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METHODOLOGY FOR THE ENERGY RENOVATION OF **HERITAGE BUILDINGS** USING **BIM**

Guidelines for the development of an Energy Efficient Heritage Building Information Model (EE-HBIM)

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The European Union is made up of 27 Member States who have decided to gradually link together their know-how, resources and destinies. Together, during a period of enlargement of 50 years, they have built a zone of stability, democracy and sustainable development whilst maintaining cultural diversity, tolerance and individual freedoms. The European Union is committed to sharing its achievements and its values with countries and peoples beyond its borders.

METHODOLOGY FOR THE ENERGY RENOVATION OF **HERITAGE BUILDINGS** USING **BIM**

Guidelines for the development of an Energy Efficient Heritage Building Information Model (EE-HBIM)


SALA MANTELLINI

FOREWORD

Among the major economic, ecological and demographic challenges facing the regions bordering the Mediterranean Sea is the ability to propose strategies to counteract the climatic emergencies that threaten the extraordinary heritage of archaeological sites, historical building complexes and cultural landscapes of these countries. The aim is to develop solutions that strengthen the climatic resilience of buildings and, at the same time, support their maintenance and reuse, protecting the quality of heritage.

Hence the importance of employing the insights and methods of interdisciplinary research to provide reliable and complex information on the decay phenomena of built heritage and its energy and environmental behaviour. Yet, a careful approach is also needed to place this cultural heritage within a framework of inclusive policies, which propose it as a resource and valuable growth engine for sustainable urban development.

The project BEEP - BIM for Energy Efficiency in the Public Sector - financed by the ENI CBC Med European programme, has demonstrated that, through a multidisciplinary and integrated digital approach and with innovative financing systems, it is possible to improve the capacity of local public administrations to carry out informed renovation's interventions, balanced between the preservation and fruitions of the buildings they manage and use.

This volume, in presenting the results of BEEP project, illustrates the different stages of this process, which starts with the monitoring and integrated management of energy and conservation data, and then analyses different scenarios and proposes design principles and adaptation strategies for the energy and environmental improvement of built heritage, including the use of renewable sources. This operational methodology was tested on nine historical buildings, housing different public institutions, in seven Mediterranean partner countries (Italy, Cyprus, Spain, Jordan, Lebanon, Egypt and Palestine). The variety of case studies, uses, climatic contexts and regulatory frameworks has demonstrated the scalability and replicability of the approach to the vast Mediterranean area, also providing criteria to assess its potential for transferability to other regions.

by **Elena Gigliarelli,**
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BEEP project Coordinator

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Glossary

AEC	Architecture, Engineering and Construction
BCF	BIM Collaboration Framework
BEP	BIM Execution Plan. Plan that explains how the information management aspects of the appointment will be carried out by the delivery team.
BI-EM	Building Information-Energy Model. A BIM-based energy model that automates the energy modelling process within the BIM software (Revit Energy Model)
BIM	Building Information Modelling. Use of a shared digital representation of a built asset to facilitate design, construction and operation processes to form a reliable basis for decisions.
BIM-BEM **BIM-BPS**	Building Information Model to Building Energy Model. A converted energy model using exported information from a BIM model
BPS or BEM	Building Performance Simulation or Building Energy Modelling (generally used as synonyms)
bSDD	buildingSMART Data Dictionaries
CDE	Common Data Environment. Agreed source of information for any given project or asset, for collecting, managing and disseminating each information container through a managed process
CFD	Computational Fluid Dynamic
COBie	Construction Operations Building Information Exchange. International standard for information Exchange about construction data focused from a BIM methodology point of view
DTV	Design Transfer View
DES	Date Exchange Schema
FM	Facility Management
GBS	Green Building Studio
gbXML	Green Building eXtensible Markup Language. A format used in order to allow a smooth transfer of BIM model properties to energy calculation applications.
HVAC	Heating, Ventilation and Air Conditioning
IAI	International Alliance for Interoperability
IDM	Information Delivery Manual
IFD	International Framework for Dictionaries
IFC	Industry Foundation Class. A neutral, non-proprietary data format used to describe, exchange and share information, smoothing the information exchange and interoperability between software applications in a BIM workflow
Information	Reinterpretable representation of data in a formalized manner suitable for communication, interpretation or processing
Information model	Set of structured and unstructured information containers, that is named persistent set of information retrievable from within a file, system or application storage hierarchy
ISO	International Organization for Standardization
LCC	Life cycle costs
LOD	Level of Development LOD. It defines the development level of information that a BIM model has, and this one is the composing part, constructive system or assembly of the building.
Level of Information Need	Extent and granularity required for a particular information deliverable at a particular plan of work stage. According to ISO 19650 it should substitute LOD.
MEP	Mechanical, Electrical, and Plumbing
MVD	Model View Definitions
Plenum	A plenum is a non-occupiable space between a ceiling and the floor above specifically intended for mechanical systems and other systems that require ceiling space
Point cloud	The result of a data collection of a building or object by laser scanner of photogrammetry, consisting in a set of points in the space that reflect its surface.
R-value	Thermal Resistance
RV	Reference View
SHGC	A value describing the solar heat gain coefficient in a glazing (window) material
Space	A space is defined as a building volume enclosed by ceilings, floor, walls or by another space's boundary. Space has a plethora of properties assigned to it to describe its energy resources, such as loads from people, lighting and equipment
U-value	Heat Transfer coefficient or Thermal Transmittance
Weather File (epw)	A single file in a format called an .epw that contains a collection of information to describe the environment of a location for each hour of the year, supplying data such as temperatures, luminescence data for sunlight, heating, and more
XML	eXtensible Markup Language
XSD	XML Schema Definition

Municipal Guest House – Karak Municipality, Jordan. The building is used for holding main events of Karak municipality and reception of municipality's visitors.

1. INTRODUCTION

1.1 GUIDELINE PURPOSE

This technical guideline proposes a methodology for the energy audit of a historical building to support its energy and environmental improvement (as shown in the Energy Audit Process Flow schema based on the EN 16247-2:2014, see § 1.4), from the analyses to the design stage up to the implementation, using Energy Performance Contracting (EPC) to attract funding.

Each section of the guideline can also be used as a technical specification for tender activities. An extended version of this document is available online at the Url: https://zenodo.org/record/6393028 and includes also reference templates for drafting the reports required by each activity.

1.2 GENERAL PROJECT INFORMATION

This guideline was developed within the ENI CBC Med BEEP project and aims to enhance the capacity of public local administrations to design and realise innovative energy and environmental improvement interventions on historic public buildings, through a multidisciplinary and integrated digital approach, using Building Information Modelling and performance-based design to develop an Energy Efficient Heritage Building Information Model - EE-HBIM. The guideline is based on the testing of this emerging technology on built heritage in seven different EU and non-EU Mediterranean countries, to demonstrate its scalability to the entire building stock of the Med area. The project will provide public administrations with a powerful method for the energy rehabilitation of public buildings to be supported with private funds through Energy Performance Contracting (EPC).

The HBIM model should integrate previously collected information on the historical building (geometric, diagnostic, environmental data), to create a comprehensive documentation of its current state. Moreover, the model will be used as a basis to inform the subsequent simulation-based energy-environmental improvement concept, through energy renovation scenarios that are both compatible with the building and capable to enhance its energy and environmental performance.

1.3 ENERGY AND ENVIRONMENTAL PERFORMANCE IMPROVEMENT OF BUILT HERITAGE: A FRAMEWORK

> *On this very subject, it should be remembered that any protection order placed on cultural assets must be accepted as one of the many limitations (economic, respect of norms, functional, energy usage etc.) which an architectural design is constantly held to abide by and resolve. It is an arduous and stimulating, but by no means impossible, challenge.*
> (Carbonara, 2017)

The construction sector plays a decisive role in the challenge for sustainable development: in Europe and the US, it is responsible for a final energy consumption of around 40%, which drops below 20% in China and is slightly above 30% as the world average (Belussi et al., 2019). The low cost of energy, together with the development of modern air conditioning systems for indoor spaces, has led, in the last century, to the overshadowing of investments in the energy efficiency of buildings. The situation began to change with the oil crisis of 1973 and the rise in energy prices after 2000, which made the investment in energy efficiency more convenient and demonstrated how the strong dependence on imports of fossil sources from external countries could pose a threat to a country's political independence and prosperity (Troi et al., 2015). In parallel, awareness of the devastating risks associated with human-caused climate change (IPCC, 2014) has also grown. This has triggered a series of international actions that started with the Earth Summit in Rio de Janeiro in 1992, continued with the Kyoto protocol of 1997 and reached the Paris Agreement of 2015. Sustainability has thus become a central pillar in contemporary life (Laine et al., 2019) from which derives the key role of energy efficiency in the 2030 Agenda for Sustainable Development (UN, 2015), and its sub-theme related to the improvement of the energy performance of buildings, which is now a central aspect in energy policies around the world. Within this framework, in December 2019 the EU released the European Green Deal, capturing its commitment to tackle climate change. Among other actions, it prioritises energy efficiency in the building sector, as the largest single energy consumer in of Union (European Commission, 2020).

The energy retrofit of a building refers to the set of actions needed to improve its energy and environmental performance. The challenge of the energy retrofit of a building consists in applying the most profitable set of technologies to obtain an improved energy performance while maintaining satisfactory levels of service and internal thermal comfort under a given set of operating constraints (Ma et al., 2012). The heterogeneity of the existing building stock, the continuous evolution of technologies and markets and the variability of the actors involved are responsible for the complexities linked to the decision-making process concerning energy retrofits (De Boeck et al., 2015; Murto et al., 2019). Despite the numerous actions taken at the public level, the energy retrofit rate is still lower than expected (Friege & Chappin, 2014), to the point that, to achieve the 2050 objectives, the pace should be doubled, if not tripled (BPIE, 2019).

1.3.1 Energy improvement of built heritage

Although Europe is one of the "early mover" markets for energy retrofit of buildings, the built heritage is still substantially exempt from the Energy Building Performance Directives because of the difficulties in finding energy efficiency solutions compatible with historical and architectural values. As stated in the EBPD (*Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the Energy Performance of Buildings*, 2010), "*Buildings and monuments officially protected as part of a designated environment or because of their special architectural or historic merit, where compliance with the requirements would unacceptably alter their character or appearance*" may be excluded from attaining energy performance requirements. Moreover, historical buildings are usually protected both by national regulation and international conventions, which introduce additional levels of preservation that hinder energy retrofit interventions. Historical buildings are neither the largest portion of buildings (Economidou et al., 2011) in the European building stock nor the most energy-intensive (Historic England, 2018; Martínez-Molina et al., 2016; Pretelli & Fabbri, 2016). Thus, the concerns that potential measures for energy efficiency would damage historical buildings have slowed down the disciplinary integration process between conservation and sustainable design.

1.3.2 Approach to energy improvement of the built heritage

A key element in drafting an energy improvement process for a historical building is the search for the right balance between interventions and building context, historical-artistic values, passive behaviour and energy use, which requires a holistic point of view (Carbonara, 2017; Historic England, 2018). This approach allows the creation of a shared knowledge framework between the actors involved in the process (Historic England, 2018) and guarantees that the chosen solutions are appropriate for the built heritage framework.

In dealing with a historical building, we can make at least two fundamental clarifications regarding the energy retrofit approach and the guiding principles of restoration:

1. According to the current Italian debate on the topic (Carbonara, 2015; de Santoli, 2015), the concept of "energy improvement intervention" is to be preferred to "energy regulatory compliance/ adjustment/ adaptation". The scholar of "Architectural restoration" Giovanni Carbonara argues that the concept of "improvement" is antithetical to the one of "adjustment", which refers to regulatory compliance, including safety and comfort. The "improvement concept" has been first introduced in the field of structural consolidation of built heritage with excellent results, i.e. without losing the general scope of an intervention on a historical building, that is its preservation for future generations (or the ones related to the concept of "Integrated conservation" expressed in the Declaration of Amsterdam (AA. VV., 1975). Similarly, the concept of improvement can also be applied to energy efficiency, as the energy and environmental behaviour of a historical building (both active and passive) can be improved through appropriate and well-balanced solutions without leading to a disruption of the building; a disruption that could occur, should one wrongly assume that the building has to be "adjusted" to current legislations and requirements, just like new or recent construction. If the "adjustment" can change the building and make it unrecognizable, destroying or impairing its cultural values (Carbonara, 2015), the improvement can help rebuild the natural functioning processes of historical structures, simultaneously enhancing their distinctive characteristics and identities linked to the local microclimate (Gigliarelli, Calcerano, and Cessari 2017; GBC 2017a). The conflict between environmental design and heritage conservation is finally over and energy efficiency measures are now fully recognised as a key protection tool to support the conservation process (Carbonara, 2015).
2. The solutions adopted must be in line with the guiding principles introduced by the international restoration charters. These are universally recognised principles produced by the critical debate on restoration, starting around the nineteenth century and developed through international restoration charters. A brief summary of these principles is given below (Carbonara, 2017):
    a. *minimum intervention:* the energy improvement design should aim at preserving the original material as much as possible and avoid unnecessary interventions;
    b. *reversibility:* the interventions must be reversible in the future, whenever possible;
    c. *distinguishability:* new works should be distinguishable against the existing ones;
    d. *physical-chemical and figurative compatibility:* the interventions must guarantee compatibility between ancient and new materials, new design solutions and historical and architectural features. This applies also to energy improvement (for example, understanding the building's bioclimatic functioning - also through historical and architectural insights on the

technologies used - is vital to reconstruct and optimise its passive behaviour);
e. respect for the material and figurative authenticity of the building.

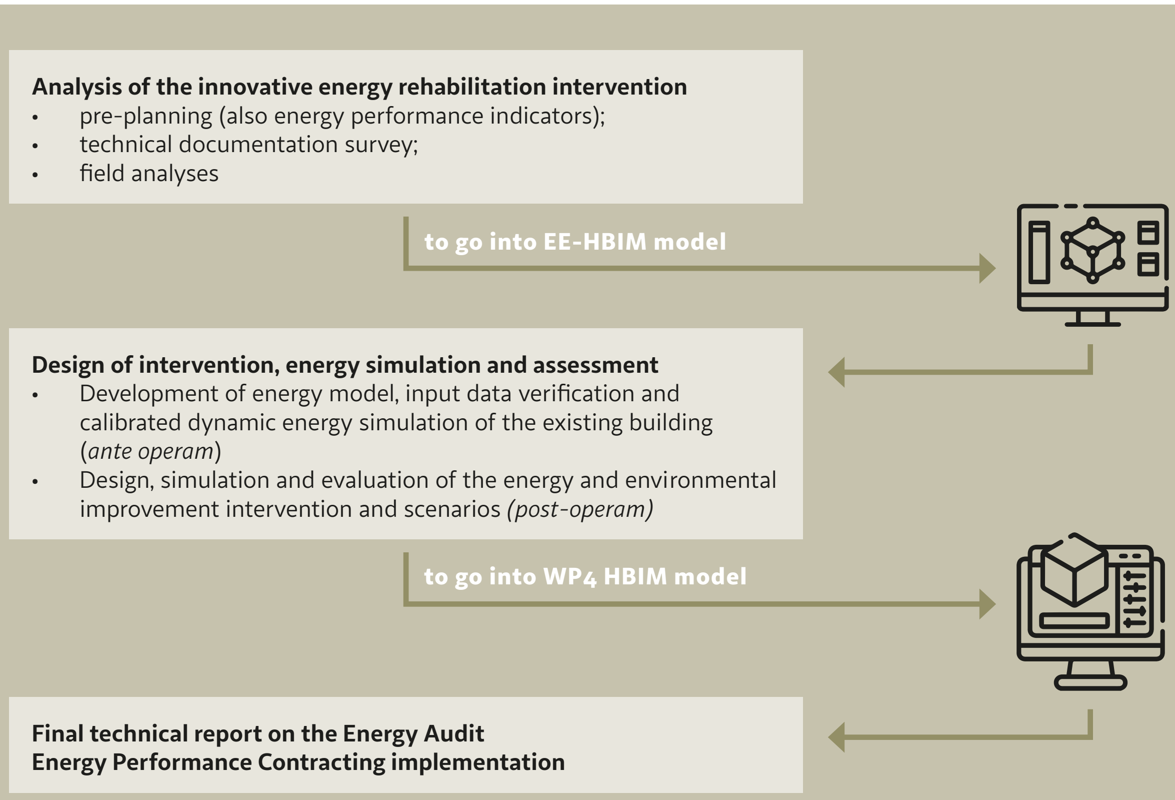
1.4 ENERGY AUDIT PROCESS FLOW FOR HISTORICAL BUILDINGS - BEEP PROJECT

The energy audit is one of the fundamental processes for the energy upgrade of a building (de Santoli, 2015). The EN 16247 defines the Energy Audit as a "systematic inspection and analysis of energy use and energy consumption of a site, building, system, or organization with the objective of identifying energy flows and the potential for energy efficiency improvements and reporting them" (*EN 16247 Energy Audit*, 2012). This guideline is based on the Energy Audit process of the EN 16247-2:2014 and introduces some adjustments to tackle the specificity of historical buildings, capitalise on the potential of new digital technologies applied to the construction sector for the built heritage (mainly, Heritage Building Information Modelling and Numerical Simulation of the energy and environmental performance of buildings) and promote the use of the Energy Performance Contracting scheme.

The results of the analysis of the innovative energy rehabilitation intervention will be incorporated into a Heritage Building Information Model (HBIM), which is defined as the digital representation of the physical and functional characteristics of a historical building, creating a shared knowledge resource for information about it (National BIM Standard buildingSMARTalliance, 2007).

Environmental and energy analyses will support the historical building energy audit, as well as the design of energy-environmental improvement scenarios. The passive behaviour of the building will be taken into consideration, in order to enhance its distinctive features and embedded passive strategies, closely linked with its climate and microclimate context, and also increase its energy performance and comfort conditions.

The proposed process flow is shown below. Each step is further analysed in the following chapters. Each activity can be outsourced following its description. The BIM model outsourcing has been described in more detail because it should follow a specific regulation (ISO 19650:2018 Organization and Digitization of Information about Buildings and Civil Engineering Works, Including Building Information Modelling (BIM) — Information Management Using Building Information Modelling —, 2018). ■



Analysis of the innovative energy rehabilitation intervention
- pre-planning (also energy performance indicators);
- technical documentation survey;
- field analyses

Design of intervention, energy simulation and assessment
- Development of energy model, input data verification and calibrated dynamic energy simulation of the existing building (*ante operam*)
- Design, simulation and evaluation of the energy and environmental improvement intervention and scenarios *(post-operam)*

Final technical report on the Energy Audit
Energy Performance Contracting implementation

The club of the British Cavalry, Nicosia Cyprus, formerly Barracks of the Danish Canadian extract in Cyprus.
To be transformed into the Cyprus Folk Art Museum

Morcos Nassar Palace, Bethlehem, Palestine. Originally a residential house, adapted in 2014 in order to be reused as the headquarters of the “Together for Life” association, which aims to integrate people with disabilities into the local community, and change the community’s perception of them.

2. ANALYSIS PHASE FOR THE INNOVATIVE ENERGY REHABILITATION INTERVENTION

The activities shown below encompass the analysis phase following the energy and environmental improvement approach on historical buildings (see §1.3):

- 2.1 Preliminary analysis;
- 2.2 Historical and architectural analysis;
- 2.3 Geometric survey;
- 2.4 Energy and environmental analysis;
- 2.5 General conservation state.

2.1 PRELIMINARY ANALYSIS FOR THE ENERGY REHABILITATION INTERVENTION

This paragraph describes the preliminary analysis intended to support the whole energy audit process of a historical building, in addition to the historical and architectural analysis.

2.1.1 Purpose of the analysis

The aim of this activity is to establish first contact with the historical public building, its owner, manager and occupants, in order to plan the subsequent analyses. The first step is the documentation analysis and the photographic and visual survey, which will provide an overview of the building. Establish-

ing contact with the building's occupants is also essential to start analysing the building's key features in terms of environmental and energy performance.

2.1.2 Pre-planning

Pre-planning in this activity should be very lean and allow to optimise the first field surveys and the first contacts with the involved stakeholders.

2.1.3 Data acquisition

The analyses should gather general data about the building, information on recent works (if any), use and current condition, as well as a brief overview of its active systems (HVAC, DHW, etc.)

The main tasks to be performed during the preliminary analysis are:

- identify the contact people for maintenance, facility management, design and documentation;
- verify the availability of the building for surveys and diagnostics, depending on the building usage (for example, environmental monitoring can be disrupting for normal building usage and requires at least one year of continuous measurements);
- carry out preliminary surveys and photographic reports of the building.

The main information to be retrieved includes:

- city planning regulation – urban plans - cadastral documentation – building prescriptions;
- drawings (plans, sections, elevations) (in printed and digital form: .dwg, .pdf, BIM models);
- documentation for the historical analysis: bibliographical and archival documentation, maps and historical cartography, studies on similar and/or coeval buildings;
- information from the occupants concerning comfort conditions (interviews);
- documentation on previous interventions on the building: maintenance, renovations, diagnostics;
- documentation on HVAC and installations: functional schemes, technical documentation, security documentation, plans;
- documentation on maintenance and facility management (maintenance plan, etc.);
- energy bills (electricity and gas) for at least one-year operation;
- energy contracts.

2.1.4 Output

Al the data collected must be organised in minutes, reports and digital folders to support the subsequent analyses.

Fig. 1. Preliminary meeting of the Italian team for the analysis of Palazzo Maffei-Borghese.

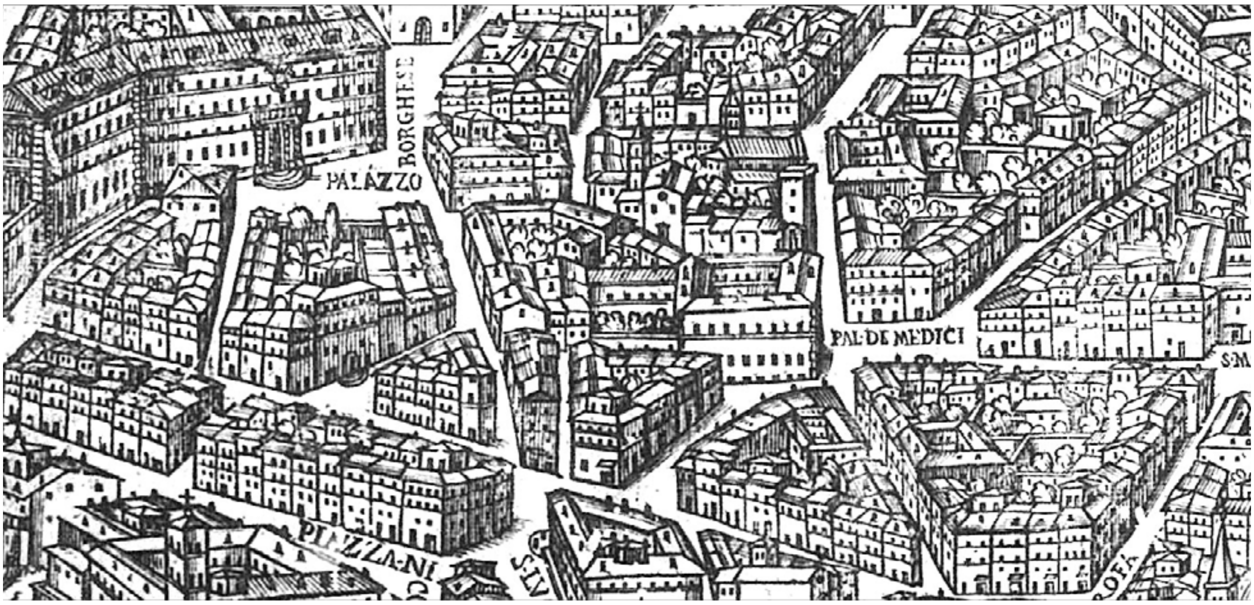


Fig. 2. View of Rome, Antonio Tempesta, 1593.

2.2 HISTORICAL AND ARCHITECTURAL ANALYSIS

The following paragraphs describe the historical and architectural analysis intended to support the energy audit process of a historical building.

2.2.1 Purpose of the analysis

The activity concerns archival research and onsite studies that are the fundamental core of the historical building analysis, as they provide a first understanding of the changes that the building went through over time and constitute a historical-critical guideline for subsequent analyses and interventions.

2.2.2 Pre-planning

Pre-planning activities to support historical and architectural analyses are already tackled in the preliminary analyses (see § 2.1), because, among the main information that should be retrieved therein, are bibliographical and archival documentation, maps and historical cartography and studies on similar and/or coeval buildings. Subsequent meetings with the building owner and manager and with scholars who might have already studied the building could provide access to additional documentation.

2.2.2.1 Deliverables

The deliverables of the pre-planning phase are:

- minute of the meetings;
- activity and mobilisation plan's specification;
- updated schedule of activities.

2.2.3 Data acquisition

The analysis path to be followed, in order to determine the characteristics of the building from a historical and architectural point of view, consists of a series of actions that involve different skills and disciplinary areas.

The first cognitive phase concerns the analysis of historical, textual, archival and image-based data, to acquire meaningful data regarding:

- pre-existing building fabrics on the site;
- purposes, methods, phases and timing of projects and transformations;
- intended use of the building;

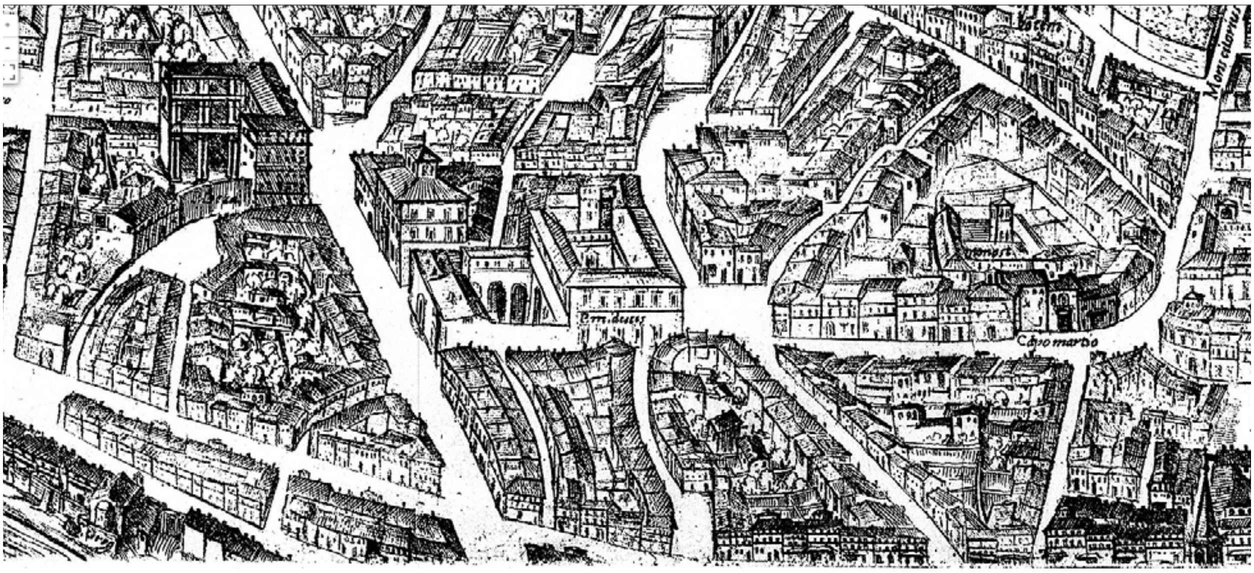


Fig. 3. View of Rome, Antonio Tempesta, 1593.

- any constraints and problems in the implementation of interventions or transformation phases;

and also:

- to identify clients, architects, workers and the organization of the working site during construction and renovations;
- to understand the functional, visual and conceptual relationships with the neighbourhood, the city and the territory.

The survey should be conducted in archives and libraries, as well as digital databases and repositories, where it is possible to retrieve useful information about the construction phases and the other changes that occurred over time.

Data from the available historical sources (such as bibliographic, archival, cadastral and cartographic) require appropriate interpretation. Through a critical analysis of the gathered material, the building's historical transformations and stratifications will be identified. This process allows to retrace the history of the building starting from the first building nucleus, to all subsequent transformations, with particular attention to the modifications, restorations and partial destructions that might have occurred over time. The interpretation of the building's construction phases and modifications should also be achieved through the interpretation of the materials and construction techniques used, as they are often indicative of the succession of interventions that have been stratified on the building.

The information deriving from the historical-architectural analysis should then be comparatively assessed with the ones of the geometric survey (see § 2.3), to conclude on the morphological and geometrical aspects of the building. This integrated approach allows a) to determine the presence of one or more buildings and therefore the construction units, b) to distinguish the original structures from those added and c) to understand the construction features to identify the structural functions and the masonry stratigraphy. Furthermore, from the comparative analysis of the results, it is possible to make an initial diagnosis of the current state of the building and to direct the research towards specific investigations through the use of field and laboratory analyses, if needed.

CASE STUDY:
MORCOS NASSAR PALACE, BETHLEHEM (PALESTINE)

The pilot building of the BEEP project in Palestine is an example of Liwan buildings. The word Liwan derives from the Persian word iwan meaning a room with three walls and a large opening to another room, referring to a large room in which valuable objects are displayed and which is connected to the main entrance and directly to the interior staircase for vertical circulation. This architectural style is based on the repetition of rooms along both sides of the liwan, providing a linear circulation between adjacent rooms.

In a previously undergone study of Palaces in the Bethlehem area by CCHP published in a book titled “Palaces and luxurious traditional Buildings in Bethlehem-2018” a chapter of this book was dedicated to Morcos Nassar Palace containing information on the palace’s architectural traits and uniqueness. This source served as a base to build on for further analytical works.

In addition to scripted materials, CCHP relied on traditional on-site visual documentation and photographic documentation and analysis to collect the needed data and assessment of the existing conditions. These techniques were both non-destructive and respectful to the building elements.

External facades, details and ornamentation, materials, openings, and levels, floorings ceilings, walls, vaults, stairs, conditions problems, and patterns documentation and assessment, etc. were traced using the needed techniques from traditional meters and laser meters, photogrammetry and direct visual documentation. Later the information was collected and processed through the various programs including AutoCAD, Revit, Photoshop and Agisoft and several photo montaging tools.

CASE STUDY:

MORCOS NASSAR PALACE, BETHLEHEM (PALESTINE)

A georeferenced geometric survey of the exterior and interior of the Palestinian pilot building was carried using traditional-direct and instrumental survey methods and photogrammetry to verify the available information, acquire the needed level of accuracy, and document the newly added changed to the site and document the information not available. Followed by developing the collection of image-based survey information (e.g., photogrammetry) on the external building elevation and the main internal elements to determine the state of these components and evaluate the addition of the new components.

The survey included a team of members from CCHP that conducted a thorough survey using traditional-direct survey and instrumental survey methods and photogrammetry of all needed data including-but not limited to external landscape and features, building external geometry, external facades, details and ornamentation, materials, openings, and levels, internal geometry, floorings ceilings, walls, vaults, stairs, materials, conditions problems, and patterns documentation and assessment…etc using the needed techniques from traditional meters and laser meters, photogrammetry, and levelling equipment. Later the information was collected and processed through the various programs including AutoCAD and Revit programs and several photo montaging tools.

LESSONS LEARNED:

Due to the simplicity of the Case study building, CAD drawings were prepared using the traditional survey procedures for the layout and levels in addition to some manual measurement efforts on site, after that all CAD drawings were imported to the Model using (Revit) Platform.

2.2.4 Output

The analyses, aimed at identifying the architectural features of the building, should be organised into a report, describing the main characteristics of the architectural complex and the transformations that the building has undergone over time.

The analysis of the building site must include:

- geographical and territorial framework;
- topography and climate;
- location, (urban, rural or other context) urban transformations, access, orientation, etc.

The analysis of the regulatory framework of the building must include a list of the main urban regulations, national and local regulations on listed buildings, national and local regulations on heritage conservation and specific regulations on the building, such as any regulatory constraints on interventions.

- The historical and architectural analysis must describe the main historical and architectural features of the building, including:
- its historical context and local architecture background;
- the analysis and assessments of changes undergone by the building over time;
- a brief analysis of the existing geometric-dimensional knowledge of the building;
- typological, architectonic and decorative characters;
- restoration or structural reinforcement interventions.

2.2.5 BIM integration

The information collected and organised provides the basis for the modelling activities of the building's construction elements in both their geometric and informative representation, based on the dimensional data collected in the geometric survey.

2.3 GEOMETRIC SURVEY

The following paragraphs describe the geometric survey, intended to support the energy audit process of a historical building, as well as the BIM modelling.

2.3.1 Purpose of the analysis

The activity regards the integration of traditional and innovative techniques (topographical, terrestrial laser scanner, photogrammetry) of geometric survey, to supply an accurate representation of the building and to provide the geometric basis for the HBIM modelling and hence for the energy and environmental modelling and simulation.

A georeferenced geometric survey, with topographical information of the exterior and interior of the building, with a level of detail that can be compared to a 1:50/1:20 drawing scale (as a general reference, LOD 500 of the American Institute of Architects (2013), is considered the minimum paramount information to develop a robust HBIM model of a historical building.

If planned accordingly, the geometric survey can also provide an invaluable source of information for the general conservation state analysis (see §2.5).

2.3.2 Pre-planning

Prior to data acquisition in the field, it is critical to conduct pre-planning meetings with the involved stakeholders (i.e. building owner representatives, building technical and management staff, occupants representatives, consultants and service providers) to discuss:

- measurement objectives: a clear and concise scope of the geometric survey effort should be established in this stage with a detailed list of the measurements to be taken, the measurements' resolution and level of detail, the required accuracy for each (which may not be the same), and the required file format for deliverables (if relevant);
- security and access constraints: ensuring unhindered access is essential to avoid additional costs incurred due to delays in mobilisation or access to target areas;
- mobilisation strategy.

2.3.2.1 Deliverables

The deliverables of the pre-planning phase are:

- minute of the meetings;
- activity and mobilisation plan's specification;
- updated schedule of activities.

2.3.3 Data acquisition

Regarding the geometric survey, the type of survey techniques to prefer depend on the current information already available on the building, linked to the building's complexity. Therefore, this guideline foresees two different paths of survey-analysis for two extreme cases that are proposed below:

- **CASE 1** if geometric information is almost complete;
- **CASE 2** if no geometric information is available.

Depending on their particular case, the actors involved can develop middle ground strategies.

2.3.3.1 CASE 1

If robust information on the geometric characteristics of the building is available (e.g. digital drawings or paper-based survey documentation at scale 1:50, including plans of all floors, all elevations and at least 3-4 sections in both axes), the activity should focus on:

- a measurement verification of the existing information;
- if needed, geometric data integration to attain the required survey accuracy;
- integration of image-based survey information (e.g. photogrammetry) on the external building elevation and the main internal elements.

Recommended instruments for improving this type of geometric survey could be a total station, photogrammetry with a calibrated camera and/or laser scanner.

2.3.3.2 CASE 2

If there is no reliable geometric information about the building available, the activity should provide:

CASE STUDY:

GUESTS HOUSE, AL-KARAK (EGYPT)

The Jordanian pilot building was built more than 100 years ago and was used as a municipal building. Towards the middle of the 19th century, it started to be used to host guests of the municipality and to organize events and other different activities, after a new, larger building was built to accommodate the activities that the case study building hosted until then.

A specialized team from the Construction and Sustainable Building Centre (CSBC) of the Royal Scientific Society, Jordanian partners of the BEEP project, made several visits to the case study site. They conducted a visual inspection of the building and its surroundings and recorded the internal and external dimensions of the building in order to prepare as-built drawings representing the reality of the building as much as possible, using modern surveying instruments (total station and level).

An image-based survey (photogrammetry) was also conducted. This type of survey could help the team to conceptualize and prepare accurate plans to represent the building. It was also considered the most suitable and flexible method to deal with the privacy of the site and its precise details, especially due to the presence of narrow places and of a mixture of old stone and new stone, as well as the historical value of the building.

CASE STUDY:

PALAZZO MAFFEI BORGHESE, ROME (ITALY)

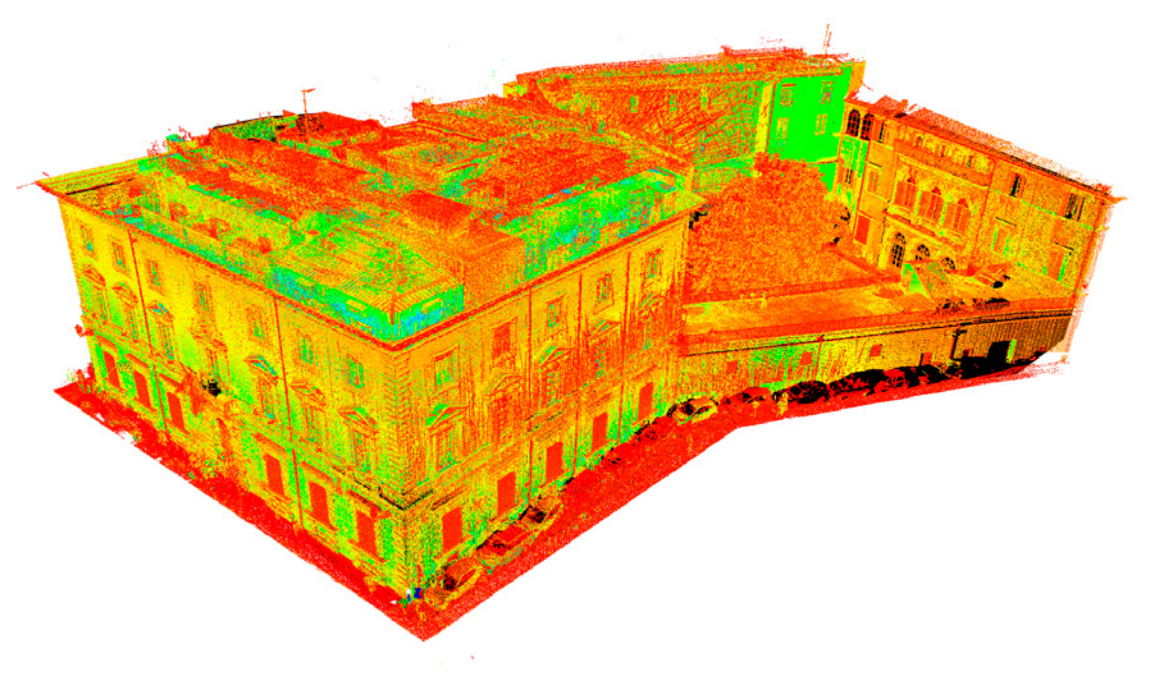
The bulk of the field geometric survey of the Italian case study was performed in a single day. The 3D laser scanner method was used. Two different types of laser scanners were specifically employed:

- Mobile/dynamic, for internal spaces, with the SLAM (Simultaneous Localisation And Mapping) system, that is the process by which the surveying tool constructs a map of an unknown environment and simultaneously keeps track of its own position while moving, for a quick scan of the volumes.
- Static, for façades and external areas, that allows to capture larger portions of a building to generate a more precise point cloud, using a sequence of gripping points.

The reasons for choosing this survey methodology were related to the characteristics of the 3D point cloud. The points have information of a geometric nature and of a colorimetric character. Both features are extremely useful when performing Heritage Building Information Modelling (HBIM). The point cloud was used as a basis for the modelling process by “tracing” over the surfaces generated by the points.

Previous experience of the survey operator in geometric surveys of architecture and in Scan-to-BIM workflows proved paramount to post-process the resulting point cloud to smoothly import it in the BIM software. The careful planning of the survey; a clear definition of the survey’s outcomes for the energy audit model use; the application of a different approach for the interior and exterior of the building, and the segmentation of the whole point cloud file into smaller, significant portions, allowed to reach a good geometric data accuracy and higher manageability of files.

LESSONS LEARNED:
Despite innovative technologies used, the graphical notes of the team’s field survey still proved crucial to understand the key architectural elements to represent for energy purposes, such as windows.



- a complete georeferenced geometric survey of the exterior and interior of the building using:
    - ☐ traditional-direct survey methods;

and/or

- ☐ photogrammetry or laser scanner data, with RGB information.

In both cases, georeferencing the building and the topographical network is recommended, although not strictly necessary for the energy audit and HBIM/BPS modelling and simulation, as it can improve the overall documentation of the building and may also be used in subsequent activities/interventions. Ground and/or aerial scans could also be performed, in order to obtain a complete representation of the building.

2.3.4 Output

2.3.4.1 CASE 1

For the verification and completion of the existing information, the activity should reproduce and integrate the existing drawings in digital vector-based files, covering (at least) the following aspects:

- plans of all the floors;
- all elevations;
- 3-4 main sections on different axis;
- significant details.

The plans must show the main dimensions of the entire building and the linear dimensions of each room, the thickness of internal and external walls and the fenestrations. The elevations (referring to a single plan common to all vertical representations), the internal heights and the surfaces of the single rooms should also be indicated. The representation scale should be 1:50 or less, for the plans, sections, and elevations, and 1:20 for the details.

For the integration of the existing geometric data with a photogrammetric survey on the external building facades and specific internal elements, the activity should produce at least the rectified photography of the external building elevation and the main internal elements as coordinate-controlled imagery or scaled rectified imagery (or other controlled methods). A resolution of 300 dpi on a scale 1:100/1:50 is generally recommended as appropriate.

It is strongly suggested, when performing a photogrammetric survey, to also produce a point-cloud of the building (at least of the exterior) because it can be really useful for the HBIM modelling activity (see § 3). In fact, technological developments in the involved equipment (cameras) and software are facilitating the process of extracting photogrammetry data to a point cloud, which is becoming increasingly easy to develop, less time-consuming and expensive.

2.3.4.2 CASE 2

The activity should produce the registered 3D point cloud of the building's exterior and interior. Data exchange format and non-proprietary format should be preferred to streamline the importing process in the most widespread BIM authoring applications. In addition to the laser intensity value, RGB colour information, acquired on a per-point basis at each scan position, is required.

Normally, very detailed point clouds can be very large in file size, resource-demanding and difficult to manage with current IT workstations in the subsequent phases of the process. Within the current workflow, the point cloud should convey the geometric base data for BIM modelling activities; therefore, attention must be paid to the trade-off between accuracy and feasibility in the use of files.

There are many workflows to help solve this issue. For example, the raw point cloud acquired can be decimated (reduced in file size) to a given level of detail. The surveyor could also perform a differentiated survey of the exterior (more detailed to capture decorations) and the interior (less detailed, just to define spaces and building envelope thicknesses). Moreover, the whole point cloud file could be divided into portions of fixed file size, corresponding to specific building sections, that can be differently integrated into the BIM model, making

CASE STUDY:

PALACIO DE CALATAYUD, VALÈNCIA (SPAIN)

Since the refurbishment of the Spanish case study of the BEEP project was planned in 2016, survey activities (traditional, photogrammetry and laser scanning surveys) had already been carried out prior to the start of the project. The existing geometrical documentation of the building was, therefore, quite complete and accurate and included:

- Alignments (from historical plans, as the plot plan with the original layout).
- Surfaces, elevations, sections, zenith plants, soils, and structure (from the plans stored in the municipal historical archives, which document some of the interventions carried out over the years on the building, and from the current state plans of the building).
- Excavation and medieval wall plans and orthophotographs (from the archaeological plans; archaeological work began at the end of 2016).

The BIM model was built from the point cloud of the building (obtained from the laser scanner), although it was necessary to optimize it because its characteristics (1mm accuracy, very large size due to the excessive detail and inclusion of exterior elements such as vegetation, etc.) made it unoperable. After the optimization process, the file obtained (5mm accuracy, manageable size) served as the basis for the BIM survey, carried out with Revit. In the initial modelling phase, the tasks of defining elements, areas and volumes, as well as the process of clash detection and resolution throughout the process, were key.

LESSONS LEARNED:

The main challenge of the BIM modelling was to incorporate the extensive initial historical building information without compromising the model's operability for later phases, such as the inclusion of the building's energy information and the generation of the IFC model for the energy analysis software.

the whole process smoother and less demanding in terms of IT resources.

Within this guideline, the suggested accuracy for the laser scanner survey is:

- the required maximum tolerance for precision of detail is: 1:20 +/- 6mm - 1:50 +/- 15mm;
- the required point density/rate of capture of measured points is: 1:20 ≤2.5mm - 1:50 ≤5mm.

2.3.5 BIM integration

Usually, geometric survey information, either 2D vectorial data files or 3D point clouds, can be imported into the most common BIM authoring applications and used as a base to model building elements. Point clouds in particular can be used to

CASE STUDY:

BRITISH CAVALRY HOUSE, NICOSIA (CYPRUS)

The British Cavalry Club -the Cypriot case study- combines attributes of colonial style and Cypriot town house architecture.

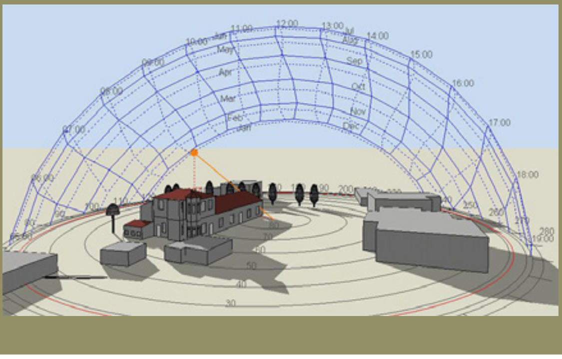
Bioclimatic charts, solar masks as well as indoor and outdoor environmental monitoring revealed the monthly and daily needs of the building for solar heating, shading, natural ventilation and the combined effect of thermal mass and night-time ventilation. Visual inspection and thermographic techniques were used for the estimation of the capillary rise, the crack analysis and the overall conservation state of the building.

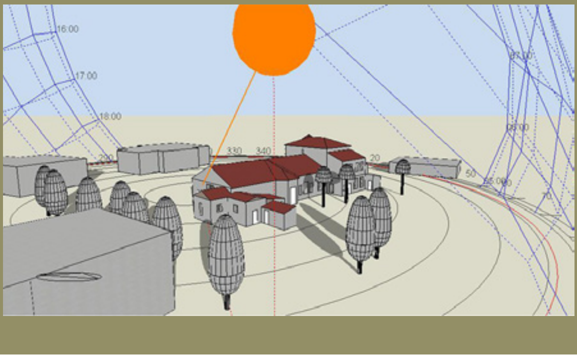
Non-destructive methods were used to identify i) the stratigraphy of the building envelope, ii) the thickness and dimensions of building components, as well as iii) the thermal properties of building materials. More specifically, the underlying materials of the walls, the rising damp, as well as the emissivity of the original plasters were identified through infrared techniques. Establishing the adequate monitoring conditions for the heat flux meter analysis was the greatest challenge for the analysis.

The thermal transmission properties of the opaque building elements were measured through the heat flow meter method described in ISO 9869, while simplifications were made in the calculation of the thermal transmission of the windows and doors, according to ISO 10077. Due to long-term abandonment of the building, previous energy bills could not be retrieved.

LESSONS LEARNED:

Establishing the adequate monitoring conditions for the heat flux meter analysis (10-15° temperature difference between outside and inside) has been the greatest challenge for the environmental analysis.





discretise and understand the main geometric configuration of the building and to obtain the single measures of external and internal elements.

2.4 ENERGY AND ENVIRONMENTAL ANALYSES

The following paragraphs describe the energy and environmental analyses intended to support the energy audit process of a historical building.

2.4.1 Purpose of the analysis

The environmental and energy analyses described in this technical guideline will serve, along with the other analyses (historical, geometric, etc.), to define the thermophysical characteristics of the opaque and transparent envelope. The environmental monitoring part, if present, will help calibrate the building model used for the dynamic energy simulation (see § 4.1) and the subsequent drafting of the energy improvement scenarios (see § 4.2). The energy Auditor (whose services may be outsourced) is the figure who follows the entire process, from the data collection phase to the development of the energy audit.

For the aforementioned purposes, the following data need to be obtained:

- climatic data;
- building occupancy profiles;
- thermophysical characteristics of the opaque and transparent envelope;
- building systems and operation profiles;
- building energy consumption and energy bills;

Non-mandatory data are:

- indoor environmental and comfort conditions in the spaces.

2.4.2 Pre-planning

Prior to data acquisition in the field, the energy Auditor should conduct pre-planning meetings

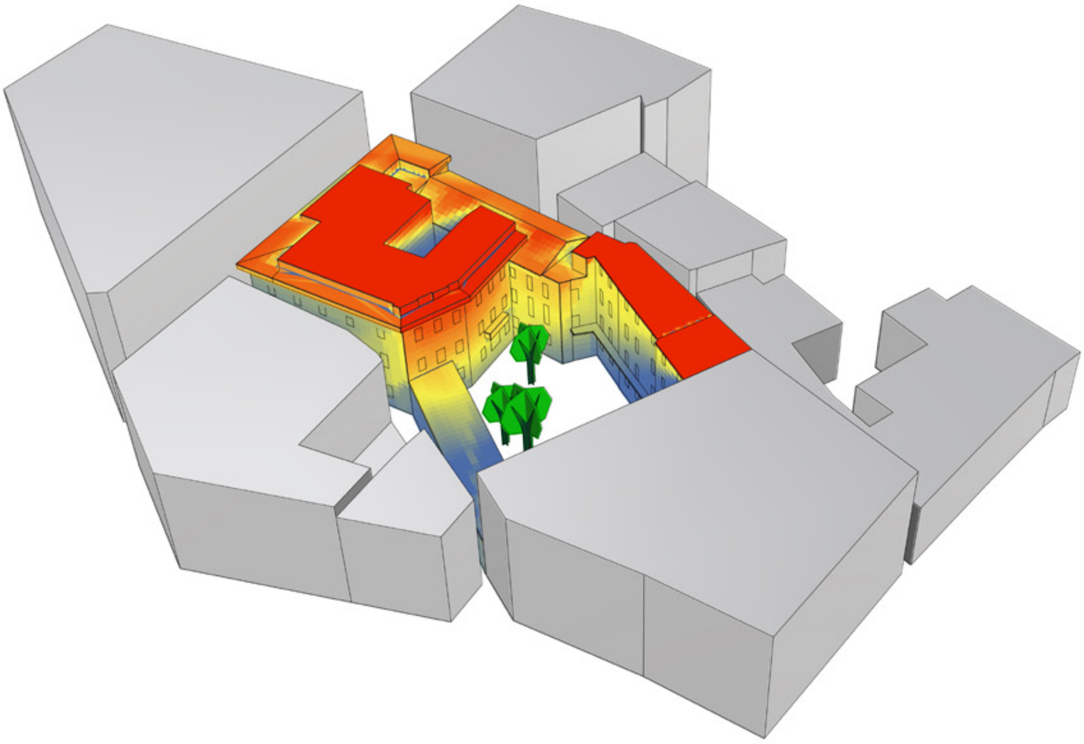


Fig. 4. Analysis of the sunshine duration on the facades of the Italian case study, to select the areas of minimum sunshine radiation to perform the Heat Flux meter analysis.

with technical representatives of the building owner and interested parties (e.g. occupants' representatives), to discuss the objectives of environmental and energy analyses, the security or access constraints, the mobilisation strategy, the details about the involvement of building occupants and to agree on all the operating procedures for carrying out the analyses.

During the meetings, the energy Auditor agrees with the organization on how to access the building and its energy systems, how to gather the available technical documentation, the data to be provided at the end and the analysis execution program. The aspects covered in the meetings are:

- purposes and measurement objectives: a clear and concise scope of the analyses effort should be established in this stage, with a detailed list of the measurements to be taken, the measurements resolution and level of detail and the required file format of the outputs;
- clear definition of each building structure to be surveyed with the appropriate tools;
- verification of existing technical documentation;
- mobilisation strategy: number of survey points, timing of field surveys during the year or the day, delivery deadlines, etc.;
- level of involvement of the building occupants;
- security and access constraints: ensuring unhindered access for the energy Auditor is essential to avoid additional costs incurred due to delays in mobilisation or access to target areas;
- health and safety.

All investigations and tests of any kind must be agreed upon in advance with the competent local Heritage Conservation Authority.

2.4.2.1 Deliverables

The deliverables of the pre-planning phase are:

- minute of the meetings;
- activity and mobilisation plan's specification;
- updated schedule of activities.

2.4.2.2 Data acquisition

The first part of the energy and environmental analysis, to be conducted by the energy Auditor, is the collection of the existing technical documentation on the energy behaviour of the building. The second part concerns a set of environmental field analyses (i.e. mandatory environmental monitoring and optional analyses).

2.4.2.3 Technical documentation

An indicative and non-exhaustive list of the technical documentation survey that the energy Auditor shall collect according to EN 16247 contains:

- Energy Management Service or/and Energy Supply contracts;
- energy-related data, mainly through the energy bills of the last three years, or from individual metering, if available, such as: energy and water consumption, delivered, produced and exported energy per energy source (if available) and short-interval (e.g. hourly) energy demand (if available);
- climatic data for energy simulation purposes (see Annex 8.1)
- any changes that occurred in the building in the last three years: changes in the use of the spaces, changes in the set-points of the environmental parameters, management interventions on the systems, energy improvement interventions, etc.;
- any previous energy analyses performed on the building, if present.

2.4.2.3.1 Deliverables

The deliverable of the technical documentation survey is a technical report containing all the documentation found on the building and an outline of the key data contained.

2.4.2.4 Field analyses

Regarding the field analyses, a mandatory and an additional data set of measurements are described below. The mandatory analyses are necessary to provide robust information on the building's use, the thermophysical properties of the opaque and transparent envelope and the building's systems. Additional field analyses are strongly recommended, as they allow stakeholders to attain a better and more accurate analysis of the building performance, and to design the intervention strategies and the related Return of Investments more efficiently. The type of survey techniques to be performed depends on three key factors:

- the tool/approach selected to perform energy simulations, which also depends on the country's regulation;
- the current information already available on the building and the building's complexity;
- the available budget and timeframe.

2.4.2.4.1 A. Mandatory analysis (data verification through visual and heat flux meter analysis)

Integrating the data collected so far by the actors involved (following the required verification), the energy Auditor shall provide the following information through site visits and heat flux meter analysis:

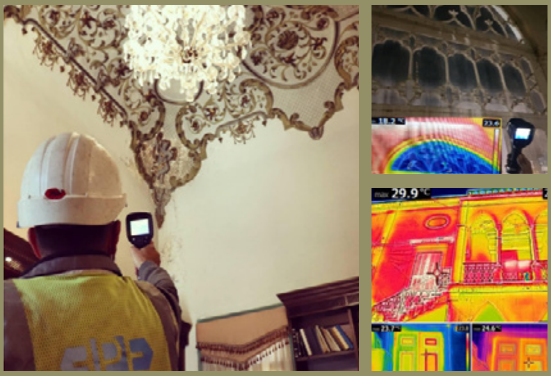
- existing technical documentation on building geometry and confirmation of the provided data deriving from the geometric survey: as-built floor area and building volume, a record of any external factor that may influence the energy performance of the building (e.g. shading by adjacent trees or buildings);
- building occupancy patterns:
    - intended use of spaces and occupancy schedule;
    - window opening patterns: time schedule for each window operation and percentage of opening (*These data are gathered through frequent visual inspection or occupant surveys);*

- information on the building systems, including:
    - heating system and cooling system: overall typology, generation characteristics, terminals position and characteristics, etc.;
    - domestic Hot Water system;
    - forced ventilation system: typology, Air Handling unit, terminals;
    - Lighting systems: lighting position and characteristics;
    - other equipment: other specific systems, building automation systems, etc.;
    - control diagrams and settings (e.g. heating and cooling setpoint and setback temperatures);
    - air changes per hour of every space *(if the building has no forced ventilation, the value can be estimated or it can be detected in detail with indoor environmental monitoring – see additional analysis B3*);
    - heating and cooling operation schedules;
    - hourly internal gains due to people, appliances, equipment, and all the heat sources in the area;
    - hourly indoor water vapour production;
    - minimum and maximum relative humidity set point (if a humidity control system is present);

- information on the opaque envelope, defined as any thermal frontier with the outside environment or with unheated rooms (e.g. perimeter walls characterized by different stratigraphy, roofing, floors, slab on ground, etc.):
    - Thermal conduction resistance [m2K/W];
    - Heat capacity [J/m2K];
    - Hypothesis on the detailed stratigraphy of the structure with thickness, conductivity and thermal capacity of each layer (including internal partitions, box awnings (if present) and portion of opaque wall under the window);
    - Presence of condensation and surface or interstitial humidity;
    - Increase in the thickness of the masonry (if any);
    - Degradation, swelling, detachment or cracking of the plaster and surface finishes;
    - Bacteriological germination, surface efflorescence, mould and fungi;

CASE STUDY:

RACHID KARAMI CULTURAL CENTRE, TRIPOLI (LEBANON)



The Rachid Karami Cultural Centre (1898), which is currently being used as a public library, relies on two energy carriers: EDL and Private Diesel generator.

After performing a walk-through audit where the number and type of energy consumption usages were identified, the average monthly energy consumption of the building was calculated. The numbers were verified using electricity and diesel bills.

A heat analysis study was performed at specific locations across the external walls. The temperature analysis aimed at determining the ambient and surface differential temperatures across the internal and external surfaces of the peripheral walls.

The IR thermography showed the heat variations in the surface temperatures along with the associated causes and defects noted. Variations detected were mainly due to the presence of cracks and cavities, gaps between adjacent panels, and damages in the wooden doors and windows.

The environmental conditions were monitored using air flow meter and illuminance meter. The ventilation system is natural; an HVAC (split unit) system is installed at specific rooms, but it is not in use. Air velocity and permeability were measured at the opening locations at specific time intervals using the single-sided method and the cross-sided method.

The light level was measured with a precision photodiode with cosine and colour correction filter. The illuminance level was measured across the centre of the room.

LESSONS LEARNED:

Heat Flux Analysis is crucial in defining the envelope material for historic buildings. Infrared thermography complemented the energy analysis with the identification of thermal bridges and energy leakage points/surfaces.

- Transparent envelope information, including:
  - Geometry;
  - Frame materials;
  - Glass type and materials;
  - Thermal transmittance [W/m2K];
  - Usage profile and shading devices (if present);
  - General conservation state of the windows (crack analyses, air tightness, water sealing).

2.4.2.4.2 Deliverables

The deliverable on the mandatory field analysis is a technical report on the analyses performed that contains the aforementioned data. The deliverable also consists of technical floor plans and technical data sheets showing in detail the data collected on the building.

2.4.2.4.3 B. Additional field analyses

When information on the thermophysical properties of the opaque and transparent envelope is incomplete or there is a need to collect more information on their properties to formulate a solid hypothesis on the stratigraphy, additional field analyses are recommended. The analyses are also relevant to provide further data to help define the input of dynamic energy simulations to be performed at later stages and calibrate it. Such additional analyses are the following:

- IR thermographies (B1);
- simplified indoor environmental monitoring (B2);
- air flow rate measurements and complete environmental monitoring (B3);
- occupant thermal comfort assessment (B4).

2.4.2.4.4 B1. IR Thermographies

IR thermographies analyses shall be performed according to local technical regulations or following international guidelines. If carried out, they should precede the heat flux meter analyses in order to help define the measuring spots of the heat flux measurements.

Additional data to be reported are:

- thermal bridges;
- air cracks;
- materials emissivity;
- capillary rise of water (estimated);
- irregularities in the installation of the materials;
- any infrared-visible degradation in the internal layers.

2.4.2.4.5 Deliverables (B1):

The additional deliverable on the thermophysical characteristics of the opaque and transparent envelope is a technical report on the analyses performed that contains thermograms and photographs taken during the analyses, pointing out the temperature levels and the building parts where defects or irregularities were found.

2.4.2.4.6 B2. Simplified indoor environmental monitoring

A short monitoring campaign of the indoor environmental indicators of air temperature and relative humidity shall be conducted for selected, characteristic thermal zones of the building. The suggested monitoring period is 2 - 3 weeks (20 days) during winter, summer and mid-season (if possible). Access to the exterior weather data during the monitoring period is strongly recommended (through a credible local meteorological station or in-situ monitoring, with the installation of a portable weather station in the vicinity). These data shall be used for the calibration of the digital model and the dynamic energy performance simulation.

Additional data to be reported are:

- time series of indoor dry bulb temperature (°c) in each selected zone;
- time series of indoor relative humidity (%) in each selected zone;
- time series of exterior dry bulb temperature (°c) (strongly recommended);
- time series of exterior relative humidity (%) (strongly recommended).

2.4.2.4.7 Deliverables (B2):

The additional deliverable of the indoor environmental monitoring is a technical report that presents the location of the data loggers, the selection of the thermal zones to be monitored, the time series of the results for each zone and each monitoring period.

2.4.2.4.8 B3. Air flow rate measurements and complete environmental monitoring

The estimation of the air flow rate and air tightness of the building envelope shall be performed according to local technical regulations or following international guidelines. For the determination of the air permeability of the building, the fan pressurization method (blower door) (ISO 9972:2015) or the tracer gas dilution method (e.g. monitoring the concentration of carbon dioxide CO2) (ISO 12569_2017) may be used. Additional data to be reported are:

- air permeability (ach).

Additional data to be monitored, if possible, are:

- air velocity (m/s);
- illuminance (lx);
- surface temperatures (°C);

- concentration of polluting agents in the air (e.g. CO2).

2.4.2.4.9 Deliverables (B3):

The additional deliverable of the air flow measurement is a technical report that describes the method that was followed and the results obtained.

2.4.2.4.10 B4. Occupant thermal comfort assessment

A questionnaire survey shall be conducted to highlight potential issues in terms of the usage profile of the building and of occupants' comfort. The questionnaire shall contain a simple checklist to collect information on the occupants and the space in which they work, concerning:

- thermal comfort assessment and thermal preference (too cold, too hot, etc.) during winter and summer;
- overall thermal comfort: general acceptance, complaints, etc.;
- visual comfort assessment for the visual task of the building usage or for glare.

The sampling rate of the occupants' responses should be defined by the energy Auditor, depending on the level of in-depth analysis required, the availability of the monitoring equipment and the occupants' commitment (e.g. seasonal distribution of the questionnaire with simultaneous monitoring of the indoor thermal environment is an option for insightful thermal comfort assessment, yet it requires more resources).

2.4.2.4.11 Deliverables (B4):

The additional deliverable of the thermal comfort assessment is a technical report that describes the method that was followed and presents the questionnaires and the results obtained.

2.4.3 Output

All the deliverables produced within these analyses should be organised in a specific report that takes into account also the BIM integration.

2.4.4 BIM integration

The data from energy and environmental analyses should be funnelled into the HBIM model. The organization of collected data can support both a check of the completeness of the data collected from the analyses and a library of the functional data to be inputted into the simulation software.

To allow this transfer from field analysis to model, data should be consistent with the BIM Execution Plan (see § 3.2.1), if any, and with BIM model parameters. Any definition of property set (Pset) for the chosen file format export (IFC, gbXML, etc.) should take the issue into account.

To be identified inside the model, all objects must be referenced with a unique alphanumeric identification code, that must be consistent with the BIM model identification system.

All these data should be integrated into the HBIM model: depending on the case study specifics, the software used for BIM modelling and simulation and the data integration process, it is paramount to define a coherent data input strategy.

2.5 GENERAL CONSERVATION STATE

The following paragraphs describe the general conservation state analyses intended to support the energy audit process.

2.5.1 Purpose of the analysis

The general conservation state analysis is considered a preliminary visual analysis useful for acquiring a detailed knowledge of the building and, mainly, to support energy analysis and encourage the selection of energy improvement technologies capable also of reducing possible decay causes while being compatible with international restoration charts. A preliminary detection and mapping of the various alteration and decay patterns found on the exposed surfaces and of the macroscopic elements of criticality affecting the structures should be developed with particular consideration for factors that can strongly affect energy efficiency, such as a very significant humidity problem in the basement, or the

CASE STUDY:

PALAZZO MAFFEI BORGHESE, ROME (ITALY)

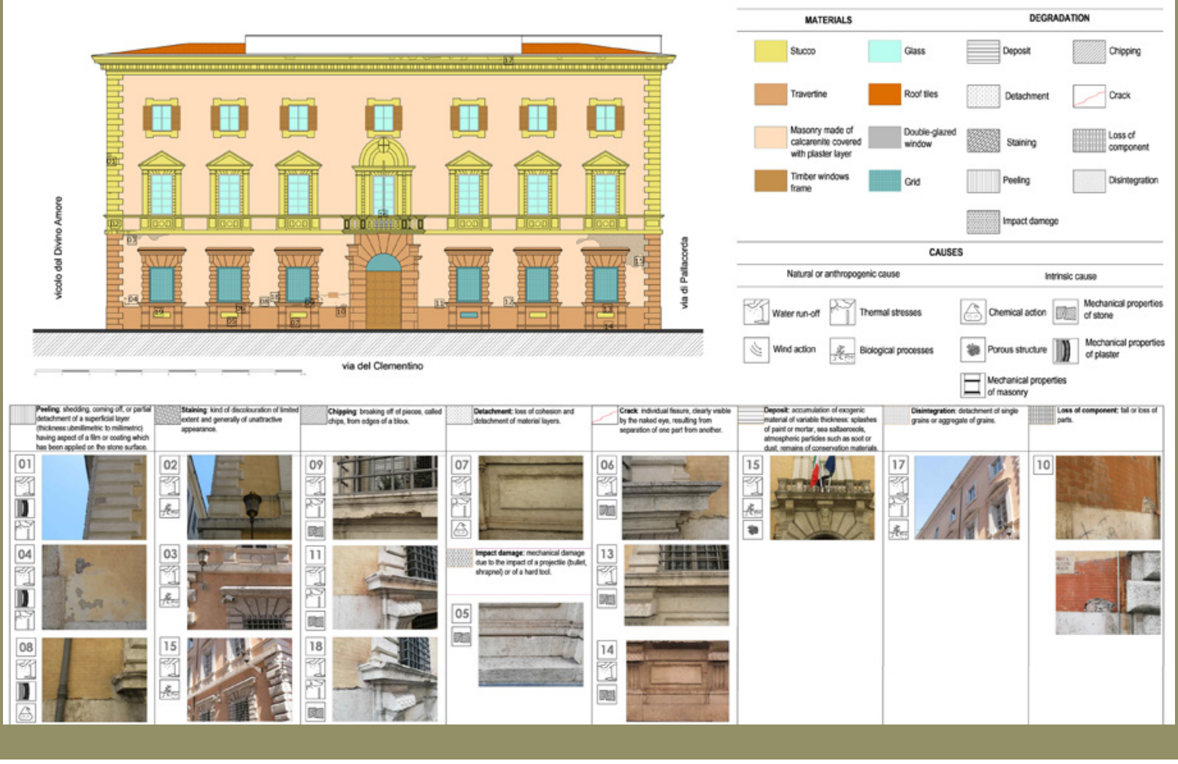
For the Italian case study, the absence of reliable drawings of the building elevations during the first months of the project forced the team to carry out a photogrammetric survey to support the general conservation state analysis.

This process, thanks to technological advancement and with the support of expert operators, guaranteed excellent results at reduced costs and time. The first step involved the photogrammetric campaign, divided into: photographic acquisition, in which the photos of the building are taken following the rules of superimposition between the frames; Structure-from-motion (SfM) and Multiview Stereo Reconstruction (MVS), in which a software reconstructs the position of the photographs and creates the dense point cloud; mesh reconstruction, in which continuous mesh surfaces are defined based on the dense point cloud; texturing, where colour is applied to the mesh through the projection, on the created surface, of the previously oriented images; model scaling. Afterwards, the team performed a field analysis of the general conservation state, with the aid of a digital support (tablet), to draw decay patterns, cracks, etc. directly on the orthophotos derived from the photogrammetry, to which all the photographs taken during the field analysis can be linked.

The general conservation state was finally represented with traditional thematic maps, as no major advantage could be foreseen in modelling them directly within the HBIM model, and the model at that time was still not available.

LESSONS LEARNED:

Although the procedure of photogrammetry for general conservation state analysis is atypical, because it derived from the absence of accurate geometric information, the process proved to be effective.



exceptional lack of air tightness of a window. Of course, if the building presents particular criticalities that cannot be understood enough with preliminary analyses and can affect the intervention strategies, further diagnostics analyses should be planned and executed.

The minimum information needed is the visual detection and mapping of the materials and the various alteration and decay patterns found on the exposed surfaces (external and internal), represented on technical sheets.

2.5.2 Pre-planning

Prior to data acquisition in the field, it is critical to conduct pre-planning meetings with the involved stakeholders (i.e. building owner representatives, building technical and management staff, occupants representatives, consultants, services providers) to discuss:

- analysis objectives: a clear and concise scope of the general conservation state analysis should be established with the required deliverables;
- security and access constraints: ensuring unhindered access is essential to avoid additional costs incurred due to delays in mobilisation or access to target areas;
- mobilisation strategy.

Any supplementary in-depth investigations that could involve destructive analyses of any kind must be agreed upon in advance with the competent local Heritage Conservation Authority.

2.5.2.1 Deliverables

The deliverables of the pre-planning phase are:

- minute of the meetings;
- activity and mobilisation plan’s specification;
- updated schedule of activities.

2.5.3 Data Acquisition

The following visual analysis and investigations relating to the general conservation state should be performed:

- material analysis: survey and mapping of structural and finishing materials and thematic mapping of existing finishes (including windows and external doors, surfaces, stone or wooden artefacts);
- decay and deterioration pattern and crack pattern analysis;
- identification and graphic representation of the construction phases of building elements.
- The analysis shall follow the local national and international regulation requirements on general conservation state analysis.

2.5.4 Output

The output must include:

- technical report on the findings;
- technical data sheets consisting of descriptive, graphic (thematic maps) and photographic sections, on the architectural surface analysis, material analysis, decay and deterioration pattern and crack pattern analysis, following the local national and international regulation requirements;
- if relevant, description and explanation of the annexes schemes, legends, etc.

The documents described above can be produced in pdf format for the descriptive and photographic section and .dxf format, scale 1:50-1:20, for the thematic maps, if not differently specified by the local regulation.

If there is no local regulation available, the following international regulations are suggested:

- ICOMOS. Principle for the Analysis, Conservation and Structural Restoration of Architectural Heritage; International Council on Monuments and Sites: Paris, France, 2003.
- ICOMOS. Illustrated Glossary on Stone Deterioration Patterns; International Council on Monuments and Sites: Paris, France, 2008.
- EN 16096:2012. Conservation of Cultural Property—Condition Survey and Report of Built Cultural Heritage; European Committee for Standardization, 2012.

2.5.5 BIM integration

If there is no specific need, it is not critical for the general conservation state analysis to feed directly into the HBIM model: to the best of our knowledge, up to this publication, there is no defined way to represent decay in a BIM model as a property of the element it belongs to (for example, a moist area as belonging to the wall it is on), primarily for limitations of the most common BIM applications; the possible workarounds does not seem a real improvement in the building information process from the traditional thematic maps referred to the building elevations yet.

Therefore, it is possible to integrate the general conservation state report as an external link to the HBIM model. For specific issues, it would be possible to link more detailed analyses, if performed, or to add specific information to given building elements, but this is not a primary goal of the process. ■

Fig. 5. Photogrammetry survey of the Italian case study “Palazzo Maffei-Borghese” in Rome

Fig. 6. Comparison between the photography and the termographic image of the main façade of Palazzo Maffei-Borghese, Rome

3. ENERGY EFFICIENCY HERITAGE BUILDING INFORMATION MODEL (EE-HBIM)

The following paragraphs describe the Energy Efficient Heritage Building Information Modelling (EE-HBIM) activities intended to support the energy audit process.

Fig. 7. EE-HBIM model of the Egyptian case study "Cordahi Building" in Alexandria of Egypt.

3.1 Purpose of the EE-HBIM modelling

The purpose if the EE-HBIM model is to act as a centralized repository to optimize the management of the large amount of information (geometrical, alphanumerical and documents) deriving from the analysis and simulation process for the energy improvement of built heritage. The advantages of the model will be its simplification and effectiveness in ensuring the permanence, consultation and implementation of data, accessible and understandable by different stakeholders.

The model should be developed in two different stages. Within Stage 1, the EE-HBIM model will integrate the previously collected information deriving from the performed analysis (geometric, diagnostic, energy and environmental data, see § 2.2, 2.3, 2.4, 2.5) to create a comprehensive documentation of the building's current state.

The EE-HBIM model of Stage 1 will be used as a basis to inform a subsequent energy-environmental

Fig. 8. EE-HBIM Model of the Spanish pilot building “Palacio de Calatayud” in the city of Valencia.

improvement design concept, through energy renovation scenarios that are both compatible with the identified historical building and capable of enhancing its energy and environmental performance.

The scenarios’ energy performance will be evaluated with specific dynamic energy simulations (see § 4).

In Stage 2, the technical characteristics of each scenario and its energy performance will be integrated within the EE-HBIM model (4D - 5D – 6D – 7D), in order to facilitate a Return Of Investment (ROI) analysis and the drafting of the Energy Performance Contract.

CASE STUDY

RACHID KARAMI CULTURAL CENTRE, TRIPOLI (LEBANON)

The model for the Rachid Karami Municipal Cultural Center was developed using Autodesk's REVIT software (version 2021). For clash detection, the Navisworks software was adopted. For energy analysis and simulation, the DesignBuilder software was used.

The point clouds (.Rcp file), as a result of scanning, were exported and linked to the Revit model and followed by the drafters to start developing the model. Historical documentation was added and updated whenever new information and data was found. The 2D material mapping was linked to the Revit file. Next, decay and alterations' mapping was performed using Autodesk's AutoCAD software.

In fact, a 3D survey of the interior and exterior of the building was performed using the laser scanning technique combined with a topographic survey that helped establish a geographic reference for this scan. The result was a georeferenced point cloud file. Once the scanning was completed and the point cloud file was prepared, the HBIM model was developed in Revit software.

All modelled objects (walls, ceilings, floors, MEP systems, doors and windows, etc.) were limited to the corresponding upper and lower levels. The use of mass systems was limited and restricted to elements that cannot be drafted except by this technique, families and nested families were used.

The 4D and 5D EE-HBIM implementation of the three scenarios (see Chapter 6) was performed to evaluate in terms of time and cost the intervention scenarios and the 6D EE-HBIM including the implementation of the three scenarios.

As for the modelling of the architectural elements, such as columns, pilasters, arches, windows and column flutes, they were modelled as families and nested families within them and subsequently inserted into the main file. Whenever necessary, components were modelled in place, especially for the kitchen caseworks and library shelving and cabinets (when not modelled as a family). All energy data were inserted by type and by material.

LESSONS LEARNED:

In the case of no bounding elements, room separators were created to limit the space and create rooms. The use of curtain walls facilitates repetitive modelling to avoid editing wall profiles and causing clashes and warnings, especially when constructing arches.

3.2 PRE-PLANNING

3.2.1 BIM Execution Plan (BEP)

Before starting the modelling process, it is critical to develop a BIM Execution Plan (BEP). In line with the definition of ISO 19650, the BEP defines the methodologies, requirements and timeframe on which the information modelling will be carried out. A BEP should detail not only how information is created and delivered, but also the 'why' (defining the BIM use), and the 'who' (assigning responsibility for it). It specifies the management, technical, commercial and project information and deliverables required for the project in a way that is specific, measurable, achievable and realistic. All stakeholders involved must adhere to and follow the BEP.

There are numerous templates for BEP following ISO 19650 requirements; based on those documents, the actors should adapt the BEP to the building's peculiarity, model uses, data available and stakeholders' skills and tools.

The BEP describes models federation, model uses, naming convention, LOD and modelling strategy, providing a flexible overall methodology for EE-HBIM. The main topics of a BEP are provided below.

3.2.1.1 Roles and responsibilities

The BEP shall indicate the project team members carrying the following roles, indicating their capability and experience to fulfil the requirements of the roles: BIM Manager, whose function is to manage the whole information process; CDE manager, whose function is to manage the Common Data Environment; BIM Coordinator, whose function is to manage each discipline model; BIM Specialist (generally more than one), whose function is to model the model containers. The same person can fulfil different roles.

3.2.1.3 Model uses

The model uses direct the main modelling approaches. Within Stage 1 and Stage 2 of the modelling process, the main objectives and their corresponding model uses are:

Phase	Objectives	Uses
Stage 1	Constructive HBIM model definition	Integration and representation of building geometrical and technical information according to the documentation collected in the analyses (geometric survey, drawings, etc.). Definition of building elements. Space, areas and volumes analysis.
	Management of the knowledge documentation on the historical building	Integration of historical documentation (information sheets, links, etc.). Integration of diagnostic information (materials and structure survey, etc.).
	Management of the environmental-energy analysis	Integration of energy and environmental analyses.
Stage 2	Support of the energy improvement interventions and scenarios and of the choice of adapted renovation stragegies and technologies	Integration of the energy improvement interventions and scenarios with data concerning time, costs and management (4D, 5D, 6D, 7D).
	Assessment of ROI of the environmental-energy interventions and scenarios	Integration of ROI evaluation method based on the interventions and scenarios' costs and energy savings.

3.2.1.3 Level of Information Need

When modelling geometrically complex objects, typical of historical buildings, it is paramount to provide a clear specification of the Level of Information Need (EN 17412 Building Information Modelling. Level of Information Need. Concepts and Principles, 2020; ISO 19650:2018 Organization and Digitization of Information about Buildings and Civil Engineering Works, Including Building Information Modelling (BIM) — Information Management Using Building Information Modelling —, 2018), that expresses the level of maturity required for a particular informa-

Basic Wall
CYI_ACR_ExteriorWall_C2b_580mm

Walls (1)

Constraints	
Location Line	Finish Face: Interior
Base Constraint	00
Base Offset	-120.0
Base is Attached	☐
Base Extension Distance	0.0
Top Constraint	Up to level: 03
Unconnected Height	8870.0
Top Offset	500.0
Top is Attached	☐
Top Extension Distance	0.0
Room Bounding	☑
Related to Mass	☐
Cross-Section	Vertical
Construction	
Order Status	
Delivery Date	
Delivery Status	
Order Date	
Structural	
Structural	☐
Enable Analytical Model	☐
Structural Usage	Non-bearing
Dimensions	
Length	5848.7
Area	37.367 m^2
Volume	20.644 m^3
Identity Data	
Image	A1_ConservationStateAnalysis_...
Comments	
Mark	
Phasing	
Phase Created	New Construction
Phase Demolished	None

Fig. 9. Object selected to view its properties in the BIM model of the Cypriot pilot building.

tion deliverable at a particular plan of work stage. It is important to avoid the delivery of too little information, which increases risk, and the delivery of too much information, which is wasteful.

Depending on the model uses, the necessary information should therefore be balanced between geometrical correspondence and alphanumeric data. The perceived benefits in terms of information quality and completeness, visualisation requirements, etc. should be carefully weighed against model functionality, file restrictions and time effort. In order to be cost-effective, the minimum level of graphical detail sufficient for the model should be specified.

The development of an EE-HBIM model requires articulating the content and detail of model objects in a shared definition: for instance, the clear description of which building components to model, their standard classification, the Level of Information Need for each of them, including both their geometrical and alphanumerical information provided through model parameters.

An effective way to organize this information is using the Model Element Table (BIMForum, 2019), that is a table in which a building is decomposed into model elements (walls, floors, etc.) according to a breakdown structure, following Omniclass classification (Construction Specifications Institute, 2019). Each model element is associated with a Relevant Attribute Table, containing attribute information to be inserted in the BIM model using specific parameters. Relevant Attribute Tables, therefore, condensed the required alphanumeric information for any given model element.

The main issues in the use of the Model Element Table, and therefore the OmniClass classification, for historical buildings, arise from the fact that all building classifications based on ISO 12006 have been developed for the contemporary industrial process of the construction sector and for the most widespread construction systems and technologies; thus, they may not be appropriate to include the complex, not standard elements and technologies of built heritage. For example, the definition of structural element reflects the separation between

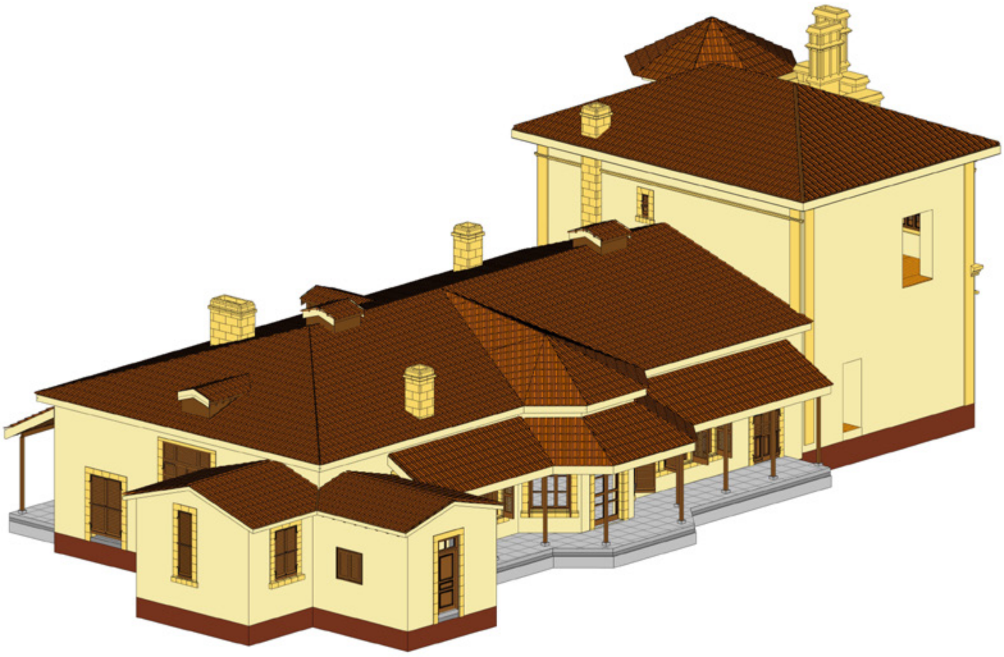


Fig. 10. Cypriot pilot building.

structural frame and enclosures that is normally not applicable to historical buildings. Top levels may still work well, as they indicate the element type in broad terms, while the detail that is introduced in lower levels can be misleading. A lite classification (top of the pyramid) with additional commentary is the likely way (Brookes, 2017).

3.2.1.4 Model federation and data segregation

The BEP shall indicate a federated model strategy, depending on the historical building dimension and on the energy simulation process adopted. It is recommended to separate at least the architectural model and the MEP model, including terminals and heating and cooling production system – useful for energy analysis. A separated structural model is more useful with a frame concrete or wood structure.

3.2.1.5 Data sharing and collaboration

A Common Data Environment (CDE) complying with ISO 19650 and ISO 27001, must be used for the management or sharing of data, to facilitate collaboration and information sharing between members of the project team. Common BIM standards must be established and agreed upon in advance.

3.2.1.5.1 Naming convention

It is paramount to define a naming specification to be used for all document types uploaded to a CDE, in line with IEC 82045-1 and BS 1192:2007(A2) 2016. For the naming convention of model elements, an existing standard can be applied; when using the Model Element Table, that is based on Omniclass classification, Omniclass standard could be applied, keeping in mind its limits when describing historical buildings (see § 3.2.1.3)

3.2.1.5.2 Modelling strategy

A description of the modelling strategy, data exchange formats and common coordinate system should be provided.

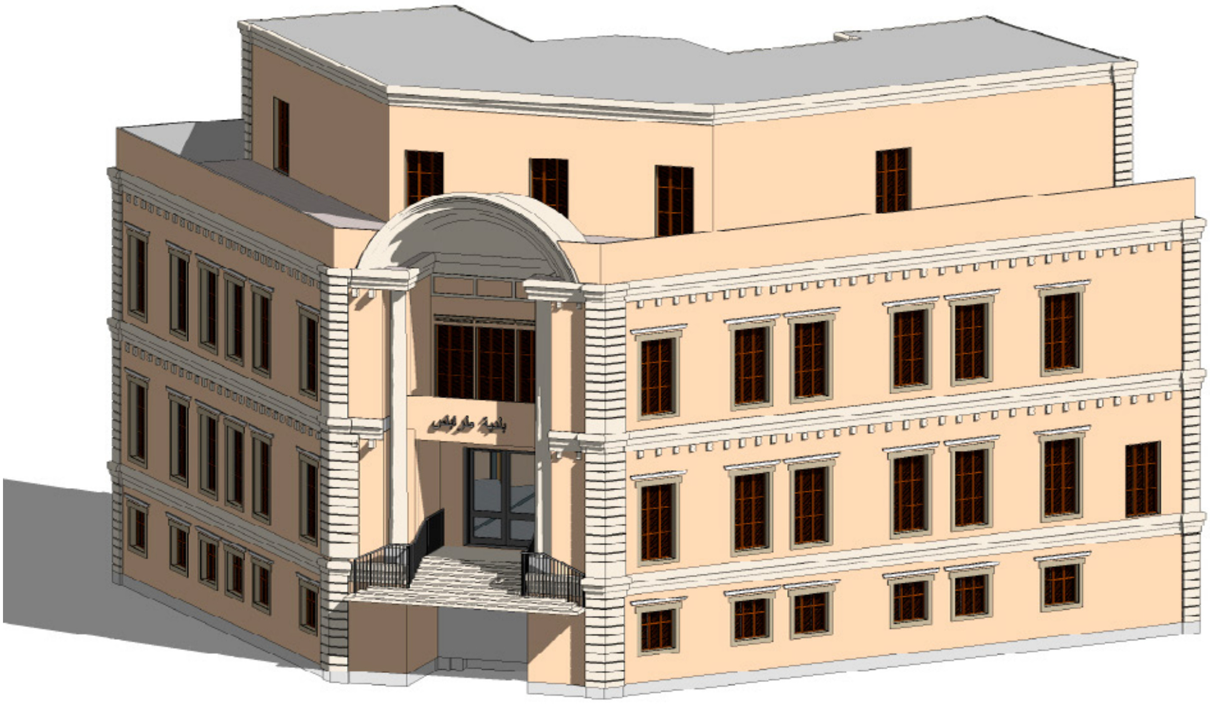


Fig. 11. Lebanese pilot building “Municipality of Tripoli”.

3.2.2 Outsourcing of the EE-HBIM model - tender process

If the BIM modelling activity is outsourced, the actors involved in the tender process shall follow the bidding procedure defined by ISO 19650. The Employer shall define an Exchange Information Requirements (EIR), that is a tender document setting out the information to be delivered, and the standards and processes to be adopted by the Consultant as part of the project delivery process, outlining the Employer’s strategic approach and specifying the management, technical, commercial and project information and deliverables required for the project.

The Consultant shall deliver a Pre-contract BIM Execution Plan (BEP) for the project as a direct response to the EIR. If selected, The Consultant shall deliver a Post-contract BEP and review its BEP regularly and additionally when there is any change to the contract.

3.3 OUTPUT: EE-HBIM MODELLING

The modelling process should be based on the geometric and technical information (geometric survey, drawings, etc.) collected during the analysis phase (see § 2). Based on the collected information, the model will represent the constructive system and technological characteristics of the building (vertical and horizontal structure, materials, etc.) as accurately as possible within the Level of Information Need. The walls, roofs and floors will be modelled with their stratigraphy (known or assumed). Decorative elements can have a simplified representation, as long as their constructive system is detailed.

The HBIM model development will take advantage of the parametric tools of native software (e. g. system families) as much as possible, avoiding non-parametric tools such as mass modelling. The correct representation of the building’s technical, constructive and environmental features is paramount, even when leading to the simplification of

CASE STUDY:

HORREYA CENTRE, ALEXANDRIA (EGYPT)

Horreya Centre (1887), one of the two Egyptian pilot buildings, was originally an Elite society club. It was later changed into a cultural centre, and it currently also houses a theatre and exhibition space.

In this case study, all geometric survey drawings were prepared and reviewed as well as site verification of measurements to start modelling. Also, the team revisited the building more than once in order to fill any missing data. Geometric survey and laser scanning were performed to get accurate 3D models of the buildings as a point cloud and as cad plans and cross sections.

After the adjustments of levels, the CAD drawings were inserted in REVIT for modelling in reference to each level, followed by the creation of walls, floors, columns and ceiling. Families were created and loaded into the project file, and finally placed. Also, model-in-place were used in different parts of the buildings, especially aesthetical details along facades. Those were always verified by the point cloud 3D laser scans.

In general, plans were extruded in the beginning to create a basic 3D model, later families for windows, doors and engraved details were created to add full details to the building. The 3D point was integrated to the model to validate any details and building exterior state of conservation.

After the BIM model was finalized, it was exported in gbXML format to the energy simulation software. A conflict between the two applications occurred when transferring, where data was missing. So, the team agreed on exporting a simple version of the BIM model. The changes and details that were made into the model through the energy simulation software were later updated in the BIM file.

LESSONS LEARNED:

The smooth workflow and required level of details that can be transferred from BIM to Energy Simulation Software were established in order to minimize modelling time required for energy simulation.

uneven features, typical of historical buildings (e.g. assuming planarity of walls), if needed.

Historical and diagnostic information (materials and structure survey, energy analyses, etc.) collected during historical and architectural analysis (see § 2.2) and general conservation state analysis (see § 2.5) should be incorporated into the model. If the information cannot be directly integrated into the elements, it can be linked using reports, sheets, drawings, etc.

In order to support environmental-energy improvement scenarios, the energy information collected in the energy and environmental analyses (e.g. transmittance values for walls and windows, occupancy data, etc., see § 2.4) should be integrated into the model. Occupancy and uses profiles for each room and/or thermal zones, if not included in the model, should be linked as external files (reports, sheets, etc.).

Regarding MEP system, HVAC systems terminals and plants should be represented. If no specific MEP system is modelled, room/areas information could include data on plants and terminals.

Regarding object insertion and constraints, all objects (walls, roofs, ceilings, floors, HVAC systems, structures, windows, etc.) must be constrained to the corresponding lower and/or upper levels.

If a federated model strategy is developed, all models should be geo-referenced according to the same absolute origin established in the union file. The reference grids of the federated files may refer to a relative origin, suitably identified due to the geometric and disciplinary complexity of the work, but these grids must conform to the georeferencing of the absolute origin. ■

Fig. 12. View of the Italian case study “Palazzo Maffei-Borghese” and the garden separating it from the adjacent “Palazzo Firenze”.

Rashid Karami Municipal Cultural Center, Tripoli – Lebanon. The building combines both the European and Ottoman styles with its distinctive high red brick roof. Originally a residential Villa, it was built by Qaisar Nawfal, a prominent figure in Tripoli.

4. DESIGN OF INTERVENTION, ENERGY SIMULATION AND ASSESSMENT

The activities described below encompass: developing the energy model and assessing the energy performance of the existing building; analysing passive and active technologies employed by the building and the market maturity for such technologies; designing the energy and environmental improvement interventions; assessing their technical feasibility; grouping them into one or more energy and environmental improvement scenarios, to be evaluated with the *post operam* building performance simulations and payback time calculations.

The above are outlined in the following paragraphs:

- 4.1 Development of the energy model, input data verification and calibrated dynamic energy simulation of the existing building (*ante operam*);
- 4.2 Design, simulation and evaluation of the energy and environmental improvement interventions and scenarios (*post operam*).

Dynamic simulations are considered a requirement in this process due to the complexities involved in historical buildings' energy and environmental performance assessments (see Annex 8.2). Country-specific regulation on energy-audits and energy efficiency of buildings should guide the selection of the type of simulation to be performed, choosing at least between the simple hourly method of EN ISO 52016-1 and a detailed dynamic model. For more information on the two approaches please refer to the study of Ballarini et al. (2020).

4.1 DEVELOPMENT OF THE ENERGY MODEL, INPUT DATA VERIFICATION AND CALIBRATED DYNAMIC ENERGY SIMULATION OF THE EXISTING BUILDING (*ANTE OPERAM*)

Although the calibrated dynamic energy simulation of the existing building could still be part of an analysis phase, given its strong connection with the design activities (it provides the performance indicator benchmarks and the starting model for the *post operam* design) it was deemed more practical to include it in this phase, also to foster a joint consideration with the involved actors on simulation as a whole.

4.1.1 Purpose of the analysis

This section provides technical specifications for the data verification and the development of the dynamic energy simulation of the historical building. The Simulation Expert (whose services may be outsourced) is the figure who follows the entire process, from the data verification phase to the de-

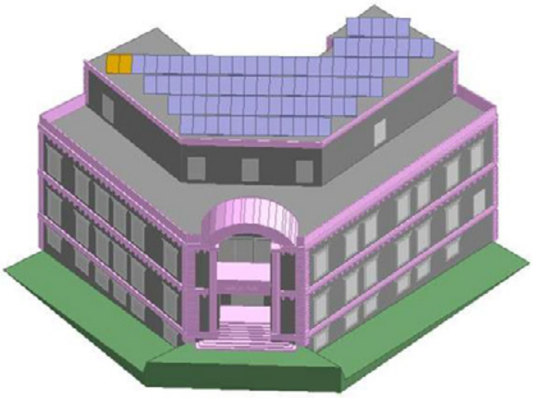


Fig. 13. The Municipality of Tripoli showing the PV and SWH panels

velopment of the energy model and the dynamic energy simulations. This, along with any other necessary analyses and modelling, will help evaluate the energy and environmental performance of the building in its current state, along with the subsequent environmental and energy improvement scenarios (see § 4.2).

4.1.2 Pre-planning

Prior to performing the dynamic energy simulations, pre-planning meetings should be conducted by the Simulation Expert to discuss the activity objectives, security or access constraints, mobilisation strategy and more details regarding (as described in EN 16247-2):

- activity objectives: a clear and concise scope of the activities should be established at this stage, compiling a detailed list of the simulations to be performed, the results' accuracy, the performance indicators and the required format of the deliverables. Also, the interventions' objectives and design limitations should be clearly stated;
- data availability: the available data (historical and architectural, geometric, diagnostic, energy and environmental data, see § 2.2, 2.3, 2.4, 2.5) regarding the current state of the building sand the available climate (see Annex 8.1) file should be checked, together with the availability of *ante operam* EE-HBIM file to streamline energy modelling activities and plan the interoperability workflow (see Annex 8.3 for the State of the Art on BIM and BPS interoperability), and the choice of the energy simulation software to be used. It is noted that the simulation software should comply with ISO 52016 and provide hourly or sub-hourly calculation options;
- security and access constraints: ensuring unhindered access for service providers is essential to avoid additional costs incurred due to delays in mobilisation or access to target areas;
- mobilisation strategy.

4.1.2.1 *Deliverables*

The deliverables of the pre-planning phase are:

- minute of the meetings;
- activity and mobilisation plan's specification;
- updated schedule of activities.

4.1.3 Data acquisition

4.1.3.1 *Input data verification*

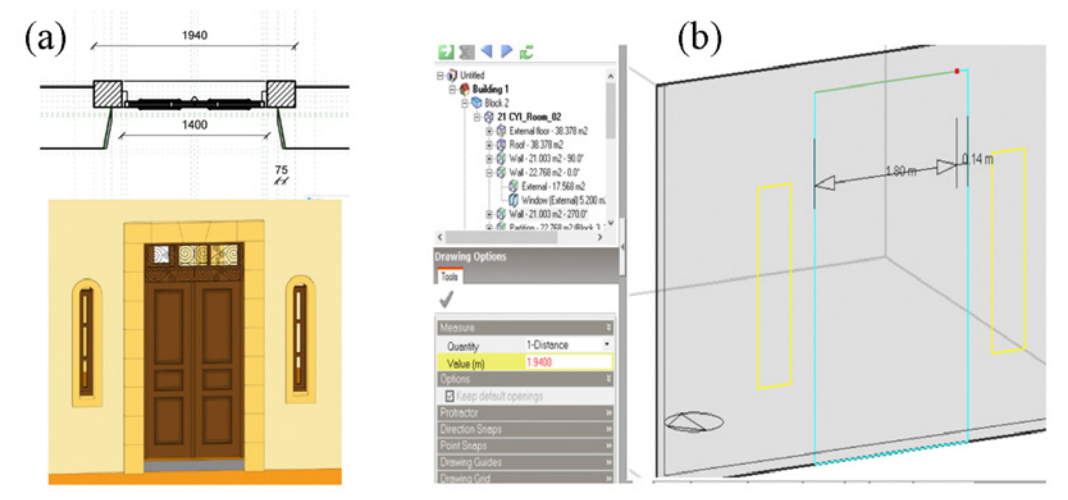
The available information on the building should be transmitted to the Simulation Expert. The HBIM model may be used as a basis for drafting the energy model to be used for the simulations (for more information on the interoperability process refer to Annex 8.3). The environmental monitoring, if present, as well as the energy analysis data, will be used for the calibration of the energy model.

During the pre-planning activities, the Simulation Expert should receive the following data in the respective forms:

- all the energy and environmental-related data in the form of spreadsheets (.xls or other database file format) and reports. These data concern: the technical documentation survey performed in the framework of the preliminary analysis (historical and architectural, geometric, diagnostic, energy and environmental data, see § 2.2, 2.3, 2.4, 2.5), robust information on the thermophysical properties of opaque and

CASE STUDY:

BRITISH CAVALRY HOUSE, NICOSIA (CYPRUS)



Quantity: 1-Distance
Value (m): 1.9400

The interoperability study between Building Information Modelling (BIM) and Building Performance Simulation (BPS) activities for the Cypriot case study of the British Cavalry Club employed a methodological workflow of experimental development and qualitative research. The task was performed by a conservation expert, BIM experts and dynamic simulation experts who checked the correspondence between information needed by the energy software (Design Builder) and the data to be input in the BIM software (Autodesk Revit) through the gbXML exchange schema. The team followed an iterative process of models exchange for examining the nature and the reversibility of the emerging errors, i.e., geometric model conversion inconsistencies, data conversion issues, data redundancy, exchange schema capacity and limitations, etc. Each interoperability test was analysed and recorded, both in terms of its conversion accuracy and data adequacy. The reasoning behind each successive test-model conditions' formulation was based on the targeted sampling, for avoiding previously experienced error-prone BIM model conversion settings or export configurations. Suggested BIM modelling rules have been documented and suitable BIM ontologies selection for appropriately exporting uncommon heritage building were highlighted, i.e., ornamental geometric elements to be excluded from the model export, doors with partly glazed area to be converted to window ontologies, global BIM parameters to be embedded in explicit BIM elements, complex structures to be constructed of simpler, typical BIM elements, etc.

LESSONS LEARNED:

BIM to BPS interoperability remains an ongoing endeavour of the research and professional practice community. Best practices and BIM modelling guidelines for improved interoperability should always be advised.

transparent envelope, previous analyses and monitoring performed, existing building design sheet and thematic maps, energy bills, occupancy schedules, HVAC systems, etc.;

- the geometry of the building in CAD format or the native EE-HBIM model, with the complete energy-related metadata integration (e.g. all the single instances of walls with their thermo-

Fig. 14. gbXML Check – Spider Web

physical characteristics, windows, generators, terminals, etc., in specific schedules in which every single object is defined).

The Simulation Expert shall then verify the data with an in-situ survey and collect further information, if deemed necessary, to complement the input data required for the drafting of the energy model.

The strategy for obtaining a valid climate file to be used for the simulation is to be discussed in the pre-planning activities. The file should represent the long-term average climatic conditions of the buildings' location (e.g. Typical Meteorological Year 2 - TMY2, Weather Year for Energy Calculations 2 - WYEC2, etc.). It can be either extracted from national databases or online weather data repositories or generated based on detailed outdoor environmental monitoring according to EN ISO 15927-4. Its final compatibility with the Simulation Software should be confirmed by the Simulation Expert (see Annex 8.1).

4.1.3.2 Model calibration

<u>In case the historical building is in use and employs HVAC systems</u>, the prime calibration parameter may be the energy consumption (kWh) on an annual and monthly basis. For this purpose, the current energy bills, or data deriving from energy meters, shall be used. The tolerance range proposed by the ASHRAE Guideline 14 (2014) or other relevant literature can be accepted. An overview of the existing literature is provided in Annex 8.2.

If additional analyses are available, particularly the "Simplified indoor environmental monitoring (B2)" (described in § 2.4.1.3.3), an enhanced calibration based on the environmental parameters of air temperature and relative humidity is recommended. In this case, the calibration process shall be also based on the comparison of simulated and measured data (i.e. data recorded during the monitoring period in specific, indicative thermal zones).

The statistical indicators of mean absolute error (MAE), and root mean square error (RMSE), shall be used. The first indicator represents the standard deviation of the differences between measured and simulated data, while the second one takes into account the average absolute error of the differences between measured and simulated values. Two dif-

CASE STUDY:

PALAZZO MAFFEI BORGHESE, ROME (ITALY)

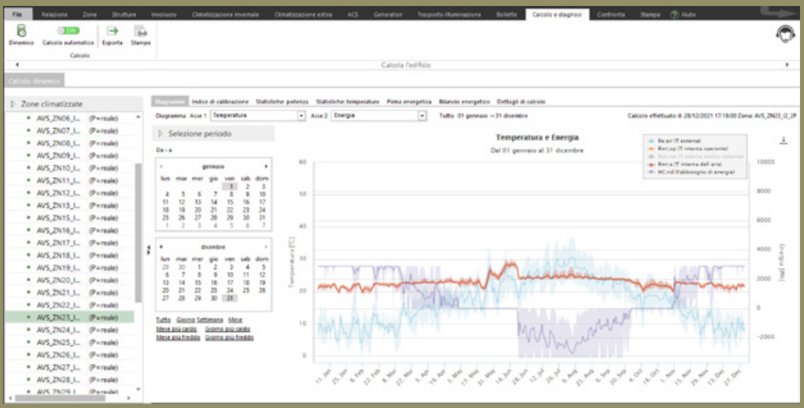
The interoperability process between the Building Information Modelling (BIM) activities and the Building Performance Simulation (BPS) model for the Italian case study Palazzo Maffei-Borghese in Rome followed a three-step process. In the first step, the involved experts met to build a shared knowledge framework, covering the choice of the two software environments (in this case, Graphisoft Archicad as BIM software and Logicalsoft Termolog as BPS software), and the discussion of the known issues of data transfer between them. This task involved a conservation expert, BIM experts and BPS experts to map and check the correspondence between data needed by the energy software and data to be inputted in the BIM software and general interoperability issues, by means of preliminary tests performed on simplified models. In the second step, the team focused on testing the data flow on a portion of the building representative of case study-specific issues, such as levels at different heights, sloped roofs, high amount of fenestration, complex ceilings, vaults). During the second step, the team drafted a modelling guide encompassing all the main steps of the interoperability process: BIM modelling, BIM exporting to IFC, IFC file check, IFC import in the BPS software and BPS post-processing. The third step involved the BIM modelling of the whole building up to the final BPS model. The modelling guide was then finalised in order to help other professionals involved in this process. Each section can be followed by its related expert without reading the others, or it can be read as a whole to grasp the reasoning behind each modelling strategy implemented.

LESSONS LEARNED:

Interoperability is an interdisciplinary process that is best delivered when experts are in constant contact and actually work together. A semi-automated method is still the best way to approach the process as it allows for manual interventions that are necessary to fine-tune each interoperability step.

CASE STUDY:

PALAZZO MAFFEI BORGHESE, ROME (ITALY)



The Italian case study Palazzo Maffei-Borghese in Rome was simulated using the simplified dynamic calculation method of the EN ISO 52016 framework. The calibration process of model was confirmed to be a very important phase in the comprehension of the historical building not also for the energy point of view but also to further investigate construction techniques, building occupancy and system usage. The calibration also aimed at identifying and simulating the actual HVAC, lighting and DHW usage profiles, employing the analysed energy bills and the indoor monitored temperature of key spaces as a reference. In total, the calibration process required 18 iterations of the energy model to be able to reach a deviation in energy consumption for heating and cooling services of -0.45% in winter and -3.87% in summer (the negative sign indicates a slight overconsumption in the simulation model compared to the respective energy services extracted from the bills of the analysed period). The process had to deal with several issues relating to: energy modelling simplifications inherent in the EN ISO 52016 approach to dynamic simulation; the current incompleteness of regulations in the EN ISO 52000 framework and the related need for hybridisation between the simplified dynamic calculation of EN ISO 52016 (usable up to the estimation of the building envelope's requirements) and the system non-dynamic calculations of EN 15316 and UNI TS 11300; lastly, with uncertainties and inconsistencies related to the building and system usage profiles. The team analysed each criticality proposing a countermeasure to progress the study, also working alongside the energy software developers for the definition of the best solution.

LESSONS LEARNED:

Indoor environmental monitoring of a whole year in several key rooms (8 in this case) proved paramount to understand the building active and passive behaviour, as energy bills alone were not sufficient, especially given the complexity of historical buildings with random usage.

ferent accuracy levels LV 1 (high accuracy) and LV 2 (low accuracy) are suggested. The tolerance range for temperature and relative humidity of the narrower range of accuracy (LV 1) and the wider range of accuracy (LV 2) are:

- LV 1: Temperature: ± 1 °C and Relative Humidity: ± 5%;
- LV 2: Temperature: ± 2 °C and Relative Humidity: ± 10%

Additional **optional** uncertainty indices that can be used, with their corresponding threshold of accuracy, according to the literature, are:

- coefficient of determination, R^2, where $R^2 > 0.75$;
- inequality coefficient, IC, where $IC < 0.25$.

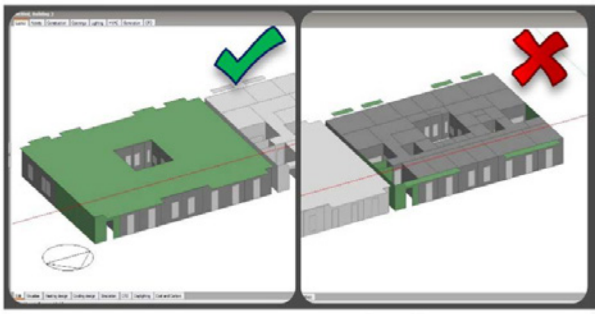
More references regarding the calibration processes are provided in Annex 8.2.

In case the historical building(s) is not in use due to abandonment or partial collapse, or/and no energy consumption data can be retrieved, the modelling of a base-case building instead of the actual building will be performed. The base-case model will correspond to an airtight building and assumptions regarding the operation schedules will be made, based on the proposed use after restoration. Typical schedules and design values shall be used, unless indicated differently by the building owners and the future use of the building.

4.1.3.3 Dynamic simulation

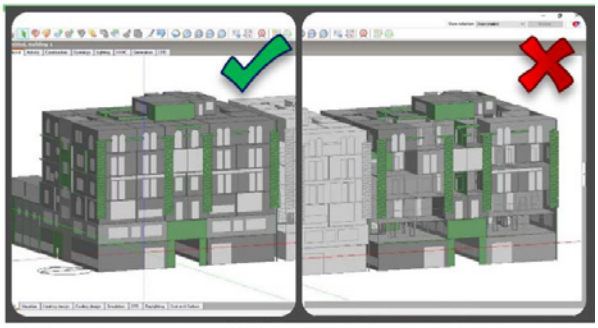
For the performance of the dynamic energy simulation, the following specifications can be used as a reference, notwithstanding the accordance with the country-specific regulation and the guideline recommendation on using at least the simplified dynamic hourly simulation method of EN ISO 52016:

- natural ventilation and infiltration shall be calculated based on dynamic modelling (infiltration calculated based on window openings, cracks, buoyancy and wind-driven pressure differences). In case of lacking data, tabular information from regulations on air changes per hour can be used;
- simulations shall be calculated based on the amount of solar radiation falling on each surface of the building zone, including the floor surface, walls and windows, while accounting for direct solar and light transmission through internal windows and also considering the effect of exterior shadowing surfaces (e.g. surrounding buildings) and window shading devices (e.g., in EnergyPlus, “full interior and exterior” solar distribution should be employed, allowing for the software check of non-convex zones);
- the simulation should be based on a minimum of 15 min steps (i.e. 4 timesteps per hour, or more);
- in the case of complex fenestrations, calculations should be carried out more often than the default 20 days.



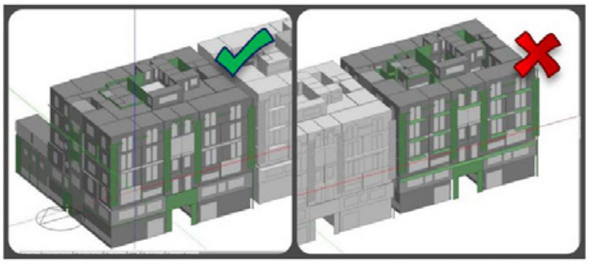
Using roof instead of floors

Just floors



Minimize open manifold block

Minimize gaps between blocks



Using floors as balconies for shading

Using roof as balconies for shading

Fig. 15. Steps taken for integration between modeling and energy analysis software

4.1.4 Output

The output should include:

- a technical report that presents:
    - the input data, with a focus on potential deviations from the data received;
    - the methodology that was adopted for the modelling of the building: the reasoning behind the thermal zones definition and the source of occupancy schedules, the

  modelling strategies (e.g. the simplification of complex or mass elements, etc.) and the analysis settings applied for the simulation;
  - ☐ the results of the validation indicators and documentation on the overall accuracy of the model.

- an .XML file or any other exchange format exported from the simulation software to be integrated in the Common data environment;
- the digital file of the validated model of the existing building or the equivalent base-case model.

4.1.5 BIM Integration

The results of the energy simulation should be exported in a document format, such as PDF, XML, XLS, IFC, compatible with BIM authoring applications. This information can be assigned directly to BIM 'spaces' and MEP systems' analytical properties/attributes or attached to the BIM model as a linked report for each design intervention respectively.

If the energy model has been modelled in the energy simulation software from scratch, the naming convention for the building spaces should be identical to that of the BIM model to ensure the proper integration of the analysis results into the BIM model.

If the energy model is generated based on a draft BIM model export, the building spaces' naming conventions included within the imported file should be maintained.

4.2 DESIGN, SIMULATION AND EVALUATION OF THE ENERGY AND ENVIRONMENTAL IMPROVEMENT INTERVENTIONS AND SCENARIOS (*POST OPERAM*)

The following paragraphs describe the design activity intended to support the energy audit process of a historical building and it is structured into three main steps.

4.2.1 Purpose of the activity

The purpose of this activity is to develop improvement interventions and then assemble them into improvement scenarios to improve the energy performance and indoor comfort conditions of the building. This will be based on the following design process:

CASE STUDY:

MORCOS NASSAR PALACE, BETHLEHEM (PALESTINE)

PASSIVE STRATEGIES EMPLOYED BY HERITAGE BUILDINGS IN PALESTINE

The climate of the Palestinian Territories is influenced by the Mediterranean climate where long, hot, dry summer and short, cool, rainy winter climate conditions prevail. Climatic variations occur in the different topographical regions. Though relatively small in area, the West Bank enjoys diverse topography, soil structure and climate conditions (ARIJ 1994).

There are seven climate zones in Palestine: (Energy Efficient Building Code, Ministry of Local Government 2004)

It is well known that most of the Palestinian modern buildings consist of walls constructed from stones, concrete, bricks and plaster with a total thickness exceeding 25 cm. Flat roofs are constructed of concrete, hollow bricks and plaster.

There are many features that describes the heritage building and the modern buildings; the percentage of openings area is 10-15% of the wall area in desert regions, while in mountainous areas it reaches 20%, people used the small size and number of openings in the northern façades in the cold regions of northern Palestine, in order to reduce thermal leakage outside and energy loss in the winter season. In addition to the use of openings in the longitudinal direction, the small width of the openings and the increase in the thickness of the walls, would work to break the solar rays and reduce amount reaching inside space in the various climatic regions of Palestine.

- Part A: based on the findings of the analysis phase (see § 2.2, 2.3, 2.4, 2.5), this part entails the study of the passive design strategies for the building and the maturity of the country market regarding passive and active technologies. The understanding and appropriate interpretation of climate limitations and potentials, as well as the passive design elements embed-

	Technique	Comments
Passive Solar heating	Direct solar gains	The building windows are distributed on all the sides, direct solar gains derive primarily from South and East. The ground floor receives less direct solar gains from East due to the existence of surrounded shadings.
	Indirect solar gains through high thermal mass building elements.	The surroundings do not limit the potential of indirect solar gains through the envelope. Absorptivity of roof is highly affected by roof surface and colour (beige); hence could be increased by high absorptivity surfaces.
Reduction of heat loss	Conduction losses through walls, windows and door	There is no thermal insulation, improvements can be implemented by adding insulations such as (PolyPan) on roof, avoiding thermal bridges created by metal window frames and doors. Reduce losses through window glass using double glassing. Reduce losses through doors employing double layer doors with insulation in between.
	Infiltration losses	Reducing infiltration by using tighter windows and doors, suing rubber seals wherever possible around doors. Using materials such as (Polysulfide, Polyurethane, and Silicon) to close joints, cracks, and faulty seals in the building envelope especially around doors and windows.
Internal gains	Occupants, electrical equipment, electrical machines and lighting fixtures	The movement of people in the building generates heat energy since there are more than 30 people, in addition to the electrical devices in the kitchen, the electric machines in the workshop and the lighting fixtures. These internal gains will help in the heating load in winter; however, will increase the cooling loads in the summer.
Natural ventilation	Openings	Windows exist on all sides of the building. Improvements can be made on the windows types and shading elements, to let the air flow enter through the windows and get the benefit from sun and light as well. In addition, staircase will help in the air flow from lower to upper floors.
Thermal mass	Stone walls were built using 2 layers of finely textured stone, where each layer is around (25-35) cm thick, and the layer in between was filled with small stone pieces and lime fill from the surrounding area. The total thickness of the walls varied from (80-120) cm.	The building employs great thermal mass resulting from its traditional thick walls. A great part of the building envelope is plastered.

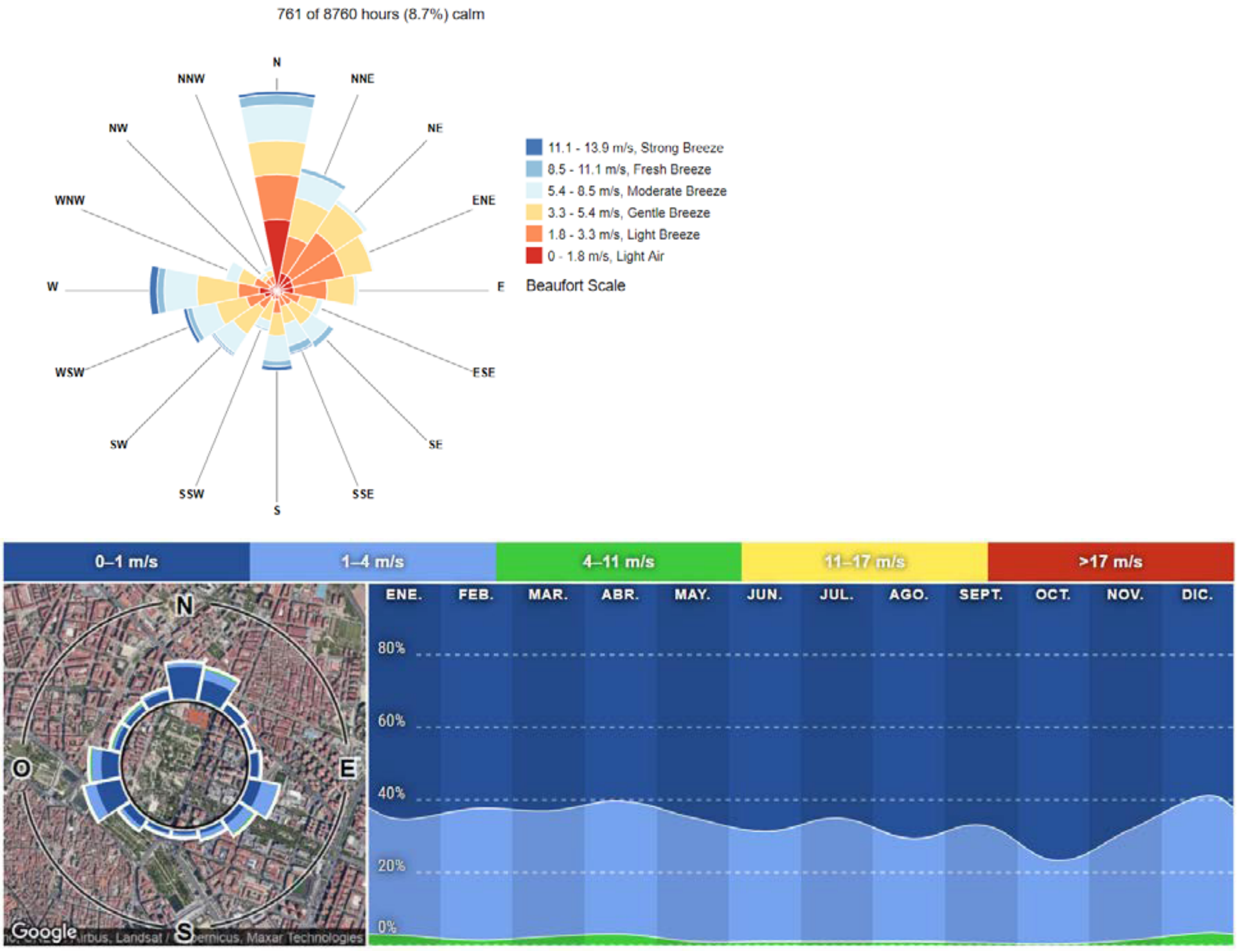


Fig. 16. The distribution and windspeed in València, colour coded into bands. The percentage of time spent at various speed ranges. Source: https://www.windfinder.com/windstatistics/valencia

ded in the historical building under study, is a crucial step in designing an energy improvement strategy. Available passive strategies and active energy systems should be considered with the objective to lower energy consumption while enhancing the comfort of occupants. An insightful overview of the state of the art regarding the compatibility of passive and active technologies in historical buildings is provided in Annex 8.4.

- Part B: based on the findings of the analysis phase (see § 2.2, 2.3, 2.4, 2.5) and on the *ante operam* simulation results (see § 4.1.3.3), several energy and environmental improvement interventions will be designed. The development of these interventions will consider several parameters and criteria (current state of the involved part, compatibility and heritage significance, technical compatibility and feasibility check, environmental sustainability, other design criteria, technical characteristics, estimated cost and time of the intervention) and will rely on passive and active technologies.
- Part C: this phase involves the grouping of energy and environmental improvement interventions into one or more improvement scenarios, evaluated and tuned thanks to the results of *post operam* building performance simulations and the further calculation of payback time, based on the cost estimation of the interven

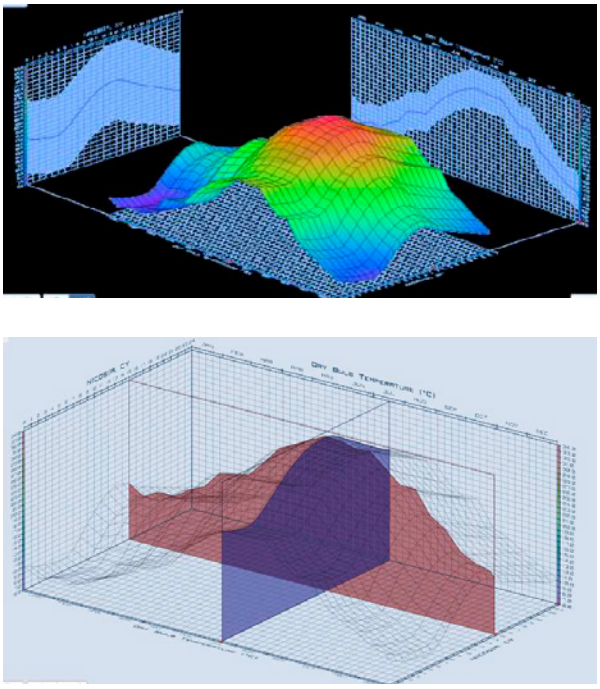


Fig. 17. Hourly and monthly distribution of Dry Bulb Temperature in Nicosia. Three-dimensional representation (top graph) and cross sections – daily (blue) and monthly (red) (lower graph). Source: https://drajmarsh.bitbucket.io/weather-data.html

tions and the simulation results. By coupling the interventions into three scenarios (short, middle and long term) it is possible to cover a wide range of possibilities, depending on the funding strategies. All the scenarios should ensure indoor comfort according to local and/or international regulations. The short-term scenario corresponds to the more cost-effective interventions from an energy efficiency and payback-period point of view. The middle-term scenario will focus on a deeper renovation. Finally, the long-term scenario will pursue the best available technologies that are compatible with the building and allow the best energy and environmental improvement, in the long run, resulting in an even longer payback period. Following the creation of the EE-HBIM model (see § 4.1.5) and the dynamic energy simulation of each scenario, final adjustments might be necessary for the completion of each scenario.

It is important to highlight that all assessment activities during interventions and scenarios' development receive feedback from each other up to the final completion (and tuning) of the scenarios.

4.2.2 Pre-planning

Pre-planning activities need to be performed with the Simulation Expert and any other expert involved in the design process (MEP experts, Restoration experts and building owner representatives). For the definitions of the energy and environmental improvement interventions and subsequent scenarios, consultation between the Energy Auditor and the Simulation Expert (if different) is paramount. Preliminary simulation results of particular zones will be discussed to assist in the definition of the design proposals (e.g. indicators of indoor thermal comfort, energy consumption rate and savings, etc.). Final adjustments in the energy and environmental improvement interventions and scenarios will be made according to the simulation results.

4.2.3 Energy and Environmental improvement design process

4.2.3.1 Part A: Analysis of passive and active technologies

The relevant passive strategies employed in heritage buildings across the Mediterranean basin and the complementary active energy systems available for integration in heritage buildings are outlined in Annex 8.4. In this document, an overview of the passive design analysis tools and methods is presented, and the potential integration challenges and opportunities of active systems in heritage buildings are outlined. This Annex presents also the country-specific findings of the partners involved in the BEEP Project.

The data to be obtained for developing a background study on the compatible active and passive energy-efficient technologies are:

CASE STUDY:

CORDAHI BUILDING, ALEXANDRIA (EGYPT)

Cordahi Building (1921), one of the two Egyptian pilot buildings, originally had a mixed use (administrative, commercial, and residential). Current use envisages a small, low-budget hotel and a bank. Future uses include a food and beverage center, as well as commercial areas, a bank, and a concept hotel. It is located in the central district of Alexandria (at Fouad Street, a famous street known for a number of heritage buildings), and its construction material is mainly limestone for the walls and reinforced concrete for the ceilings.

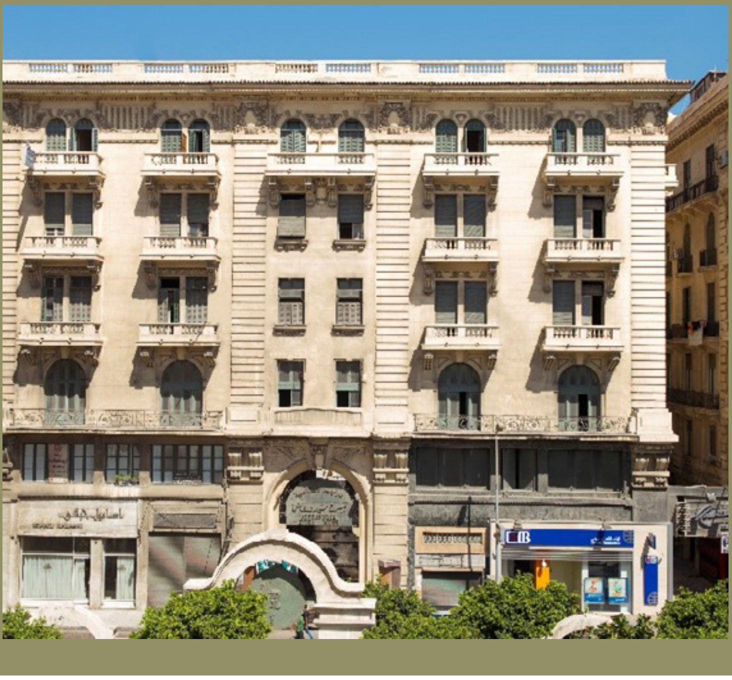
Due to the heritage value of the building, many limitations applied to the selection of appropriate intervention scenarios. Several building elements were tackled such as windows and roof insulation. Every selected element went through numerous interventions to reach the optimum selection. Building energy simulation was performed for every intervention on its own to calculate the single impact on heating, cooling, and lighting energy, and hence, the optimum selection was decided.

The passive measures proposed for this building were:

- Internal insulation. The selection of mineral fibres 10cm wall insulation cost overall annual savings of 5% in heating loads.
- Roof insulation. The selection of XpS 10cm roof insulation cost overall annual savings of 52% in heating loads.
- External shading devices. The selection of external microlouvre blinds provided overall annual savings of 16% in cooling loads while preserving the heritage image of the building. All types of internal shading provided no added value, they added more heating loads. And hence, no internal shading was selected.

LESSONS LEARNED:

In the Egyptian context, it is advisable to start with all passive techniques to reach the optimum performance possible, then proceed with active techniques.



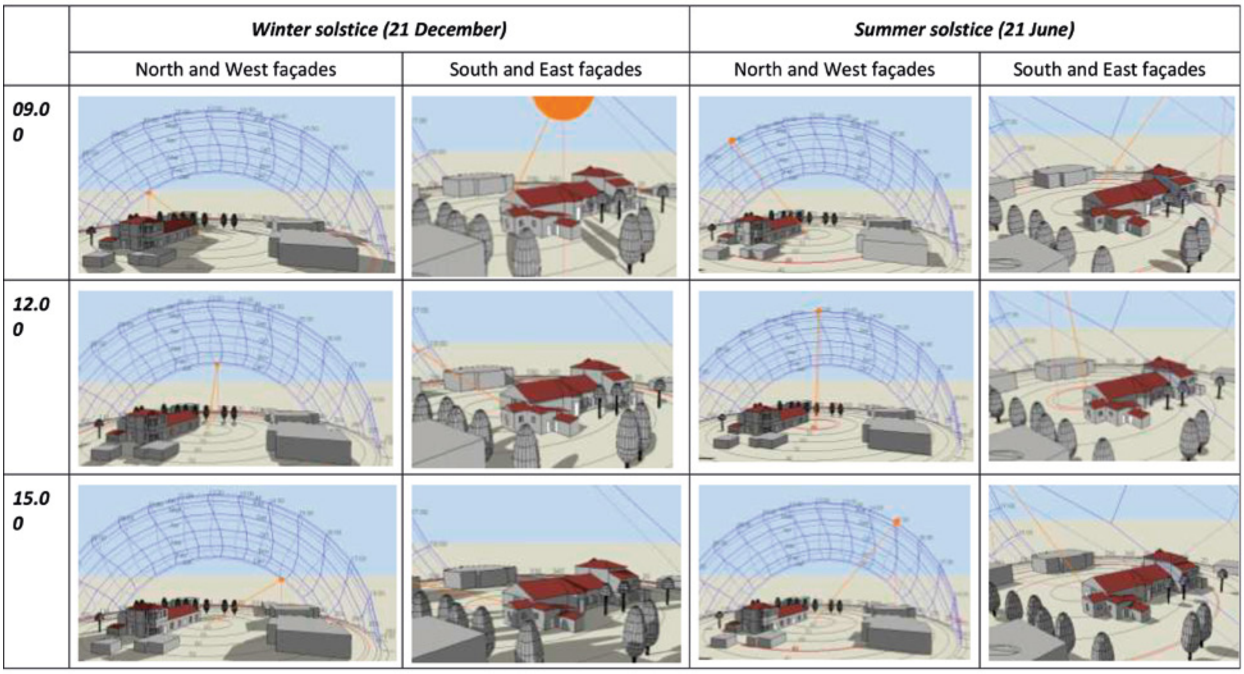


Fig. 18. Shading analysis in the Cypriot pilot building.

- overview of the environmental responsiveness of built heritage: brief and general overview of the main passive techniques that are employed by vernacular heritage in the country through relevant bibliography;
- identification of the recommended passive design strategies according to local climatic conditions, by using bioclimatic charts and climate analysis tools;
- opportunities, impediments and challenges in applying passive design strategies to the building;
- outline of the current situation, trends and challenges (market maturity) regarding the implementation of innovative RES or building envelope technologies, for application in existing buildings;
- accounting for compatibility issues in heritage buildings;
- Opportunities, impediments and challenges regarding active systems integration to the building.

4.2.3.2 Part B: Design and assessment of energy and environmental improvement intervention

Several assessment criteria and methodologies are developed to assess the energy and environmental improvement interventions. Reflecting on the existing methodologies, the following assessment criteria are suggested for the development of the design process:

- compatibility and heritage significance: compatibility with a) the guiding principles of restoration, as expressed through the International Charters of Restorations (§ 1.3), and b) the national regulatory framework; potential risks of architectural, aesthetic or visual impact, or risks regarding the building's setting;
- technical compatibility and feasibility check: description of the technological and mechanical compatibility with the other systems and components of the building; potential hygrothermal risks; structural risks; corrosion risks;

CASE STUDY:

BRITISH CAVALRY HOUSE, NICOSIA (CYPRUS)

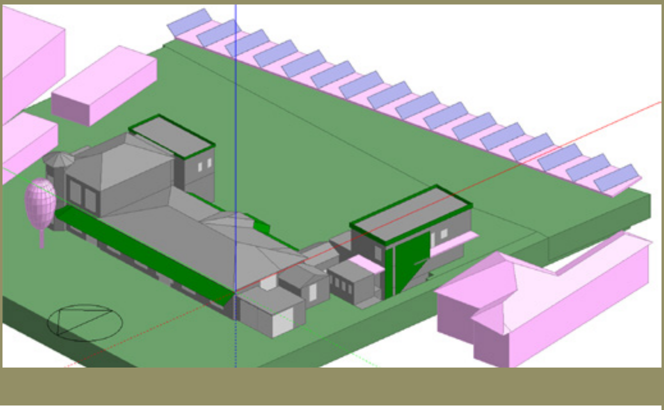
In the Cypriot case study, the most challenging stage was the calibration of the model. As no energy bills could be retrieved and the building was partially collapsed, environmental monitoring was not easy and introduced a certain level of uncertainty. Modelling was also challenging, due to the building complexity (morphology and building materials) and the variety of the operation schedules (various building uses).

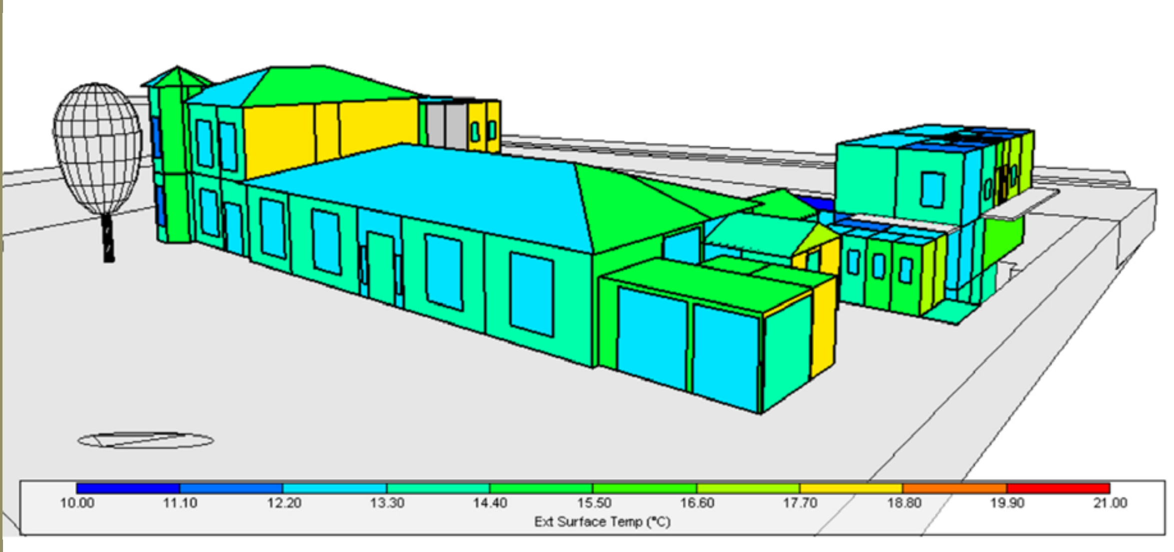
Building geometry was simplified for performing the energy simulation. Additionally, as the building is in a severe structural condition, a base-case model was assumed corresponding to an airtight building. The operation schedules were carefully defined by the authors following interviews with the future occupants of the building. For the definition of the temperature setpoints, standard values were used, according to the planned use of each thermal zone. A sensitivity analysis was performed to quantify the decisive design parameters and their impact on cooling. The input variables that were analysed included: a) the roof construction (with variable width of roof insulation), b) glazing type, c) cooling system seasonal CoP, d) cooling set-point temperature and e) infiltration rate (ac/h).

The selection of the energy improvement measures was based on a risk-benefit scheme, while emphasis was given in preserving the morphology and typology of the building, highlighting the principle of integrity and authenticity.

LESSONS LEARNED:

In the case of abandoned and partly airtight heritage buildings, the challenges of dynamic energy simulation mainly concern the modelling and verification of the input variables as well as the calibration process.





salt reaction risks; biological risks and reversibility;

- environmental sustainability of the intervention: description of whether the intervention is characterised by specific environmental sustainability principles, i.e. whether the intervention minimises environmental pollution and emission of substances in the indoor environment, whether it uses as much as possible renewable resources, recyclable/reused materials, low embodied energy, etc.;
- other design criteria: technical characteristics to be evaluated in the materials and components to be used, methods of carrying out the intervention and laying of materials, possible instrumental checks to be performed before and after the intervention, possible problems to be taken into account in the design and execution of the intervention, etc.;
- description of the technical characteristics of the intervention and comparison with the existing technologies through tables, images, schemes, drawings, etc;
- estimated cost and timing of the intervention (usually referred to as 5D and 4D of a BIM process). Data acquisition should be achieved based on previous work experience/similar projects or by requesting a quotation from companies. Time and cost estimation should contain the following information:
  - intervention name and code;
  - quantity related to the intervention, per unit or per measure;
  - measuring unit;
  - estimated cost of the intervention as per unit or measure;
  - estimated amount of time for the realisation of the intervention.

The above data should be presented as a table.

4.2.3.3 Part C: Design, simulation and assessment of energy and environmental improvement scenarios

Energy and environmental improvement scenarios (one or more) are developed by grouping selected energy and environmental interventions based on a first estimation of the most cost-effective or urgent interventions to be performed. A suggestion

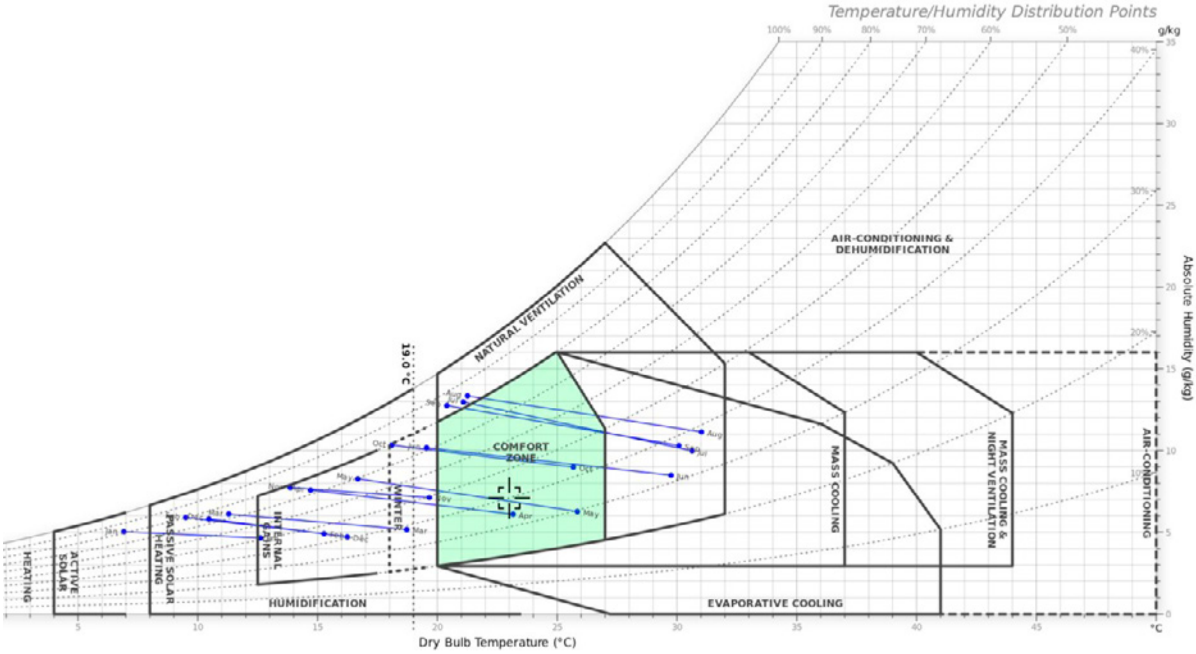


Fig. 19. Givoni comfort diagram for Bethlehem. Source: https://drajmarsh.bitbucket.io/psychro- chart2d.html

could be to group interventions into three scenarios (namely short, medium and long-term), to be able to address a wide range of possibilities and allow for greater design flexibility based on the available funding strategies. For the economic evaluation of the energy retrofit scenarios, the indicator of payback time is suggested. The use of this indicator is widespread as it is easy to understand by non-experts and requires simple calculations. On average, a short-term scenario should have a payback time between 5 and 10 years, a middle-term scenario should have a payback time between 10 and 20 years and a long-term scenario should have a payback time of over 20 years. The assessment of the scenario is based on the *post operam* simulation results of the selected scenarios (*post operam* energy consumption and related *post operam* energy bills).

4.2.4 Output

4.2.4.1 Part A: Analysis of passive and active technologies

The output of this part of the analysis is a thorough report discussing the parameters mentioned in § 4.2.3.1.

4.2.4.2 Part B: Design and assessment of energy and environmental improvement intervention

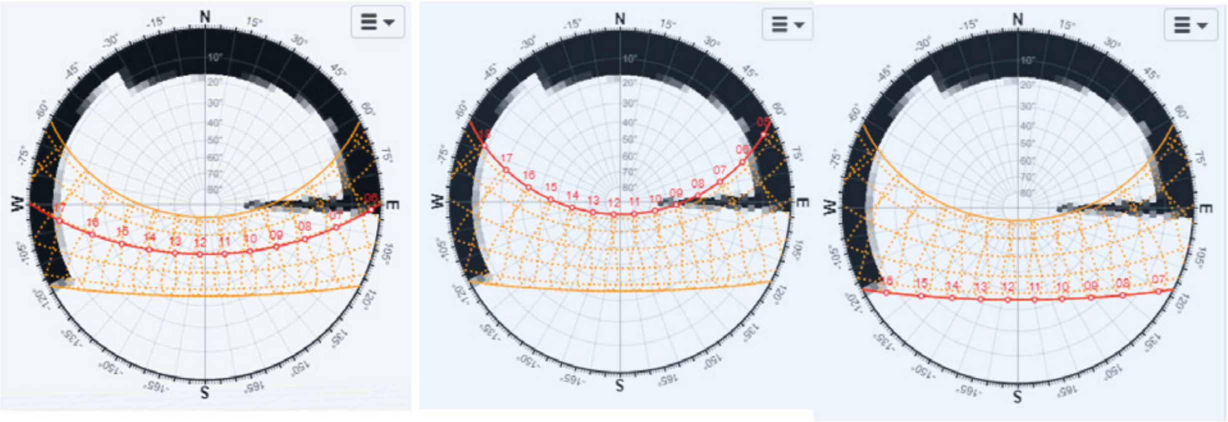
The output of this part is a report describing the energy and environmental improvement intervention designed and their assessment according to the assessment criteria mentioned in § 4.2.3.2.

4.2.4.3 Part C: Design, simulation and assessment of energy and environmental improvement scenarios

The output of this part can be divided into a dedicated *post operam* simulation results report and a synthesis report on the energy and environmental improvement scenarios, including the main simulation results from the previous report on the *ante operam* simulations. The latter can be very effective to discuss the assessment with non-expert stakeholders.

The *post operam* simulation results report should include:

- a technical report that presents:
  - a brief description of the input data, with a consideration of their uncertainty;
  - a comparative analysis of the results on a monthly and yearly basis; graphs and comparative tables summarising the results of the energy and environmental improvement scenarios and the existing base-case model. The indicators to be reported for the existing building (or



6A 6B 6C

Fig. 20. Solar shading mask in the location of the case-study building in Bethlehem, where B: at summer solstice, C: at winter solstice. created through the application: Source: https://drajmarsh.bitbucket.io/shading-box.html)

the base-case scenario) and the retrofit scenarios are:

a. final and primary energy demand per scenario (kWh/m² annual);
a. energy consumption per energy source, at least on a monthly basis (kWh/m² annual);
a. energy use or/and production from Renewable Energy Sources (RES) per system, on a monthly basis.

- the .XML files, exported from the simulation software, of the three retrofit scenarios, to be integrated in the Common Data Environment;

CASE STUDY:

CORDAHI BUILDING, ALEXANDRIA (EGYPT)

Numerous active strategies were envisaged for the energy and environmental improvement of the Egyptian case study Cordahi Building (see 𝕊...), within a mix of active and passive solutions. The building is partially vacant therefore, the annual energy consumption data is not available as there are no electricity bills for the whole building. Therefore, the annual cost is based on the simulation calculation.

As the project is still under construction, hence the normal selection of the HVAC system was VRF-Air cooled-heat recovery-DOAS, when other techniques were simulated, this choice proved to be the optimum scenario and hence was not modified. According to the simulations, the proposal to integrate the water heating system with the building's central heating system can provide 66% annual savings in DHW loads. The use of LED lamps could produce overall annual savings of 91% in lighting and 46% in cooling loads, while artificial lighting control could supplement an additional 3% overall annual savings in lighting loads.

Several PV panel types were tested via simulations, with different orientations and distribution; the optimum selection provided 102MWhr annually. Replace the glazing of the whole building with BIPV glazing could generate a net energy of 77MWhr annually, after discounting the increased lighting energy due to the less transparency of the used panels compared to clear glass. Solar panels (for DHW) were distributed on the whole area of the floor to experiment with the amount of savings compared to the PV panels with the same square area. The overall annual savings were 182MWhr.

- the digital files of the three models that correspond to the energy retrofit scenarios.

The synthesis report on the energy and environmental improvement scenarios should include a brief description of the building, with an overview of the energy consumption from § 2.4, and also a comparative analysis of the energy and environmental improvement scenarios proposed, in which:

- the interventions involved in each scenario should be clearly stated;
- each scenario should be briefly described, highlighting the related synergies between the foreseen interventions;
- for each scenario, a selection of the most important parameters should be presented in a comparative assessment with the existing building conditions (e.g. the energy consumptions and energy bills, the expected energy production from RES, the expected cost and timing of implementing the interventions) and the payback time.

4.2.5 BIM Integration

Similarly to § 4.1.5 on BIM integration, all energy improvement scenarios results should be exported in a data format, such as PDF, XML, XLS or IFC, compatible with the BIM authoring software. This information can be assigned directly to BIM 'spaces' and MEP 'systems' analytical properties/attributes (using global project parameters, if available) or attached to the BIM model in the form of a linked report for each design intervention respectively.

<u>If the energy improvement scenario involves the creation of additional elements</u>, such as the construction of new interior walls and ceilings, or suggests the construction of new building spaces/MEP systems, all of the affected building components and spaces should be assigned to different construction phases; if not available in the BIM software, the information should be provided as element parameter. Using the construction phase filters, energy simulation results of the particular improvement scenario may be assigned to affected spaces and MEP systems only. In the case of a high-complexity improvement scenario, in which a great proportion of the building undergoes extensive modification, a replica of the BIM model should be made and all BIM elements should be assigned to the new construction phase. In this respect, energy simulation results should be assigned similarly to the BIM model of the current building. In any case, depending on the building, specific BIM modelling strategies can be deployed.

<u>If the energy improvement scenario involves the modification of the building envelope</u> <u>or the upgrade of MEP systems only</u>, such as thickness differentiation caused by thermal insulation layer addition, the phasing mechanism for assigning energy simulation results should be adopted.

4.2.5.1 4D and 5D implementation

4D and 5D (time and costs) implementation should be conducted for each energy and environmental improvement intervention separately. The integration of this information can aid the design process assessment of the energy improvement scenarios. If third-party 4D or 5D simulation software will be used, the sorting of information and subsequently the methodology for implementing the 4D and 5D in the EE-HBIM model should be formulated before the activity. 4D and 5D intervention data can be added to the BIM model through the use of unique construction phase IDs to the respective BIM elements' modifications/additions. If the 4D and 5D simulation is implemented in a third-party software, the results should be exported in an open format, such as PDF, XML or XLS and linked to the EE-HBIM model. ■

The internal cloister of the Palazzo Maffei-Borghese in Rome, current state.

The proposal of the bioclimatic photovoltaic buffer space and shading systems with natural ventilation.

5. *POST OPERAM* ENERGY EFFICIENCY HERITAGE BUILDING INFORMATION MODEL (EE-HBIM)

The following paragraphs describe the development of the Stage 2 of the Energy Efficient Heritage Building Information Model (see § 3.1), to integrate the improvement scenarios of the building, as well as the corresponding 4D and 5D BIM dimensions of time and costs.

5.1 PURPOSE OF EE-HBIM MODELLING

As described in § 3.1, the purpose of the EE-HBIM model is to act as a centralised repository of the information on the building obtained from the analyses, simulations and improvement scenarios' planning.

Stage 1 (see § 3) corresponds to the ex-ante model of the building. Stage 2, outlined in this chapter, focuses on integrating, in the previously developed EE-HBIM model, the improvement scenarios designed, simulated and assessed in § 4. The technical characteristics and energy performance of each scenario are modelled to facilitate a ROI analysis and the drafting of an Energy Performance Contract.

5.2 PRE-PLANNING

5.2.1 Update of the BIM Execution Plan

After the simulation phase and improvement scenarios development phase, the Building Execution Plan prepared for the *ante operam* EE-HBIM model (see § 3.2.1, Stage 1) may need revising, to illustrate how interoperability between the BIM authoring software and the energy simulation software has been handled and to explain how to the improvement interventions and/or scenarios will be represented. Moreover, BEP shall reflect any adjustment in the workflow and any modification needed to accommodate specific requirements.

5.2.2 Outsourcing of the EE-HBIM model - tender process

If the BIM modelling activity is outsourced, the tender should generally comprise both Stage 1 and Stage 2 of the EE-HBIM model. In this case, the BEP adjustments shall be defined by the Consultant.

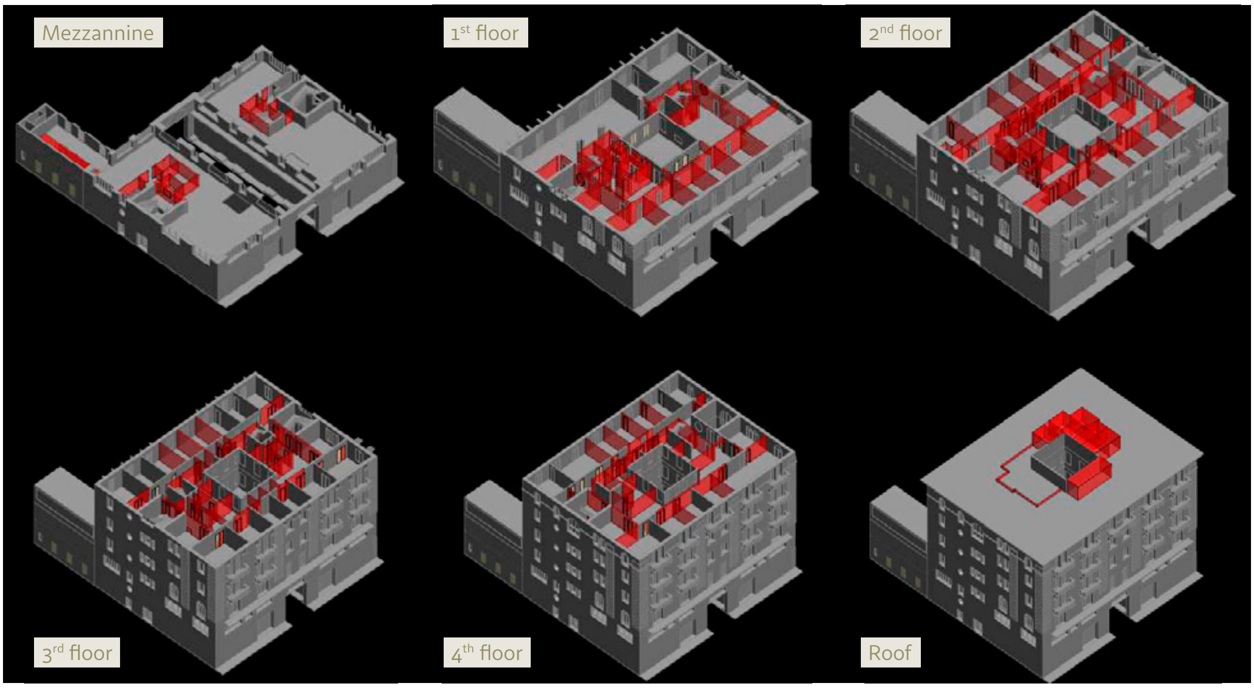


Fig. 21. BEEP Pilot Building in Egypt – Cordahi Building

If, however, the is a different Consultant for Stage 1 and 2 or only Stage 2 is outsourced, the actors involved in the tender process shall follow the bidding procedure defined by ISO 19650, as described in § 3.2.2. The Employer shall define an Exchange Information Requirements (EIR), that is a tender document setting out the information to be delivered, and the standards and processes to be adopted by the Consultant as part of the project delivery process, outlining the Employer's strategic approach and specifying the management, technical, commercial and project information and deliverables required for the project.

The Consultant shall deliver a Pre-contract BIM Execution Plan (BEP) for the project as a direct response to the EIR. If selected, The Consultant shall deliver a Post-contract BEP and review their BEP regularly and additionally when there is any change to their contract.

5.3 OUTPUT: UPDATED EE-HBIM MODELLING

The improvement scenarios modelling represents an update of the *ante operam* EE-HBIM model (see § 3); this previous model, therefore, shall be the basis of any further development. All modelling principles and guidelines presented for the *ante operam* EE-HBIM model (see § 3.3) apply to this update as well.

The actors involved shall define specific strategies to implement improvement scenarios within the *ante operam* model, integrating all the relevant information produced, such as simulation data, time, costs, technical specifications, etc. The strategies depend on model uses, building characteristics, type of intervention and BIM authoring application selected. Some typical methods involve the use of different linked models, the use of design options, the revision of existing elements, the modelling of new additional elements, etc.; different methods can be combined as appropriate. Cost and time considerations shall be added, also with reference

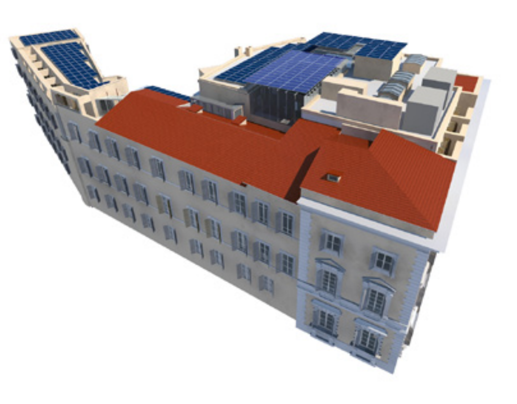
CASE STUDY:

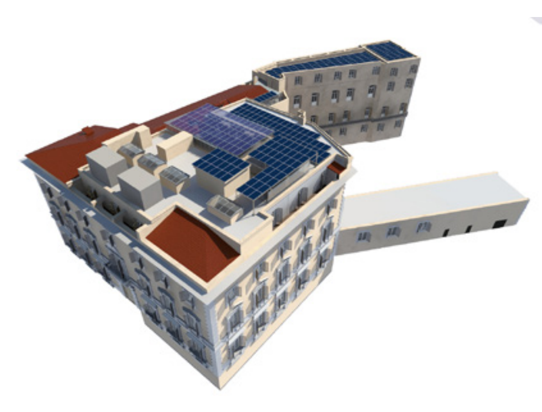
PALAZZO MAFFEI BORGHESE, ROME (ITALY)

The preplanning activity for the Italian case study Palazzo Maffei-Borghese in Rome mainly involved the planning of the interoperability process between BIM and BPS software, thus affecting the main BIM post-operam strategy as well. Once selected the data to be transferred from the BIM to the BPS model and identified the data that could only be further deepened inside the energy model, the team decided to favour a Common Data Environment (CDE) organisation of the simulation outputs. That means that the information on the whole development of the HBIM process resides in a data repository that represents the agreed information source for the project, thus guaranteeing security, accessibility, traceability and version history for all the files. The CDE allowed the coordination among models in different software when direct interoperability was limited, enhancing consistency. The *ante operam* HBIM model was used to support the quantity take-off of the improvement scenarios, while the energy model was used to perform regulatory check and performance checks on the scenarios. The summary table of the collected data during the analysis phase continued to be implemented during the design phase, serving as the reference point for data consistency between the HBIM model and the energy model, especially for the connection of data related to abstract elements like thermal zones (present only in the energy model) and rooms (present in the HBIM model and in the energy model), and for all the detailed information that further populated the energy model compared to the HBIM model. Moreover, the same document became the core reference for monitoring and keeping track of the energy model's calibration iterations, comparing calibration model's consumption with energy bills' consumption, managing improvement interventions and scenarios. Although the interventions were integrated in the CDE, through dedicated reports, the HBIM *post operam* model was used to test and verify design solutions that required the geometric modelling of new objects, such as the bioclimatic photovoltaic buffer space in the internal cloister, the restoration of windows' shadings, the integration of a photovoltaic system and the new sizing of HVAC systems on the roof.

LESSONS LEARNED:

Planning the data flow in advance, from the analysis phase up to the design phase, by making use of a BIM-based approach, improved the capacity of the team to access and keep organised all the gathered data.





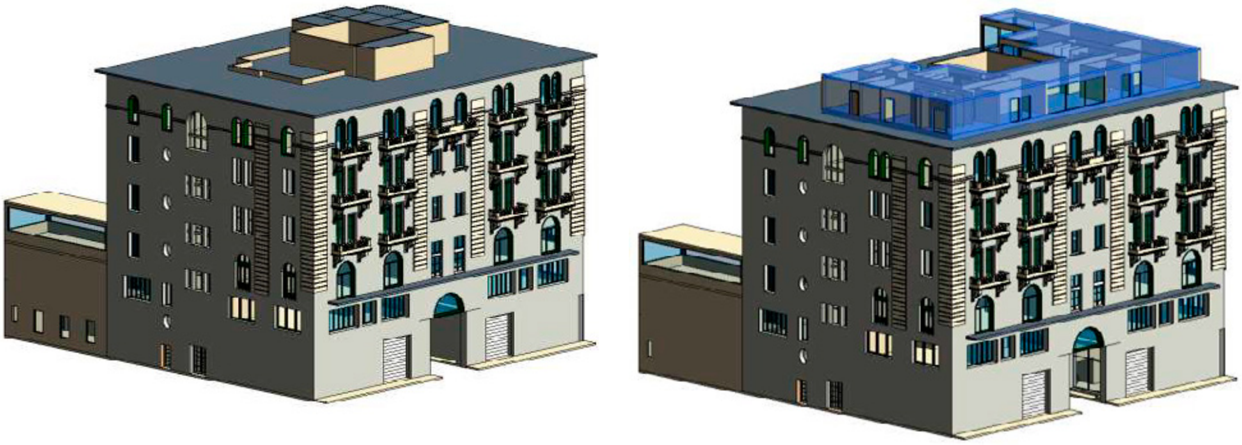


Fig. 22. BEEP Pilot Building in Egypt – Cordahi Building

to other phases (see § 4.2.3.2 and § 4.2.3.3) where the scenarios are described. To enhance clarity and consistency, if a naming convention was developed for the interventions, it shall be used in the modelling phase as well.

The improvement scenarios shall be represented with the same level of information, to facilitate comparisons: geometrical modelling of the interventions (architectural objects, MEP objects, either revised from the existing one or newly modelled), non-geometrical data integration (simulation data, time, costs, technical specifications, etc.), compromises between geometrical accuracy and parametric object definition, use of constraints, etc. shall be consistent. ■

Fig. 23. BEEP Pilot Building in Jordan: Municipal Guest House - Karak Municipality

6. ENERGY PERFORMANCE CONTRACTING IMPLEMENTATION

6.1 PURPOSE OF EPC

The recent change in the European and national regulatory framework on energy efficiency has led to a review of the performance standards and procedures. The transposition of Directive 31/2010/EU, Directive 27/2012/EU and Directive 844/2018/EU does not only concern the areas of energy efficiency of buildings from a technical and technological point of view, but also proposes the development of models and tools for the financing of interventions and for the development of Energy Performance Contract (EPC). The main activity in this domain is the definition of guidelines for the creation of new formats for the EPC contract, based on technological innovations in the field of energy efficiency. The European Commission has been working closely with the Member States for the development of an application model for Public Administration (PA), in order to involve private operators and encourage the aggregation of demand, generate economies of scale and use EPC, also with the involvement of private operators (ESCO).

The objective of this paragraph is to provide an easy and quick tool of use and consultation for the experienced public manager, preparing and managing Energy Performance Contracts, and for the public administrator who is entrusted with the political choice of activation of such contracts. EPC contracts are atypical, as their content is highly technical; in fact, in addition to the legal content (guarantees, jurisdiction, security rules, etc.), they have also an economic content (financing arrangements, calculation of performance, etc.) and a technical-engineering content (energy audits, redevelopment and plant engineering).

6.2 DEFINITION OF EPC

Energy Performance Contracting (EPC) is a financing mechanism used to support energy efficiency measures and renewable energy installations without worrying about financial barriers. The Energy Efficiency Directive 2012/27/EC (EED) defines EPC as follows:

> “*energy performance contracting* means a contractual arrangement between the beneficiary and the provider of an energy efficiency improvement measure, verified and monitored during the whole term of the contract, where investments (work, supply or service) in that measure are paid for in relation to a contractually agreed level of energy efficiency improvement or other agreed energy performance criterion, such as financial savings;”. (DIRECTIVE 2012/27/EU, 2012)

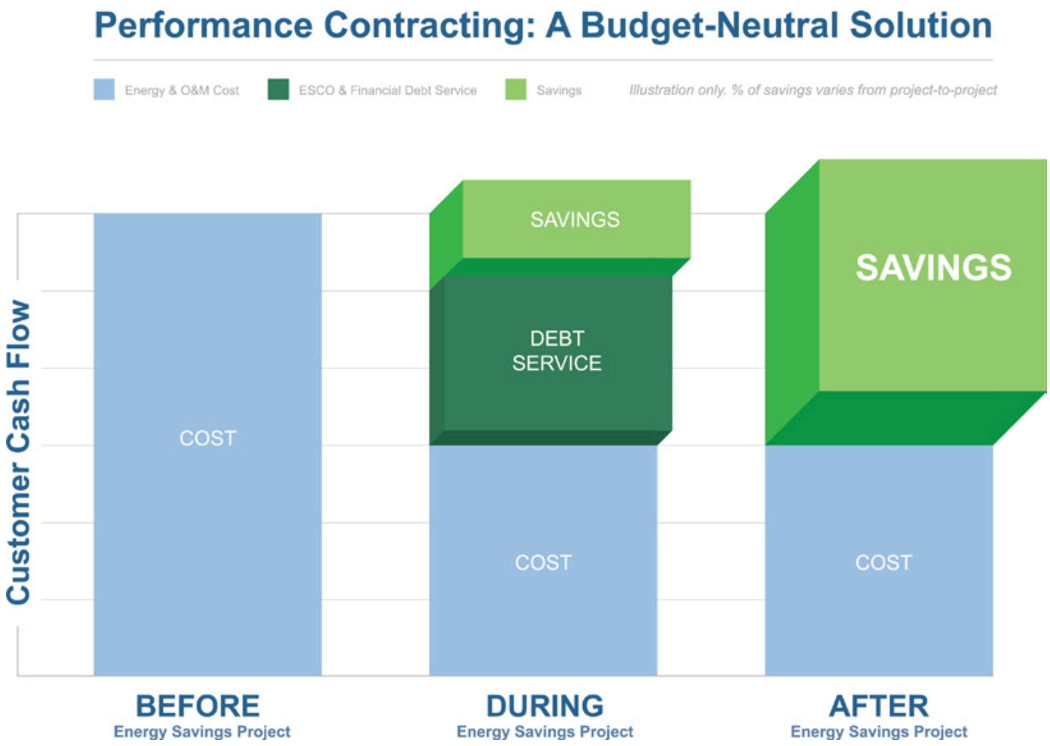


Fig. 24. EPC contracts cash flow. Source: https://www.eurogreenenergy.ro/solutions/financial-options/espc-energy-savings-performance-contract/

Thus, in an EPC contract the energy service company (ESCO) is committed to provide guaranteed energy improvements to the customer's territory while the finances are covered from the achieved energy savings. The concept of EPC is illustrated in Figure 1.

The EPC foresees that the investments made by third parties are repaid with the energy savings obtained during the contract through a link between ESCO remuneration and performance (e.g. financial savings).

Some of the main advantages of such contracts are:

- overpassing financial barriers;
- no risk at the customer side;
- improving energy consumption;
- integrating new technologies in buildings;
- promoting green buildings;
- contributing in reaching national energy goals.

There are many models of EPC contracts; however, the most famous models are as follows:

Shared Savings: In this model, the ESCO does not guarantee to reach a certain amount of savings. However, both the client and the ESCO share a predefined percentage of the savings as agreed in the contract. If no savings are achieved, the client pays the energy bill while the ESCO must pay for the financial obligations associated with equipment purchases.

Guaranteed Savings: In this model, the ESCO guarantees a certain amount of energy savings each year of the contract. If the agreed amount of savings is not reached, the ESCO shall pay the shortage to the client. However, if the savings exceed the agreed amount, the excess is divided between the customer and the ESCO according to the particular contract.

The EPC contract can be financed either by the client, the ESCO or a third-party financer. However, the most famous method is a bank loan with low-interest value. In an EPC, the ESCO can provide the following services:

- energy audit;
- design engineering;
- construction management;
- arrangement of long-term financing;
- commissioning;
- operation and maintenance;
- measuring and verification.

It is important to note that the level of measurement and verification depends on the scale of the project. The International Performance Measurement and Verification Protocol (IPMVP) is adopted in EPC contracts, where the ESCO chooses the convenient option that best fits the particular case between options A, B, C & D.

Shared Savings Model	Guaranteed savings model
ESCO does not guarantee to reach a certain amount of savings.	ESCO guarantees a certain amount of energy savings each year of the contract.
Both the client and the ESCO share a predefined percentage of the savings as agreed in the contract.	If the agreed amount of savings is not reached, the ESCO shall pay the shortage to the client.
If no savings are achieved, the client pays the energy bill while the ESCO must pay for the financial obligations associated with equipment purchases.	If the savings exceed the agreed amount, the excess is divided between the customer and the ESCO according to the particular contract.

6.3 EPC IN THE EUROPEAN CONTEXT

The European Union has set ambitious targets to increase energy efficiency. As part of the Europe 2020 Strategy, Member States have agreed to reduce greenhouse gas emissions by at least 20%, increase the share of renewable energy to at least 20% of consumption, and achieve energy savings of 20% or more. The energy savings target was translated in the Energy Efficiency Directive from 2012 and 2018. According to the burden-sharing principle, Member States were free to choose individual national targets, as long as the general EU-wide target would be reached. The European Commission is tracing periodically the progress towards this target, through specific reports. The latest of such assessment document, launched in November 2015, noted that, according to a Commission evaluation from 2014, the level reached by 2020 would fall below the 20% by 1-2%. Currently, the national indicative targets of Member States fall short of the collective 20% by 2.4%[1]. The European Commission, upon analyzing the financing market for energy investment across Europe, concluded that “energy efficiency market has strong investment potential, but is still small, fragmented, risky, and relies predominantly on direct or indirect subsidies”.

European Union set more ambitious goals with the Clean energy for all Europeans package (finished adopting in 2019), with at least 40% cuts in greenhouse gas emissions (compared to 1990 levels); at least 32% share for renewable energy (with an upward revision clause by 2023); at least 32.5% improvement in energy efficiency (with an upward revision clause by 2023).

With the Green New Deal, European Union promotes the new target of 55% greenhouse gas emissions by 2030, presenting a Target Plan 2030[2], proposing a

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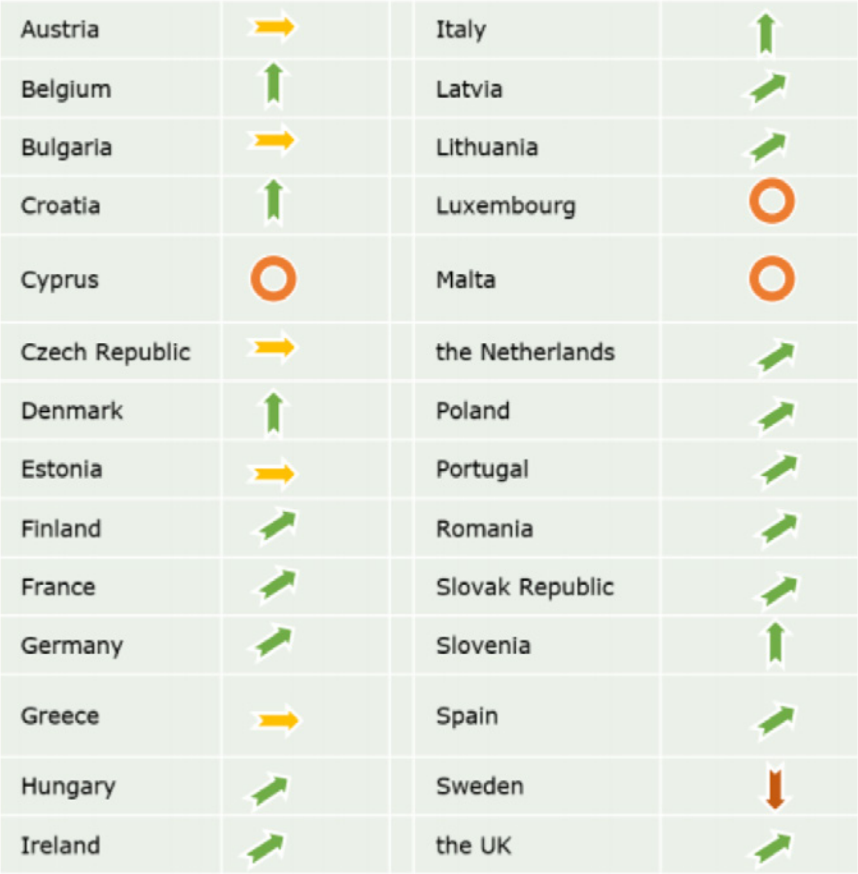
[1] European Commission, 2015, COM(2015) 574 final, https://ec.europa.eu/transparency/regdoc/rep/1/2015/EN/1-2015-574-EN-F1-1.PDF

[2] See https://ec.europa.eu/clima/policies/eu-climate-action/2030_ctp_en#:~:text=The%20Commission's%20proposal%20to%20cut,becoming%20climate%20neutral%20by%202050%20.

renovation wave to improve housing quality in the EU, also including innovative financing schemes under InvestEU. These could target housing associations or ESCOs that could roll out renovation, including through EPC[3].

While developed countries may easily achieve results with regular ESCOs, a government-led so-called "super ESCO" is needed in developing countries, due to weak institutions. In particular, while Germany, France, UK, and Austria have a large energy services market, other countries lack policy effectiveness and have weak inter-institutional cooperation, where decision-making is not based on impact studies, and ineffective communication between public authorities, energy companies, and consumers occurs (Murafa, 2017)it examines, using two case studies, enablers and disablers – from an economic, legal and institutional/managerial perspective – for advancing this arrangement across the EU. The EU has set a 20% energy savings target by 2020 (roughly equivalent to turning off 400 power stations.

The EPC status in Europe depends mainly on the ESCO market. The development of the ESCO market in Europe was studied and disseminated in the Energy Service Market in the EU report. The results are shown in table 1.



Austria	→	Italy	↑
Belgium	↑	Latvia	↗
Bulgaria	→	Lithuania	↗
Croatia	↑	Luxembourg	○
Cyprus	○	Malta	○
Czech Republic	→	the Netherlands	↗
Denmark	↑	Poland	↗
Estonia	→	Portugal	↗
Finland	↗	Romania	↗
France	↗	Slovak Republic	↗
Germany	↗	Slovenia	↑
Greece	→	Spain	↗
Hungary	↗	Sweden	↓
Ireland	↗	the UK	↗

Table *1*: ESCO market development between 2015 and 2018 *(Boza-Kiss et al., 2019)*

Note that the green arrow refers to the growth of the market, with fast increase (point upwards), or slow increase (pointing halfway), while the yellow arrow signifies no change or stable market, and red arrow shows a decrease in the market. The donut shape refers to countries with low ESCO market.

Also, according to the same report issued in 2019, it was found that France and Germany have the largest markets, followed by Italy. The biggest Energy Performance Contracting market in terms of the

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[3] See https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1596443911913&uri=CELEX:52019DC0640#document2, § 2.1.4.

number of companies, projects and market volume is led by Germany (Boza-Kiss et al., 2019).

The European Parliament and the Council of the European Union assured the importance of developing the market for energy services to ensure the availability of both the demand for and the supply of energy services by promoting energy performance contracting in (DIRECTIVE 2012/27/EU, 2012). Capacity building workshops were then organized during the EPC campaign done in 2013.

The current status of the EPC market in Europe differs from one country to another. Some countries are advanced (Germany) where as others are still in their earlier stages. The main barriers facing the implementation of EPC contracts include:

- lack of awareness from the demand side of the market for energy services;
- poor understanding of energy efficiency and epc by financial institutions;
- small size of projects;
- incompatibility of legal and regulatory frameworks;
- low understanding of measurement and verification protocols;
- administrative hurdles;
- lack of motivation;
- limited government support.

The introduction of the EPC Code of Conduct in 2015 has helped to increase knowledge and grow the ESCO market in some countries (Bulgaria, (Boza-Kiss et al., 2019).

6.4 BIM FOR EPC

The Table below shows how BIM could improve EPC essential tasks:

Table 2: BIM advantages in improving EPCs

EPC essential tasks	Problems/issues	Possible solutions with BIM
Involvement of owners / tenants	It is difficult to communicate technical solutions to non-technical final users	BIM allow for simplified visualization of technical data (3D, render, etc.).
Energy refurbishment	The refurbishment project is done in successive phases and often architects, structural engineers and HVAC engineers experience difficulties in interacting with each other, with subsequent interferences/ problems up to the implementation phase.	Design is done in a shared environment (Common Data Environment) where it is possible to coordinate the different models coming from the different professionals contributing to the refurbishment.
Construction phase	Construction is a complex phase that is hard to efficiently manage.	BIM can help manage the construction phase.
Expected budget	The construction sector has a chronic problem of price uncertainties.	BIM can help manage prices and quantity take-offs.
Evaluation of the refurbishment project(s)	It is difficult to evaluate different options	BIM can help simulate different design scenarios, assisting also decision support systems.
Facility management costs	Facility management (when present) often relied on traditional, not parametric technologies, leading to redundancies and inconsistencies.	BIM promotes facility management implementation and facilitates integrated control of information and operation.

Public tenders	Public tenders often lack complete, reliable documentation.	BIM can provide a robust data repository with all the tender information, constraints, and requirements.
Tenders assignments	Tenders are usually assigned through the examination of paper-based documents.	BIM model must represent the entire building in all these parts, proving more susceptible to detailed assessment. Code checking and clash detection on BIM models can be successfully used to evaluate bidders.
Project life-cycle	The presence of several stakeholders is prone to inconsistencies during planning, design, implementation and operation phases.	BIM can promote a life cycle approach in the construction sector
Evaluation of return of Investment (RoI)	RoI is inherently uncertain	BIM allow for a better evaluation of costs and time by making the construction workflow more reliable and robust.

6.5 ESSENTIAL PARAMETERS OF EPC

An economic feasibility study is crucial before starting any project. Such study would determine whether an investment is profitable or not. Decisions of bankers and financial firms are mostly based on a feasibility study results. The payback time and the return of investment are the main identified drivers.

Payback time and simple payback time

The payback period determines the time needed for the investor to recoup the cost of the investment. Upon the calculation of the payback period, the investor can compare different scenarios to determine the shortest period to return his investment. The integration of the BIM technology allows better determination of the payback period giving more credibility to the calculated value. It also makes it easier to explore more options for retrofitting the building without consuming time and effort.

Payback time indicator is suited for the economic evaluation of the proposed energy retrofit scenarios, as it requires simple calculation, its use is widespread as it is easy to understand by non-experts. A simplified method for the economical assessment of the investment can be considered if the annual savings are constant. In this case, the simple payback time can be easily calculated as the ratio of the initial investment, to the annual net savings.

For example, if the energy bill was reduced by 3,500$ per year after installing a solar PV on-grid system, then the simple payback period will be 2.85 years considering the initial investment to be 10,000$.

“Simple payback period = “ “Initial Investment” /”Annual Savings” “ = “ “10,000” /”3,500” “ = 2.85 years”

While the payback period shows the duration required for the return of investment, it does not show what the return of investment is. Thus, the profitability of the project will not be clear for the investor. To properly explore the profitability of the investment, the return of investment (RoI) can be integrated.

Return of investment

The Return of Investment is a financial ratio used to calculate the benefit an investor will receive in relation to their investment cost. It is a performance measure used to evaluate the efficiency or profitability of an investment or compare the efficiency of a number of different investments.

RoI is commonly measured as a ratio of the net income over the capital cost of the investment. The higher this ratio is, the higher the benefit. It acts as an indicator that can separate low-performing investments from high-performing ones.

6.6 EPC IMPLEMENTATION IN SEVEN MED COUNTRIES

Italy_ An EPC can be supported at most by a BIM-based process when it is able to streamline the organization with field data gathered during the analysis phase and work with it to support design solutions at best. Moreover, BIM can support the EPC during the operation and management phase making the EPC and its implementation after the realization of interventions as dynamic as possible.

The Italian EPC market is defined as “Sizeable and developing” with a positive trend that follows the growth of the market of ESCOs and is foreseen to continue its increase for the period 2020-2023.

Spain_ Due to a current lack of knowledge on EPC especially on the contracting side (and even more so in public administration) the market is still not sufficiently mature. An increase in skills is essential for the dissemination of this type of process.

The Spanish energy services market was still considered to be small and underperforming in 2018, despite growing steadily during the last previous years. The Spanish National Association of Energy Services Companies (ANESE) showed great interest in the possibilities related to time, costs, and sustainability data integration (4D, 5D and 6D dimensions) through BIM.

Cyprus_ As the real-time data is key for achieving more precise and updated calculation of the energy performance of a building it is also key that this data is made available between all stakeholders and BIM can help in streamlining this process.

Both the sector of EPC and the adoption of BIM technology are in their initial stages in Cyprus. No cases of BIM for EPC are reported or implemented yet. The ESCO market penetration so far is considered to be at its initial stages.

The potential for the market development of energy services in Cyprus has been described as promising, given the poor energy performance levels of the Cypriot building stock.

Jordan_A digitized workflow is appealing for the stakeholders involved in the process both during the design phase, when it can streamline the analysis phase and make the results more transparent and reliable, and during the operation and management phase of the implemented interventions.

Using EPC in Jordan is very limited due to its applying difficulty and the problems that resulted consequently between the building owners and the ESCOs regarding distribution the profits.

In addition, Jordan still lacks the required legislation for supporting ESCOs and EPC based EE implementation.

Palestine_ Data management during the design phase can be greatly implemented by a BIM-based process that can also decrease project costs and allow a faster delivery of the results.

The take-on rate of EPC in Palestine remains low at present and there is a lack of understanding and professional skills about how to apply the technique effectively.

Until now, there is no implementation for BIM in Palestine.

Lebanon_ As a concept, EPC contracts could be an attractive solution for contractors, clients, and investors however such formats require a certain extent of economic and financial stability in Lebanon.

The lack of funds is the main barrier refraining from implementing energy performance contracts in Lebanon. However, there are several other items leading to not performing such contracts such as the lack of experience and knowledge in the Lebanese market, although there are a lot of Lebanese professionals having CMVP certificates (Certified Measurement and Verification Professionals) which is essential in understanding such contracts.

On the legal side, there are no sufficient laws and regulations that can govern such contracts. Power Purchase Agreement (PPA) can be performed in Lebanon, with limited production to the project's grid, for large scale projects only and under the direct supervision of the Ministry of Energy and Water. Technically, the grid is unstable with daily cut-offs.

Moreover, the opportunity of equipment leasing through EPC contracts can facilitate the installation of energy efficiency measures in residential and public buildings.

Egypt_ In Africa, Egypt with other countries is co-operating with global institutions in order to create fund, increase awareness and implement ESCO association. These are the recent followed strategies for the promotion of ESCO in their countries. ■

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8. ANNEXES

ANNEX 1

REFERENCE ON CLIMATE DATA

1. INTRODUCTION

Dynamic building energy simulation requires climate data on an hourly basis for an entire year, to estimate the energy and environmental performance of a building. The selection of relevant and accurate weather inputs is crucial to limit the global uncertainty of building energy simulation's results. Their use is related to the stage of a) the calibration of the energy model of the existing building (current state) and b) the simulation of the energy improvement scenarios. The following paragraphs aim to provide an overview of the technical characteristics of weather files and briefly outline workflows for the creation of new climate files from scratch or the modification of existing climate files.

2. CLIMATE DATA REQUIREMENTS

Based on a single-year data set, the "Test Reference Year" (TRY) was one of the earliest attempts to create weather data files (NCDC, 1976). The use of TRY is strongly discouraged, as it does not support solar data and no single year can represent the typical weather patterns (Crawley, 1998). Thus, the climate data to be used for the dynamic energy simulation should represent the long-term average climatic conditions of the building's location. To this aim, "typical-year" weather files have been developed that are extracted from many years of historical weather data, often from the most recent 15-30 years.

The Typical Meteorological Year (TMY), released by the National Renewable Energy Laboratory (NREL), uses a multi-year weather data series of around 27 years, while the TMY2 of approximately 30 years. The TMY considers 9 climatic parameters, i.e. minimum, mean and maximum daily dry bulb temperature, minimum, mean and maximum daily dew point, mean and maximum daily wind velocity and daily global horizontal radiation. In the TMY2, the weather quantities are 10, since it also incorporates the parameter of direct solar radiation (Hensen & Lamberts, 2011). TMY3 files have also been developed, following a similar approach (Wilcox and Marion, 2008).

The "Weather Year for Energy Calculations 2" (WYEC2) was developed by ASHRAE based on TRY format, but it includes solar data (measured where available, otherwise calculated based on cloud cover and type) and also represents long-term average climatic conditions (ASHRAE, 1985).

Depending on the Building Performance Simulation (BPS) software selected, different file formats for climate data may be required. Specific information should be retrieved from the user documentation manual of the selected BPS software. The most widespread file formats for weather data are:

- EPW (EnergyPlus Weather Format)
- TRNSYS (Transys energy file)
- TMY3 (Typical Meteorological Year 3)
- IWEC2 (International Weather for Energy Calculations 2)
- CLM (ESP-r weather format)
- WEA (Daysim weather format)
- DDY (ASHRAE Design Conditions or "file" design conditions in EnergyPlus format)
- STAT (expanded EnergyPlus weather statistics)

2.1 CLIMATE DATA SOURCES

Most BPS software applications usually contain features for easy access and selection of a compatible weather file through available built-in weather data repositories. In this case, the selection is usually automatic, based on the building's location.

If this option is not available, a climate file can be either extracted or purchased from national databases or online weather data repositories. Some of the available sources are outlined below:

- Free climate data can be downloaded from the repository: http://climate.onebuilding.org/
  The TMYs provided derive from a variety of organizations. The prime file format is .epw. Ad-

ditional file formats that can be retrieved are: .clm, .wea, .ddy as well as .stat.

- Free climate data can be downloaded from the repository: https://energyplus.net/weather

  Weather data for more than 2100 locations are available in .epw format. Additional file formats that can be retrieved are .txt, .ddy and .stat.
- ASHRAE Weather Year for Energy Calculations 2 (IWEC 2) can be purchased from: http://ashrae.whiteboxtechnologies.com/IWEC2
  The database contains weather observations at least four times per day (on average) of wind speed and direction, sky cover, visibility, ceiling height, dry-bulb temperature, dew-point temperature, atmospheric pressure, liquid precipitation, and for at least 12 years of record up to 25 years. No measured solar radiation data are available yet; the hourly total horizontal solar radiation is calculated using an empirical model based on sun-earth geometry, reported cloud cover, temperature difference from three hours before, relative humidity and wind speed.
- A wide set of environmental parameters and whether files can be purchased from: https://meteonorm.com/en/meteonorm-version-8
  Meteonorm generates representative typical years for any place on earth based on real data sources and sophisticated calculation tools. It may contain more than 30 different weather parameters. The radiation database includes long-term monthly averages. Daily, hourly or minute values are generated stochastically. In addition to global radiation, hour-to-Hour and day-to-day variability and distributions are modelled as realistic as possible, but may include deviations from measured data. Various file formats are available, e.g.: .EPW, .TMY2, .TMY3 .CSV, PVSol, etc.

In case the climate data for the particular building location are not available or the location is too far away from a weather station, there is no generally accepted procedure for the selection of a suitable weather data source. One option is to use a weather generator tool (e.g. Meteonorm) that can extrapolate weather data from weather stations in the vicinity. An alternative option is to identify some candidate sources with approximately the same latitude and elevation as the site (within 30-50 km and a few hundred meters of elevation). Then, the comparison of monthly statistics derived from candidate files (using a simulation program weather utility[1]) with climatological summaries for the building's location will generally allow the selection of an acceptable match. If no similar source is found, data synthesis or adjustment procedures should be considered (Hensen & Lamberts, 2011).

2.2 CREATION AND MODIFICATION OF CLIMATE FILES

Climate data files can be generated, based on detailed outdoor environmental monitoring, as described in EN ISO 15927-4:2005. ISO 15927-4 specifies a method for constructing a reference year of hourly values of appropriate meteorological data suitable for assessing the average annual energy for heating and cooling. A thorough analysis and improvement suggestion of the Standard is provided by (Pernigotto et al., 2014).

Given the fact that the above procedure requires meticulous calculations and skills, along with a very detailed climate data set, which is not always readily available, adopting adjustment processes by modifying an existing climate file (with the use of file-converter applications) is often preferred.

The following steps provide an example of the process, summarising the modification of an EnergyPlus weather file (*.epw). Steps 1 to 7 may be followed when a candidate climate files, from a location close

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[1] e.g. the .epw viewer: https://mdahlhausen.github.io/epwvis/

to the site (approximately the same latitude and elevation), is available, but need to be modified through available long-term climate data of the building's location; steps 3 to 7 may be followed, when available long-term data from the building's location are available in spreadsheet format.

1. Select the existing – candidate weather file .epw (of the nearby location),
2. Export the file in .csv format or spreadsheet and use it as a template,
3. Replace the data of the template (the nearby location) that need to be modified, by copy-pasting the new data column-by-column. In this process, the physical relationships between the variables should be maintained[2],
4. Ensure the year is set to 2002 in all rows,
5. Save the new file as .cvs file,
6. Use a weather file translator (file-converter applications) to convert the template .csv file to .epw format. Many BPS software incorporate easy-to-use file-converter applications (e.g. Design Builder can convert . tmy2, .iwec, .csv, .fmt, .clm files into .epw[3])
7. Rename the .epw file as required.

It is noted that, for the conversion/modification of other file formats, specific technical guidelines can be provided by the technical documentation of the selected BPS software.

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[2] This can be done by using the free tool "Elements", which is used to alter spreadsheet-type weather data. When changing a parameter (e.g. dry-bulb, wet-bulb, etc.), the tool asks the user to define what other parameters to hold constant in order not to violate physics (e.g. >100% RH). This is also applied to solar radiation data (beam, diffuse, and total).

[3] https://designbuilder.co.uk/helpv4.2/Content/_Edit_hourly_weather_data.htm

ANNEX 2

STATE OF THE ART ANALYSIS ON BUILDING PERFORMANCE SIMULATION ON HISTORIC BUILDINGS

1 INTRODUCTION

Building Performance Simulation (BPS[1]) allows the study and optimisation of energy performance in an interrelated way, through the creation of a behavioural model of a given historical urban fabric, building or wall element, reduced to a certain level of abstraction (Augenbroe, 2002). The main innovation introduced by the simulations, as compared to previous methodologies, is the possibility of treating them as an integrated system of related elements that can be optimized and not as the sum of elements designed and optimised separately (Hensen, 2004). The purpose of simulations is not only to reveal the interactions between building, occupants, HVAC systems and outdoor climate, but also to facilitate the use of environmentally and energy-efficient design solutions (Hong et al., 2000). The simulations, in fact, support users in understanding complex phenomena by providing relatively rapid feedback on the performance implications of the design hypotheses (Clarke & Hensen, 2015). Yet, the application of these tools on historical buildings is still in an experimental phase and subject to certain challenges.

2 ADVANTAGES OF USING BUILDING PERFORMANCE SIMULATION ON THE BUILT HERITAGE

In the field of historical built heritage, building performance simulations are particularly interesting because they provide innovative non-destructive applications in both pre-diagnostic and diagnostic (Gigliarelli, Calcerano, Calvano, et al., 2017).

In fact, these tools:

- facilitate the understanding and analysis of complex phenomena, dynamically studying the exchange of energy between the building and the surrounding environment, including biophysical (water, soil, vegetation) and bioclimatic (radiation and ventilation) factors;
- provide retroactive feedback on the evolution of decay phenomena and on energy and environmental implications of conservation interventions. We refer to the specific heat, air and moisture transport's software for the predictive analysis of building envelopes, or to the possibility of dynamically studying the trend of physical quantities related to comfort (but also to the possible formation of degradation phenomena) within each room of a building;
- allow, through environmental analysis, to investigate the constructive phases of historical architecture in ways so far completely unexplored, halfway between virtual and experimental archaeology (e.g. allowing to study the initial functions of the building's spaces and/or devices to improve indoor comfort), providing further elements to enrich the historical analysis.

Moreover, the simulation-based study of the bioclimatic behaviour of historical urban fabrics provides additional knowledge of the building, allowing to model its passive behaviour, paving the way for design solutions capable of enhancing its distinctive characteristics and identities linked to the local microclimate (GBC, 2017; Gigliarelli et al., 2016).

3 ENERGY MODELLING TOOLS USED IN THE CASE OF HISTORIC BUILDINGS

Currently, several simulation software applications are available for the evaluation of the energy performance of buildings. These tools can be classified as stationary, semi-dynamic and dynamic. Stationary and semi-dynamic approaches are simplified methods that consider a limited number of factors. They are more related to the evaluation of energy performance in standard conditions of use and input data are usually provided by standard references from national databases, used for energy labelling. In particular, results from stationary tools are simplified, as they do not consider the periodic trend of

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[1] Also referred to as Building Energy Modelling – BEM or Building Energy Simulation –BES.

temperature nor the thermal inertia of structures. Semi-dynamic software (also called sketch design software) takes these parameters into consideration, yet they require simplified inputs for climatic data and building description. On the contrary, dynamic simulation software applications are able to evaluate all factors accurately, but they need detailed inputsfor climatic conditions and building properties.

(Akkurt et al., 2020) and Calzolari (2016) studied the criticalities of applying BPS, generally used for new or existing buildings, to the built heritage. Pracchi (2014) and Heath et al. (2010) each simulated a historic building using multiple BPS software programs and found large discrepancies between results, illustrating how these limitations (§ Chapter 4) can have downstream effects on retrofit decision-making. Despite the complexity, whole building dynamic software tools are acknowledged as more suitable for the modelling of historical buildings, due to their flexibility and capacity to produce more accurate results (Adhikari et al., 2013).

Simulation software is extremely useful in calculating environmental conditions and energy consumption in buildings prior to intervention, as it allows the behaviour of the different climate conditioning systems and installations to be predicted (Webb, 2017). The capacity of numerical tools to minimise the computational time for evaluating a finite set of alternatives, based on various criteria, is extremely valuable for the development of multiple criteria decision analysis tools. The project *Climate for Culture* coupled climate modelling with whole building simulation tools. The project scope was to provide information on future indoor climate change and address the risks to cultural heritage. Various online tools were produced, as well as a Decision Making Support System for stakeholders. Similar tools were also developed through several projects focusing on retrofitting historic buildings, such as SECHURBA[2] (AA. VV., 2011; Gigliarelli et al., 2018) and EFFESUS[3].

A thorough review of studies on historical buildings employing numerical tools (CFD or BPS) is provided in the work of Martínez-Molina et al. (2016). The studies are grouped per building use and method of analysis (e.g. monitoring, simulation, CFD, etc.). In the case of museums, libraries and theatres, most of the studies focus on the regulation of the microclimatic environment: an important aspect to minimize the ageing and degradation of materials and artworks (Muñoz-González et al., 2018). Tronchin and Fabbri (2017) used Building Performance Simulation to optimise energy consumption and ancient manuscripts' conservation in the Malatestiana Library in Cesena (Italy). A methodology for microclimatic qualification's assessment is described in the study of Corgnati, Fabi, and Filippi (2009), which is based on medium/long field monitoring of environmental parameters and microclimatic quality evaluation in museums. Silva, Coelho, and Henriques (2020) discussed the indoor microclimatic monitoring of a church in Lisbon (Portugal) and compared the results with other case studies in different European geographical areas, to propose a new method of analysis specifically dedicated to temperate climates (Silva & Henriques, 2014). The work of Camuffo et al. (2010), Schellen and Neuhaus (2010), Muñoz González et al. (2020), Varas-Muriel, Martínez-Garrido, and Fort (2014) focused on simulating active environmental conditioning systems such as heating, ventilation, air-conditioning and cooling (HVAC) in churches. In the recent work of de Rubeis et al. (2020), an extensive review of similar studies is provided, reporting the results of researches employing air-to-air heat pumps, adaptive ventilation (Napp & Kalamees, 2015) or variable heating and cooling setpoints (H. L. Schellen & van Schijndel, 2011).

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[2] SECHURBA Research Project: Sustainable Energy Communities in Historic Urban Areas'. 2011 https://ec.europa.eu/energy/intelligent/projects/en/projects/sechurba

[3] EFFESUS Research Project: Energy Efficiency for EU Historic Districts' Sustainability'. 2016 https://www.effesus.eu/

Different indoor conditions, such as natural lighting, were analysed in other studies employing whole building simulation tools. Balocco and Calzolari (2008) performed a research on natural lighting design in a medieval church in Florence, Italy. A solar radiation control showed that the installations ensured energy savings for cooling and lighting as well as guaranteeing users' lighting comfort. Michael et al. (2017) coupled natural lighting field measurements with numerical simulations in vernacular buildings in Cyprus to assess lighting comfort. Nocera et al. (2018) developed a calibrated model based on the Radiance software to improve daylight performance in a classroom of the Caserma Gaetano Abela in Sicily (Italy).

Additional analysis and uses of numerical tools concern the estimation of air quality and the use of innovative materials. Cataldo et al. (2005) studied air quality in a historical building by integrating different non-destructive methods, such as microclimatic tools and ground penetrating radars. Bernardi et al. (2014)PCMs' technology needs to be adapted to specific requirements. Besides the important objectives of economic return and human comfort, the indoor microclimatic conditions have to be suitable for conservation purposes. The application of PCMs' technology to Cultural Heritage has been investigated within the European MESSIB (Multi-source Energy Storage System Integrated in Buildings showed the efficacy of phase change materials when used as thermal energy storage units in historical buildings. The study revealed that direct contact between phase change materials and heritage objects is not recommended, as mechanical damage could result.

A numerical tool used for predicting indoor and outdoor airflow, heat transfer and indoor thermal comfort, gaining ground over the last decades, is Computational Fluid Dynamics (CFD). There are a few applications of CFD in the sector of building conservation. Balocco and Grazzini (2009) investigated the ancient natural ventilation system inside a historical building in Palermo, Italy, and analysed a simple cooling technique. Papakonstantinou, Kiranoudis, and Markatos (2000) modelled thermal comfort conditions in the Hall of the National Archaeological Museum of Athens, while D'Agostino and Congedo (2014) investigated the adequacy of natural ventilation in a historical building located in the South of Italy. The model determined a great variability of the thermo-hygrometric parameters among the ventilation solutions. Kristianto, Utama, and Fathoni (2014) investigated the thermal comfort conditions in the Minahasa Traditional House, suggesting greater silts height and roof openings for enhanced airflow in indoor spaces. Finally, Du, Bokel, and van den Dobbelsteen (2014) coupled field measurements and dynamic thermal and CFD simulation through the platform of Design Builder to investigate the thermal performance of the vernacular Chinese house. Pisello et al. (2014) used BPS to support the energy refurbishment of Palazzo Gallenga Stuart in Perugia (Italy), estimating a 50% reduction in energy consumption, Cellura et al. (2017) for a rural building in Sicily (Italy).

Gigliarelli, Calcerano, and Cessari (2017) focused on a multiscalar approach supported by an HBIM platform and further analysed the BIM to BPS interoperability on historical buildings' applications (Gigliarelli et al. 2017; 2019).

Despite the extensive use of numerical tools and particularly whole building energy modelling and CFD software, several researchers have expressed concerns regarding the predictive accuracy of such tools. Huerto-Cardenas et al. (2020) reviewed the main approaches used by researchers for BPS model validation with special reference to historical buildings through microclimatic parameters, highlighting the main issues and advantages of the different methods reviewed and defining suitable validation thresholds.

4 MODEL CALIBRATION APPROACHES

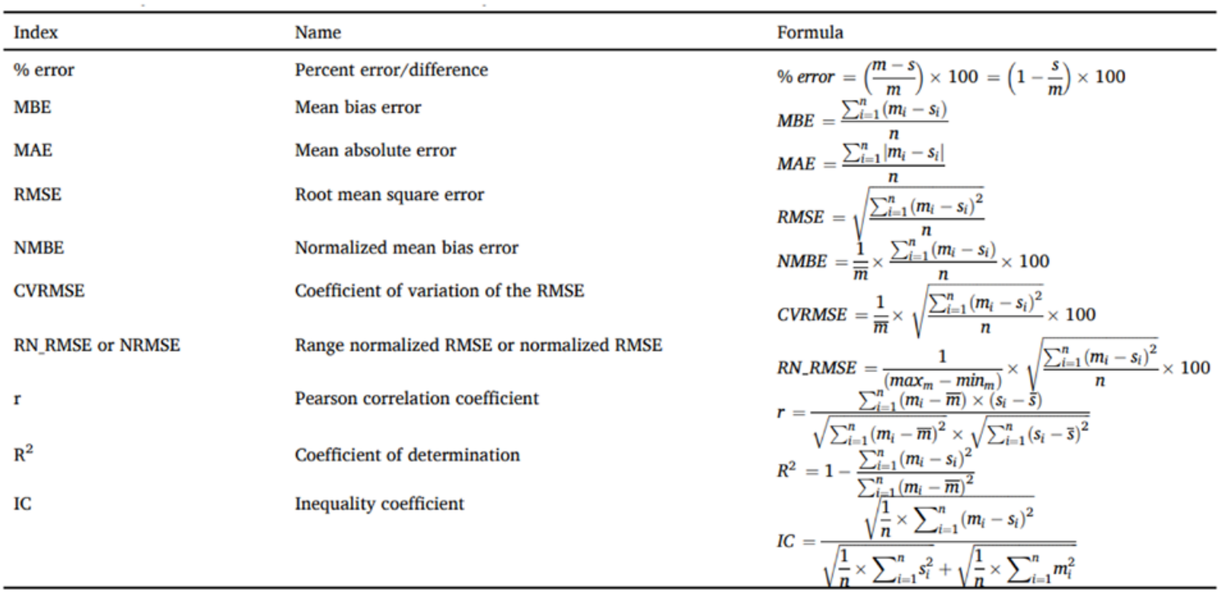
The use of dynamic simulation tools represents a great opportunity to predict the behaviour of extremely dynamic systems such as buildings. However, as models always represent a simplification of real cases, the reliability of the predictions provided by simulation models requires a thorough calibration process. The ASHRAE Guildeline 14: 2014 defines calibration as "..*the process of reducing the uncertainty of a model by comparing the predicted output of the model under a specific set of conditions to the actual measured data for the same set of conditions*". Therefore, in-situ experimental data acquisition (e.g. energy consumption data or environmental conditions) is imperative to compare the predicted output of the model to the actual measured data.

In the case of historical buildings, for which building construction is often little known, the calibration phase is of particular importance (Roberti et al., 2015). However, there is no established methodology or indicators for estimating the level of accuracy of models. Huerto-Cardenas et al. (2020) who reviewed the challenges regarding the validation of dynamic hygrothermal simulation models for historical buildings, reported the increasing use of microclimatic parameters for calibration and validation purposes in heritage BPS. This is mainly related to the availability of environmental data that are acquired through high-accuracy measurement equipment for occupants' thermal comfort assessment or risk- assessment of building materials and objects. An additional reason for using microclimatic parameters is the lack of energy consumption data, generally adopted in the model validation. This latter issue can be attributed to the absence of heating/ cooling systems, which is often the case for many historical buildings, or due to difficulties in retrieving energy consumption data. The following are often used to provide more accurate model inputs and help calibrate the model: whole building energy consumption, indoor air temperatures, in situ material properties, laser scanning of building geometry and blower door pressurization tests of airtightness (Webb, 2017). Yet, the most frequently used microclimatic variables involved in model calibration are: indoor dry-bulb air temperature (Ta) and Relative Humidity (RH) (Huerto-Cardenas et al., 2020). In the study of Rajčić, Skender, and Damjanović (2018), three categories are used for the estimation of the prediction accuracy: excellent, acceptable and low. The difference between simulated and measured data is interpreted as "excellent" when it lies within ± 1 °C and ± 5% from the median for temperature and relative humidity respectively, "acceptable" when values fall within ±3 °C and ±10% from the median, while "low" when both values are out of these ranges.

A summary of the main uncertainty indices for estimating a model's accuracy is provided in Table 1. ASHRAE Guildeline 14: 2014 recommends the use of the following indicators for calibrated simulations: Coefficient of Variation of the Root Mean Square Error (CV(RMSE)) and the Normalized Mean Bias Error (NMBE). The monthly thresholds are ±5% and 15% for NMBE and CVRMSE respectively. The hourly ones are ±10% and the 30%.

Roberti, Oberegger, and Gasparella (2015) proposed a calibration methodology based on the minimization of Root Mean Square Error (RMSE) through particles warm optimization algorithms implemented in the Genopt software and applied it to a medieval building located in the historic centre of Bolzano (Italy). The results obtained a remarkable accuracy of the model, that was validated on hourly indoor air and surface temperatures in winter. Coelho, Silva, and Henriques (2018) discussed a validation process of historic building simulation models by comparing measured and simulated temperature and water-vapour pressure quantifying Coefficient of Determination (R^2), coefficient of variation of the root mean square error, normalized mean bias error and goodness of fit. The case study that was presented is a 13th-century church in Lisbon (Portugal), whose indoor conditions were monitored over a year. The authors conducted a sensitivity analysis for three parameters, namely, air change rate, solar heat gain coefficient and short-wave radiation absorption coefficient. They concluded that the best results are obtainable by considering a monitored weather file rather than data provided from databases, and that the parameters of soil and slab interface temperature have a significant role.

Cornaro, Puggioni, and Strollo (2016) suggested retrofit solutions for a complex historic building in



Index	Name	Formula
% error	Percent error/difference	$\% error = \left(\frac{m-s}{m}\right) \times 100 = \left(1-\frac{s}{m}\right) \times 100$
MBE	Mean bias error	$MBE = \frac{\sum_{i=1}^{n}(m_i - s_i)}{n}$
MAE	Mean absolute error	$MAE = \frac{\sum_{i=1}^{n}\lvert m_i - s_i\rvert}{n}$
RMSE	Root mean square error	$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(m_i - s_i)^2}{n}}$
NMBE	Normalized mean bias error	$NMBE = \frac{1}{\overline{m}} \times \frac{\sum_{i=1}^{n}(m_i - s_i)}{n} \times 100$
CVRMSE	Coefficient of variation of the RMSE	$CVRMSE = \frac{1}{\overline{m}} \times \sqrt{\frac{\sum_{i=1}^{n}(m_i - s_i)^2}{n}} \times 100$
RN_RMSE or NRMSE	Range normalized RMSE or normalized RMSE	$RN\_RMSE = \frac{1}{(max_m - min_m)} \times \sqrt{\frac{\sum_{i=1}^{n}(m_i - s_i)^2}{n}} \times 100$
r	Pearson correlation coefficient	$r = \frac{\sum_{i=1}^{n}(m_i - \overline{m}) \times (s_i - \overline{s})}{\sqrt{\sum_{i=1}^{n}(m_i - \overline{m})^2} \times \sqrt{\sum_{i=1}^{n}(s_i - \overline{s})^2}}$
R^2	Coefficient of determination	$R^2 = 1 - \frac{\sum_{i=1}^{n}(m_i - s_i)^2}{\sum_{i=1}^{n}(m_i - \overline{m})^2}$
IC	Inequality coefficient	$IC = \frac{\sqrt{\frac{1}{n} \times \sum_{i=1}^{n}(m_i - s_i)^2}}{\sqrt{\frac{1}{n} \times \sum_{i=1}^{n}s_i^2} + \sqrt{\frac{1}{n} \times \sum_{i=1}^{n}m_i^2}}$

Table 1: Main uncertainty indices used to evaluate the accuracy of BPS model, based on the statistical analysis of measured (m) and simulated (s) data. Source: Huerto-Cardenas et al. (2020)

Italy by using numerical tools coupled with data obtained through a short-term monitoring campaign. Pigliautile et al. (2019)existing and historical buildings are still too much energy needy, with a relatively low indoor comfort conditions for both occupants and artworks preserved inside, especially within heritage buildings. Such high architectural value buildings correspond to almost one third of the Italian building stock and they typically need to be re-functionalized for hosting residential, office, or institutional uses, i.e. museums and exhibition areas. In this view, the present research aims at developing a replicable method for assessing and enhancing indoor comfort in historical buildings frequently characterized by too high relative humidity and thermal losses through the envelope. More in details, an innovative envelope material for indoor application, i.e. hygro-adsorbing plaster, has been tested in an ancient Italian castle and its effect has been assessed by means of coupled monitoring and calibrated dynamic simulation. The experimental campaign shows an increase of the Performance Index (PI discussed an innovative methodology based on experimental monitoring and dynamic simulation, to assess the impact of passive solutions on occupants' thermal comfort and artworks preservation. The case study considered was the castle of Pieve del Vescovo, located near Perugia (Italy). The simulation model was performed via DesignBuilder software and EnergyPlus engine. The iterative calibration process involved the modification of the external wall materials' width and the internal thermal gains. The statistical analysis of the calibration phase considered mean bias error and root mean square error.

De Rubeis et al. (2020) analysed the thermo-hygrometric conditions of the church of Santa Maria Annunziata of Roio in L' Aquila (Italy), both for artworks preservation and occupants' comfort. The analysis was carried out by means of EnergyPlus coupled with Design Builder software. In this case, the weather file used for the simulation was created employing the data measured by a nearby weather station (i.e. dry bulb temperature, wind speed, atmospheric pressure, relative humidity and solar radiation). The approach of their work is divided into two steps: the first calibration phase of the model was performed by comparing measured and experimental indoor air temperature and manually and iteratively varying parameters of the model, namely temperature setpoints and air leakage, to improve its accuracy. In the second phase, the ability of the calibrated model to predict the behaviour of the building was assessed through the statistical indicators of Mean Bias Error (MBE), Coefficient of Variation of the Root Mean Square Error (CV(RMSE)), the deviation between simulated and measured indoor air temperature trends and the Coefficient of Determination (R^2).

An additional parameter with a significant impact on potential differences between the modelled (theoretical) and the actual energy performance of buildings, in general, is occupant behaviour. While this parameter has been studied (Brohus et al., 2010), in the case of historical buildings user-driven energy efficiency remains problematic (Berg et al., 2017). Research and empirical data remain insufficient, while the existing methodologies assessing occupant behaviour are predominately qualitative. Certain interplays between user-related energy consumption and awareness of a building's cultural heritage values are reported, calling for more quantitative approaches regarding occupant behaviour in historical buildings (Berg et al., 2017; Kavgic et al., 2010).

5. OPEN ISSUES REGARDING THE APPLICATION OF A SIMULATION-BASED DESIGN APPROACH IN HISTORIC BUILDINGS

The term simulation-based design refers to a process in which simulations are the main tool for evaluation and verification, aimed at eliminating inefficient design scenarios with the least possible waste of resources (Mefteh, 2018). Given the impact of strategic decisions on the energy and environmental characteristics of buildings, simulation-based design should be a fully integrated tool in the decision-making process regarding architecture (Lechner, 1991; Reiser et al., 2008). In order to apply a simulation-based design approach to the built heritage, several points still need to be thoroughly addressed. Among these are:

1. The uncertainty of the data measured on site for the characterisation of the building materials to be used in the energy modelling;
2. Simplifications and assumptions, mainly referring to:
   - ☐ complex and irregular geometries (most modelling software require simplifications of the building shape, which sometimes fail to adequately represent the complexity of heritage buildings and the number of surfaces, and consequently accurately calculate the energy flow between them);
   - ☐ the lack of homogeneous and standardized construction elements (this might correspond either to the case of complex façades with several historical phases, or the case of a single wall with irregularities (Roberti et al., 2015), which often may be deteriorated or partly damaged and therefore may have variable thermophysical properties);
   - ☐ the inertial behaviour of the building mass, which requires specific corrections and precautions to be adequately simulated by software created to simulate buildings constructed based on other structural systems than massive load-bearing elements (Mazzarella & Pasini, 2017);
   - ☐ important envelope moisture buffering and related complexities to its calculation (Paolini et al., 2016);
   - ☐ thermal stratification in large spaces (Webb, 2017);
   - ☐ occupant behaviour that is subject to social, economic and cultural values and insufficiently documented in the case of historic buildings (Berg et al., 2017).

3. The need to build a “critical” database of case studies and of historical wall stratigraphies with thermophysical characteristics, to help energy modellers with the definition of those characteristics where destructive tests are not

available, and more in general to help consolidate the energy modelling approach on historical buildings, to identify "groups" of particularities (if any), tendencies and reverse "*the lack of publicly available detailed data relating to inputs and assumptions*" (Kavgic et al., 2010);

4. The need for a reflection on the limits of a deterministic approach (deriving from simulation tools) applied to naturally heterogeneous cases, such as the ones of historical buildings. The above challenge calls for an approach that is tolerant to the ambiguities / limits of knowledge, inherent in the input data of the modelling of a historical building (with reference also to a possible probabilistic approach). Knowledge transfer from the diagnostic phase of the conservation process where there is a strong link between hard science specialists, humanities and conservation experts would also be beneficial, to help finding a compromise between different analysis systems approaches, to be used in parallel for the reconstruction and the energy and environmental behaviour of the built heritage. Simulation-based design on built heritage should follow therefore the path of other disciplinary fields, such as the structural diagnosis (Croci, 2000) that was capable to find a methodological compromise between procedures that, despite their uncertainties, represent to date the best possible formulation of a problem based on data, hypothesis and interpretation (Gigliarelli et al. 2019);
5. The need to develop an interdisciplinary debate on the subject, allowing for the integration of different views and competencies;
6. The need to create a set of guidelines based on the existing literature on the calibration and validation of energy models of historic buildings (Huerto-Cardenas et al., 2020; Roberti et al., 2015), while respecting the "case by case" approach according to the complexity of each case. This is important to identify the best energy diagnosis path to use (including not only application but also economic and time constraints), according to the principle of gradual complexity of the analyses performed in relation to the gradual deepening of the level of information required for a specific purpose.

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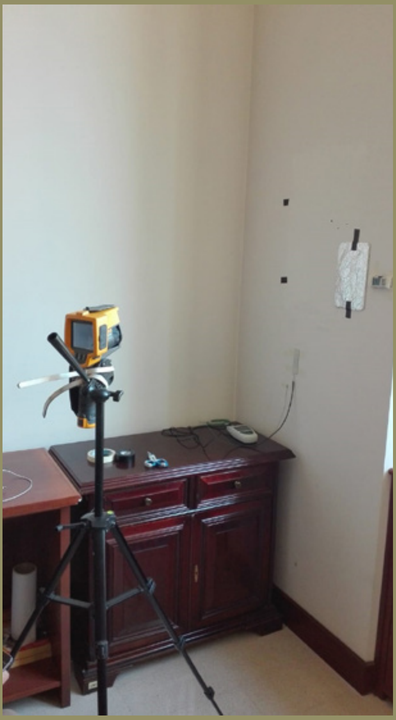

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ANNEX 3

STATE OF THE ART ANALYSIS ON BIM AND NUMERICAL SIMULATION INTEROPERABILITY

1. INTRODUCTION

1.1 Background

The building sector is responsible for contributing up to 30% of the global greenhouse gas emissions (GHG) and for consuming almost 40% of the total energy production. The implementation of Energy Efficiency (EE) in the built environment is one of the principal objectives of the European Union's (EU) action plan for sustainable development (EBPD, 2010). For restraining the energy consumption and environmental footprint of the building stock, EU and various international institutions formulated a series of policies and regulations, which lead to the establishment of new standards around energy rehabilitation strategies and the promotion of smart technology solutions. In addition, these directives set a new reference point for energy performance requirements and consequently bring forward the concept of nearly zero energy buildings (nZEB). The realization of Energy Efficiency objectives within tight financial budgets and durable result expectations stresses the need for advanced control over the life cycle costs (LCC) of buildings (Liu et al., 2015). The impact of design decisions on the energy and environmental performance of a building is much higher if these decisions are close to the early design stages (Lechner, 1991). Under these lines, the early involvement of MEP engineers, the need for early energy-related insights, as well as the continuous monitoring of the building's energy performance responses are becoming essential key aspects for the entire building planning and asset management process.

The tight interrelation of these objectives points out the importance of a well-formulated approach of rapid deployment, which requires collectiveness and collaboration among the involved professionals. The necessity for shifting over to a renewed, integrated planning practice is commonly considered a step forward to better deal with cost-effective energy-saving developments (Ryan & Sanquist, 2012).

In the last decade, Building Information Modelling (BIM), defined as the use of a shared digital representation of a built asset to facilitate design, construction and operation processes to form a reliable basis for decisions (ISO 19650-1:2018 Organization and Digitization of Information about Buildings and Civil Engineering Works, Including Building Information Modelling (BIM) — Information Management Using Building Information Modelling — Part 1: Concepts and Principles, 2018), became a popular approach which encapsulates the above capacity for sustainable building development. BIM puts in place all the necessary tools for activating an integrated design and planning workflow. This is accomplished through the embodiment of building information within the geometrical model itself. Hence, native BIM software acts as a core database of information of multiple dimensions, classifying the building's operational, financial, managerial, ecological and maintenance attributes and functions. However, exporting BIM data for Building Performance Simulation (BPS) applications depends on data exchange formats and their subsequent file standards compatibility. When information is fully defined and appropriately registered, a single export can save a significant amount of time, effort and potential error occurrences, as compared to reproducing the respective Energy Model in a native BPS environment (Pinheiro et al., 2016).

The transferring of information between BIM and BPS software is carried out under Open BIM standards, through the data exchange schema (DES) of Industry Foundation Class (IFC) or Green Building eXtensible Markup Language (gbXML) (Augenbroe, 2002; Di Biccari et al., 2022; Kamel & Memari, 2019; Pinheiro et al., 2016). Amongst the majority of BPS software packages, gbXML is considered a more straightforward option for use with many BPS software packages, since the schema output is lighter in size and dedicated to energy-related information exchange (for a comparison of the two file formats see §4.5). However, despite the potential of BIM technology for generating a collective and automated design and planning workflow, the interoperability of BIM to BPS is yet not fully functional nor effortless (Gigliarelli et al., 2019; Hijazi et al., 2015; Kamel & Memari, 2019; Rahmani Asl et al., 2015). An exported BIM model may result in decomposed or unjustifiably interpreted geometry, with numerous incidences of improper or inadequate data conversion.

1.2 Glossary

AEC	Architecture, Engineering and Construction
BCF	BIM Collaboration Framework
BI-EM	*Building Information-Energy Model. A BIM-based energy model that automates the energy modelling process within the BIM software (Revit Energy Model)*
BIM	Building Information Modelling
BIM-BPS	*Building Information Model to Building Energy Model. A converted energy model using exported information from a BIM model*
BPS	Building Performance Simulation
bSDD	buildingSMART Data Dictionaries
CFD	Computational Fluid Dynamic
DTV	Design Transfer View
DES	Date Exchange Schema
FM	Facility Management
GBS	Green Building Studio
gbXML	Green Building eXtensible Markup Language
HVAC	Heating, Ventilation and Air Conditioning
IAI	International Alliance for Interoperability
IDM	Information Delivery Manual
IFD	International Framework for Dictionaries
IFC	Industry Foundation Class
ISO	International Organization for Standardization
LCC	Life cycle costs
MEP	Mechanical, Electrical, and Plumbing
MVD	Model View Definitions
Plenum	A plenum is a non-occupiable space between a ceiling and the floor above specifically intended for mechanical systems and other systems that require ceiling space
R-value	Thermal Resistance
RV	Reference View
SHGC	A value describing the solar heat gain coefficient in a glazing (window) material
Space	A space is defined as a building volume enclosed by ceilings, floor, walls or by another space's boundary. Space has a plethora of properties assigned to it to describe its energy resources, such as loads from people, lighting and equipment
U-value	Heat Transfer coefficient or Thermal Transmittance
Weather File (epw)	A single file in a format called an .epw that contains a collection of information to describe the environment of a location for each hour of the year, supplying data such as temperatures, luminescence data for sunlight, heating, and more
XML	eXtensible Markup Language
XSD	XML Schema Definition

1.3 Purpose

The purpose of this section is to explore and address the current state of BIM to BPS interoperability development, its causes, challenges and current workflow approaches in AEC daily practice. It seeks to provide critical insights into the current obstacles the AEC industry is facing around this subject, to streamline the selection and implementation of the most efficient semi-automatic workflows available. This purpose is outlined in the table below:

In scope of this chapter	Out of scope of this chaper
Description of the problem formulation Literature review of existing BIM to BPS workflows/ conversions Comparison of IFC and gbXML data schema Guidance for an effective BIM to BPS Interoperability Advice on establishing a successful semi-automatic workflow Advice on avoiding/reducing parallel modelling between the two software environments	Advice on IT solution Software or scripts Suggestions on the use of specific software packages or versions Explaination of Energy Simulation Models

Table 1: Document chapter scope

2 SCHEMATIC REPRESENTATION OF A PROBLEM

The need of the AEC industry to engage in a more collaborative design and planning practice is commonly considered a great development for enhancing the final resolution (richness and accuracy) of a building outcome in all its critical aspects. BIM technology provides a complete digital solution for modelling, storing, editing and managing building information while promoting a clear role designation to the involved professionals. During a project's development, the engagement of project engineers with numerical simulations at different project phases is of primary importance. For this reason, BIM authoring software should be able to exchange model information seamlessly. From research literature and professional practice reports, the interaction of the two is still away from being smooth and error-less (Di Biccari et al., 2022; GSA, 2015; Hijazi et al., 2015; Kamel & Memari, 2019; Rahmani Asl et al., 2015).

Currently, AEC firms rely on a plethora of design and simulation software applications, when it comes to explicit tools and services for project collaboration. Communication and interoperability between these tools depend on data exchange formats and their compatibility (Augenbroe, 2002), which within the BIM pipeline is typically ensured by a Common Data Environment (CDE). A CDE represents the agreed source (and repository) for collecting, managing and disseminating information for any given project (ISO 19650-1:2018 Organization and Digitization of Information about Buildings and Civil Engineering Works, Including Building Information Modelling (BIM) — Information Management Using Building Information Modelling — Part 1: Concepts and Principles, 2018). It aligns the process of model collaboration with the established industry collaboration protocols to enable multiple users to perform collaboration operations on model content management, content creation, viewing and reporting and system administration. In particular, the exchange of digital models should be filtered in order to map only the segment of data that is essential for the particular numerical simulation, i.e., in the case of BPS, simplified building geometry and thermal data. Currently, project files exported from BIM software are usually too condensed in information and too large in size for the basic needs of simulation software to operate correctly. Therefore, project professionals are often called to manually remodel and reregister the information before executing the building numerical simulation. This lack of compatibility leads to increased time-consuming processes which are also prone to human error, inconsistencies and redundancies, especially in large construction projects, with multiple planning and design phases. Approximately 80% of the total resources needed to perform a building simulation are consumed on unnecessary replicating actions (Ryan & Sanquist, 2012).

Despite the aforementioned workflow obstacles found in process of the model data transfer from BIM to numerical simulation software, in the case of BIM to BPS conversion, the level of complexity becomes even higher. Contrary to a native BIM model, BPS input data are much more abstract, in terms of the building's geometrical input as well as of alphanumerical information. Therefore, the transfer of data from BIM to BPS demands serious simplification of the building geometry from 3D objects to 2D surfaces. For this reason, the exporting process is also subjected to geometric computational conversions, also known as 'healing computations'. Current efforts occupied with the BIM to BPS interoperability issue utilise both the IFC and gbXML data schemas. Specifically, a schematic representation of the interoperability problem is presented in Figure 1.

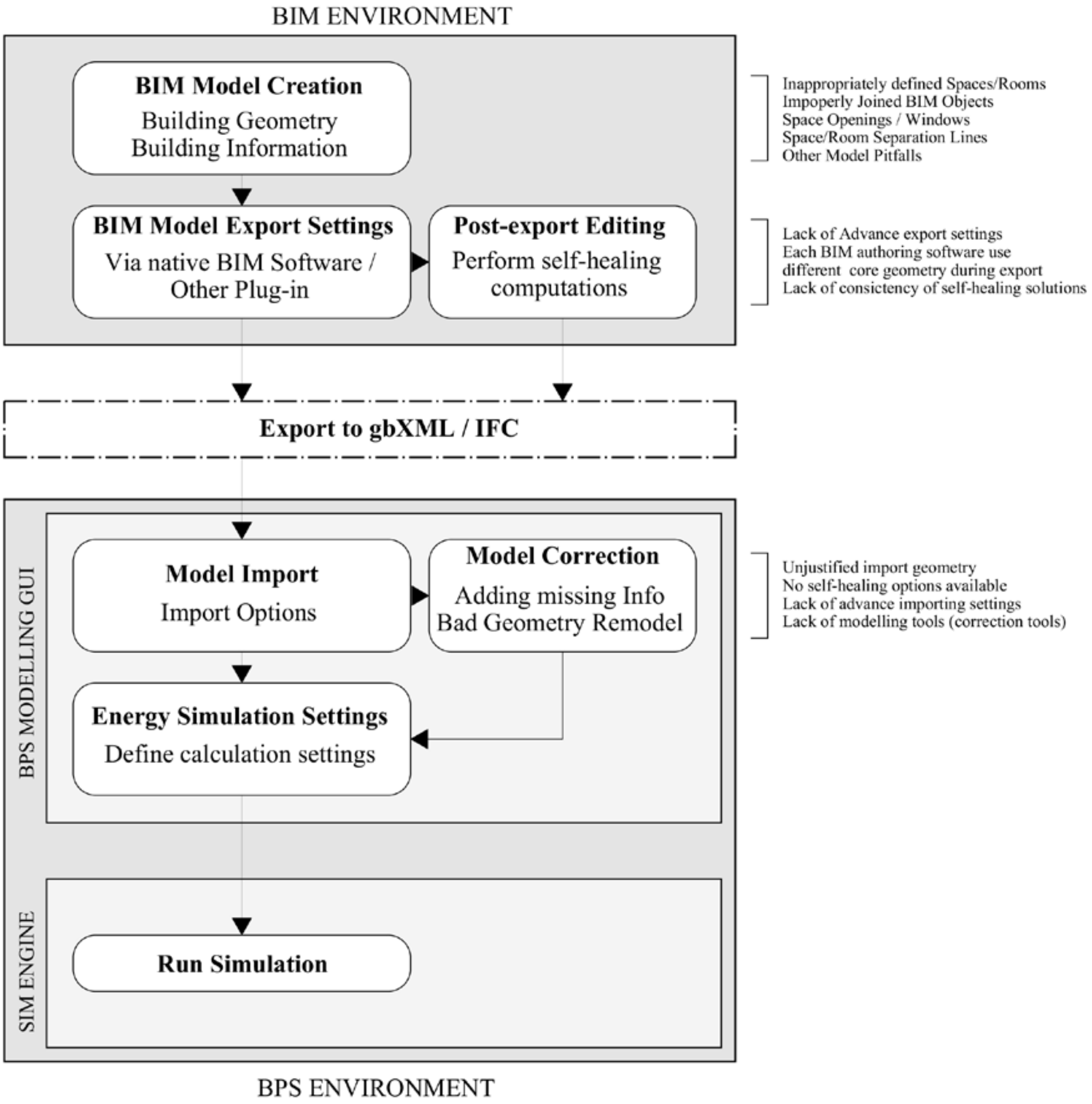

Fig. 25. Schematic representation of BIM to BPS Interoperability problem

3 BIM FOR BPS

3.1 Building Information Modelling

A Building Information Model refers to the digital model of a building that contains a wide spectrum of information from a variety of construction industry fields. This model includes input from all construction stakeholders, including the architect, structural engineer, mechanical engineer, energy engineer, and others, that defines building attributes from the beginning of its lifecycle until its demolition (Sacks et al., 2018). According to the literature, the majority of BIM definitions refer to the model as a series of actions of broad changes in design, construction and facility management, instead of a digital object in itself. In particular, BIM is described as a set of policies, processes and technologies, which set the standards for a holistic collaborative methodology for building design and construction (Succar, 2009). BIM technology is described as one of the most promising developments happening in the AEC industry, which enables and integrates design and construction workflow.

3.1.1 BIM maturity levels

The level of implementation of BIM technology depends on the level of complexity of a building project but, more importantly, on how the model will be used (Jayasena & Weddikkara, 2013). For scalability reasons, this characteristic is formally described as BIM maturity. In short, the level of maturity defines the level of collaboration between industry professionals. In Figure 2, the schema of BIM maturity levels developed by the BIM Industry Working Group is presented (BIWG, 2011). The diagram was developed for the British Government Construction Client Group and is rapidly adopted throughout Europe. These levels are formulated based on the industry standards of the disciplines involved.

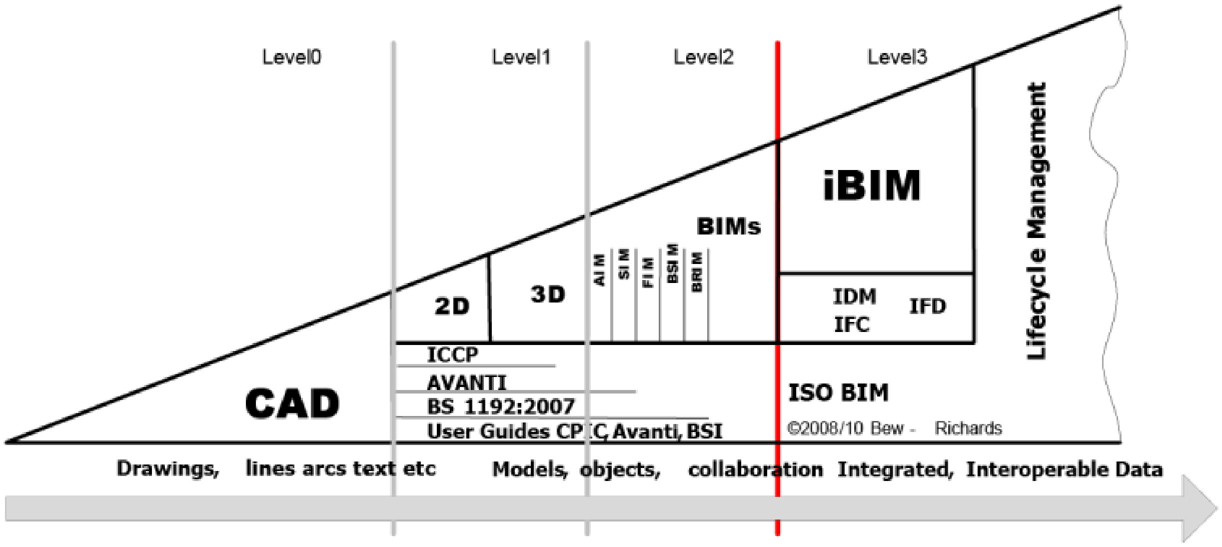

Fig. 26. Maturity scheme – BIM Industry Working Group (BIM Industry working group (BIWG 2011).

The implementation of a BIM model at maturity level 3 means that all previous levels' requirements are fully respected and realised. At level 0, only CAD drawings and spreadsheet calculations are executed. This level includes no digital models and is commonly referred to as the document-oriented level. Level 1 is the first step towards a basic BIM model. At this stage, a 3D model of the building is developed, however, it still cannot be used for cost, operations or other calculations. This option can be achieved at maturity level 2, where building information is assigned to the building objects. At final level 3, building information is shared between the involved professionals through open BIM standards. Level 3 provides a full utilisation of BIM technology and ideally sets the standards for seamless collaboration.

Facilitating a frequent and structured collaboration between the involved parties is boosted at BIM maturity levels 2 and 3. Consequently, the interoperability between native BIM software and other numerical simulation packages becomes critical. A seamless exchange of information between the two software environments may accelerate the building development workflow or even enable automation.

3.1.2 Level of Development (LOD) and Level of information Need

Another important aspect of BIM implementation is the definition of the level of information, both geometrical and alphanumerical, within a BIM model and its elements. A very common term to express this concept is the Level of Development (LOD). This term is used to describe both the geometrical and alphanumerical level of information incorporated in a model for each modelling phase of a project's development (Boton et al., 2015). The Level of Development is divided into a scale of 5 levels, namely, in the US version, L100, L200, L300, L400 & L500 (Choi et al., 2015)it is especially important to provide concurrent construction process to BIM models with construction automation. In particular, the schematic Quantity Take-Off (QTO. L100 represents the level of information of a conceptual design, whereas, L500 indicates a geometry at an as-built level, with information reaching the operation and maintenance level. Similarly to the level of maturity, the decision of LOD for a BIM model is directly related to its purpose and uses.

ISO 19650 (ISO 19650-1:2018 Organization and Digitization of Information about Buildings and Civil Engineering Works, Including Building Information Modelling (BIM) — Information Management Using Building Information Modelling — Part 1: Concepts and Principles, 2018) introduces the corresponding concept of Level of Information Need, that defines the extent and granularity of information to be provided to satisfy the information related purposes of each model element. Compared to LOD, it stressed the importance of the "right" amount of information to be delivered, to avoid redundancy and waste (Churcher & Davidson, 2019). Moreover, it is intended as a general framework to be adapted to the specific BIM process, without providing a strict template, but leaving a lot of flexibility to implementation; therefore, it is well suited for interoperability workflows, that require ad-hoc solutions.

When it comes to BIM for BPS interoperability, the Level of information Need becomes probably the most important aspect for consideration, in avoiding convergence issues (Sacks et al. 2018). While a L500 (that could correspond to a specifically defined, very high Level of Information Need) model creates the best conditions for the ultimate control and management of a construction project, when a very high detail is required, it makes things difficult for the energy professionals involved. Since BPS environment support only simplified geometry of single surfaces for each room/space face, a L500 BIM model carries unnecessary information for the former. In geometrically heavy models, the establishment of a proper and automated conversion/simplification of the geometry is constantly at risk. Although the data schema of gbXML may manage better the transition of only energy-related alphanumerical information, the conversion/simplification of the model geometry remains an unsolved process of the export workflow; for a comparison of approaches see (Dong et al., 2007; Garwood et al., 2018; Guzmán Garcia & Zhu, 2015; Hijazi et al., 2015; Lam et al., 2012; Ouellette et al., 2022; Pinheiro et al., 2016)and 54% globally. Therefore, there is substantial scope to accurately simulate and efficiently assess potential energy retrofit options for industrial buildings to lower end use energy. Due to potentially years of facility renovation and expansion Building Energy Modelling, also called Building Energy Simulation, applied to industrial buildings poses a complex challenge; but it is an important opportunity for reducing global energy demand especially considering the increase of readily available computational power compared with a few years ago. Large and complex industrial buildings make modelling existing geometry for Building Energy Modelling difficult and time consuming which impacts analysis workflow and assessment options available within reasonable budgets. This research presents a potential framework for quickly capturing and processing as-built geometry of a factory, or other large scale buildings, to be utilised in Building Energy Modelling by storing the geometry in a green building eXtensible Mark-up Language (gbXML.

3.2 BUILDING PERFORMANCE SIMULATION (BPS)

The design of the built environment is a complex task involving the interaction among technical domains, diverse performance expectations and emerging uncertainties. Building Performance Simulations provide a means to deal with these complexities allowing the exploration of design solutions and their impacts (Clarke & Hensen, 2015), mainly in terms of environmental and energy performance. Despite the effect of strategic decisions on the energy and environmental characteristics of a building being much higher when these decisions are close to the early design stages (Lechner, 1991), BPS is mainly used as a performance confirmation at later stages of design, instead of a support through the whole design process (Bambardekar & Poerschke, 2009; Morbitzer, 2003). While the implementation of energy and environmental simulation at a later stage of the design process will impact only the few design parameters that are still flexible (Morbitzer, 2003), resolving usually in a fine-tuning of the HVAC systems, and having a less meaningful impact upon the quality of the building design, an early energy simulation engagement will instead affect the design trajectory, in terms of the building's shape, form and size (Morbitzer, 2003). Therefore, to design high-performance buildings, it is important to assure informed decision-making during the early design phases, which also includes the use of BPS tools (Attia et al., 2012). BPS can also contribute positively during the building's operation stage, by determining the optimum operational schedule of the HVAC systems, dynamic shading systems and other technical services. An effective utilisation of BPS can achieve an optimum balance between cost, comfort and energy efficiency.

3.3.1 The importance of an effective BIM to BPS interoperability

The sustainable development of a building project requires an iterative energy analysis that starts from the conceptual design phase to the detailing and finally the operation stages. This iterative process, enhanced by the BIM technology's advantages, may enable reaching the full potential of sustainable building design (Pinheiro et al., 2016). An effective BIM to BPS interoperability solution can enable the following advantages:

- save time for unnecessary remodelling processes and reduce error-prone manual re-input of data;
- facilitate energy engineers to perform energy simulations using the updated version of the model at every design or operation phase of the project;
- automatically implement changes to the model between phases A and B;
- take advantage of BIM parametric modelling tools to test new design ideas or perform optimization techniques based on energy-related criteria, in a short amount of time;
- bridge the gap between BIM professionals and energy engineers, by providing energy analysis feedback back into the BIM model.

3.3.2 BPS Information Requirements

Figure 3 provides an overview of the input data necessary to perform an Energy analysis. Input data differ in the case of a static or a dynamic simulation. The classification of data is based on the four following categories: Environmental Data, Building Data, Occupants Data, Heating & cooling loads and Building service systems & operational schedules. The scope of this paragraph is to provide a basic understanding of the level of information needed to be registered in a BIM model before exchanging with BPS software.

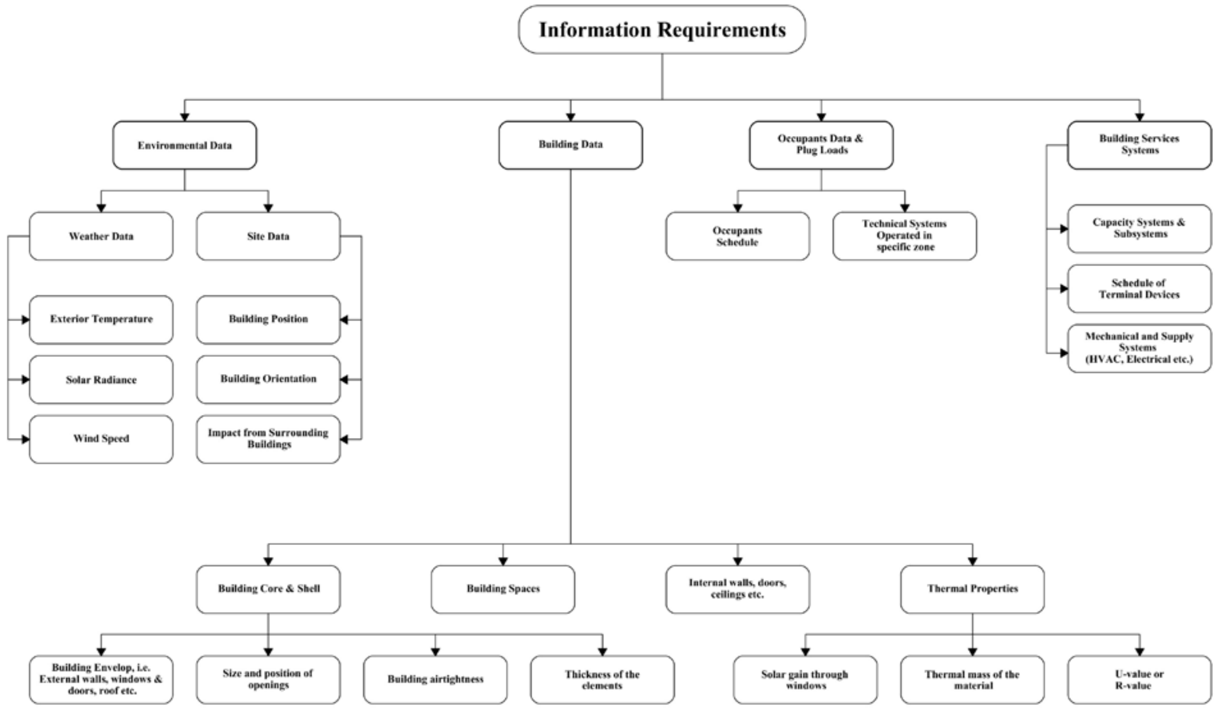

Fig. 27. BPS Information Requirements (Karlapudi, 2018).

4 INTEROPERABILITY AND DATA EXCHANGE SCHEMAS

4.1 Interoperability

The term interoperability is used here to describe the process of data sharing or exchange between BIM software and numerical simulation software, to remove the need for data model regeneration (Sacks et al. 2018). According to the literature, one of the biggest obstacles in solving current interoperability misfunctioning and enabling the wider adoption of BIM-based energy analysis is the data exchange between the BIM and BPS models (Costa & Madrazo, 2015). The problems generally arise from the different logic with which the two software environments evolved (Di Biccari et al., 2022; Gigliarelli et al., 2019; Hijazi et al., 2015), which reduced the possibility for simulation software to exploit the potential offered by object-oriented programming of BIM software (Abanda et al., 2015; Jeong et al., 2014)one cannot ignore how it has overwhelmed many professionals who cannot easily distinguish between the uses of these software systems. Previous studies about different BIM systems have generally been limited in scope focusing predominantly on operational issues. This study aims to conduct a comprehensive and critical appraisal of a wide range of BIM software systems currently being used in managing construction project information. To achieve this, five main methods are adopted. These include a systematic review of the literature, a structured questionnaire survey, action learning, focus group discussions and email surveys. It has to be noted that, although it is impossible to examine the totality of BIM systems, the study adopts a holistic approach looking at most of the major BIM system categories and 122 application examples which are common in the architecture, engineering and construction (AEC. The difficulties in a seamless conversion of BIM-based data into a coherent BPS model depend on simplifications and assumptions required for making the energy simulation models (Ahn et al., 2014)Engineering, and Construction, and the relative need to convert/transform data in the process. The lack of a standardised process in building energy modelling (Gigliarelli, Calcerano, Calvano, et al., 2017; Guruz et al., 2016; Hitchcock & Wong, 2011) and the gap still present between design and energy modelling are the main limitations that impede the process (Wilkins & Kiviniemi, 2008). The transfer of both geometric and informative data between software is still imprecise (Lam et al., 2012; Pinheiro et al., 2016) and requires strong supervision/manual intervention, thus reducing the main benefits of an exchange process that is as automated as possible. Another typical problem occurs when modelling strategies optimised for other model uses, i.e., architectural or structural optimisation, are in conflict and do not allow an orderly division of the objects modelled for exchanges between disciplines, as it usually occurs between Architectural, Structural and MEP BIM (Tchouanguem Djuedja et al., 2019). A seamless exchange of data between the two (BIM software and numerical simulation software) heavily depends on the proper filtering of the data, i.e., eliminate redundancy and maintain a simplified exchange process.

4.2 Open Standard Exchange Schemas

Software interoperability between BIM and other simulation software is achieved through digital format exchange using common proprietary or open standards. The following open and neutral file exchange formats are currently being used to enable interoperability between BIM and BPS:

IFC: Industry Foundation Class

This is a global standard file format mostly used for solving interoperability between different native BIM software. IFC is designed to store information of the geometry, including its respective classification, properties and quantities.

gbXML: Green building eXtensible Markup Language

This industry-supported file format is tailored to make the exchange of information from a CAD-based BIM environment to a BEM environment. gbXML is dedicated to storing element attributes that are dominantly energy-related.

Each data schema has its own advantages and disadvantages when it comes to BIM for BPS conversion. In the literature there are many comparisons of the above exchange languages (Dong et al., 2007; Hijazi et al., 2015; Lam et al., 2012; Pinheiro et al., 2016), however, errors still occur irrespective of the file format that is used (Kamel & Memari, 2019). Manual adjustments are still necessary to resolve incorrect or improper conversion/translation or storing of the information. To improve interoperability, the developers of IFC and gbXML continue to work on updates to the exchange schemas. However, the lack of knowledge about different native BIM software is considered a major obstacle to reaching and providing a solid interoperability solution to the market today (NBS, 2014, 2015), and the same is true also for the lack of knowledge about different BPS software and their heterogeneity in addressing the simulation tasks (input data needed, approach, etc.). Currently, there many research efforts on providing native BIM plug-in tools for model correction or stand-alone post-export editing tools for solving the interoperability problem. More information about current solutions is provided in §5.

4.3 Industry Foundation Class (IFC)

IFC[1] is an open meta-data schema used to transfer building information from one software to another among all professionals of a design, construction and facility management project. IFC is developed by buildingSMART and its formulation is based on open international standards. The purpose of buildingSMART is to deliver a good quality data exchange schema to match the information needs of the entire building industry, hence IFC include terms, concepts and specifications from the involved disciplines. IFC has been structured into four conceptual layers: Resource Layer, Core Layer, Interoperability Layer and Domain Layer (Figure 4), with a total of approximately 800 entity definitions, thousands of data attributes and many more standardised object properties.

Resource Layer: it is the lowest layer in the IFC data schema architecture and provides commonly used resources. It can be used or referred to by classes in the other layers.

Core Layer: it consists of the elementary structure of the IFC and defines most abstract generic concepts. Further dedicated input is handled by the following layers.

Interoperability Layer: it is specialized information added to core layer objects. This info is shared among multiple model domains.

Domain Layer: it is the layer responsible for additional information to model objects that will be used by domain experts.

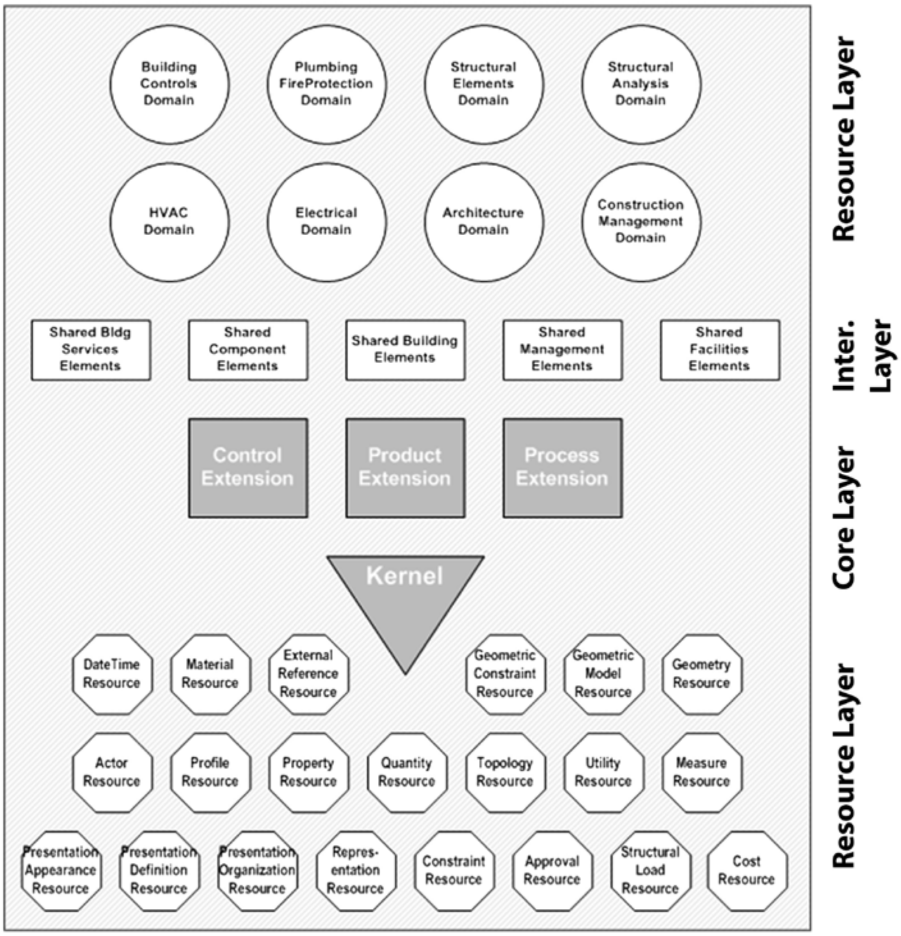

Fig. 28. IFC Data schema with four conceptual layers (buidingSMART 2020).

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[1] For more information see https://technical.buildingsmart.org/standards/ifc/

The official latest IFC version currently in use is IFC4.1, released in 2018 (buidingSMART, 2020). Compare to its previous versions, IFC4.1 can define a model at a higher level of detail. In the context of building energy analysis, IFC 4.x can describe different building boundaries and store additional HVAC information. Extensions made to the IFC4.1 schema include:

- description of alignment as a combination of horizontal and vertical alignment;
- linear Placement according to ISO 19148;
- IfcSectionedSolidHorizontal as a new geometry representation particularly useful for describing infrastructure facilities.

4.4 Green building eXtensible Markup Language (gbXML)

The gbXML[2] schema was developed by Green Building Studio (GBS) in 1999. The schema stores data in the form of eXtensible Markup Language (XML) language, turning it into a machine and human readable language. XML enables users to modify the language and, thus, it allows for customization on data domain exchange. Specifically, its use and purpose can greatly differ according to its semantic structuring. gbXML facilitates the exchange of explicit building information, such as weather data, building geometry, HVAC systems, lighting and thermal zones, thermal loads, schedules, etc., making it more appropriate for supporting interoperability between BIM native software and engineering tools (Ham & Golparvar-Fard, 2015a). The gbXML schema is rich in data and can store up to 500 types of building elements and attributes. Each building component, from architectural to MEP model, holds its own information and has its own reference ID. The following figure shows the hierarchy of information organisation of the schema (Figure 5).

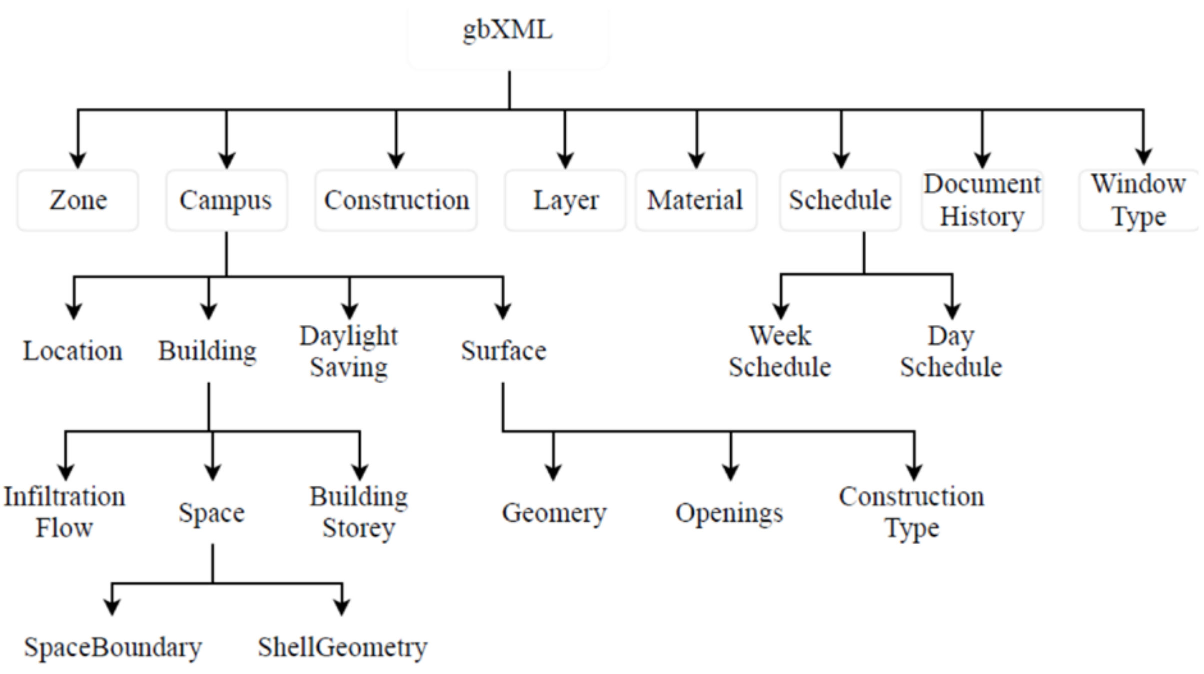

Fig. 29. Simplified hierarchy of information organisation in gbXML schema (Ham and Golparvar-Fard 2015).

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[2] For more information see https://www.gbxml.org/About_GreenBuildingXML_gbXML

The concept of reference ID is to form necessary relationships between other components. For example, a wall, roof or slab component is defined as a surface, which in turn defines the geometry, construction information and information about the opening on that surface. The construction information includes all wall layers; within each layer, it stores the material and thermal information separately and link them to the construction type. The details of the type of opening are linked to the actual components using reference ID.

The primary "Building" component of gbXML defines the building, including information on the different storey levels, which further defines space types included in it. The "Space" component is assembled by "Room binding elements", such as wall, roof, floor etc. Bounding elements consist of two nodes, "Shell Geometry" and "Space Boundary". Shell Geometry defines the inner surface of the adjacent wall, while Space Boundary defines the coordinates of the centreline of the Bounding Element. In the case of an internal wall, which is separated by two consecutively located spaces, the centreline and both faces of the wall are defined. "Operating schedule" and "Occupants' schedule" are defined separately and linked to the space through the reference ID mechanism.

4.5 Data exchange schemas comparison

Data exchange schemas are constantly under development and they are increasing their added value in dealing with interoperability improvement. This is acknowledged by many researchers (Cemesova et al., 2015; Cheng & Das, 2014; Guzmán Garcia & Zhu, 2015; Ham & Golparvar-Fard, 2015b)Engineering and Construction (AEC. Each schema carries its advantages and drawbacks. According to Moon et al. (2011), the gbXML schema is more dedicated to BIM for BPS exchange operations and officially supported by many BIM software providers. However, the IFC schema is the more developed data model for buildings in the AEC industry, able to transfer all building information data (Sacks et al. 2018). In this context, IFC may provide an interoperability solution for all types of numerical simulations' needs. In the case of BIM to BPS, however, IFC causes time-consuming simulation runs or even software crashes. gbXML, on the other hand, may be more compact and more popular in the AEC industry, although it still does not allow to perform a complex geometry exchange between a native BIM software and a BPS. This is because the gbXML schema can only accept rectangular planar shapes. Compared to the "top-down" approach of the IFC, the gbXML employs a "bottom-up" process, which makes it more accessible and flexible to handle.

4.6 Conversion from BIM to BPS

Currently, the conversion of a BIM model to a BPS model could be achieved in a fully automated, semi-automated or non-automated (manual) fashion.

- The fully-automated concept refers to the idea of automatically and instantly generating a fully-defined BPS model from a BIM model. This idea is currently being promoted by the software house Autodesk, seeking to create a fully-automated BIM to BPS exchange between its applications *Revit* and *Green building studio*, via gbXML exchange schema. Today, this approach can be applied only in the case of small-scale buildings of conventional rectangular shape, and, in any case, it does not take into consideration the need of the energy modeller to design his own simulation, by making simplifications or modifications compared to the starting BIM model (e.g. for the definition of thermal zones).
- The semi-automatic concept refers to the idea of exporting only the necessary (and/or possible to transfer) data from a BIM model, e.g., building geometry, spaces, material thermal properties, etc. The exported file is then imported into third-party BPS software to be post-processed into the final energy model and then run for the simulation. Depending on the complexity of the exported BIM model, additional modelling or information registration work in the BPS software may be necessary.

- The non-automatic, or manual, conversion process is the case usually followed today by the energy modelling industry. In this case, the user is required to remodel the building from scratch in the BPS modelling environment before running the analysis.

4.7 The 'H' factor in BIM to BPS Interoperability

Heritage buildings add an extra layer of complexity in both geometry and information data implementation. This complexity adds extra difficulty to the issues that stem from the application of the energy simulation methods to historical buildings (A.4.3.2 paragraph 2.3), partly because of data transfer/exchange. Regarding the geometric aspects, the process for converting geometry from walls with thicknesses in the BIM environment to two-dimensional surfaces in the energy model (BPS) is challenged by the particularities of built heritage. Specifically, historical buildings frequently have walls with variable thickness and floors' height changes (Gigliarelli et al., 2019), while they typically feature complex geometric shapes, such as vaults or domes, that cannot be easily modelled in BIM and then converted into an energy model. Moreover, they usually necessitate additional consideration about the way their thermophysical behaviour and the relation between surfaces can be adequately represented in the energy model. In the representation of a historical building envelope, even the transfer of information data can encounter specific problems, as it is substantially dependent on the heterogeneity of the layers and the properties of the materials (also due to variable patterns of decay on the same type of wall), as well as the considerable lack of standardisation. There do exist solutions towards the right direction, which usually need extensions to fit the specificities of built heritage, for example, the COBie Information Delivery Manual (IDM) for historical buildings[3].

5 INTERNATIONAL GUIDELINES

Even though the topic of BIM to BPS interoperability is still in its infancy, research started more than ten years ago. The following table lists the documents which attempt to systematise this transfer of data, highlighting the critical aspects of both the process and operation:

Table 1: ***International Guidelines (Di Biccari et al., 2022)***

Title	Author-year	Main Topics covered
Information Delivery Manual (IDM) Development for Building Information Modelling (BIM) and Building Energy Modelling (BEM) Workflows Also known as: "Technical Report for BIM-BEM Workflows" A technical report providing an overview of requirements for developing IDMs and corresponding data exchange specifications between building information modelling and building energy modelling, simulation, and analysis throughout a project lifecycle	(Ouellette et al., 2022)	The document is the result of a buildingSmart international expert team of stakeholders involving also the International Building Performance Simulation Association in which BIM and BPS software developers, users and professionals, built a shared knowledge framework through a bottom-up approach, to define subsequent action for improving BIM to BPS interoperability.
GUIDELINES for OptEEmAL BIM Input Files.	(Giannakis et al., 2019)	The guidelines develop an IFC BIM-based building energy model generation methodology to streamline the process and reduce errors. The BIM authoring tool investigated is Autodesk Revit, and the consortium also produced a dedicated IFC exporter.

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[3] https://technical.buildingsmart.org/standards/information-delivery-manual/idm-database/

Project Execution Planning guide, version 1.2.	(Computer Integrated Construction Research Group, PENN State University, 2019)	The guide contains a flowchart for BIM-based energy analyses highlighting the information exchanges and the stakeholders involved.
A study of national BIM guidelines from around the world determining what future Swedish national BIM guidelines should contain.	(Kralsson & Rönndahl, 2018)	A comparative study of BIM guidelines from ten countries (Australia, Belgium, Canada, Finland, Hong Kong, New Zeland, Norway, Singapore, UK and US), containing an appendix on the simulation and energy analysis.
IBPSA Project 1 - BIM/GIS and Modelica Framework for building and community energy system design and operation.	(IBPSA, 2017)	The project focuses on the creation of new computational tools based on Modelica to build the basis of the next-generation computing tools focusing on open standards IFC and CityGML.
EDSL Guide for Revit gbXML Files	(Cadline, 2016)	The guide focuses on the creation of a useable Revit model for gbXML exporting for EDSL TAS Engineering simulation software.
BIM Guide 05 Energy Performance, version 2.1	(GSA, 2015)	The guide aims at helping the US General Service Administration in the development of their BIM execution plans, also taking into account energy modelling. The guide contains insights into the role of BIM within the energy modelling process and case studies.
RP-1468 -- DEVELOPMENT OF A REFERENCE BUILDING INFORMATION MODEL (BIM) FOR THERMAL MODEL COMPLIANCE TESTING	(Clayton et al., 2013)	The report contains guidelines for mapping a Revit BIM model into a description (the most relevant subset of information) for energy modelling in DOE-2 simulation software.
Task 2.2.12 – CMU Report 02: Identification and Analysis of Interoperability Gaps between Nbims/Open Standards and Building Performance Simulation Tools.	(Lam et al., 2012)	The report focuses on interoperability gaps between IFC and gbXML open standards and energy modelling. IFC and gbXML are also compared.
HESMOS - Deliverable D2.1: BIM Enhancement Specification	(Liebich et al., 2011)	The project developed an Information Exchange Requirement for an Information Delivery Manual for a BIM to simulation process.
Implementation guide: space boundaries for energy analysis	(Weise et al., 2011)	The guide is addressed to software developers for supporting the exporting of space boundaries in IFC format, also tackling the issue of the specific Model View Definition.
Information Delivery Manual (IDM) for BIM Based Energy Analysis as part of the Concept Design BIM 2010.	(Weise et al., 2011)	The guide addresses the data flow between BIM and simulation workflows, stressing the need for energy analyses from the conceptual design phase.
An automated IFC-based workflow for building energy performance simulation with Modelica	(Andriamamonjy et al., 2018)together with more attention for openBIM and growing software support for the most recent version of the Industry Foundation Classes (IFC 4	This paper describes the essential elements of an integrated workflow, achieved with the already available technology, Information Delivery Manual (IDM) and a newly developed Model View Definition (MDV). This MVD is tailored to the needs of Building Energy Performance Simulation (BEPS) that uses the Modelica language together with a specific library (IDEAS) and can easily be adapted to other libraries.

6 LIMITATIONS & ONGOING RESEARCH

6.1 Limitations

The principal obstacles in the conversion process from BIM to BPS environment lay mainly in the quality of data already existing in the BIM model as well as the exporting data schema translation. These limitations cause the following issues:

- inadequate or fragmented spaces and thermal zones;
- missing (mainly lost during the improper translation) or additional (result for example of an incorrect translation of the three-dimensional envelope into surfaces) building components;
- wrongly placed walls and openings;
- misinterpreted wall-to-wall or wall-to-window joint conditions;
- wrong boundary conditions;
- wrong conversion of informative data.

These errors are generated mainly due to the modelling process followed in the native BIM software, in conjunction with the inability of the exchange schemas to interpret the geometry in a solid and comprehensible manner. Another contributing aspect to the complications above is the immense level of data currently incorporated in a BIM model, such as furniture, architectural ornaments, mechanical systems, electrical and plumbing objects, etc.

6.2 Ongoing Research

The joint application of BIM and numerical simulations of building energy performance on historical buildings is still not widespread in literature nor in professional practices (Di Biccari et al., 2022). Even the conversion of BIM or the application of energy simulation to the case of built heritage entails additional methodological considerations. The application of these methodologies to historical buildings aims at maximising the potential offered by new technologies. The application of this approach constitutes a complex variant (Gigliarelli, Calcerano, Calvano, et al., 2017; Gigliarelli et al., 2019) of the studies that currently address the issue of interoperability between BIM and simulations in the case of new constructions (GSA, 2015; Kamel & Memari, 2019; Maile et al., 2013; Senave & Boeykens, 2015). One of the most significant case studies in terms of the joint use of the two technologies can be found in the Italian industrial research project METRICS - Management and Requalification of Historic Centres and Buildings, funded by the PON Research and Competitiveness 2007-2013 (Gigliarelli, Calcerano, and Cessari 2017). The objective of METRICS was the development of innovative approaches and methodologies for the energy improvement of historical centres. The project addressed the issue with a multiscale, multidisciplinary and holistic approach, which involved the use of HBIM technology as a basis for the environmental energy analysis of buildings and the development of intervention strategies both on the urban scale and on the single building. Among other objectives, this project focused on the interoperability between HBIM and dynamic simulations software environments (Gigliarelli, Calcerano, Calvano, et al., 2017; Gigliarelli et al., 2019).

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ANNEX 4

ANALYSIS OF ACTIVE AND PASSIVE ENERGY EFFICIENCY TECHNOLOGIES COMPATIBLE WITH BUILT HERITAGE

1 INTRODUCTION

The reuse of historical buildings for public purposes is currently being increasingly encouraged by city authorities across Europe (Philokyprou, 2014). Specifically, the reuse and adaptation of heritage buildings as museums and office spaces for public administrations is a very common practice in many European countries. For these architectural functions, the indoor microclimate is highly important (Jeong & Lee, 2006) and recently became the focus of researches in preservation of built heritage and retrofit interventions. Many strategies for the enhancement of indoor comfort and the energy efficiency of buildings of these uses are developed and explored internationally (Pavlogeorgatos 2003; La Gennusa et al. 2008), in addition to the conservation of the building.

The European Green Deal, released in December 2019, captures the commitment of the European Union to tackle climate change and, among other actions, it prioritises energy efficiency in the building sector, as the largest single energy consumer (European Commission, 2020). In this respect, the European Union has highlighted the importance of the digitalisation of buildings' retrofitting process – see European Energy Performance of Buildings Directive (Directive 2002/91/EC). In addition, the European Green Deal highlights the need to boost renovation to meet the agreed energy efficiency and climate objectives, because of the very low annual rates of renovation of the building stock in Member States. Specifically, the annual renovation rate of the building stock varies from 0.4% to 1.2%. This rate will need to at least double to reach the EU's energy efficiency and climate objectives (European Commission, 2019). As a consequence of the above, today there is clearly a requirement to all countries to reduce energy use in the existing building stock. The project EFFESUS (2016) reported that, in Europe, the percentage of buildings built before 1945 varies between 6.1% (Turkey) and 47.4% (Luxembourg), with a mean average value of 23.1%. Therefore, the impact of the built heritage stock in terms of energy consumption and CO_2 emissions can be significant, as also stressed by the Climate Heritage Network in its reply to the European Green Deal (Potts, 2021).

However, historical buildings, that are considered to have important architectural and cultural qualities worthy of preservation, are usually excluded from legislation regarding minimum energy performance requirements. The potential for retrofit of built heritage is significant, due to the current composition of the building stock in Europe and the preferred attitude of the public towards the older stock (Sodagar, 2013). Over the last decades, there is a growing interest in the energy retrofit of historical buildings, as they do not always comply with contemporary concepts regarding thermal comfort (Martínez-Molina et al., 2016) and face the challenge of resilience in the light of climate change (Košir, 2019a). Therefore, as entirely passively conditioned buildings are rarely attainable, a balanced interplay between passive and active building elements is often the final goal of an efficient retrofit strategy. *Passive systems* collect and transport heat by non-mechanical means, and operate on the energy available in the immediate environment. In contrast, *active systems* import energy, such as electricity, to power mechanical systems (e.g. heat pumps). Buildings that incorporate passive features combined with basic low-tech active elements, e.g. fans, are termed *hybrid* buildings. Older buildings are capable of adapting to the new energy efficiency (EE) norms; therefore, the challenge is to achieve the desired effect without damaging the architectural and historical value of buildings, while retaining the feasibility of the investment (Ding, 2013). The preliminary evaluation of the climatic potential of a buildings' location is a key tool for planning both the enhancement of passive design aspects. The incorporation of active systems or energy microgeneration systems are also gaining ground over the last years, yet integration issues may arise in the case of historical buildings (Historic England, 2018).

Available design strategies and active energy systems should be considered, with the objective to lower energy consumption while enhancing the comfort of occupants, although comfort is very difficult to quantify in exact values that satisfy everyone (Hegger et al., 2012). Indoor comfort includes several parameters of the indoor environment, such as temperature humidity, air quality, lighting and noise levels, as presented below. In this context, there have been attempts to study the indoor environment holistically (Bluyssen, 2009). All aspects of comfort that can be improved should be considered by the designer when selecting a scenario for implementation. According to the ISO 7730 (2005) standard, thermal comfort is described as being "that condition of mind which expresses satisfaction with the thermal environment". Factors of the thermal environment according to ASHRAE (2019) are metabolic rate (depending on the activity), clothing insulation, air temperature, radiant temperature, air speed and humidity.

Drawing on the above, this chapter presents comprehensively the relevant passive strategies employed in historical buildings across the Mediterranean basin and the complementary active energy systems available for integration. To this aim, an overview of the passive design analysis tools and methods is presented; the potential integration challenges and opportunities of active systems in historical buildings are outlined; and several cases of integration of active systems in historical buildings are presented.

2 PASSIVE DESIGN STRATEGIES

2.1 Tools and methods for passive design analysis

The understanding and appropriate interpretation of climate limitations and potentials is a crucial step in the design of the energy retrofit process. The most widely used approach to analysing climate data with respect to the passive design of buildings is to assess the indoor environmental conditions that should be achieved to obtain occupants' comfort (Givoni, 1969; Olgyay, 1963; Szokolay, 2014). The analytical method for climate analysis was introduced in the early 60s by the pioneers of the field, Olgyay (1963) and Givoni (1969). Olgyay (1963) was the first to attempt to devise a bioclimatic chart. In his bioclimatic chart, Olgyay related relative humidity (RH) with the dry bulb temperature (DBT), taking into consideration the impact of solar irradiance and air movement. However, Olgyays' chart was suggested for lightweight buildings located in humid regions where indoor and outdoor temperatures are close, therefore its applicability is limited.

Givoni (1969) and Milne and Givoni (1979) proposed a chart that adopts the psychometric format, overlaying it with the hourly weather data of a location. Designated ranges of temperature and relative humidity mark the "comfort zone", where most of the people would feel comfortable. If local outdoor temperatures and humidity fall outside the "comfort zone", the potential applicability of selected bioclimatic measures (e.g. passive solar heating, natural ventilation, high thermal mass, etc.) is recommended. The particular chart has been modified though the years to incorporate additional insights and improvements. However, it should be noted that it provides a partial description of conditions required for comfort, neglecting other environmental variables (e.g. radiant temperature and airflow rate), as well as clothing and activity (metabolic rate). While environmental-based criteria describe relatively universal requirements in which all humans feel "comfortable" (rational or heat balance approach – Fanger (1970)), a varying tolerance for discomfort is noted, depending on age, sex, health, cultural conditioning and expectations (adaptive thermal comfort approach – de Dear and Brager (2002)). The latest revision of the chart by Givoni himself (1998) extends the acceptable indoor comfort parameters in regions where, due to economic, social and/or climatic circumstances, a larger range of temperatures is acceptable by the occupants (Figure 1). This version is the one most often used today (Desogus et al., 2016; Katafygiotou & Serghides, 2015; Manzano-Agugliaro et al., 2015).

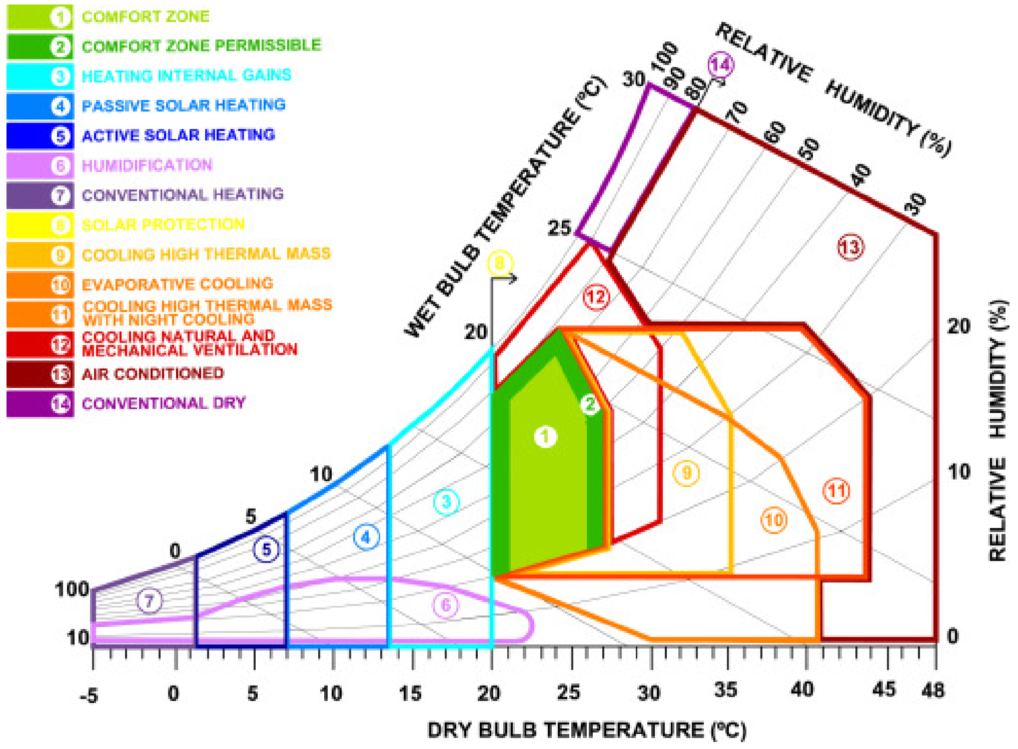

Fig. 30. The Givoni chart as presented in Manzano-Agugliaro et al. (2015).

Computer-based simulation and energy design tools make it possible to utilise site-specific hourly weather data to analyse data for bioclimatic design. Climate Consultant 6.0 (University of California, 2017) is a digital tool for analysing locations' climate characteristics, which uses Givoni's chart as a basis. In order to address the solar irradiation parameter in the calculation, it overlays the values of received irradiation onto the displayed data points in the psychrometric diagram. By plotting minimum and maximum daily temperatures on Givoni's chart (or Olgyay's), an evaluation of the diurnal temperature variation is possible. This is valuable information regarding the applicability of various passive strategies (e.g. night cooling). A more effective solution on how to incorporate this aspect in a bioclimatic chart was provided by Evans (2003). Evans introduced the comfort triangles bioclimatic chart, which is a quasi-dynamic evaluation of climate parameters based on the relationship between the average temperature and the average diurnal temperature variation.

Concluding on the outlined limitations and virtues of the bioclimatic potential analysis, it is highlighted that the use of the bioclimatic charts should be viewed primarily as a climate evaluation tool and not as a building design tool (Košir, 2019b). However, the results of this analysis are extremely valuable if implemented appropriately, and may substantially influence decisions regarding the energy retrofit approach.

2.2 Main passive design strategies across the Mediterranean region

The term *passive system* was adopted in the early 1970s to describe thermal delivery systems that are driven by natural phenomena and without power-driven mechanical devices. Edward Mazria, in his *Passive Solar Energy Book* (Mazria, 1979), defines a passive solar heating or cooling system as ‘a system in which the thermal energy flows naturally by means of radiation, conduction and convection’. In temperate climates, passive design aims at providing heating during the heating period (winter), whilst avoiding overheating during the cooling period (summer). Passive heating involves the distribution, storage and conservation of collected solar energy. Accordingly, passive cooling involves overheating prevention, mainly through shading and ventilation (Norton, 2014). These processes are illustrated in Figure 2.

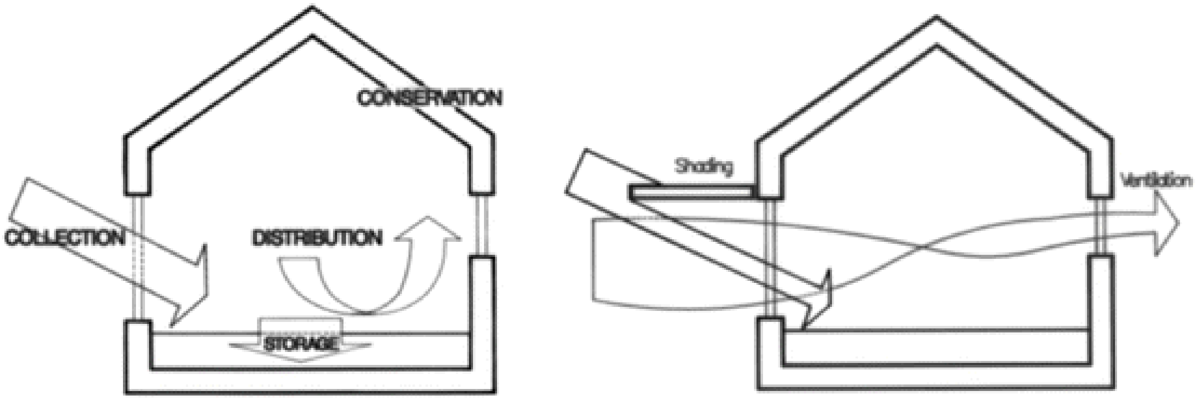

Fig. 31. Passive solar energy collector (left) and overheating avoidance (right) in temperate climates. Source: Norton, 2014.

2.2.1 *Natural ventilation*

Built vernacular architecture incorporates numerous possibilities for enhancing natural airflow. This is achieved by exploiting wind and buoyancy-driven pressure differences, which often have a combined effect (Gładyszewska-Fiedoruk & Gajewski, 2012). The wind induces a pressure distribution on the building envelope, which is determined by wind speed and direction, building shape and nearby obstructions. Apart from wind, differences in temperature and hence air density create an imbalance in the pressures of interior and exterior air masses, thus creating a vertical pressure gradient.

Passive solar buildings with conservatories or atria often ultimately rely upon ventilation and infiltration to provide the medium of heat transfer. Ventilation and infiltration are both dependent upon a) the wind speed and direction, b) the temperature difference between the building and the ambient environment, c) the aerodynamic shape of the building, d) overall building airtightness (type and position of openings) and e) surrounding topography and obstructions. A designer may, given appropriate analytical tools, use these effects to optimise air flow (Allard, 1998; Asimakopoulos, 1996; Aynsley, 2007; Grosso, 1997; Lechner, 1991).

2.2.2 *Thermal mass*

The transient characteristics of the thermal response of the building and its envelope are crucial for the appropriate evaluation of the building’s energy balance. In fact, several passive design strategies, such as passive solar heating and night-time ventilation, are based on the transient behaviour of buildings (DeKay & Brown, 2014). The employment of thermal mass can reduce the peak heating or cooling load (Ahmad et al., 2006), and subsequently the building energy consumption.

In order to evaluate the thermal inertia effect, two dynamic indicators are widely used: the time lag and the decrement factor (Asan, 2006; Kontoleon & Eumorfopoulou, 2008). The time lag depicts the heat transmission delay, i.e. the time needed for the heat wave of a specific period to propagate from the outdoor to the indoor surface of a wall. Figure 3 shows the benefit of a massive building compared to a lightweight one in terms of the potential reduction of cooling and heating loads (Asimakopoulos, 1996).

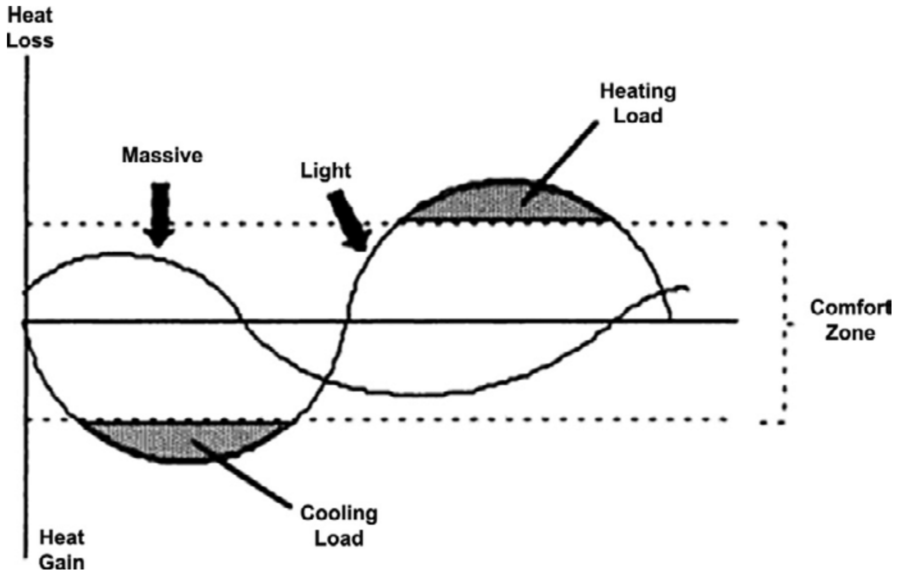

Fig. 32. Daily Building heating and cooling loads for buildings of massive and light construction. Source: Asimakopoulos, 1996.

The decrement factor defines the reduction of indoor temperature oscillations in comparison to the external temperatures – Figure 4 (Košir, 2019a). Heavy mass buildings exhibit large thermal lag (i.e. 8–12 h) and substantial decrement factor resulting in relatively constant and comfortable indoor temperatures (Ogoli, 2003)Kenya, during the warm period between January and March 1997. Walling for two test chambers was natural stone while for the other two was timber paneling. Further to this, roofing for two test chambers was heavy concrete tile while for the other two was lightweight galvanized corrugated iron (GCI.

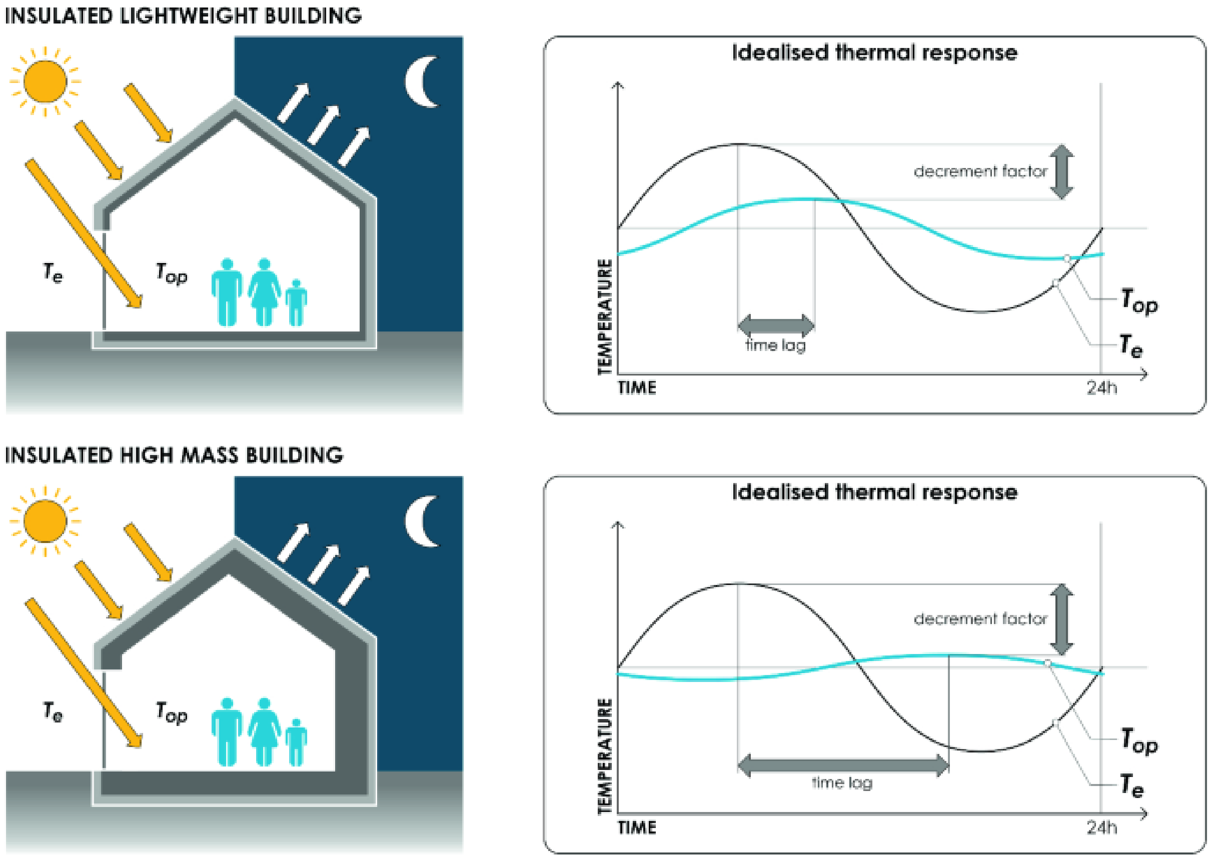

Fig. 33. Idealised thermal diurnal performance of extremely lightweight (top) and high mass (bottom) building. Te and Top correspond to outdoor and indoor temperature respectively. Source: Košir 2019.

Contrary to high-mass buildings, an extremely lightweight building with an envelope composed of materials with high thermal conductivity (λ in W/(mK)) and low density (ρ in kg/m^3) and specific heat (Cp in J/(kgK)) would represent almost no obstruction to the transmission of heat. Therefore, the indoor temperature during the day would be expected to be higher than the external air temperature due to the added effect of solar radiation (Haggard et al., 2010) whenever you need it. Rich in background detail, at-a-glance tables and diagrams, equations, and more, the Passive Solar Architecture Pocket Reference is a handy resource for architects, engineers and students. Coverage includes: definitions load determinants and Responses (including world wide biomes and climates, building metabolism and response, thermal sources and sinks, passive building responses to sources and sinks, tuning the building to the environment, optimizing insulation & thermal mass for comfort. The situation would be reversed during the night because of radiative losses of the building envelope to the night sky. The application of thermal insulation to a lightweight building results in a considerable improvement of its thermal performance and consequential energy use. However, the time lag and decrement factor are less affected by the addition of an insulation layer. Consequently, a lightweight insulated building envelope will provide inferior indoor thermal conditions compared to a high-mass insulated building (Košir, 2016).

2.2.3 Reduction of thermal losses

In order to reduce thermal losses during the heating period, the following measures are suggested:

- Minimize conductive heat flow. This strategy is achieved by using insulation (further in § 4).
- Minimize infiltration. "Infiltration" refers to uncontrolled air leakage around doors and windows and through joints, cracks, and faulty seals in the building envelope. Infiltration (and the resulting "exfiltration" of heated or cooled air) is considered the largest and potentially the most intractable source of energy loss in a building, given that insulation measures have been taken (Watson, 1989).
- Create buffer zones: Additional measures inhibiting thermal losses is the proper distribution of low-use or auxiliary spaces to provide climatic buffers and subdivide the interior, creating separate heating and cooling zones (Watson, 1989).
- Minimize winter wind exposure: Winter winds increase the rate of heat loss from a building by accelerating the cooling of the exterior envelope surfaces by conduction, and also by increasing infiltration (or more properly, exfiltration) losses (Watson, 1989). The use of windbreaks is commonly used to reduce the impact of such winds. Two design techniques serve this function (Allard, 1998):
  a. the use of neighbouring landforms, structures, or vegetation as a physical barrier for winter wind protection, and
  b. proper building form and orientation that minimizes winter wind turbulence.

2.2.4 Internal gains:

Internal gains are provided by people who occupy the space, artificial lighting, any machinery that generates heat energy and any process that might also generate heat. All humans emit heat to their surroundings due to their metabolic activity, which is related to the activity they are performing (i.e. sedentary, sleeping, etc.). The heat can be released as sensible or latent heat. Accordingly, the electrical energy used by lighting or equipment (computers or other domestic appliances) is ultimately released as heat. The energy is emitted by means of conduction, convection or radiation. Internal gains are important to modify the indoor temperature and provide comfort, especially during mid-seasons.

2.2.5 Passive Heating

Direct solar gains. Early approaches of passive design concerned primarily direct solar radiation harvesting (beam radiation). The strategy of direct solar gain, in its simplest form, refers to the practice of orientating windows, sunspaces or other integral conservatories towards the south (in the northern hemisphere) (Norton, 2014). The ancient Greeks were aware of the principles of passive solar design, while the Romans enacted laws to protect a building's access to the sun (Hakim, 2008) that are accessible in actual technical treatises (Vitruvius Marcus Pollio, 15 C.E.; Xenophon, IV sec B.C.). Passive heating from direct solar gain incurs little or no extra cost and it is a simple, self-functioning operation.

Passive solar features on buildings are frequently at ground level. In urban locations exhibiting high housing densities, a dwelling may often experience levels of overshading at lower sun angles by neighbouring buildings. Therefore, ground-floor passive solar elements may often prove ineffective. On the contrary, roof-space windows do not cause loss of privacy as can be the case with large glazed areas; however, there is a high risk of overheating, not only in the summer but also towards the end of the heating season (Givoni, 1998a). With fixed shading devices, the seasonal geometry of solar radiation permits some control of unwanted solar radiation. However, care must be given to the orientation, inclination and geometry of fixed overhangs and fins.

Indirect solar gains: Besides the impact of direct solar radiation, heat can be stored in building elements when: a) they absorb radiant heat emitted by the building space which has direct solar gains, e.g. the ceiling of a room whose floor absorbs direct solar radiation, or b) when the elements are heated by heat transfer through the movement of hot air. The last method is less efficient; however, it represents the main heat transfer method to remote building places (e.g. isolated gains form a sunspace, Watson, 1989). Energy storage in the walls, ceilings and floors of buildings can be enhanced by encapsulating suitable phase change materials (PCMs) within these surfaces (Saffari et al., 2017).

2.2.6 Passive cooling

The term 'passive cooling' was defined by (Cook, 1989) as any building design technique that not only combats outdoor heat but also transfers indoor heat to natural heat sinks such as the sky (upper atmosphere), the atmosphere (ambient air) and the earth without the use of motorised mechanical components (Cook, 1989). By contrast, Givoni (1994) puts more emphasis on the architectural and climatic issues involved in the utilisation of the same natural heat sinks. According to Santamouris and Asimakopoulos (2013), passive cooling broadly covers all the measures and processes that contribute to the natural control and reduction of the cooling needs of buildings. It includes all the preventive measures to avoid overheating in the interior of buildings, as well as strategies for the transfer of internal heat to the external environment, whether generated within the interior or entering through the envelope of the building. The fundamental strategies for enhancing passive cooling are outlined below:

- Ensure shading. As midday solar altitude angles are much higher in summer than in winter, it is possible to shade windows during the summer period, without preventing winter solar heat gain. Widespread shading techniques refer to the following:
    a. Minimize reflectivity of ground and building surfaces outside windows facing the summer sun.
    b. Use neighbouring landforms, structures, vegetation or special architectural elements such as semi-open spaces (porches and galleries).
    c. Shape and orient the building envelope accordingly, to minimize exposure to the summer afternoon sun (West).
    d. Provide seasonally operable shading, including deciduous trees.
- Promote ventilation. Cooling by air flow depends on two natural processes, cross-ventilation (wind-driven) and stack-effect ventilation (driven by the buoyancy of heated air, even in the absence of external wind pressure (Allard, 1998; Aynsley, 2007). Key points and architectural elements can be noted regarding this strategy:
    a. Occupant interaction with the building envelope: Given that the temperatures of the external environment during noon and afternoon are higher than the ones of the indoor environment in the summer, it can be deduced that applying day-time ventilation is not beneficial in terms of heat exchange. Yet, it might be associated with the preference for increased air movement or a series of driving forces regarding physiological, psychological, social, environmental and contextual background (Fabi et al., 2012). Thus, having energy-aware occupants is a great asset in the management of various passive design strategies, ventilation being the most important one. As Berg et al. (2017) point out, users should be involved in actions aiming to raise awareness regarding the values of historical buildings; which, in turn, may be a driver for raising awareness also in terms of energy. In this way, they can actively become part of the energy improvement's decision-making process.
    b. Solar chimneys: Solar chimneys are passive solar thermosyphonic systems enhancing natural ventilation in buildings, removing indoor air by stack-effect. Besides day-time use, a solar chimney with massive heat storage walls is a natural ventilation device able to extend operation long after sunset, or exclusively being used for night cooling of internal environments (Koronaki, 2013). Such a cooling operation scheme is particularly effective in hot and dry places. Calcerano et al. (2017), investigated the potential of coupling natural ventilation and thermal storage systems to improve

hygrothermal comfort and reduce energy consumption during the summer season in an existing building in the Mediterranean. For the thermal chimney, the study estimated a discomfort hours reduction potential between 61,5% and 26,20% and an energy reduction potential between 58,28% and 6,36% depending on the thermal mass of the simulated building and the climate context.

c. Windcatchers: A windcatcher is a roof-mounted device that supplies fresh airflow into a room and expels indoor air under the action of wind pressure and buoyancy forces. During daytime, by the movement of external wind at roof level, a positive pressure on the windward side of the structure and, at the same time, a negative pressure on the leeward side are produced. This pressure difference is highly sufficient to deliver fresh air to indoor spaces and extract stale and warm air out. During night-time, in the absence of air movement or in low wind conditions, the windcatcher device operates using the natural buoyancy of thermal forces like a chimney (Jomehzadeh et al., 2017) the impact of cooling systems cannot be ignored where along with ventilation and heating systems totally account for 60% of energy consumed in buildings. Passive cooling systems can be a promising alternative to reduce energy consumption. One of the oldest passive cooling system that is still being used today is windcatcher. By manipulating pressure differences and the buoyancy effect, an adequate level of ventilation in buildings can be provided by windcatchers. Since most of the previous windcatcher studies assessed the design characteristics, the current investigation focused on the indoor air quality (IAQ. Ghadiri et al. (2011) found that a vernacular windcatcher with a height of 6 m has the potential to decrease air temperature from 25 °C to 21 °C in the hot and dry region of Yazd. Jomehzadeh et al. (2020)external building features (microclimate provide a recent review of the impacts of geometry, microclimate and macroclimate on the performance of a windcatcher. According to their results, windcatchers with a square cross-section and curved roof demonstrate better ventilation in the room compared to other configurations. It is also highlighted that the integration of a windcatcher with other natural ventilation systems such as solar chimney and wing wall has a considerable effect on ventilation efficiency (Jomehzadeh et al., 2020)external building features (microclimate

- Enhance radiant cooling (night-time ventilation): The effectiveness of night ventilation consists of the circulation of colder nocturnal air in the building, which removes excessive heat and consequently reduces the rate at which the internal temperature rises during the following day (Givoni, 1998b). The suitability of this strategy is attributed to climates with high daily air temperature fluctuations and relatively low night temperatures (Givoni, 1994; Santamouris, 2006; Shaviv et al., 2001). Blondeau, Spérandio, and Allard (1997) analysed experimental results and showed that night ventilation succeeded in decreasing the diurnal indoor air temperatures from 1.5 to 2 °C, even when the average daily air temperature fluctuation was 8.4 °C. Similar results were derived from the analysis of raw data collected in a traditional dwelling in Cyprus, with the external air temperature fluctuating about 8 °C (Michael et al., 2017).

An extensive review of night ventilation research undertaken in the last 20 years is provided by Solgi et al. (2018). According to the reviews' conclusions, it is highlighted that, to optimize night ventilation systems, coupling with other passive or active systems is of paramount importance. Such systems are windcatchers (Jomehzadeh et al., 2017)the impact of cooling systems cannot be ignored where along with ventilation and heating systems totally account for 60% of energy consumed in buildings. Passive cooling systems can be a promising alternative to reduce energy consumption. One of the oldest passive cooling system that is still being used today is windcatcher. By manipulating pressure differences and the buoyancy effect, an adequate level of ventilation in buildings can be provided by windcatchers. Since most of the previous windcatcher studies assessed the design characteristics, the current investigation focused on the indoor air quality (IAQ, earth-to-air heat exchange systems, atriums or other novel thermal energy storage like phase change materials (PCMs) (Saffari et al., 2017).

- Promote evaporative cooling. Water utilization as a heat sink in the evaporative cooling technique has been applied for centuries in Middle Eastern countries such as Iran, Egypt and Jordan (Saadatian et al., 2012). The main concept is providing evaporating moisture into the incoming air through various means:
  a. Evaporative cooling towers: This element works well in arid conditions enhancing the mechanism of natural ventilation, by using gravity to drive air flow without wind or fans to cool and humidify air (DeKay & Brown, 2014). The cooling tower can also operate as updraft shafts for stack-ventilation during the day when outdoor air is cooler than indoor air or at night while employing night-time ventilation (Ford et al., 2012.
  b. The use of the underground water canal known as Qanat is another traditional technique used for evaporative cooling. This is integrated with a windcatcher design to decrease the air temperature and humidify the indoor environment. Warm dry air enters the underground water channel and travels a distance to reach the building. During this passage, the interaction between warm air and cool water causes the evaporation of water, which leads to a decrease in air temperature. On the other side, the wind blowing around the windcatcher causes a negative pressure on the leeward side of the opening, which exhausts the warm indoor air and replaces it with fresh cooled air coming from Qanat (Hughes et al., 2012).
  c. Humidification can be achieved using exterior vegetation, water ponds or fountains), and patios complemented by the presence of water and vegetation that help to reduce the temperature and increase the relative humidity by conducting an evapotranspiration process.

2.3 Lessons learned from vernacular architecture

Indigenous and long-established building practices employed by vernacular architecture have slowly been perfected in traditional societies (Noble, 2007; Rapoport, 1980; Yannas & Weber, 2013). Indeed, vernacular forms incorporate passive design strategies that are specific to a given climate, site, building function and use. Yet, they were also shaped according to prevailing cultural and architectural preferences (Rapoport, 1980). The elevated degree of climatic adaptability of vernacular heritage has been documented in various studies (Cook, 1997; Vellinga et al., 2008; Zhai & Previtali, 2010) among which the emblematic work of Oliver (1997) and Coch (1998), who describe the interrelation of vernacular forms and climate worldwide.

Building orientation and compactness is a prime consideration to reduce its exposure to the intensity of the sun (Fathy, 1986). Earth sheltering (or earth-contact) techniques such as banking earth against the walls of a building or covering the roof have several climatic advantages; e.g. thermal storage and attenuating indoor temperature fluctuations (daily and seasonally), wind protection and reduction of envelope heat loss or gain (winter and summer). Examples of vernacular subterranean settlements can be found in Matmata in Tunisia, Matera in Italy, Guadix in Spain and Cappadocia in Turkey (Vegas et al., 2014).

The courtyard has been among the most prevalent architectural typological elements in the Mediterranean and the Middle East (Dipasquale et al., 2014). Besides the socio-cultural value of this space, many studies confirm that the presence of the courtyard contributes to a significant reduction in the cooling load during the warm months (Almhafdy et al., 2015; Ghaffarianhoseini et al., 2015)researches on natural ventilation inside courtyard using CFD techniques are rare. Courtyard aspect ratio and cantilevered roof are selected for investigation using CFD in IES<VE> software. Wind and air temperature was obtained and thus, the thermal comfort is evaluated by the Predicted Mean Vote (PMV. Courtyard houses prevail in temperate and hot climates. The prime bioclimatic virtues of this typological element concern the enhancement of natural ventilation, shading through the seasonal vegetation and evaporative cooling employed through the watering of plants and the common practice of wetting outdoor floor surfaces (Philokyprou et al., 2017). During summer nights, cool air descends into the courtyard and the surrounding rooms. The building structure is therefore cooled, ensuring lower temperature levels during the next day. Proper vegetation in the courtyard prevents the sun from reaching the building envelope and the courtyard floor. Thus, heat flow from the exterior to the interior is retarded, also depending on the thermal mass of the walls. By late afternoon, the courtyard floor and the indoor rooms become warmer, as most of the trapped air escapes by sunset. After sunset, the air temperature drops rapidly and the courtyard begins to radiate heat to the clear night sky. Cool night air then begins to descend into the courtyard, completing the diurnal cycle.

Several studies focus on environmental design strategies applied in Mediterranean vernacular architecture (Correia et al., 2014). Cañas & Martín (2004) state that the main strategy adopted in the Mediterranean coast of Spain was protection against solar radiation through proper orientation of the building, shading systems, small openings, light colouring of the façades and use of proper vegetation. Bioclimatic design strategies and respective guidelines for regions in Greece with dominant Mediterranean climatic conditions were reported by Kolokotroni and Young (1990). According to this study, the proposed strategies for areas located in the Mediterranean basin included southern orientation of buildings, compact building form, movable shading devices and light-coloured external surfaces. A series of alternative scenarios for heat capacity, insulation protection level and size of openings were also presented in the aforementioned study. According to Imessad et al. (2014), in Mediterranean climates like northern Algeria, the combination of different passive cooling techniques such as insulation, thermal mass, window shadings and night ventilation is the most effective practice from both points of view of energy savings and indoor thermal comfort.

In the hot and arid regions of Iran, the main domestic vernacular passive cooling systems are: thick adobe walls, semi-open spaces (iwans and loggias), underground rooms, wind towers, domes, and air vents; all indicating an intimate knowledge of the environment, as well as sophisticated indigenous building technology. The seasonal use of rooms, the feature of courtyards and vegetation as well as the extensive utilization of the roof (e.g. for sleeping) are simple solutions to the extremes of a hot (and cold) arid climate (Foruzanmehr, 2018). Schoenauer (2000), suggests common passive cooling methods in the Middle East: water features and plants in the courtyard, semi-open living spaces, windcatchers, high ceilings, shading devices and compact houses. Semi-open spaces, such as porticos or eyvan[1], verandas and galleries, were oriented to take advantage of the climate. Wind traps, equipped with cooling jars and linked to a vertical air duct, brought fresh and humidified air into the dwelling and helped in general to create better air circulation in the house. A disproportionately high ceiling in the living rooms enhanced air circulation. By sitting at floor level, the occupants enjoyed the coolest indoor environment.

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[1] recessed porticos with open arches facing the courtyard or the interior patio

Summarising the strategies employed by vernacular architecture in the wider Mediterranean region:

Building Geometry and layout- B

1. central courtyards with greenery, vegetation and water features;
2. underground living spaces;
3. semi-open living spaces (e.g. talars, eyvans, loggias);
4. high thermal mass (e.g. thick stone or adobe masonry);
5. domes and vaulted roofs;
6. windcatchers2;
7. vertical air vents;
8. building form that reduces wind turbulence;
9. distribution of interior rooms in order to create buffer zones.

Occupant behaviour - O

1. sleeping on rooftops;
2. seasonal use of rooms (i.e. different summer and winter living spaces);
3. watering of courtyards or/and outdoor paving surfaces.

Microclimate – M

1. use of vegetation as a) wind barrier, b) shading element, or c) buffer zone;
2. use of water elements;
3. finishing flooring materials with low reflectivity and high thermal mass (e.g. earth, stone).

Urban design - U

1. proper building orientation;
2. compact urban texture/fabric;
3. twisting and covered streets.

3 CONTEMPORARY CHALLENGES IN THE INTEGRATION OF ACTIVE SYSTEMS IN BUILT HERITAGE - INTERNATIONAL RESTORATION FRAMEWORK.

Energy efficiency refurbishments of historical buildings began to emerge in the late 1970s and early 1980s, as a consequence of the two oil crises, which created an unprecedented interest in energy retrofit (Martínez-Molina et al., 2016). A more global approach, within the scope of sustainability, was introduced through the proceedings of the Faro Convention, released in 2005 (COE, 2005), which marked the time when reducing energy consumption in built heritage, during the conservation process, became a challenge for researchers (Vieites et al., 2015). However, until today, historical buildings and monuments that are officially protected, due to their special architectural or historic merits, are excluded from attaining energy performance requirements (*Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the Energy Performance of Buildings (Recast)*, 2010). Despite the lack of a regulatory framework for minimum energy performance requirements in historical dwellings, the potential for energy savings and emissions reduction by retrofitting this particular building stock has been widely acknowledged. This is achieved through the work of several research programs (e.g. SECHURBA, CLIMATE FOR CULTURE, 3ENCULT, RIBUILD, EFFESUS) and studies (GBC, 2017; Gigliarelli et al., 2017; Historic England, 2018; MIBACT, 2015; A. (EURAC research) Troi & Bastian, 2014) that have been carried out over the last years.

The use of contemporary materials and techniques, such as steel and glass, is often adopted in architectural intervention and energy retrofit projects. This practice is in line with international principles on conservation, as the new additions differ from the original fabric, and, at the same time, establish an interesting impact on the aesthetic value of the

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2 e.g. “Badgir” in Iran, “Malqaf” in Egypt, “Barjeel” in Iraq and the Gulf, “Bating” in Syria (Jomehzadeh et al., 2017)

existing structure. Universally recognised principles on conservation promote changes with reversibility and minimum impact on the authentic fabric (the Burra chapter - ICOMOS (1999)). Emphasis is given to preserving the morphology and typology of built heritage and thus highlighting the principle of integrity in terms of material selection (The Venice Charter - ICOMOS (1964)). Environmental and social aspects in conservation are highlighted in the Declaration of Amsterdam (ICOMOS, 1975), as well as in more recent documents, such as the Faro Convention (COE, 2005). Critical views regarding authenticity and cultural values embayed on the material expression of heritage artefacts are discussed in the Nara document (1994). A brief summary of the principles outlined in the main conservation charters is provided by Carbonara (2017). As mentioned, energy improvements in historic dwellings should cater for:

a. *minimum interventio*n: the energy improvement design should aim at preserving the original material as much as possible and avoid unnecessary interventions;
b. *reversibility*: the interventions must be reversible in the future, whenever possible;
c. *distinguishability*: new works should be distinguishable against the existing ones;
d. *physical-chemical and figurative compatibility*: the interventions must guarantee compatibility between ancient and new materials, new design solutions and historical and architectural features. This applies also to energy improvement projects (for example, understanding the building's bioclimatic functioning - also through historical and architectural insights on the technologies used - is vital to reconstruct and optimise its passive behaviour);
e. respect for the material and figurative authenticity of the building.

The challenge of integrating Renewable Energy Sources (RES) technologies in a sensitive historic context consists in promoting reversible and compatible technologies that will increase the economic value and avoid any kind of damage. The installation of solar panels e.g. is critical as their presence is not always coherent with the historical building in terms of aesthetics, colours, shapes, dimensions and surfaces (Lucchi et al., 2014). According to the Washington Charter of ICOMOS (1987) (Article 8), "*new functions and activities should be compatible with the character of historic town or urban area*". Furthermore, "*adaptation of these areas to contemporary life requires the careful installation or improvement of public service facilities*". Active solar systems are considered contemporary elements. Thus, according to Article 10 of the same charter, these "*should be in harmony with the surroundings*" and should not be discouraged since (they) can "*contribute to the enrichment of an area*"(Bougiatioti & Michael, 2015; ICOMOS, 1987).

4 ACTIVE TECHNOLOGIES & INNOVATIVE MATERIALS FOR HERITAGE BUILDING INTEGRATION

According to the EU Strategy on Heating and Cooling (European Commission, 2016), the two main pillars for integrating efficient heating and cooling into EU energy policies are a) the prevention of energy leakage from buildings, and b) the maximisation of the efficiency of heating and cooling systems. A third pillar, which is a key point in reaching nearly zero energy consumption in buildings, is the incorporation of innovative technologies for the production of energy from renewable sources. The groups of relevant technologies and solutions that can contribute to this aim are summarised below:

Energy management;

This is mainly a diagnostic tool, as actions can easily be taken when the energy production and the technical systems are identified and quantitative information about the energy use of the different energy consumers, e.g. heating, cooling, lighting, domestic hot water and ventilation systems, is available. The best option for achieving high-level energy management is through performing energy monitoring and energy audits and also raising awareness of the occupants' impact on energy consumption.

Reduction of heating and cooling demands;

The most relevant retrofitting solutions for ensuring lower heating and cooling demands (kW) are improving the thermal insulation of the building's envelope and enhancing the passive strategies for heating, cooling and ventilation (either through interventions on the building envelope e.g. installing solar shading devices, or the surrounding environment e.g. the use of vegetation).

Equipment efficiency;

High energy efficiency equipment is an important asset. One of the least difficult technologies to apply is energy-saving light bulbs, which provide the same lighting conditions with less electrical power input. The considered energy-efficient equipment may also include efficient boilers and cooling equipment, heat recovery systems in the air handling units and water efficient measures to reduce domestic hot water consumption and its energy need.

System efficiency;

Implementing smart controls of the technical systems can increase their overall performance, therefore considerable energy savings may occur. Regarding the lighting system, the simplest energy-saving solution is the control of the lighting with movement sensors or dimming possibilities depending on the outdoor lighting levels.

Renewable energy.

Renewable energy sources are 'clean' energies; thus, they ensure the sustainability of energy production and the lowest primary energy use. The relevant energy production equipment from renewable energy sources include: heat pumps, geothermal systems, solar thermal panels and photovoltaic panels, solar-powered absorption chillers and biomass boilers.

4.1 Reduction of heating and cooling demands

Humidity control and pathology

Decay and failure issues that mainly refer to humidity patterns, surface deterioration, condensation, plaster decay, etc. are linked with energy performance aspects, therefore, the improvement of the building pathology is an imperative step towards its energy retrofit. Wetness conditions in the basement or foundation area will need particular attention in buildings seeking to reduce energy consumption. Besides the integrity of the building fabric, the relative humidity of indoor air influences the health and wellbeing of building occupants (Park, 1996). Treatment interventions should mainly focus on the rising damp, through the separation of the structures from the wet soil by implementing a horizontal non-ventilated cavity that reduces the abutting surfaces, while the indoor spaces may still benefit from the thermal inertia of the soil (De Fino et al., 2017). Additional measures aiming at controlling moisture migration are: a) the application of vapour barriers to the warm side of the building envelope, that however introduces drastic changes in the hygrothermal behaviour of the historic walls, b) the use of vapour open insulation materials without vapour barrier to keep the original vapour transport of the walls and enable summer drying potential (Andreotti et al., 2020), c) the replacement of the waterproof membrane on the roof and d) the implementation of hygroscopic materials in plasters used for finishing internal spaces, as they can passively buffer moisture through adsorption and desorption of vapour (Maskell et al., 2018).

4.1.1 Improvement of airtightness

Improving the airtightness of buildings is a cost-effective means of reducing space-conditioning energy consumption. Air tightness is the fundamental building property that impacts infiltration. Infiltration, or air leakage, is the movement of air through leaks, cracks, or other adventitious openings in the building envelope (Sherman & Chan, 2004). Air leakage occurs at joints of the building fabric, around doors and windows, cracks in masonry walls etc., as well as where pipes and cables pass through the building (Hall, 2008). However, in old buildings, infiltration is the primary source of outdoor air to control adequate indoor air quality (IAQ). Improving air tightness will need to be coupled with a ventilation system to provide sufficient airflow (Sherman & Chan, 2004), and the thermohygrometric behaviour of the walls should be understood and taken into account when increasing the air tightness of the building to anticipate any possible side effect. Spray-applied foam is commonly used to block air leakage at holes and cracks; when used in small quantities, is reversible with little impact on the surfaces to which it is applied (ASHRAE Guildeline 34, 2019).

4.1.2 Thermal inertia

Utilizing short-term Thermal Energy Storage (TES) is a key ingredient in strategies used to control energy demand. The ability of TES materials to absorb excess energy, and to store and release it at a later time is known as thermal inertia (see § 2.2), and when such heat transfer is timed correctly, thermal inertia can be used to improve thermal comfort and reduce auxiliary energy demand (Farid et al., 2004) the latent heat storage method provides much higher storage density, with a smaller temperature difference between storing and releasing heat. This paper reviews previous work on latent heat storage and provides an insight to recent efforts to develop new classes of phase change materials (PCMs. The simplest method to store thermal energy is in the form of sensible heat storage, which stores thermal energy by increasing the temperature of a solid or liquid. The main downside of this method is the volume of space occupied by the SHS material for the amount of stored energy needed (Ahmad et al., 2006). When reducing material usage and reducing the weight of the construction are important, latent heat thermal energy storage techniques may be preferred.

- <u>Phase change materials (PCMs)</u> are well-known examples of materials using latent heat thermal storage. PCMs are substances with a high heat of fusions, melting and solidifying at predictable temperatures (Zalba et al., 2003). The use of PCMs is also recommended to improve the performance of lightweight building elements, where the latent heat stored during the melting process performs a similar function to the thermal mass in high-mass buildings (Košir, 2019b). Nevertheless, the amount of incorporated PCMs must be substantial in order to have a noticeable effect. At the same time, care must be taken that PCM re-solidifies in the diurnal cycle to be ready for melting the next day (Košir, 2019b).

Another technique for enhancing passive solar heating gains through exploiting the benefits of thermal mass is the incorporation of solar spaces or the element of a Trombe wall.

- The classical <u>Trombe wall</u> is a massive wall covered by exterior glazing with an air channel between the layers; the glass is located at a short distance from the wall leaving no habitable space between the two layers. This massive wall absorbs and stores solar energy through the glazing. Some of this energy is transferred through the wall into the indoor area of the building (the room) by conduction. Meanwhile, the colder air enters the air channel from the room through a lower wall vent, is heated by the wall and flows upward due to buoyancy (Manzano-Agugliaro et al., 2015). A review of the opportunities and challenges of this element is provided in the work of Saadatian et al. (2012). A new technical scheme to apply Trombe wall technology for wall conservation in modern historical buildings was recently suggested by Du & Jia (2019).
- <u>Glazed galleries</u> are architectural elements that capture solar radiation during cold seasons and maintain the energy by using enclosures, floors and generally capacitive materials, which later return the energy with a phase difference (Manzano-Agugliaro et al., 2015). The conversion of semi-open spaces into indoor spaces with extended frameless glazed surfaces is a commonly used practice in historical buildings.

Besides the extension of valuable living spaces, this practice is in line with the creation of buffer zones and/or solar spaces. In the case of south adjacent spaces, it is important to assure that the glazed surfaces are operable or removable, to enable the seasonal use of such a solar space and avoid overheating during the summer (Thravalou et al., 2018).

4.1.3 Addition of thermal insulation

The position of the thermal insulation in relation to the thermal mass of the building envelope plays an important role (Asan, 2000). Exterior insulation is generally recommended as it consists of the least expensive and technically least demanding solution (A. Troi & Bastian, 2015). However, in half-timbered or decorated stucco facades, or when there is insufficient space for exterior insulation, interior insulation is advisable. In this case, a complete interior insulation system is required, involving the integration of moisture management and careful design of details such as window reveals and internal wall connections. Internal insulated high-mass buildings will basically perform as lightweight buildings because the mass of the envelope is effectively excluded from the internal environment by the thermal insulation (Hudobivnik et al., 2016). Even relatively small thicknesses (e.g. ≈20 mm) of thermal insulation will substantially reduce the convective and radiative interactions between the indoor environment and the envelope's thermal mass. Also, placing the thermal insulation layer towards the warmer side of the wall (i.e. the interior) will eventually cause a greater temperature difference between the exterior and interior environment, which might lead to condensation within the wall, especially at the former interior layer, which will be covered by the insulation (A. Troi & Bastian, 2015). In order to prevent the accumulation of moisture in the wall cross-section, vapour retardant foils, dense interior transpirant plaster, or vapour-resistant insulating layers can be used (A. Troi & Bastian, 2015). Andreotti et al. (2020) studied also the solution of vapour open insulating materials to preserve the original vapour transport within the envelope. Furthermore, the use of internal insulation (where possible due to a lack of both materic and pictorial internal decorations) alters the comfort conditions of the internal space by modifying the radiative exchange between the occupants and the surrounding surfaces. In the absence of other massive elements (floors), this aspect should also be considered. Another problem could arise from the creation of new thermal bridges in the envelope.

In addition to the reduction of conductive heat losses, the use of efficient insulation materials is important to also reduce the impact of urban noise. Unfortunately, the use of natural or recycled materials is not particularly widespread. According to a 2017 analysis report, the plastic foam segment accounts for the largest share, among all material type segments, in the world thermal insulating materials' market (Building Thermal Insulation Market, 2016). Their use can cause environmental issues due to the use of non-renewable materials and to the disposal phases of end-of-life products, in particular for plastics.

Latest research advances (e.g. research projects AERCOINS, HIPIN, NANOINSULATE, FOAMBUILD) focus on insulation technologies that not only possess very high thermal insulation capacity, but also are thinner, lighter, non-flammable, and with lower CO2 and Volatile Organic Compound (VOC) emissions (Quenard, 2014). Two types of materials are now available on the market: a) Vacuum Insulation Panels (VIP), with a large number of manufacturers around the world, and b) Advanced Porous Materials (APM), such as aerogel or other porous materials (porous silica etc.). These materials have thermal conductivity values, λ, below 15 $mWm^{-1}K^{-1}$ (and may reach up to 5 $mWm^{-1}K^{-1}$), as opposed to common insulating materials that reach minimum λ values of 29 $mWm^{-1}K^{-1}$. A Vacuum Insulation Panel can be considered an "opaque glazing" element with similar handling & installation constraints of a window system. Therefore, such materials remain difficult to handle and to install on-site, while they are also more expensive than common insulation materials (e.g. mineral, expanded perlite or PUR foam boards); yet they are often the most attractive solution if the cost of reduced floor area is taken into account.

De Fino et al. (2017) proposed several energy retrofit interventions in the case of the historic districts of Monopoli and Maglie in Italy. For plastered walls, the addition of high-performing insulation panels on the external facade was suggested e.g. aerogel, VIPs and multi-layer reflective boards, including a thermo-insulating plaster coating (e.g. hydraulic lime with EPS additives). For exposed walls with an interior cavity, the suggested intervention concerned the filling of the inner cavity with high-performing insulation mixtures (e.g. hydraulic lime with nanoparticles). In their study, the insulation on the internal facade of the walls was not considered, to keep the thermal inertia of the building components and prevent interstitial condensation. Regarding the thermal upgrade of the roof component, the following measures were suggested: a) the replacement of the inclined screed above the slab with high-performing insulation lightweight concrete (e.g., with expanded clay, pumice, expanded glass), b) the addition of a high performing insulation panel above the screed (e.g. aero-gel, VIPs, multi-layer reflective boards) and finally, c) the addition of coatings or boards with phase change materials (PCMs) on the internal side, to enhance the attenuation and time shift of the summer temperature peaks through controlled latent heat storage and release (e.g. pre-cast PCM boards or PCM-embedded thermal plaster).

4.1.4 Windows & fenestration

In the framework of the research project 3ENCULT, the two-layer concept regarding the upgrade of historical windows was introduced. In this case, a box-type window and a casement window were installed, separating the outer layer of the original 'historic' window from a new inner layer (A. Troi & Bastian, 2015). The secondary glazing approach is also suggested in the English Heritage guide on energy Conservation in traditional Buildings (AA.VV., 2008) and in the energy efficiency guidelines of the Italian Ministry of Cultural Heritage and Activities (MIBACT, 2015).

Nowadays, dynamic tintable and smart windows are available, that can alter the solar factor and/or the transmittance of the glazing. Chromogenic glasses refer to glazing in which transmission properties are variables. Four modes of switchable effect can be employed; a) Electrochromic, b) Gasochromic, c) Photochromic, containing a coating of silver halide, which changes form clear to dark in the sunlight, and d) Thermochromic, which has a coating of vanadium oxides, which exhibit a reversible semiconductor-to-metallic phase transition when the temperature rises (Soltani et al., 2008). Electrochromics and gasochromics enable control of transmittance independent of both insulation or ambient temperature. Low heat loss through windows may be achieved, via multiple panes, low long-wave emittance coatings and the inclusion between panes of inert gases, aerogels or a vacuum either singly or in combination (Kubie et al., 2000). Vacuum glazing comprises two contiguously sealed glass panes with low emittance films on one or both glass surfaces with the vacuum gap, separated by an array of tiny support pillars to maintain the glass separation under atmospheric pressure (Fang & Eames, 2006). The thinness of vacuum glazing and its excellent thermal performance make it highly suited to retrofit in buildings having the potential to significantly reduce heating (Eames, 2008). A recent study explores the potential of phase change material (PCM) placed in a glass container; particularly, a triple-glazed window in which the outer cavity was filed with paraffin (Wieprzkowicz & Heim, 2020). According to the results, windows with liquid PCM can assure good sky view and visual comfort, while PCM in a solid state negatively influences these conditions. Nevertheless, lower light transmittance contributed to the limitation of the glare effect. The most effective utilisation of PCM properties was obtained by combining different kinds of paraffin in one window, dividing it into sections (Wieprzkowicz & Heim, 2020). However, it should be emphasized that the intervention on windows and fenestration should be planned in tight collaboration with the conservation expert. Reflections on the historical and aesthetic compatibility may concern not only the shape and appearance of the frame but also the window typology, the surrounding framing, the window-to-wall connection, fittings and additional equipment such as window shutter and the glass itself. This is the case of the replacement of the fixtures in the Waaghaus in Bozen (another 3ENCULT case study), where the original proportion between glass area and sash bars and windows frame and the optic appearance of original historical glazing were identified as one of the elements to be preserved (Exner et al., 2010).

4.1.5 Hybrid heating and cooling systems:

Hybrid ventilation systems combine mechanical and natural forces in a two-mode system where the operating mode differs according to the season and daily fluctuations (Lomas et al., 2007).

Ventilation systems with heat recovery are gaining ground in energy retrofit projects of existing buildings, including historical buildings (Pukhkal et al. 2014; Passive House). A Heat Recovery system efficiently pre-warms fresh filtered air drawn into a building with the heat extracted from stale air leaving the building, using a heat exchanger.

Modern windcatchers have been developed to take the advantages of traditional windcatchers and eliminate their limitations, to adopt them with advanced building principles and technologies. Contemporary versions of windcatchers consist of the commercial four-sided windcatcher with solar panels, louvers, solar-powered fans and adjustable dampers (Jomehzadeh et al., 2020). The louvers in commercial windcatchers are designed not only to direct the external air into the occupied space but also to prevent the penetration of rainwater and other objects entering the building. Dampers and diffusers are employed to control the air flow rate through windcatchers with respect to external wind speed (Hughes et al., 2012).

Mechanically assisted evaporative cooling is achieved with an economizer-cycle evaporative cooling system, instead of, or in conjunction with, refrigerant air-conditioning. The spraying of water on the roof (if the existing roof has little insulation) and the spraying of water indoors to reduce the temperature of the overhead air are contemporary techniques involving low-tech mechanisms. Care must be taken in dimensioning the system properly, as the air that is saturated with water vapour can create a problem; it lacks the ability to absorb any additional amount of humidity, which can cause condensation when the temperature falls (Erell et al., 2011). In 2010's Solar Decathlon competition, Nottingham's team presented a hybrid downdraught cooling system installed in a central lightwell and ventilation shaft located on the roof (Ford et al., 2012). Eight misting nozzles were incorporated into the skylight, providing evaporatively cooled air into the central double-height space, which in turn promoted the air flow to first-floor (Ford et al., 2012).

4.2 System efficiency

4.2.1 Lighting

The restoration of the natural lighting and daylighting harvesting systems originally included in a historical building is generally recommended. However, in many cases, additional illumination might be required to showcase architectural elements or to provide increased ambient illumination or higher lighting levels for art and tasks. With the introduction of LED lighting or miniature LED downlights, luminaires have been reduced in size to the extent that they are better integrated into architectural elements and concealed from the occupants - installed in cornices, purlins, narrow and shallow soffits, window casements, etc. (ASHRAE Guideline 34 2019). LED light sources offer high-efficacy, low operating costs, and a wide range of control options (including changing the colour emitted by an LED lamp, light outputs, and colour temperature choices). LED lighting equipment often requires remote control gear (LED drivers, transformers, power supplies, etc.) and often more specialized dimming equipment. This can raise the initial cost of the lighting system, but this premium is rapidly paid back through a reduction in energy use and maintenance costs.

Where dimming is required or desired for energy efficiency or function, the options vary from fluorescent, compact fluorescent, to LED lamps, ensuring that compatible dimmable luminaires and controls are specified. Where dimming is not necessary, lower-wattage ceramic metal halide (CMH) lamps are recommended as they are particularly well suited for building facade lighting. In areas where significant natural light (daylight) is available, daylight harvesting can be accomplished with the use of light sensors coupled with controls that will balance daylight and electric light once set to a specific light level requirement. Coordination for daylight harvesting works best if sets of luminaires are on separate switches to permit controlled partial electrical lighting to supplement daylighting (ASHRAE Guideline 34 2019).

4.2.2 Controls (lighting, temperature and humidity)

Dimming and automatic switching controls will maximize energy savings and, in many cases, extend the life of lighting and HVAC equipment. Controls include wall box dimmers, wired and wireless lighting control systems, occupancy sensors and door jamb switches. Wireless systems are particularly suitable for historical buildings, as they are much less invasive and do not require cutting and patching of wall, ceiling and floor surfaces for wire runs. Many advances in controls have been made recently that permit both programming and remote control online through smart phones, tablets, and computers (ASHRAE Guideline 34 2019).

The seasonal adjustment of temperature set points is recommended in historical buildings to control relative humidity and maintain its levels within the limits necessary for sustaining thermal comfort and indoor air quality for building occupants. Allowing for seasonal adjustment and unoccupied setbacks for temperature and humidity set points is an energy conservation measure, which, when applied, should reduce energy consumption by the HVAC systems in the building (ASHRAE Guideline 34 2019). In museum environments especially, consideration for the artefacts and interior building fabric should also be taken into account when determining the most appropriate set points and setbacks.

4.3 Renewable energy

Heritage buildings may often have limited potential for renewable energy systems integration, due to legislative protection status or dense urban surroundings. Thus, the enhancement of energy optimization should not only focus on the building level but also on the urban fabric in proximity. Recent studies (Jansen et al., 2020) have proven the importance of decentralised heat production from PV-thermal (PVT) collectors and collective seasonal underground storage.

Agugliaro et al. (2015) have examined the concept of modern strategies applied to Mediterranean buildings, referring to the most prominent technologies: thin building integrated photovoltaic films on buildings; spraying of water on roofs; placement of buried pipes as heat exchangers, for preheating and cooling the ventilation air.

A Building Integrated Photovoltaics (BIPV) system is a PV system integrated into the building envelope (e.g. roof, façade, window, etc.). Thus, it replaces a building element i.e. a conventional construction material. Technologies that are available for building integration (BIPV) are among others the following:

- Flexible (foil) BIPV: Flexible BIPV is a relatively new product that allows for attractive integration options in a building as it is lightweight and flexible, which is beneficial to its ease of installation (Jelle & Breivik, 2012). Photovoltaic cells are often made of thin-film cells to maintain flexibility and to be effective in high temperatures (e.g. in non-ventilated roofs). Flexibility is achieved mainly due to its very thin structure, combined with its ability to be installed on flexible substrates (stainless steel sheets or polymer film), giving it a handy and compact form (Chopra et al., 2004).
- BIPV tiles are photovoltaic modules (without a metal frame), usually integrated with the same logic and properties of conventional roof tiles, thus allowing easy roofing to be reconstructed (Heinstein et al., 2013). BIPV tile products may cover the entire roof or selected parts of the roof.

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5.2 Main Restoration Charters

- The Athens Charter for the Restoration of Historic Monuments –1931 https://www.icomos.org/en/167-the-athens-charter-for-the-restoration-of-historic-monuments
- INTERNATIONAL CHARTER FOR THE CONSERVATION AND RESTORATION OF MONUMENTS AND SITES (The Venice Charter 1964) https://www.icomos.org/charters/venice_e.pdf
- The Declaration of Amsterdam -1975 https://www.icomos.org/en/and/169-the-declaration-of-amsterdam
- European Charter of the Architectural Heritage -1975 https://www.icomos.org/en/charters-and-texts/179-articles-en-francais/ressources/charters-and-standards/170-european-charter-of-the-architectural-heritage
- Charter for The Conservation of Historic Towns and Urban Areas (Washington Charter 1987) https://www.icomos.org/charters/towns_e.pdf
- The Nara Document on Authenticity (1994) https://www.icomos.org/charters/nara-e.pdf
- The Aalborg Charter (1994) http://www.sustainablecities.eu/fileadmin/repository/Aalborg_Charter/Aalborg_Charter_English.pdf
- The Faro Convention (2005) https://rm.coe.int/16800837463

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