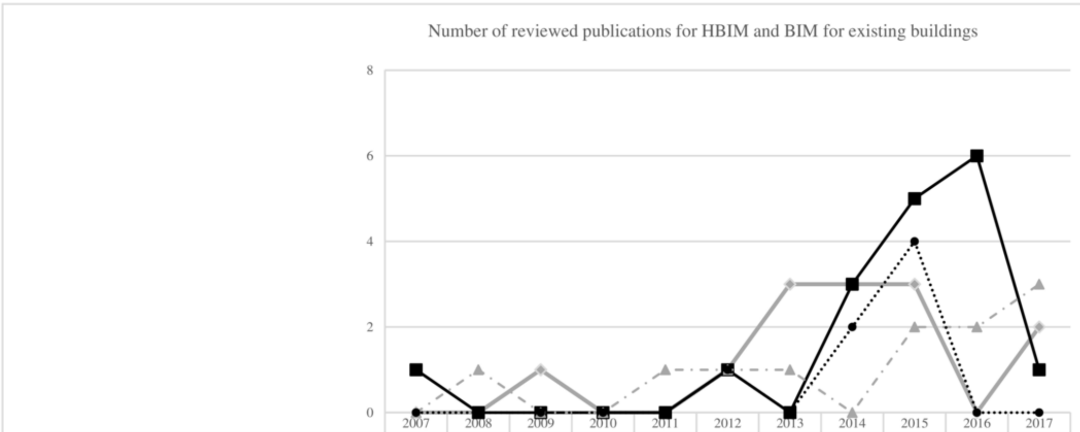
The efficient application of the BIM potential stands on the definition of the Information Management rules, depending on the association of actors involved in the refurbishment process: private or public owner, professionals and contractors. First of all, the work group must respect a strict organisation to achieve the defined objectives, without redundancy or contrasts; therefore responsibilities and duties are assigned according to the hierarchical position and reciprocal relations. Subsequently, the group cooperates to define the Information Requirements meeting the project objectives and the Information Exchange (ie) method to import and export data and information in and from the Information Model [16]. Facility Management (FM) activities are managed using Construction Operations Building information exchange (COBie), or CMMS (Computerised Maintenance Management System), EDMS (Electronic Document Management System) and BAS (Building Automation System) [17] compiled through the involved parties or installed sensors, with specific roles and responsibilities, and

Table 1
Distribution of papers reviewed.

Journals	2004	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	Total
Structural Survey		1		1						1	1		4
Automation in construction								2	4	2			8
ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences							1	5	1	3		1	11
Procedia Engineering										2	1	1	4
Journal of Construction Engineering and Management							1						1
Springer Berlin Heidelberg										1			1
Journal of Cultural Heritage											1		1
SCIRES-IT											1		1
Journal of Professional Issues in Engineering Education and Practice						1							1
Journal of Management Engineering										1			1
Springer International Publishing									1				1
International Journal of Architectural Heritage												1	1
Survey Review											1		1
Advanced Engineering Informatics										1			1
Science China Technological Sciences											1		1
Journal of Architectural Conservation										1			1
Procedia Environmental Sciences											1		1
Journal of Construction Engineering and Project Management										1			1
Energy and Buildings									1				1
International Journal of 3-D Information Modelling								1					1
Computing in Science & Engineering								1					1
Energy Procedia										1			1
Built Environment Project and Asset Management										1			1
The Open Construction and Building Technology Journal									1				1
Journal of Cultural Heritage												1	1
Visualization in Engineering											1		1
Informes de la Construcción								1					1
ASCE-Computing in Civil and Building Engineering											1		1
GeoResources Zeitschrift											1		1
International Journal of Sustainable Development and Planning												1	1
White paper													
Autodesk						1				1			2
Leica Geosystems									1				1
World Transit Research									1				1
Web site Smarly.de									1				1
Conference Proceedings													
Proceedings of CAA		1											1
International Conference on Construction in Developing Countries					1								1
IEEE Industry Applications Society Annual Meeting					1								1
Third International Conference Remote Sensing Geoinformatics Environment										1			1
Int. Work.Remote Sens. Disaster Management										1			1
MATEC Web Conference											1		1
International Conference on Quantitative Infrared Thermography							1						1
Lecture Notes in Computer Science									2				2
eWork and eBusiness in Architecture, Engineering and Construction - Proceedings of European Conference on Product and Process Modelling, ECPPM									1		1		2
International Conference on Virtual System & Multimedia (VSMM), IEEE			1				2				1		4
Proceedings of CIB WT8 Conference										1			1
DigitalCommons@University of Nebraska - Lincoln						1							1
European Workshop on Structural Health Monitoring - EWSHM							1						1
International Conference on Computing in Civil and Building Engineering									1				1

Table 1 (*Continued*)

Journals	2004	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	Total
International Symposium on Virtual Reality, Archaeology and Cultural Heritage	1												1
Konferanse “Løfter Bae-Næringen”										1			1
WIT Transactions on The Built Environment										2			2
Regulations			1						1	1		1	4
Books						1						1	2
Total per year	1	2	2	1	2	4	6	10	16	23	13	6	87



	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
HBIM, Historic Building Information Modelling	0	0	1	0	0	1	3	3	3	0	2
BIM existing buildings, facilities, structures	1	0	0	0	0	1	0	3	5	6	1
Cultural Heritage Modelling, CH modelling, Heritage BIM	0	1	0	0	1	1	1	0	2	2	3
BIM Facility Management, maintenance	0	0	0	0	0	1	0	2	4	0	0

Fig. 2. Trend of published papers and contributions in BIM for existing buildings, from 2007 to 2017.

providing maintenance information [5]. The contents of the files are established by the Information Requirements (IR). The attributes inserted in this structure might be also mapped in XML and IFC format [18]. However, the Information Exchange (IE) COBie and its related Model View Definition (MVD) are partially adapted for inspections, monitoring and maintenance of existing buildings, chiefly historic buildings [5]. In fact, COBie collects data related to the decomposition of spatial and technical information acquired throughout the design and construction, the environmental issues, the safety and the building operational phase for new buildings. The BIM model can operate as a single archive for consultation and query of such data stored within FM systems and computable by customised databases or automated task programming.

4.1.3. BIM services for knowledge sharing and reuse

An effective information management generates accurate documentation about existing buildings, containing requirements and criteria aiming at automating performance assessment and decision-making on the refurbishment. In this regard, the use of digital documents gives the opportunity to upgrade and expand the data, with savings of long-term resources. Therefore, different BIM services of knowledge sharing and reuse were analysed. A BIM model can function as a web database that documents the inherent attributes of the parametric architectural objects. Their inclusion in the shared object library allows knowledge of the tectonics of assets, materials, building components [19,20]; additional information related to intangible data such as local culture and historical memories, as well as maintenance program. Moreover, a navigable timeline can also be created by introducing temporal parametric data to represent events and actions that occurred over time [7] and current decay situation. It is evident that the amount of information is enormous, and problems of data management in an extremely sized file can be solved with the BIM repository, in which building model is used as coordinating centre, synchronised to share data among different applications and databases. The BIM repository is a server system or a database that collects the entire set of objects data, useful to facilitate the information management. Its capabilities (queries, handover, updating and management) allow filtering only data related to the planning phase to be conducted [1], thus limiting the data size and generating linear data flows. Currently, further technologies are spreading for digital information about the historical and archaeological heritage [21,22]: Virtual Reality (VR) and Augmented Reality (AR). A VR environment can be created with three-dimensional reconstructions by laser scans and photogrammetry (to represent the actual state), or navigable BIM models in order to present future/virtual scenarios. When used in refurbishment of the built heritage, VR also improves the visualization of representative data, with the possibility of interacting within the simulations [21,22,23,24]. The interactive activities with VR permit querying exterior and structural data, proper settings, internal relations, information, tags, etc. Experimental projects have been developed for storing information in freeze models of investigations and preliminary analysis on existing buildings, browsed as digital documentation through Virtual Reality technology. Such investigations could be further improved by remote visualization of detected and analysed decay patterns and pathologies; an ongoing approach in digitising and sharing information of the cultural heritage, above all with difficult accessibility, is managing diagnostic data through a touchless system for Augmented Reality [25]. The AR technology also allows the representation of the alternative scenarios of the project; the difference with the VR is that the user interacts - asking computer-generated data - on a real-world scene [20,26,27]. The use of digital models implies the management of upgraded Big Data, causing difficulties while navigating the model. The online BIM repository could be connected to the AR environment via web service-oriented architecture (SOA) to create the so-called BIM-cloud [28]. Another technology for knowledge sharing and reuse in BIM are Radio Frequency Identification (RFID) and the Internet of Things. When Volk et al., 2014 [5] analysed the level of integration of RFID and BIM, open issues on difficult installation, limited interoperability, level of detail and automation of elaboration process for built asset management were identified. Despite this being an underdeveloped topic, some studies have been carried out. The employment of RFID devices has been investigated in a pilot project for Facility Management and Operation to connect BIM to non-value added tasks such as search, access and validation of information in maintenance records, specifications and operational manual, for time saving [29]. Generally, RFID tags are combined with laser scanner with the aim of creating complete 3D models of the built environment to be tracked during the construction phase, on waste and resource (materials, workers, etc.), as well as handover in the construction site [30]. Recently, Zhang and Bai, 2015 [31] developed an automated and graphical approach to structural condition monitoring based on RFID devices that communicate displacements to a BIM computing environment. The Internet of Things (IoT) works via cloud databases connected to BIM model of dynamic energy [32] and structural monitoring, as well as team communication.

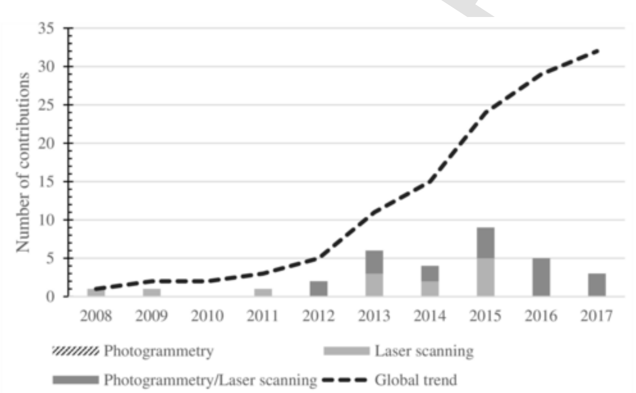
4.2. HBIM model, diagnosis and performance assessment

4.2.1. Geometric survey, augmented visual inspection and parametric models

The analysis of the current literature on BIM for existing buildings or HBIM (H-BIM) proves an increasing number of publications of parametric modelling starting from three-dimensional reconstructions via reverse engineering methods and visual inspection techniques, thus combining traditional and innovative geometric surveys, as shown in Fig. 3. Since the first applications of BIM for existing buildings [33,2], the generation of realistic BIM models was carried out combining prior available drawings and laser scanning techniques. Dore et al., 2012 [34] proposed the generation of 3D cultural heritage models from laser scanning and photogrammetric acquisitions, due to their latest developments which provided some solutions to limitations in geometrical surveying.

The first step is the acquisition of complex geometries as point clouds via laser scanning (LiDAR - Light Detection and Ranging) or photogrammetry/video-grammetry in terrestrial and aerial configurations respectively, for territorial and/or detail scale acquisitions. The required functionality of the BIM model influences the LoD, and subsequently, technical decisions about data capture, processing and BIM model creation [5]. The 3D laser scanning belongs to the category of *Active* Reality Capture methods for acquiring discrete data, while photogrammetry is a *Passive* image-based alternative. According to survey objectives, the remote sensing is performed with equipment installed on space probes, satellites, and aircraft, Remotely Piloted Vehicles (RPVs) or Unmanned Aerial Vehicles (UAVs). Recently, remote sensing is less performed with conventional aerial platforms because of the widespread diffusion of UAVs applications, firstly applied in the military sector and then for civilian purposes [35]. The devices installed on UAVs ensure the acquisition of inaccessible spaces because of the height (i.e. roofs) or restricted dimensions [35]. In addition, the acquisition of the building elevations with satellite images - more suitable for land monitoring - would be affected by atmospheric phenomena and restriction of investigated areas because of the nearly parallel observation cone. Likewise, the use of terrestrial laser scanner or photogrammetric devices would not acquire parts of the building due to their short distance or presence of objects impeding the view [36].

In the latest investigations, research teams stretched out to combine LiDAR and photogrammetry for 3D BIM modelling to solve some critical factors. One is the detection of transparent, reflective or dark surfaces [37,5], via photo-shots that scan surfaces with different light exposure and unfavourable optical properties. The other consists of intensive data processing and three-dimensional modelling of scanned point clouds in terms of expensive and powerful technical resources (equipment, hardware, software) and time-consumption in data management [5]. Indeed, laser scans and point cloud processing require different tools than 3D photo-reconstruction. After registering each scan in the Project reference system, by means of the proprietary LiDAR software, they are managed and edited in specific software tools for point cloud processing and modelling, such as 3DReshaper® or ReCap Pro®, as file *.pts., *.xyz, etc. The alignment of partial point clouds can be generated via ICP (Iterative Closest Point) algorithm [38,39], or within HBIM plug-in prototype by Dore et al., 2012 [34] which employs embedded scripting language to align segmented point clouds in their true geo-reference. On the other hand, the 3D photo-reconstruction uses the same tools for photo alignment and matching, point cloud generation, optimisation and 3D meshing. Some tools for photogrammetry solution are Photoscan Agisoft®, ReMake® and ReCap 360 Autodesk®.



	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Photogrammetry										
Laser scanning	1	1		1		3	2	5		
Photogrammetry/Laser scanning					2	3	2	4	5	4
Total=32	1	1	0	1	2	6	4	9	5	3

Fig. 3. Trend in parametric modelling from acquired point clouds in HBIM methodology.

The generation of point clouds from aligned and stitched image starts with the application of the Structure for Motion (SfM) algorithm within dedicated tools which estimate the three-dimensional environment from the two-dimensional image sequences that may be coupled with the local motion signals [36]. Among other tools, ReMake is more user-friendly and easy to use, as it does not include the manual stitching correction property to assist the pattern-matching algorithms. This method permits the detection of common points within images to align and calculate the depth of the scene, setting a number of pixels with same colour and distance. The processing time from sparse to dense point clouds depends on the considered amount of points. The measurement errors, that can occur with photogrammetry, due to its function algorithm of image matching that is sensible to object movements, decrease by employing strict acquisition plans, professional equipment and accurate programs for photo-modelling [40]. Each software product has different algorithms to neglect the background noise.

After checking the adequate alignment of scans and shoots with Cloud Compare software, computing the point cloud file by the RANSAC (RANdom SAmple Consensus) algorithm, the following step is the point cloud cleaning with the elimination of all the unusable parties. Before the actual BIM modelling, the representation of geometry and texture, in order to achieve a photo-realistic appearance occurs, with the generation of 3D meshes and textures (*.obj) from optimised discrete-based or image-based data point clouds, forming a multi-triangulated surface. Nowadays, the tools for 3D photo-reconstruction develop along with cloud computing to ensure heavy processing without a powerful machine (i.e. ReMake® and ReCap 360 Autodesk®). In fact, the available software tools archive the selected photos in the A360® storage drive, to be converted in 3D reconstructions by cloud-driven algorithms. Some methods for generating 3D meshes from complex point clouds already exist. The most robust algorithms for 3D mesh reconstruction from point clouds are Poisson and Ball Pivoting surface reconstruction. Poisson surface reconstruction is used to match the best-fitting surface of a dense point cloud, estimating the most suitable shape to reduce deviation error among mesh and the best approximate shape and local curvature [41]. Subsequently, optimised methods interpolate the missing points, ensuring a more detailed reconstructed surface. Dense point cloud is also the input for the surface reconstruction via the Ball-Pivoting algorithm, involving considerable time for processing and intensive use of the memory, two issues that might be solved with the integration of further processing algorithms (i.e. Digne algorithm and hole filling, varying ball radii).

The mesh noise may be reduced, firstly, via decimation that decreases the number of vertexes and increases the triangle size, then via densification, reducing the triangle size. This method is appropriate when the cloud contains a high number of points [41]. After the first step, the filling of holes and the refinement of the mesh is performed via smoothing operations. However, the acquisitions of surfaces with decorative elements (laborious activity of smoothing surfaces) and complex geometries, especially in huge buildings, are still very time consuming.

Cho et al., 2015 [42] experimented with the generation of a BIM model - containing real geometrical and thermal information - starting from the 3D mesh, for energy simulation software products. The discretised mesh is created from the point clouds as acquired by a hybrid system consisting of thermo-camera, digital camera and laser scanner (laser, RGB-D and thermo-graphic cameras). The modelling of an entire building requires the elaboration of meshes for each single item as *.obj [41].

As BIM is an object-oriented methodology, the recognition and segmentation of each building component, within point clouds or meshes, represents the fundamental steps that can be performed manually, semi-automatically or automatically through robust algorithms of object recognition and point cloud/mesh segmentation [5]. Among the most consolidated and approximated methods, some already analysed [5], researchers experimented with the plane segmentation algorithm for existing buildings with plane surfaces [43,44], optimised by RANSAC algorithms against outliers and high plane-detection rates [45]. Other algorithms, investigated for identifying and classifying objects within meshes or point clouds, consist of the colour recognition with spectral imaging [46] and shape recognition [47].

Prizeman, 2015 [48] proposed some principles for a place recognition, detecting the construction type from historical photographs and data capture, in order to additionally consider the building components with curved shapes (such as curved and decorative ceilings). Indeed, the most relevant criticality is the automation in modelling complex and varied shapes, eventually decayed, from point clouds or meshes [49].

Macher et al., 2014 [50] proposed to convert point clouds into meshes only for complex surfaces and high level of detail.

It is possible to extract geometric data and textures by the polygonal meshes obtained from photo-modelling and point clouds; both pieces of information are available for modelling the building and its parts within software tools for solid reconstruction and representation. The three-dimensional models elaborated with the SfM algorithms and laser scans can be used to measure dimensions, analyse materials and structural characteristics, as well as to locate decay patterns and pathologies from the photographic acquisition.

Reverse engineering results should be converted into parametric objects of building components in order to contain geometric, topological and semantic attributes. This flow switches from the reverse engineering process to the "point-to-BIM" or "scan-to-BIM" [19]. The modelling of parametric objects adds complexity to the reconstruction of three-dimensional meshes, since software tools are not yet developed enough to automatically recognise and convert objects within meshes in BIM objects.

Another method is the direct modelling of the parametric objects in Revit, by employing point clouds not converted in polygonal meshes thus avoiding loss in terms of details, data quality and accuracy [51,52,38]. The research works by Oreni et al., 2014 [51] and by Barazzetti et al., 2015 [52] concern the generation of non-Uniform Rational Basis-Spline (NURBS) fitting with boundaries points of clouds. Quattrini et al., 2015 [38] followed this method to reduce number of steps, but they recognise that features for automatic extraction from point clouds is required within the available software tools. This generates a challenge in semplifying the existing morphologies and employing ReCap as point cloud-processing engine. Therefore, it is possible to employ some add-ons, for instance "Scan to BIM®" or "Edge-wise®", to support the modelling of architectural objects free shapes from point cloud to mesh after automatic recognition. In fact, such operation could be useful in cultural heritage modelling [53]. These tools permit the direct conversion of elements with primitive shapes into parametric objects (walls, pipes, etc.).

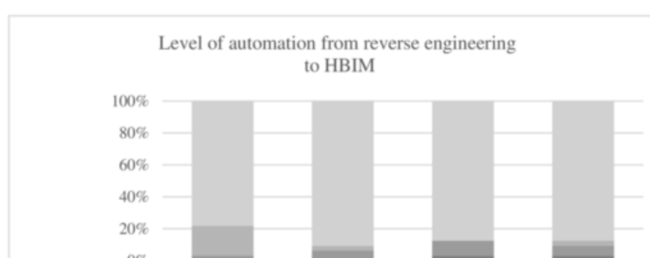
The diagram of Fig. 4 illustrates the level of automation from reverse engineering to BIM. The study has been carried out comparing contributions in which georeferencing automation, object recognition/segmentation, conversion from point clouds to BIM objects (pointclouds-OBIM) and mesh to BIM objects (mesh-OBIM) are specified. The analysis involves 32 contributions presenting several case studies for HBIM from point clouds acquisition and processing. Some works do not declare the degree of automation or the performed methods. The automatic georeferencing of point clouds into BIM modelling tools is mostly carried out (18,8%) by GPS devices and geodetic grids during acquisitions. The object recognition and segmentation still succeed as semi-automatic process (6,3% vs 3,0% of direct scan-to-BIM tools), because customised algorithms are not widely implemented into available software tools and they are related to plane/primitive shapes, while historic buildings present complex geometries. The use of point clouds or meshes as input for parametric modelling (pointcloud-OBIM and mesh-OBIM) presents the same total frequency as manual operations (3,1%), semi-automatic occurrence is higher because the automation is considered by authors as a smaller number of steps, within the processing of almost plane shapes. Further investigations are needed for BIM generation of curved and decorated surfaces. Therefore, the most used technique is still the manual modelling of parametric objects using three-dimensional reconstructions as geometric reference [54]. Recently, companies of BIM platforms have been collaborating with laser scanner manufacturers in order to speed up the conversion of point clouds into intelligent BIM models [55]. Generally, complex and irregular geometries, accurately detected with laser scans or photogrammetry, are modelled using Boolean operations (extrusion and revolution), or through NURBS [54].

Fig. 5 summarises the analysed processes from data acquisition to BIM.

4.2.2. The implementation of diagnostics and monitoring data in BIM

The development of refurbishment interventions involves high levels of knowledge thorough pre-diagnosis of degradation phenomena of materials and components, and diagnosis of causes producing anomalies, settlements and pathologies, to ensure effective improvements and being less invasive.

Depending on the type of intervention, specific and accurate information is required whose reliability depends on matching outcomes of pre-diagnosis and outcomes of diagnostic activities and monitoring.



	Georeferencing	object recognition/ segmentation	pointcloud-OBIM	mesh-OBIM
Undeclared	78.1	90.8	87.5	87.5
Automatic	18.8	3.0	0.0	3.1
Semiautomatic	3.1	6.3	9.4	6.3
Manual	0.0	0.0	3.1	3.1

Fig. 4. Level of automation from reverse engineering to HBIM.

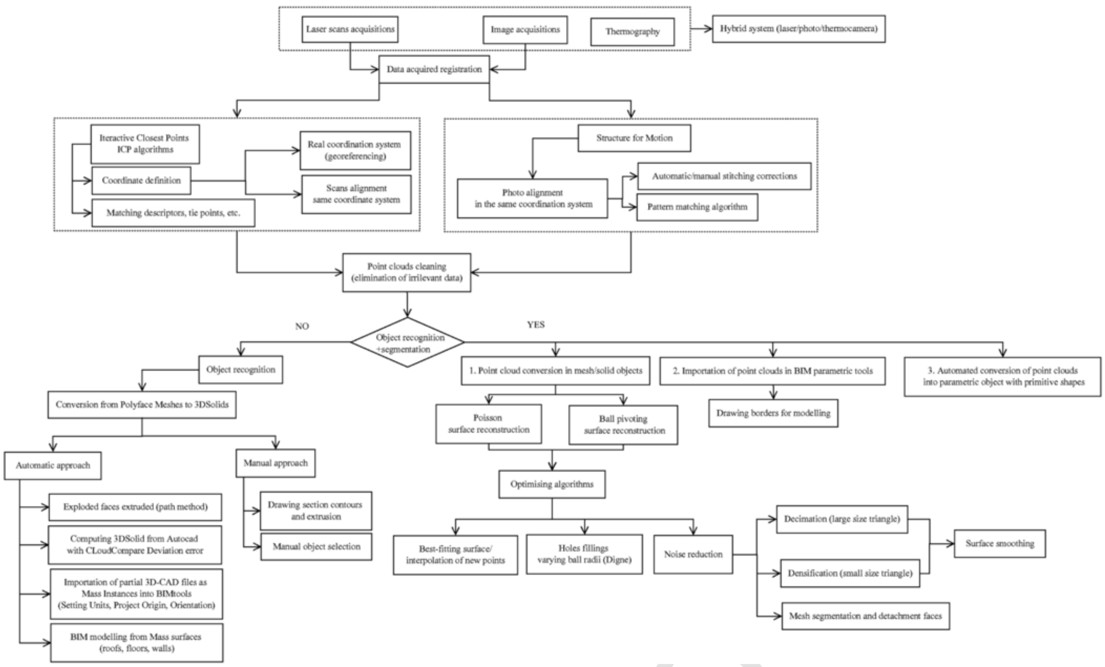


Fig. 5. Processes from data acquisition to BIM.

The pre-diagnosis is composed of some sub-activities such as visual inspection, historical and archival research, and direct survey in order to gather preliminary data on geometrical and material characteristics, construction techniques, previous interventions, and to detect damages.

Such process is relevant in case of structural reinforcement and energy retrofitting. The objectives of the refurbishment are defined according to the identified residual performances of the building and its architectural, structural and technical components, with regard to variable environmental factors (indoor microclimate, outdoor climate, occupancy density, geological conditions, etc.).

The complexity of these tasks calls for in situ and laboratory tests to assess quality and deterioration of materials and components. All the gathered information might be inserted into the parametric objects to be consulted and queried for planning refurbishment and conservation measures of the Built Heritage [6].

Therefore, the review of the latest scientific contributions and professional works about HBIM/BIM for existing building is herein further developed in order to outline the interest in introducing diagnostics and monitoring in BIM models, in order to give a contribution to support the decisions.

As Volk et al., 2014 [5] underlined, a complete assessment of existing buildings might be performed combining data capturing with diagnostic methods (ground penetrating radar, radiography, sonic tests, etc.) and installed tags. Thus, this literature review aims to detect gaps in condition assessment of existing buildings and general trends in diagnostics and monitoring within BIM. The final goal is to overcome the gaps and address some improvements in the refurbishment sector.

4.2.2.1. Integrated applications of BIM with diagnostics and monitoring for energy retrofitting The energy retrofit is defined by Khodeir, 2016 [56] as building upgrading with positive environmental performances and economic impacts in terms of reduced energy consumption and CO_2 emission.

The preliminary phase consists of assessing the existing building by collecting data and information about the material decay, identifying the residual performance and detecting building elements that necessitate upgrading.

In this perspective, a fundamental requirement for defining a robust methodology is the clarification of information/data and methods of acquisition, integration and reuse for energy simulations within the BIM methodology.

The most common approach for energy retrofit is simulating the current situation and the possible alternatives, trying to limit inaccuracies [57]. The current situation is generally modelled by assigning standardised thermal parameters to the building components. The use of such parameters, selected within software databases or from the literature, involves some estimation errors of the actual energy consumption of the building during the operational phase. Therefore, the measurements of current thermal performances [42] and subsequent calibration [58] are relevant. Energy retrofits on existing buildings are generally performed with BIM tools, also to determine relative financial savings, in two phases that involve different information:

- the analysis of energy performance (Building Energy Performance Analysis);
- the control and monitoring of energy demand, combined with Building Energy Management Systems (BEMS) and Building Automation (BAS).

Among 19 analysed papers and works on energy retrofitting, seven of them illustrate acquisition methods of current building conditions (thermal parameters, environmental measurements) for energy simulation. Four research papers have been carried out in other domains; however, diagnostics and monitoring are still not related to HBIM for energy retrofitting. Herein, an analysis of these methods, not yet thoroughly investigated on historic buildings, is proposed (Table 2) in order to identify possible solutions for Historic Building Information Modelling, when the degradation of the materials compromises the energy performances.

The analysed scientific contributions, integrating Ilter and Erger, 2015 [4] and Cho et al., 2015 [42] works with further research papers, show new approaches (Fig. 6) to optimise the results of energy simulations using: 1) measured parameters of humidity and temperature with wireless sensors networks (WSN) and 2) transmittance properties of building components evaluated with thermo-graphic surveys. In this way, current thermal conditions and actual heat transfer capacity are

Table 2
Analysis of literature on energy retrofitting and methods of thermal data/information capture for existing buildings, HBIM and other applications.

	Existing buildings	BIM	HBIM - similar denominations	BIM	Other applications	BIM
Thermal properties diagnosis	[59]	•	–	–	–	
	[42]	•				
	[60]	•				
	[61]	•				
Monitoring humidity, temperature, energy consumption, etc.	[62]	•			[63]	•
	[64]	•	[32]			
	[65]	•	[66]			•
			[67]			

captured and inserted into BIM as properties influenced by the deterioration of the materials [42].

The thermal transmittance values, calculated once the temperature variations on the surface are known as reported in thermic images, are mapped and associated with parametric objects through importing/exporting of gbXML format - Green Building extensible mark-up language [59,42], which also allows automatic updating of the BIM model. The use of measured parameters, rather than standardised ones, ensures greater reliability of the energy analysis with a reduction of inaccuracies [60].

On the other hand, the second approach to energy simulation exploits the Virtual Model Retrofit platform to manage the design decisions of energy retrofitting by integrating real-time environmental data (temperature, humidity and CO2), faults detected in technological systems (HVAC), requests and perceptions from the occupants.

In this procedure, the BIM model is used in the platform as a database to retrieve preliminary data to collect results for future energy simulations during the entire life cycle, facility management, and access to the smart grid [62].

Alwan (2016) [61] proposes a prototype protocol, Housing Building Refurbishment Plan (HBRP), which concerns the management of inputs within the BIM model, made available for maintenance and refurbishment of the existing housing stock. The Protocol affords for connecting the BIM model with an Asset Management tool, Construction-Operations Building Information Exchange (COBie), so that the thermal images, captured during continuous monitoring, can be collected. The researcher recognises the potential of infrared thermography as a diagnostic tool for degradation of building components (lack or damage in insulation layers) involving heat loss; therefore, he confirms the need to integrate the results into the model, avoiding the analysis as independent and supplementary task.

The integration of BIM and BEM demonstrated to be useful in evaluation of the impacts on energy needs and costs for each defined refurbishment strategy [68]. In a long term perspective, the adoption of BIM for BEM in existing buildings gives the opportunity to record the current situation, the maintenance history and the real performance, as outcomes of surveys and analysis into a BIM model [69]. BIM can also support operation and control of BEMS to ensure thermal comfort conditions and to optimise the performances of the technological systems [63,64], by activating Building Automation (BA) devices installed. In BEMS, the automatic processes of acquisition, comparison and analysis of real-time energy data are based on the use of WNS, which has recently become smart through the Internet of Things. For instance, the Cyber Physical Systems (CPS) are used to connect the physical environment in software and hardware platforms through sensor networks to support the decisions [32], in order to reduce energy consumptions and CO_2 emissions. The information captured in real time (temperature, humidity, etc.) appear in the BIM model [66]. The cloud-based platforms manage the distribution of the energy resources at the urban scale, within a smart grid [67].

Another open issue regards the possibility to import the automatically extracted building elements from the point cloud, into the energy simulation software, as analytic models in order to reduce time in the modelling process, as well as to improve data accuracy and integrity. In addition, a general method of object recognition and extraction for as-built modelling is needed, including different types of existing building technologies [43].

This information could be utilised as criteria and sub-criteria of a multi-criteria and multi-agent analysis or inputs in deep learning algorithms for decision-making support of the design alternatives.

In this direction, sustainability properties and energy performance parameters might be employed to assess the best solutions and interventions for building redevelopment (or refurbishment). Pavlovskis et al., 2017 [70] introduced the energy efficiency, by energy category, as environmental criterion within a Multiple Criteria Decision Making (MCDM) approach.

Zainudin et al., 2016 [71] utilised the BIM methodology for assessing the Adaptive Reuse Project of a demountable Traditional Malay House (TMH) by the Leadership in Energy and Environmental Design (LEED) guidelines and the Malaysia's Green Building Index (GBI) rating assessment. This consists of evaluating building orientation and daylight performance by simulations in Autodesk Green Building Studio, taking into account some categories such as sustainable sites, water efficiency, energy and atmosphere, materials and resources, indoor environmental quality. The considered parameters for daylight evaluation include floor area, window area, window geometry, visible transmittance, known materials, and window height. The purpose is the selection of the alternative with the highest rating considering energy costs, water needs, energy consumptions and use of renewable energy, reduced use of materials, preferring recycled ones, reduced carbon footprint and waste, managing site and logistics.

Information exchange succeeds via connection of BIM model and external databases with energy simulation applications. Table 3 illustrates some reviewed works that develop workflows within DB, clarifying DB application, case study, AEC phase for adoption and functions. This analysis includes papers not related to HBIM topics.

4.2.2.2. Integrated applications of BIM with diagnostics and monitoring for structural reinforcement Further analysis involves risk assessment and detection of criticalities/vulnerabilities of the structural behaviour for accurate projects of conservation and reinforcement. This phase consists of planning and executing the diagnosis, which generally includes in-situ inspections, laboratory tests, and structural (static and dynamic) health monitoring, even though control of environmental factors (temperature and humidity) affecting the building response.

Firstly, in situ investigations consist in visual inspection, whose results might be recorded mapping anomalies, deformations, cracks, pathologies and humidity patterns. A method for decay mapping consists of linking CAD drawings or views [77] [41] as 2D lines and textures within objects undergoing obsolescence and settlements with the

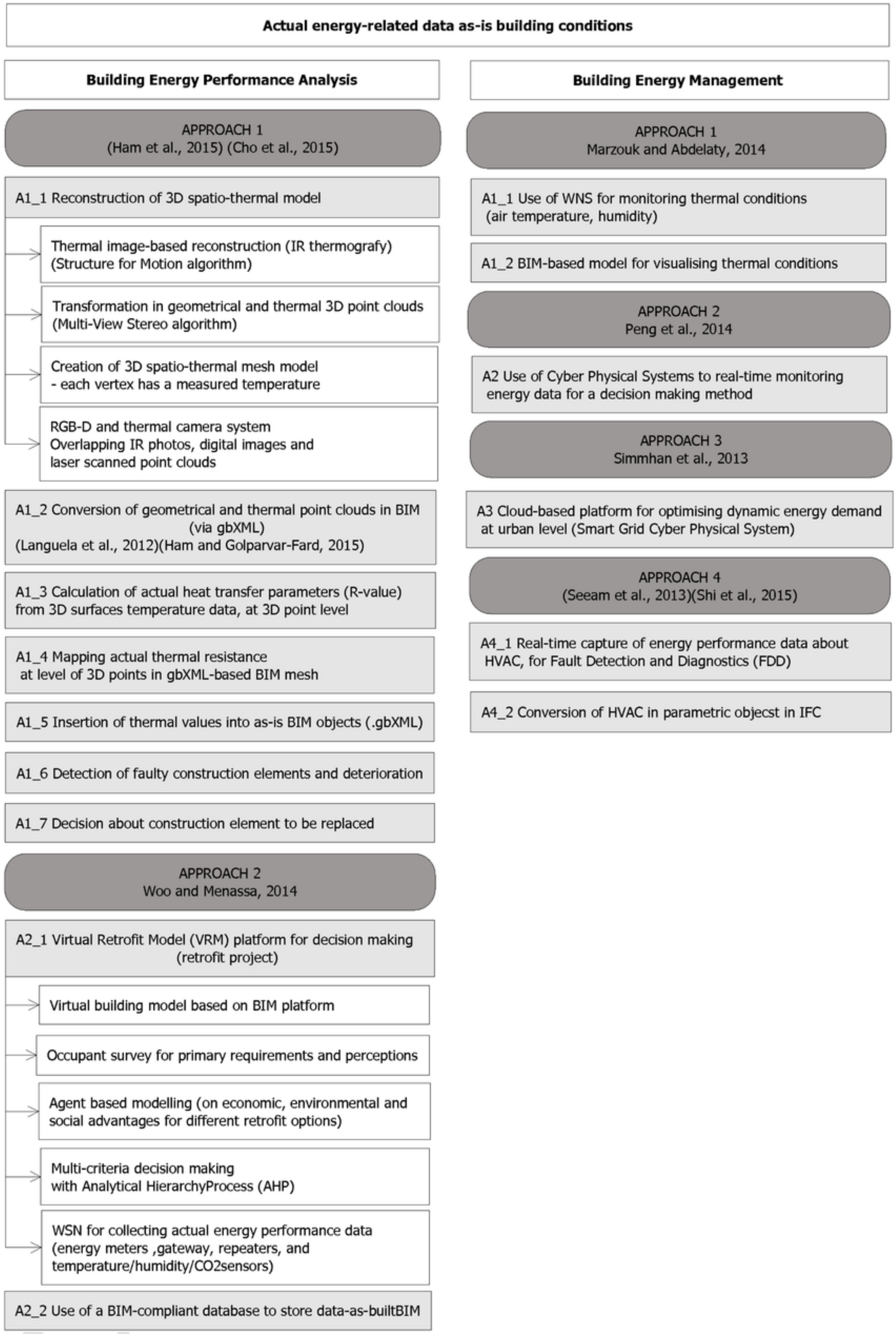


Fig. 6. New approaches for optimising energy simulations.

consequence of losing the three-dimensional geometry and creating time consuming workflows to report them in each view.

In recent years, preliminary in situ investigations have benefitted from the use of visual data for diagnostics and monitoring of buildings and infrastructures. The visual data is similarly acquired by photo-cameras also installed on UAV systems. These techniques allow monitoring deformations and cracks [78]. In fact, the combination of digital images and point clouds can contribute to the semantic en-

Table 3
BIM model and external databases as tools for energy simulation applications.

Authors	External database	Case studies	Phase	Functions
Kassem, 2015 [72]	Microsoft Excel®	Northumbria University's city campus, UK	Refurbishment Maintenance Operation Asbestos removal	Space information (i.e. for room finding), integrated asbestos register, emergency equipment, escape routes, accessibility and essential maintenance, fault reporting, development and refurbishment, option generation, and assessment of building performance.
Woo and Menassa, 2014 [62]	Microsoft Access®	TIC building with solid masonry structure (1913), Wisconsin County Research Park (USA)	Energy retrofit	Transfer of up-to-date energy information from wireless sensor network into the Revit model using DB Link, a Revit API (Application Programming Interface).
Sampaio and Simões, 2014 [73]	Microsoft Access®	Small fraction of real estate development in Cascais, near Lisbon, Portugal	Maintenance	Inspection sheet: anomalies, causes, solutions and repair methodology detected on building components. It is connected to a User Interface created with Visual Basic.
Ham and Golparvar-Fard, 2015 [60]	Updated databases of actual thermal properties	Existing residential building (early 1980s); this approach can be used for new buildings	Building energy retrofit	Recording actual thermal properties of BIM elements to estimate the time series trend of thermal characteristics of building elements and their impact on the energy load.
Murphy et al., 2013 [19]	Users database storage created with Ruby® on Rails and Javascript	European classical architecture components and parts	Conservation, restoration HBIM	Uploading of ortho-image or segmented point cloud.
Dong et al., 2014 [74]	PostgreSQL® Database connected with the BACnet (Building Automation and Control networks) module in BCVTB (Building Control Virtual Test Bed)	Recruit barracks, BIM enabled information infrastructure for FDD (Fault Diagnostic and Detection)	Operation Building Energy Management	Handover and storage of dynamic information (flows, humidity, temperature, etc.) acquired in real-time by physical sensors within a Building Energy Management Systems (BEMS) in building, and management of static information about building geometry, envelope's thermal performance, HVAC equipment properties, building occupancy, etc.
Gerrish et al., 2015 [75]	SQL server	BIM as lifecycle building performance management tool	In-Use performance	Storage of historical time-series performance data about energy consumption, air temperatures and equipment performance.
Wang et al., 2011 [76]	BEDEC database (Life Cycle Assessment LCA)	An university campus	All	Storage of embodied energy and CO2 emissions associated with building materials, considering raw materials supply, transport and manufacturing.

richment - manual, semi-automatic, or automatic – of three-dimensional models, including geometric data, visual survey of the conditions and connections among building components.

Ham et al. 2016 [78] have been trying to improve the modelling techniques for a complete "as-built" and "as-damaged" information model. Their research highlights the possibility of generating a three-dimensional map of buildings damaged by earthquakes by acquisitions by RGB-D sensors and 3D rotating scanners [72] [79]. In addition, images can be used to identify and locate crack patterns on elevations [80]. The same techniques have been used to evaluate the structural damage of infrastructures [78]. Ye et al. 2014 [81] have developed a machine learning process to classify damaged buildings based on properties recognised by images. Despite evident potentialities, these activities have not yet been integrated into the BIM methodology in a complete and effective way. The next step is performing in situ tests, after accurate planning. For this purpose, papers on management of structural/technical diagnostic tests and monitoring within BIM approach have been studied, considering the investigation of existing buildings and infrastructure fields (Table 4).

Fig. 7 presents five publications on diagnostics and monitoring in BIM for structural refurbishment of existing buildings, rehabilitation of infrastructures and general applications, from 2013 to 2016.

The analysis shows an increasing research interest in diagnostic and monitoring for structural reinforcement in BIM. However, it should be noticed that the topics are still underdeveloped in the refurbishment domain; actually, among 6 contributions, out of 87 reviewed papers, none is applied within the HBIM methodology.

Nevertheless, as tested in the infrastructure domain, BIM demonstrated great capability in collecting a variety of data, from different sources and analyses [86].

There is an analogy between rehabilitation projects of road networks and refurbishment of the built heritage, namely the assessment of the existing conditions before the interventions; this assumption explains why the infrastructure field has been considered. In fact, in both cases, the design should take into account constraints from the morphology of the existing structures and spaces, as well as the regulatory requirements. Some northern European companies (Vianova, Norway and Plowman Craven, UK), experts in onsite measurements, have already undertaken some procedures to digitalise the properties detected with radar techniques, processed with proprietary software tools and comprised in CAD and BIM tools. In particular, the Norwegian buildingSMART chapter works with various infrastructure construction companies on the development of parametric modelling including the results of radar surveys [82]. In this way, it is possible to model the pipework below the road surfaces according to significant information on layout and position.

Among the research works related to BIM to evaluate the structural behaviour, Crespi et al., 2015 [84] marginally address the topic "diagnostics" (semi-destructive and non-destructive tests) for material-constructional characterisation of Castel Masegra (Sondrio, Italy) before performing the structural analysis by the Finite Elements Model (FEM). The thermal images have revealed masonry degradation by monitoring surface temperature and humidity in areas, otherwise inaccessible. Additionally, the semi-destructive tests with single and double jacks have been performed to estimate the masonry stress and the actual stiffness values. Moreover, the masonry stratigraphy and thickness, and the typology of the foundations have been identified by local coring. The thickness of the vaults was evaluated by removing some portions of the finishing layers. However, they do not illustrate the methods of codifying, inserting, using and managing the diagnostic information (values

Table 4
Management of diagnostic tests and monitoring within BIM approach.

Diagnostics	Objectives	Existing building	Infrastructure	General application	Open issue	Observations
Radar techniques	Detecting and modelling pipework below road surfaces, with information on layout and position	–	[82]	–	Uncertainties in interpreting results	Aggregation of multiple types of data from different sources within a single reference model generated into BIM environment for accurate and rapid investigation
	Damage survey and diagnostic investigation for Building Condition Assessment	[83]	–	–	Sharing information about diagnostic survey in a unique model	Data sharing via: 1. database connections to the DBMS (DataBase Management System), employing the Revit BIM model as master of data source. 2. web services and cloud-based BIM applications, together with VR and AR
Weakly destructive and non-destructive tests (thermo-graphic inspection, flat jack, core)	Material-constructive characterisation	[84]	–	–	Missing explanation of information exchange from Building Condition Assessment to FEM (Finite Elements Model)	Employment of investigations supports testing model reliability, with calibration of hypotheses
Monitoring	Objectives	Existing building	Infrastructure	General application	Open issue	Observations
Structural Health and Safety Monitoring via RFID BT	Displacements and alarms	–	–	[31]	Development of method for other instrumentation, also with direct contact, for structural deformation monitoring	BIM as an ideal 4D graphical computing environment for Structural Health Monitoring (SHM) and management considering amounts of sensor data
Structural Health and Safety monitoring with e.g. LVDTs, inclinometers and strain gauges	Progressive displacements in structural elements	[85]	–	–	- Required specific IFC - Acquisition, storage and processing of Big Data with high size	IFC extension needed, for example including new IfcSensor-Type
		–	[12]	–	Limited interoperability	

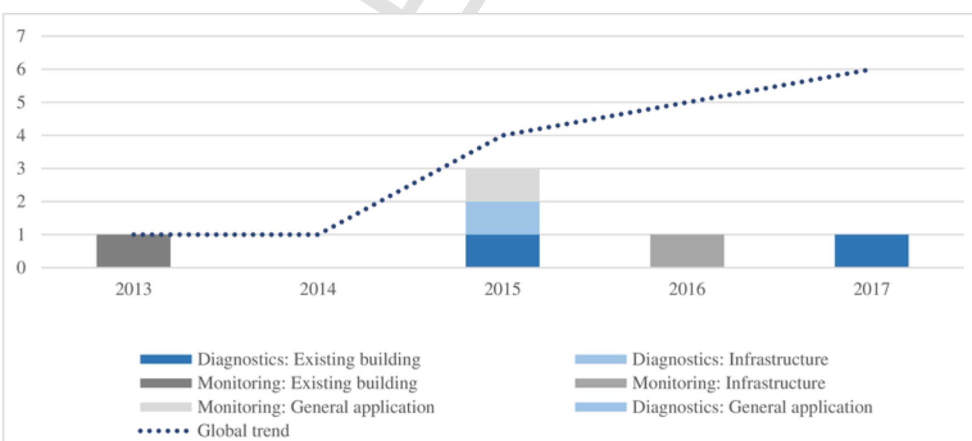


Fig. 7. Trends in diagnostics and monitoring in BIM for refurbishment of existing building, rehabilitation of infrastructures and general applications.

of logged parameters, installation plan of the equipment, images, diagrams, comments), thus without recommending a protocol instructions.

Instead, Bruno and Fatiguso (2018) 83] proposed a method to share and reuse knowledge acquired through archival analysis, damage survey and diagnostic investigation and the formalisation of the Information Requirements as input in BIM model. This method consists of the attachment of diagnostic information on equipment description, survey process, images, videos, comments, etc. of performed radar acquisitions and borescopy. This data is manually recorded into the model as attributes within parametric objects of architectural components and diagnostic profiles. The detected criticality concerns sharing information on diagnostic survey in a unique model in each refurbishment step, due to the large size of the model itself and the difficulty in handling several data sources. In this regard, the employment of databases connected to the BIM model through the DataBase Management System (DBMS) could represent an effective solution. An alternative one consists of developing web services and cloud-based BIM applications, together with VR and AR for BIM operative employment in construction site.

With regard to the data digitisation and management by static structural monitoring systems (e.g. Linear Variable Displacement Transducer (LVDTs), inclinometers and strain gauges), Rio et al., 2013 [85] have proposed a procedure on the development of a digital three-dimensional model of a real instrumented building, using the IFC standard. The preliminary study has highlighted the lack of structural kinematic sensors into the reference class IfcSensorType, within the IFC 2×4 RC2 standard.

The procedure involves the creation of a generic custom Property Set (in line with the IFC template) to hold the attributes of the sensors for structural monitoring. These attributes include name, function, properties, materials, openings, composition, representation and relationship parameters, frequency set point, temperature set point, date and time of acquisition, type of relationship between sensor and relative building component.

However, the inclusion of a new IfcSensor-Type as IFC instances is needed for improved information management and risk mitigation. On the other hand, the issues connected to the acquisition of Big Data, by the monitoring activity, relate to the data storage and process within an information system. The management of data - continuously collected and updating - can be critical due to the size of the processed files. In addition, the person in charge of data collection and storage may not agree to share it. These two questions can be resolved by approving the maintenance of separate Structural Health Monitoring (SHM) acquisitions by the central digital model, thus sustaining the control of the activities under the liability of the technicians. Consequently, an independent specific model is linked to the central digital model, in the form of programmed database, using the IFC standard.

This approach belongs to intelligent structural health monitoring systems if sensors with internal capacities of data processing and analysis are used. When the information refers to SHM systems and implements monitoring techniques, it is called “monitoring-related information”. A semantic conceptual model prototype was proposed on intelligent monitoring of civil infrastructures [12], a solution that could also be developed to monitor existing building.

In the research work by Zhang and Bai, 2015 [31], the connection of RFID tag-based breakage-triggered (BT) strain sensor and corresponding structural element in BIM allowed detecting the structural damage conditions whenever the recorded values exceeded some pre-set strainthresholds for contactless scanning of structural deformation conditions. The issue generated by IFC on loss of data fidelity has been solved by connecting BIM/FEM software and sensors via a Database Server and a BIM for SHM portal, enabled to alert engineers and decision makers about damaged elements. Table 5 illustrates some case studies carried out connecting BIM tools and external databases for infrastructural monitoring; these methods could be effectively implemented in SHM in historic buildings showing static and seismic criticalities.

5. Gaps in knowledge and future developments in HBIM for performance assessment

5.1. *Open issues*

5.1.1. *Geometrical survey, augmented visual inspection and parametric models*

The identified gaps in knowledge in this section on geometrical survey and augmented visual inspection for parametric modelling regard:

i) High number of steps from point cloud, mesh to 3D solid and BIM parameterisation, when working on complex shapes. They require an import of the converted files in diverse software products and a combination of several methods according to the morphology of existing building;
ii) Incompatibility of current software products with the automatic generation of parametric objects from point cloud/mesh for irregular building components and decorations;
iii) Difficult recognition and segmentation of building components with curved and complex shapes (such as curved and decorative ceilings) within point cloud/mesh;
iv) Partially realistic BIM models when a complex parameterisation is required for heterogeneous geometries and for decorated curved surface (i.e. frescoes on vaults).

The most significant gap in knowledge, connected with some of the abovementioned issues, consists of the low development of algorithms for automatic recognition and conversion in parametric objects (solved with primitive geometries, as currently feasible). After recognition and segmentation, the automation of BIM modelling from point clouds or meshes of complex building components, with varied shapes eventually decayed, can contribute to also accomplishing the gaps as in i), ii), iii). Another possible solution, proposed by some authors [19,41], could be the dissemination of a library for existing buildings. It should be observed that such solution could be effective when modelling architectural building typologies (i.e. churches, castles, etc.) belonging in the same historic period. The case is different when considering historic aggregates of cities, mostly built by the owners - following personal requirements, rather than current constructive techniques - or transformed artefacts, as the HBIM library does not represent the solution because it imposes a certain level of standardisation.

The gap in knowledge iv), partially solved supporting BIM models with 3D realistic reconstructions of Computer Vision, could find a full resolution if new software applications were to be developed to configure the parameterisation and semantic enrichment directly in the textured reconstruction (photo-reconstruction and high resolution meshes from laser scanning). In this approach, the creation of three-di-

Table 5
Case studies carried out connecting BIM tools and external database for monitoring infrastructure.

Authors	External database	Case studies	Phase	Functions
Jeong et al., 2015 [87]	NoSQL (Not Only SQL), MongoDB® for querying	Yeongjong Bridge in Incheon, Korea	Management, maintenance and inspection	Management of bridge structural health monitoring data in a Bridge Information Modelling (BrIM).
Sternal and Dragos, 2016 [88]	Reference database	A laboratory test structure	Maintenance Operation	Recording autoregressive models coefficients for structural assessment obtained from processing time series of newly collected accelerations.
Zhang and Bai, 2015 [30]	External database in the ODBC (Open Database Connectivity) format	A laboratory test structure	–	Custom defined shared parameters “RFID tag” and “damage flag”, recording structural deformation condition.

mensional photo-models or meshes from point clouds and photos could include the geometric measurements, the appearance with further information, such as reports on the performance assessment, as well as comments on causes and effects of pathologies, settlements and previous interventions.

5.1.2. Integrated applications of BIM with diagnostics and monitoring for energy retrofitting

Some of the identified gaps in knowledge on integrated applications of BIM with diagnostics and monitoring for energy retrofitting are still the ones identified by Ilter and Erger (2015) [4]:

i) Low level of development of effective hybrid systems made up of digital cameras, thermal imaging cameras and laser scanners for survey of complex buildings, beyond the inner spaces;
ii) Lack of interoperability among BIM modelling tools which do not support the gbXML format;
iii) Need for adequate BIM tools to model any geometry for energy simulation and decision support, so that the gbXML schema would not lose thermal data, even the measured data;
iv) Need for techniques that are able to isolate, within the thermal images, only data on building components to be investigated, although not accessible;
v) Need for methods and strategies to retrieve diagnostic data for accurate and complete results (Cho et al. 2015) 42].

Further open issues are related to:

vi) Time-consuming approaches for mapping properties and building components;
vii) Need for energy analysis in dynamic (real) heat transfer mode, and not only in static (ideal) mode;
viii) Required real-time updating of energy performances and involved parameters for adaptive solutions.

Among these open issues, iv) again results from the difficulty in recognition and segmentation of building components when working on laser scanned or photo-acquired point cloud/mesh (Section 4). The loss of properties due to the handover of gbXML in energy simulation software - with limitation in interoperability - could be solved by utilising database files, in which any building component is identified. Mapping them into the energy application via programming scripts for automatic connections and exchanging lists of material and current thermal data (i.e. employing Dynamo® Autodesk as graphical interface programming, or macros) could streamline energy simulations. The synchronisation of continuous measurements and monitoring with BIM models, for communication and activation of adaptive solutions according to the environmental conditions, is a common issue. This could find accomplishment in experimenting with SCADA (Supervisory Control and Data Acquisition) solutions, such as RFID and the Internet of Things (IoT) with communication via cloud databases connected to the BIM model. The energy analysis in dynamic (real) heat transfer mode could be solved with the above-cited methods. However, a Decision Support System could be useful to create a multi-criteria evaluation of the project scenarios.

Indeed, the involved parameters could be utilised in multi-criteria and multi-agent analysis, to calculate benchmarks and key performance indicators, or as inputs in deep learning algorithms in decision-making support of the design alternatives. For instance, the analysis of indexes could provide global and local views of building energy performances via dashboards or maps, in order to track the energy consumptions, for sustainable retrofitting and operation.

5.1.3. Integrated applications of BIM with diagnostics and monitoring for structural reinforcement

The gaps in knowledge are listed below:

i) Low level of integration of diagnostic tests in the HBIM approach for material/constructional characterisation, performance assessment and structural monitoring;
ii) Scarse employment of 3D laser scans or photogrammetric techniques, integrated in the HBIM approach, for augmented visual inspection and monitoring of progression of decay and cracks with the general scope of semantic enrichment over time;
iii) Pathologies, decay and settlements still mapped in 2D views, with a laborious method that causes a loss of real geometry and semantic information;
iv) Incomplete IFC standards for monitoring.

The complete diagnosis of current building conditons is a relevant stage in planning refurbishment of existing building, in order to eliminate risks and safeguard the historic memory. In this scenario, the above identified four gaps have to find a solution, above all because this is the domain less investigated in the HBIM approach.

The aspects ii) and iii) are connected to the gap in knowledge as defined in Sub-Section 5.1.1. The recognition of pathologies and cracks within the 3D textured model could represent a key future development. Undeniably, the identification of degradation phenomena, directly in 3D reconstruction, can reduce time of drawing in 2D views, keep real appearance, 3D geometry and real extension of decay. This gap could be solved by integration of algorithms of deep learning (convolutional neural networks) for image recognition, after training applications to identify the targets. The gap related to scarce inclusion of diagnostic tests in HBIM can be solved by proposing some guidelines for acquisition and use of information acquired toward the refurbishment actions. This can occur in the view of codifying the performance requirements within a system oriented to 1) automatic diagnosis of performances by comparison of data and information from several sources, 2) generation of criteria for decision-making, 3) driven-decision on compatible interventions. For this purpose the available methods could include artificial intelligence technologies (neural networks, expert systems, etc.).

For instance, some experimentations should focus on the definition of guideline for the integration of:

1. Preliminary in situ investigations to evaluate internal stratigraphy, integrity of structural elements and presence of damage and vulnerabilities:

a. Photogrammetric and topographic survey to detect deformations and out of plumbs;
b. Radar tests and video-endoscopy to detect structural elements (e.g. vault stratigraphy, presence of voids and cavities, presence of reinforcement interventions);
c. Sonic and ultrasonic tests to determine the composition of structural elements (monolithic elements, multiple layers), consistency through the estimation of the sonic wave's propagation speed (presence of cracks and internal cavities);

2. Test of environmental vibration and dynamic identification to determine the modal parameters (frequencies and modal shapes), to interpret the dynamic building response;
3. Laboratory tests on samples of masonry, not extracted from the structure but characterised by similar properties:

a. Axial compression test (monotonic and cyclic type);

4. Evaluation of health and safety status of the structures through Finite Element analysis.

Another issue is getting the data easily and operatively during the diagnosis and execution phases; a solution proposed is employing user-friendly operative methods for consultation of diagnostic data via Virtual Reality and Augmented Reality. Certainly, remote visualization of detected and analysed decay patterns and pathologies is an ongoing approach in digitising and sharing information on the cultural heritage, above all with difficult accessibility, for managing diagnostic data through a touchless system for augmented reality [25].

However, these technologies do not yet experiment with methods of codifying, inserting, using and managing the diagnostic information (values of logged parameters, installation plan of equipment, images, diagrams, and comments).

Further issues connected to the acquisition of Big Data, by monitoring activity, relate to data storage and process in an information system. The management of data - continuously collected and updated - can be critical due to the size of the processed files. A semantic conceptual model prototype was proposed for intelligent monitoring of civil infrastructures [12], a solution that could also be developed to monitor existing building.

Additional research development should experiment with visual recognition using convolutional neural networks (i.e.Watson by IBM®) combined with change detection algorithms within images (radargrams and thermograms) and photos in order to discover layers and presence of voids.

Another potential function of integrating BIM with diagnostics and monitoning in an automated DA-HBIMM framework would be the analysis of structural vulnerabilities, the calculation and mapping of defect condition ratings within a BIM platform as Decision Support System.

A general line of research consists of developing deep learning algorithms for diagnosis of pathologies and settlements, based on acquired knowledge, taking the progress of expert systems and artificial neural networks in medicine as starting points for automatic evaluation of disease symptoms.

6. Proposal of a diagnosis-aided HBIMM methodology

The review of the state of the art of Building Information Modelling leads to outlining a methodological proposal, Diagnostic-Aided HBIMM (DA-HBIMM), for the creation of an "as-built" model (Fig. 8), and identifies the critical points that require further developments. The concept of Historic Building Information Modelling and Management [3] is based on the recognised relevance of data collection for the diagnosis, with the perspective of future investigation of methods for machine-driven diagnosis and project.

The purpose is to accelerate the investigations of the Diagnosis-Aided HBIM for supporting the refurbishment with lean and automatic processes, from diagnosis and performance assessment to intervention design. The proposed framework points out how an accurate knowledge phase is paramount for the reliable diagnosis, above all if developed into an automatic system for performance analysis.

Initially, *Part 1* of DA-HBIMM illustrates methods and tools, such as contractual conditions and organisational models, for the organisation of the project team toward effective cooperation at the preliminary stage (*1.Ontological Knowledge Structuration*), as reported in Section 3 "Information management and exchange tasks". The *1.1 Work Organisation* involves the professional assignments, establishing competencies and responsibilities, oriented toward the BIM activities. The work plan defines the macro-phases of the HBIMM-aided refurbishment, in terms of tasks and model/data requirements. The definition of the LOD for refurbishment clarifies data and model requirements, digital exchange models and ontological information. In this paper, the extension of the information requirements for diagnosis and performance assessment is considered a key aspect. A classification of data/information is needed for the knowledge representation and management of decisions, involving data mapping for each building component model and work phase. This classification involves information management techniques, such as ontologies, MVD and IFC, to eliminate inconsistencies, redundancies, providing communication protocols.

The macro-phase 2 consists of the *Preliminary Information Collection* for creating a *2.1 Knowledge Framework* after raw geometric survey, preliminary analysis of materials/construction techniques and typological studies based on historical and photographic records, archival documentation and prior available drawings, in order to discover traditional constructive methods and past transformations and events, which probably have caused the current degradation.

This step addresses the following ones, handing information for detailed planning of more systematic investigations.

One of the following phases is represented by *3. Reverse engineering* that delivers a geometric, textured and measurable three-dimensional model after *3.1 Data acquisition* and *3.2 Data Elaboration*.

The methods for geometric surveys are 3D laser scanning and photogrammetry. Nevertheless, the review of the state of the art reveals some potential in combining laser scanning and photogrammetry (hybrid system), for instance to the problematic detection of transparent, reflective or dark surfaces via photogrammetric acquisitions. The other critical aspect is the intensive elaboration of scanned point clouds in terms of resources and labour time. The data acquisition via UAVs consents the augmented visual inspection of inaccessible environments because of height, risk of collapse or spatial tightness.

The method for *4.1 3D model parameterisation* affects the workflow for data elaboration. The current methods of parameterisation (*4.Point-to-BIM/Scan-to-BIM*) are classified as a) "Point cloud conversion in mesh/solid objects", b) "Import of point clouds in BIM parametric tools" and c) "Automated conversion of point clouds into parametric objects". The processes are illustrated into Section 4 and gaps in knowledge are analysed in Section 5.1.1.

In the first method, the point clouds are initially aligned, cleaned and refined, they are subsequently converted into 3D meshes by performing methods and algorithms such as Poisson or Ball Pivoting surface reconstruction and optimising algorithms. The object recognition and segmentation are carried out as manual or automatic operations on meshes which are utilised for parametric modelling. Meshes need to be converted into 3D solids with faces extrusion, via automatic and manual operations. This approach is the most time consuming of all because it consists of several steps of conversion and processing, besides being executed in different software applications.

In the second method, the reference lines traced from the point clouds, are used for modelling by Boolean operations, analytical formulas and NURBS (Non-Uniform Rational Basis-Spline). The third one consists of the automatic recognition and creation of parametric objects from the point clouds, using specific plug-ins (i.e. Scan-to-BIM® and EdgeWise®) - implemented with recognition methods and modelling algorithms - currently feasible only for objects with primitive geometries.

The recognition and segmentation of objects within the mesh require further automation through feature detection algorithms, in order to abandon the current manual technique. In addition, in particular situations, the *4.2 BIM object library population* for existing buildings could support modelling architectural building tectonics belonging in the same historical period, cases where a certain level of standardisation could be acceptable. The analysis of traditional processes of acquiring incremental knowledge gets the definition of a sub-system of activities that must necessarily be included within the DA-HBIMM methodology

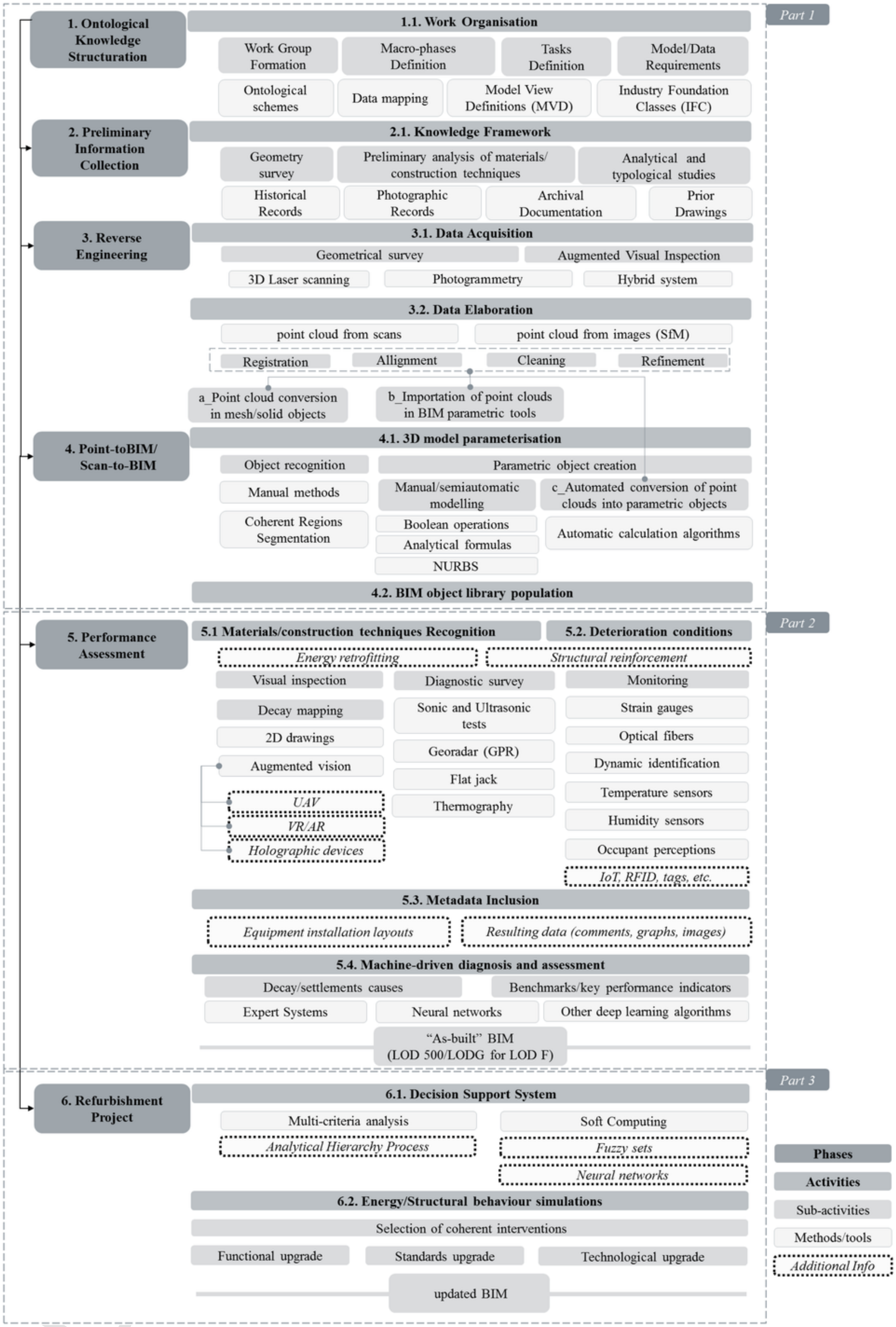


Fig. 8. Structuration of the HBIMM process.

for diagnosis and performance assessment (*Part 2*) - the core of the methodology itself - aimed at *5.1 Material/construction techniques Recognition* and detecting *5.2 Deterioration conditions*. This information is made available to simulate structural behaviour, energy performance, as well as to plan energy retrofitting and structural reinforcement.

In particular, *5. Performance Assessment* generates knowledge for the semantic enrichment of BIM models with the purpose of evaluating the residual performances. This activity involves all the tasks as analysed in Section 4.2.2 "The implementation of diagnostics and monitoring data in BIM". The first step is the visual inspection for mapping cracks, pathologies, anomalies in 2D views and drawings, as experimented with so far, or involving augmented visions using laser scans and photogrammetry for Computer Vision methods (gaming, holographic devices, immersive Virtual Reality, Augmented Reality).

Actually, 3D reconstructions of Computer Vision could support the BIM models through a realistic representation of heterogeneous geometries, crack and pathologies patterns, and decorated curved surface (i.e. frescoes on vaults). In addition, Virtual Reality and Augmented Reality are user-friendly and operative knowledge reuse methods of remote visualization of detected and analysed decay patterns and pathologies during the diagnosis and the execution phases. This methods could be additionally developed with the informative parameterisation and semantic enrichment directly executed in the textured reconstruction, in order to navigate the model, to consult geometric measurements, and to visualise degradation phenomena, appearance, reports on diagnosis and performance assessment, as well as comments on causes and effects of pathologies, settlements and previous interventions.

The critical use of large size of files can be overpassed with the semantic model on web-platforms.

As complementary verifications, non-destructive tests could be performed for the recognition of materials and construction techniques, as well as for the detection of deterioration conditions.

The infrared and thermal testing can detect constructive technologies mapping superficial temperatures and provide temperature values to estimate thermal properties to be recorded onto correspondent parametric objects. The continuous monitoring of temperature and humidity via SCADA (Supervisory Control and Data Acquisition) solutions, such as RFID and Internet of Things (IoT), is relevant to energy analysis in dynamic heat transfer mode. An incorrect exchange of these properties, via gbXML, toward energy simulation engines could be overcome by computer programming automatic links among the BIM model and external databases via programming tools (Dynamo® Autodesk, as graphical interface programming, or macros).

The diagnosis and monitoring of structural performance require the execution of non-destructive tests (georadar, sonic and ultrasonic tests, etc.) in order to investigate extensively decay phenomena and constructive techniques below component surfaces, to be accepted after local destructive diagnostic tests on representative building components, so as to extend the results to similar components.

The real-time synchronisation and update of the BIM models should include environmental and structural – both static and dynamic – measurements, whereas occupant perceptions can drive more comfortable and sustainable solutions. For instance, the structural monitoring can measure the deformations which have the greatest influence on the global structural behaviour analysed by dynamic identification or the progression of cracks, air temperature, humidity and wind. The methodology introduces activity *5.3 Metadata Inclusion* concerning information on investigation and installation plan, target elements (column/pillar, wall, time, etc.), acquisition profile typology, number of survey points and their geo-location.

For instance, some metadata which characterise the dynamic identification tests for existing buildings are listed below:

- Perturbation force type: 1) environmental vibrations (employed in the case of historical and architectural heritage), 2) forced vibration;
- Optimal number and type of acceleration sensors;
- Layout of installation: installation points and their location, including installation instructions of the acquisition system;
- Sampling frequency;
- Time capture window.

Consequently, the measured results would concern:

- Dynamic parameters (frequencies and modal shapes) through dynamic identification of different algorithms which converts the acceleration signal spectra from the time to the frequency domain;
- Interpretation of the structural response in acceleration;
- Comparative indexes of dynamic parameters obtained by different algorithms at the end of the validation test (e.g. Modal Assurance Criterion, damping ratios, etc.)

In this process stage, the preliminary knowledge, the recognised pathologies and cracks, the experimental data could enter algorithms of deep learning (expert systems, neural networks, etc.) for automatic *5.4 Machine-driven diagnosis and assessment*, trained by human expertise.

Photographs, thermal and radar images in particular, could be processed with visual recognition algorithms based on convolutional neural networks (i.e. Watson IBM®) to discover material layers, cavities, voids, and cracks. This method could be developed to monitor settlements and pathologies if combined with change detection algorithms in order to distinguish their temporal evolution. The computer programming can provide capabilities of plotting graphs, in order to visualise time series, numerical analysis and generate maps of vulnerability and defect condition ratings within a BIM platform.

6.Refurbishment project consists of the selection and detailed design of the most coherent interventions after the accurate diagnosis and performance assessment, also responding to required functional, standards or technological upgrading. The selection could be aided by specific *6.1 Decision Support System* - based on soft computing (i.e. fuzzy sets, neural networks) or multi-criteria analysis and *6.2 Energy/Structural behaviour simulations*.

This automated process could support engineers and architects in the selection of suitable interventions, the immediate activation of mitigation measures and the notification of risks to the users. In case of energy retrofitting, a Decision Support System could lead to the suitable intervention with a multi-criteria evaluation of the project scenarios. As a matter of fact, the involved parameters could be utilised in multi-criteria and multi-agent analysis, or as inputs in deep learning algorithms to calculate benchmarks and key performance indicators supporting the choice of a design alternative.

7. Conclusions and future remarks

This paper is a critical analysis of the state of the art about HBIMM. It shows the continuous and growing interest in the topic at international level. However, despite some recognised advantages of BIM in the refurbishment process, its potential should be further investigated and exploited. One of the future research lines concerns the progressive refinement of the acquisition techniques for geometry and morphology and the automatic conversion of 3D surfaces into parametric models, because at the present state models of complex masonry vaults and decorative elements still feature simplifications and inaccuracies.

Furthermore, a real "as-built/as damaged" BIM model of existing buildings requires a high semantic level with original documents and observations of the building conditions by visual inspections, diagnostics and monitoring. As a result, it generates a great amount of data, which is difficult to manage due to scalability issues. In this regard, a future challenge would be the implementation of services of BIMcloud and BIM repository, with the purpose of reducing the size of BIM deliverables and shift from file-based BIM to data-based BIM. Another relevant contribution in automation in construction for refurbishment will be ensured by the conjunction of BIM with automation systems which would positively improve quality control during diagnosis, design and work execution. Nevertheless, the study of current BIM implementation reveals a limited number of case studies involving survey of damage patterns, identification of relations among structural elements and material-construction characterisation.

Some scientific and technical works report the evolution of methodologies for energy simulation using onsite measured thermal transmittance values - as calculated from digital thermal images (thermography) – rather than standardised ones.

Therefore, a methodology to include survey results on the assessment of the building conditions has yet to come; in this regard, the paper proposes a methodology for Diagnosis-Aided HBIMM with future involvement of artificial intelligence for automation, possible due to the possibility of computer programming in BIM platform. The automatic diagnosis could be performed within a machine-driven platform for analysis of the preliminary knowledge, the recognised pathologies and cracks, the experimentation through algorithms of deep learning, using human knowledge as knowledge base. In addition, the visual recognition of images through convolutional neural networks can contribute to faster pathology/cracks patterns mapping and recognition of settlements from acquired photos, or directly from the 3D reconstruction model. The same techniques can be employed to analyse thermographic and radar imaging, in order to support material-constructive characterisation. Thus, limited errors in detecting causes of settlements and pathologies reduce risks for users, costs and environmental impacts thanks to the selection of the most coherent intervention.

This integration of BIM and automation is required because the incremental and accurate knowledge by investigation of physical and performance parameters is the aim of the designers in refurbishment projects, representing the stable principle for non-invasive interventions to ensure the valorisation of the Cultural Heritage.

The scarcity of applications and research works on integration of diagnostic data calls for future developments. In addition, the challenge to create and handle computable diagnostic data and to make the diagnosis automated could help the designers in decision-making of adequate interventions by logic algorithms.

For this purpose, the research in the field of infrastructural rehabilitation could support a similar development for existing buildings.

Future trends should also regard the improvement of methods and tools for automatic conversion of point clouds and/or photogrammetry in BIM parametric models, by reducing inaccuracies and rigid simplifications, as well as the extension of the IFC standard for digital control of existing buildings by solving some interoperability issues.

Finally, future research is recommended for automatic transfer of real-time data from diagnostic investigations and monitoring to BIM centralised model, via SCADA devices (i.e. IoT or RFID) in order to alert experts and users about hazardous situations, and activate machine-learning algorithms for risk mitigation activities and regulate energy consumption and human indoor comfort. Consequently, efforts are needed for access and management of information, for instance by improving Virtual Reality and Augmented Reality technologies, with the purpose of developing a set of operative educational, entertaining and technical tools from BIM model and its dataset.

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