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# The Energy-Oriented Management of Public Historic Buildings: An Integrated Approach and Methodology Applications

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**Abstract:** In the European framework, there is a strong drive to develop integrated approaches aimed at understanding and improving the energy behavior of public historic buildings within urban contexts. However, the examples already provided tend to address the issue from mono-disciplinary perspectives, losing the opportunity for a coordinated view. The research suggests a methodology to reach the definition of a three-dimensional database, which incorporates spatial models and energy information, with the final goal of merging heterogeneous information that is useful to interpret the overall framework and to design sustainable development scenarios. The platform achieves GIS (Geographic Information System) and BIM (Building Information Modeling) integration by using the CityGML data model, for supporting multi-scale analyses without break of continuity, ranging from urban to building level. The discussion combines the applicative case with the theoretical background, deepening the role of a solid knowledge framework as a basis for sustainable interventions on public historic buildings. To better explain and test the methodology, a case study on the University built heritage of Pavia is presented and three possible outputs deriving from the database are discussed. The example demonstrates the strength of the approach, which is able to provide a variety of results coming from a unique source of information, ensuring coherence and unambiguousness at all levels of investigation.

**Keywords:** public historic buildings; multi-scale energy modelling; energy-oriented management; spatial relational database

## 1. Introduction

Historic buildings are generally considered those built before 1945, even if, a wide diffusion of older constructions [1] characterizes several European countries and, particularly, Italy. According to the most recent statistics, which date back in 2010 [2], 23.4% of buildings in the European Union were built before the end of the Second World War and the related renovation rate is still extremely slow [3]. These buildings are usually recognized as low-energy-performance buildings [4], mainly due to the obsolescence of both their envelopes and HVAC (Heating, Ventilation and Air Conditioning) systems. Therefore, with the aim of integrated sustainable development of our cities, more attention should be paid to the energy efficiency of this category of constructions, as already happens in the case of new buildings. The EU Directive 2010/31/EU [5] indicates that member states may decide not to set or apply minimum energy performance requirements to officially protected buildings, because of their special architectural or historical merit, in so far as their character or appearance may be unacceptably altered. This note means that this part of built heritage can also be subdued to energy improvement actions and that the maximum effort to follow the EPBD (Energy Performance of Buildings Directive) indications should be made. At present, we have both knowledge and technologies to ensure responsible intervention, applying energy efficiency as an effective tool to promote protection [6]. Furthermore, the reuse of spaces that are part of the local cultural heritage can represent a contribution to strengthen the identity of a population and its traditions [7]. Therefore, historic building renovation may become a primary need for buildings' "active life", even if heavy artistic and architectural constraints limit admissible interventions. Moreover, historic buildings are often used by public bodies that, as indicated by the EPBD, should be exemplary in the field of energy efficiency of buildings [8]. The national plans have set higher targets concerning energy performances and renovation rates for these buildings, and the repercussions of these indications are necessarily found also in the cases involving historical buildings. For this reason, where different and often conflicting requirements fall on public historic buildings by considering them from a single point of view, it is necessary to overcome the duality, by developing a holistic approach aimed at their management.

In the European context, several efforts have been made in order to analyze and improve the energy performance of historic buildings, starting from public properties. In the recent past, the European Commission promoted some research projects aiming at a deeper knowledge of the problem. Therefore, a collection of methodological proposals and guidelines was issued in order to find the best way to also apply the EPBD indications to historic building stocks. As an example, in the 3ENCULT (Efficient Energy for EU Cultural Heritage) project [9], generic replicable factors were collected and presented as suggestions and guidelines, recognizing, however, that each historic building has unique needs and requires its own tailor-made solution. In any case, it is possible to highlight a series of replicable recommendations for local decision-makers.

A deeper knowledge of the widespread historic built heritage can help to collect information useful for applying common rules for increasing energy performance. An attempt to organize a database with the main features and state of conservation of historic buildings was developed in the EU Project "Climate for Culture" supported by the FP7 Program (Seventh Framework Programme) [10] with a collection of data by questionnaire survey leading to a simplified classification of historic buildings. In the database, an organized set of information about state of preservation, indoor climate conditions and requirements, and environmental risks to the interiors was proposed. On the basis of the analyzed case studies (35 buildings in 11 countries), measures required to improve the internal climate conditions aiming at the preventive conservation of interior decorations and to reduce damages linked to the influence of external climate conditions were studied. With the EFFESUS (Energy Efficiency for EU Historic Districts' Sustainability) EU Project, a more systematic investigation led towards a typological tree structure with a limited number of physical categories to be modelled for energy calculations [11]. The subdivision into physical categories facilitates the analysis of many subcategories, by means of the same physical model. The method, applied on the historic building stock of Visby, a World Heritage Site, helps to demonstrate that a wide stock (more than 1200 buildings) could be represented by nine typical buildings. In this framework, the CityGML data model was used for building modelling, data collection and categorization.

On the basis of the outlined context, the present research proposes the definition of a multi-scale support tool for understanding and communicating the energy behavior of existing building stocks, which realizes a chain of interoperable instruments, able to analyze the urban landscape from the territorial to the building scale. The design of the workflow has been supported by a methodological discussion on the mechanisms that drive knowledge and transformation processes applied to existing buildings, which is examined in the discussion section. The paper is particularly focused on the case of public historic buildings because, even though the theme of energy refurbishment of existing buildings has been widely discussed in the last decades, a knowledge gap is recognizable regarding this subcategory. They are, in fact, always considered from a single point of view—as public spaces to be upgraded in their performance [12] or as cultural heritage to be protected [13]—losing the coordinate objective of an integrated governance. The new approach tries to overcome the duality between historic and public buildings through an integrated methodology able to exploit data interoperability within a multi-scale knowledge framework. Moreover, an applicative example is presented for the case of university buildings, which may be considered as a class on its own as they share common strengths and weakness. They are widespread among Europe, at least in cities hosting historical universities, and usually embed both social and heritage values. This is why they are usually involved in complex decision-making processes and represent therefore a stimulating testing ground for the present investigation.

The paper is organized as follows. Section 2 introduces the methodology and discusses the organization of spatial models and energy data for the definition of the database. Section 3 describes an applicative example on the buildings owned and managed by the University of Pavia (Italy) and proposes three possible outcomes deriving from the database. Section 4 provides a methodological discussion aimed at linking the theoretical background with the applicative approach. Finally, Section 5 presents conclusions and future perspectives.

## 2. Materials and Methods

The investigation of building assets constituting public historic stocks requires a synergy between a broad territorial/urban vision and a more detailed interpretation of the objects involved, seen as cultural heritage [14]. In the present workflow, with the aim of developing coherent and respectful refurbishment scenarios, the analysis should move from the urban context, via the building stock, to individual constructions, combining spatial and energy data at each step. Since multiple data types coming from different sources are involved, interoperability plays a fundamental role in the process. In fact, to define an operable information system, all the data involved need to be harmonized within a common platform, in which knowledge should deepen at each level, from general to particular.

To define a repeatable workflow, the process should start from widely available input data and make use of standard file formats, classification systems, and, as much as possible, open software and contents [15]. The targets were met by creating a relational database able to collect and manage spatial and energy data, suitable for archiving and representing information in a well-structured architecture. With this aim, the jointed exploitation of GIS (Geographic Information System) and BIM (Building Information Modeling) allowed the achievement of a multi-scale work environment.

Although GIS and BIM were mainly created for different purposes—the first for the management of large data set on existing natural and built environment and the latter for the detailed representation of new constructions [16]—there are several contact points between them. Properly due to their attitude of representing reality at different scales, interesting opportunities derive from their use within integrated solutions [17]. The opportunities offered by an automated connection of GIS and BIM have recently been reviewed in numerous studies [18–21], but, even though different approaches have been identified [18] in the current state of the art, issues related to both geometry and semantic compliance cause a persistent need for manual intervention [21].

In the present research, the information integration is achieved by using CityGML 2.0, which is an open data model designed by OGC (Open Geospatial Consortium) with the aim of giving an ontology with basic entities, attributes and relationships proper of the built environment. CityGML organizes the information by combining the geometric, topologic, semantic, and appearance properties of city objects [22], and allows multi-scale and multi-level representation on account of its definition in five Levels of Detail (LODs). It is compliant with the ISO/TC211 international standard on geographic and spatial information, it supports interoperability with BIM, and it is suitable for transpositions towards database architectures, due to its well-structured ontology. The whole process for the achievement of the spatial database is described in the next sections, and it is summarized in Figure 1 (as already presented by the authors for an earlier stage of advancement in [23]).

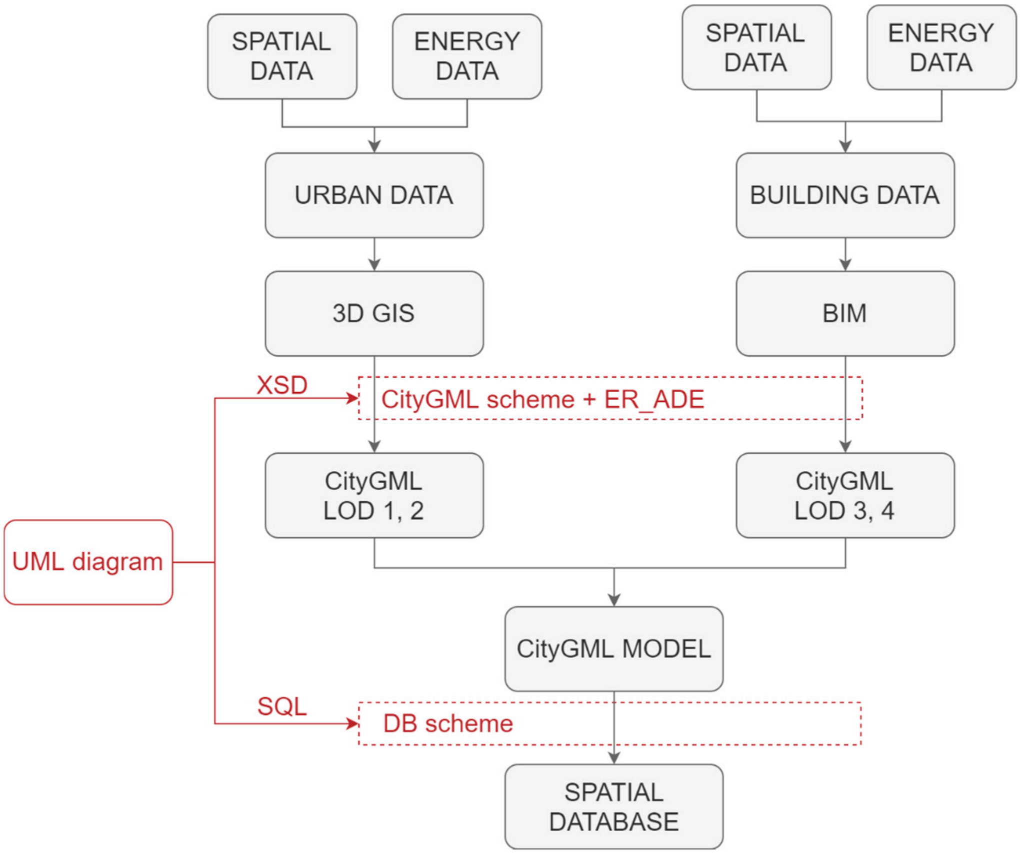



**Figure 1.** Process flowchart from input data to spatial database. (XSD—XML Schema Definition, ER_ADE—Energy Refurbishment Application Domain Extension, UML—Unified Modelling Language, SQL—Structured Query Language, DB—Database).

### 2.1. *Spatial Model*

Spatial models make it possible to give better communication skills to data sets. In the present study, the integration of numerical data within 3D graphic representations of cities and buildings aims at improving the dissemination of energy-related information to different classes of stakeholders [24]. For technical users, owners and the facility managers, an immediate representation of energy demands and thermal properties—as well as the opportunity to perform simulations on those data—could be used as a support for decision-making, while, for final users, an understanding of information on the energy behavior of buildings may stimulate energy-aware consuming.

#### 2.1.1. City Models

To reach the definition of a multi-scale information system, it is essential to acquire information at different insight levels. The urban survey should consist of two data sets: a two-dimensional cartography with the building footprints and a sparse cloud coming from an aerial LiDAR (Light Detection and Ranging o Laser Imaging Detection and Ranging) campaign. The informative layers are put together within ArcGIS Pro 2.2.0, where the volumes representing the built environment are extracted to achieve a three-dimensional GIS (Multipatch Shapefile). Subsequently, the transformation from 3D GIS to CityGML is achieved by making use of Safe FME, a powerful data conversion application employing Visual Programming Languages (VPL). This passage is extremely delicate, as it requires the migration of non-structured data towards a model which organizes information in a hierarchical ontology and represents relationships other than geometries and data. From the 3D GIS, it is necessary to separate classes of elements and to explicitly define parent–child relationships with the aim of reproducing the syntax characteristic of CityGML. The achieved city model meets the specifications of the lower LODs of CityGML: LOD1, with the volumes of the buildings extruded to their maximum high, and LOD2, which includes the geometries of the roofs.

#### 2.1.2. Building Models

As a complement to the city model, BIM models are created for the buildings included in the asset under examination. The input data, resulting from archival researches and on-site surveys, should include two-dimensional sheets (plans, elevations, sections etc.) and, at best, LiDAR point clouds. The informative models are built manually inside authoring software, to be finally exported in IFC. The conversion between IFC and CityGML is less burdensome than the previous one because the two data models are similar in their organization, being both characterized by hierarchical and semantic structures. The transformation takes place again within the Safe FME environment with a script able to convert IFC classes in CityGML ones, being careful to re-write the relationships between objects when this is needed.

The CityGML model derived from BIM is more detailed than the one coming from 3D GIS, and it constitutes higher levels of detail within the CityGML classification. In particular, it matches the requirements of LOD3 and 4, which are characterized by the same geometry and informative depth but are differentiated by the representation of internal spaces in LOD4. For the aim of this study, it is sufficient to reach the definition of CityGML LOD3, which usually includes the characteristics of the building envelope. However, the representation of the internal environment could be useful for further applications of the informative system.

At this stage, the CityGML model is complete, including the urban context at broader levels of detail (LOD 1 and 2) and the building stock with higher accuracy (LOD 3 and 4). This makes it possible to activate deep analyses on the buildings which are the object of the study, while ensuring their inclusion in a wider context, useful for the performance of simulations at urban and territorial scales.

#### 2.1.3. CityGML Data Model

CityGML is a standard data model, in which each piece of information finds a precise position in a hierarchical structure. However, its modular and extensible configuration allows the introduction of new feature classes and attributes through the design of compliant thematic expansion (Application Domain Extension—ADE) to enrich the scheme, while maintaining its semantic structure [25]. Numerous extensions have already been developed and validated by OGC, and, in particular, two studies have addressed upgrading of the standard with relation to the domain of energy [26] and heritage [27]. The present work considered both of them, in order to define a customized one called ER_ADE (Energy Refurbishment Application Domain Extension), suitable for monitoring and simulating energy behavior of existing buildings with reference to the UNI EN 15603:2008 standard, by taking into account the fundamental features of historic buildings. The creation of the Application Domain Extension followed the recommendation issued by OGC, designing the structure through UML (Unified Modeling Language) class models [28]. The main interventions on the CityGML scheme were implemented in the building module, where attributes were added in order to represent the main features for energy evaluations, as displayed in Figure 2, where each box represents a feature class with the name (in bold) and the list of the attribute, while the arrows describe the relations, detailing the cardinalities and the inheritance and aggregation rules. With respect to the original scheme, and in consideration of the inheritance rules detailed in the CityGML specification document [29], attributes CHDeclarationDocument, hasCHDeclaration, ownership and preservationAuthorityName were added to the CityObject class; attributes demonination, AATStylePeriod, heatedArea, heatedVolume, annualTermalEnergy, annualElectricalEnergy, hasEpc, epcClass were included in the AbstractBuilding feature class; BSArea, BSThickness, hasAuthor, timeOfBeginningExistence, timeOfEndingExistence, ifcElementType, deterioration, isThermalBoundary, transmittanceU, emissivityE, absorptionCofficientA, aFin, aHor, aOv, boundaryCondition, exposition were added to BoundarySurface class and the attribute solarFactorG was introduced in the Opening class.

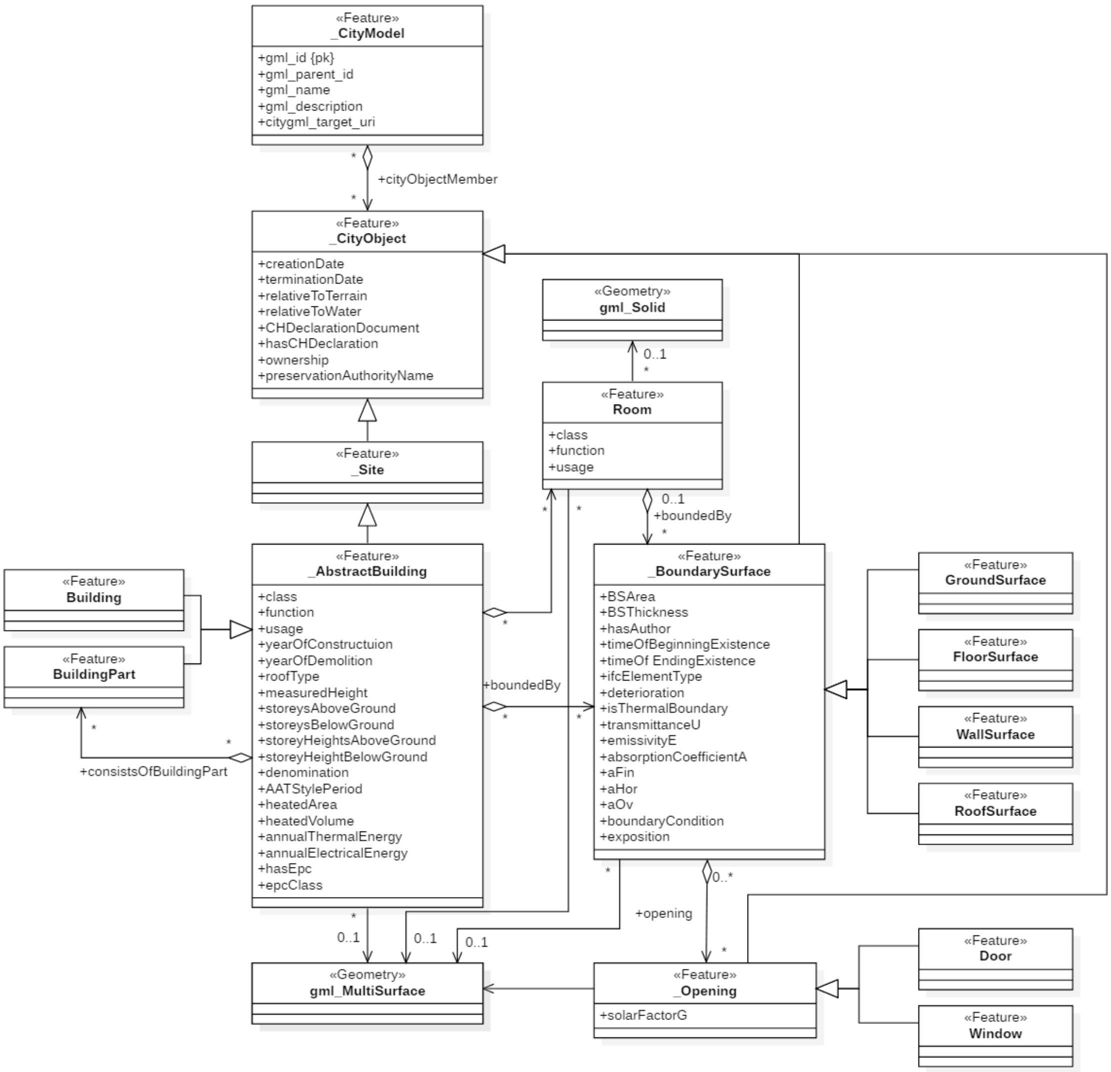



**Figure 2.** UML diagram of the ER_ADE.

## 2.2. *Energy Data*

In this study, energy data were coupled with informative models in order to build a set of interoperable tools which allow visualization and monitoring at city level and simulations at building level. The need to find homogeneous data sets, available within the European context, led to reference to community regulations and, in particular, to two specific instruments: Energy Performance Certificates (EPC) and Energy Audits.

### 2.2.1. Urban Level

Energy Performance Certificates were introduced in Europe with the issuing of the first directive (2002/91/EC) and are nowadays implemented by all the member states [30]. Even though they are founded on accurate analyses which consider the building envelope, the HVAC system and the energy source, their power lies in their easy communicability related to energy classes. Actually, EPCs are not yet mandatory for all kinds of buildings, but their deployment is spreading sharply, with the idea that making the users aware of energy use and consumption should enhance their behavior [31]. Along with the diffusion of EPCs, national or regional data sets collecting the related information are becoming common, permitting simpler access and comparison of data. This step forward activated a new line of research, which seized the opportunity of EPC availability to understand the energy performance of urban areas and extract relevant statistics [32,33].

The present methodological proposal integrates, within a multi-scale flux of information, a specific analysis of the urban context, by geo-referencing the EPCs and including their main data within the 3D City model. In this way, it has become possible to directly compare urban and building features (urban zone, construction period, typological and dimensional characteristics etc.) with energy data and to create knowledge about the built environment.

#### 2.2.2. Building Level

With regard to assessment of the energy performance of buildings, the 2012/27/EU Directive defined another tool. The energy audit is a procedure aimed at achieving an adequate knowledge of the energy needs of existing buildings, with the purpose of identifying cost-effective refurbishment solutions. Compared with energy performance certificates, it involves an evaluation referred to the real operating conditions. Energy audits are compulsory only for the assessment of industrial and enterprise buildings but can be valid investigation tools for energy refurbishment processes—and are therefore preferred to EPCs, when available, due to their reference to actual and not reference operating conditions. In the current study, energy audits were used to evaluate the energy behaviors of the case-study buildings.

### *2.3. Relational Database*

Once the comprehensive model was defined, the last phase of work provided for its transfer towards a relational database, from which it would be possible to visualize, interrogate and analyze the data either with or without relation to their geometric representation. To this end, the PostgreSQL DBMS (DataBase Management System) was implemented along with its extension, PostGIS, for the management of the spatial features. The database scheme was derived from the structure of CityGML with the addition of the ER_ADE, making use of the already-mentioned UML diagram, which can be converted into DDL (Data Definition Language) commands of SQL (Structured Query Language). Since the data structure of the CityGML model and the one of the database are the same, all the information are in a 1:1 relationship and, therefore, the data transfer can proceed without further adaptions.

The disposition of the complete data set within a structured database allows many possibilities of data access and analysis. The interrogation through the geometric representation of information can be accomplished with the activation of a connection inside GIS software, such as the open solution QGIS. In this environment, from the software GUI (Graphic User Interface), the database can be interrogated by making use of an SQL shell, and the query results can be sent to the visualization window, obtaining highly communicative graphic outputs.

## 3. Application to the Case Study

The integration of spatial and energy data within a database makes it possible to access the data from multiple platforms and, therefore, to conceive various applicative outputs. In the present paper, three applicative examples are displayed with relation to the case study of the city center of Pavia (Italy) and its university buildings:

- The geolocation of EPC data in the urban context;
- The visualization of thermal and electrical demands of the building stock;
- A detailed energy assessment performed on a single building.

These aspects are examples of a wider range of exploitation possibilities that spatial databases can offer for the management of existing building stocks [23,34,35].

Pavia is an historical city founded by the Romans and situated in the southern part of the Lombardy Region. Its historical center, situated on the river Ticino, has about 1500 buildings, most of which are listed. The University of Pavia is one of the most ancient in the world, founded in 1361 and developed through the centuries; its history has deeply influenced the development of the city. At present, the University of Pavia owns and manages 230,000 $m^2$ of built surface, of which 77,000 $m^2$ is constituted by historic buildings within the city center (Figure 3). Pavia may also be considered as a case study worth of interest, because the methods applied and the results obtained may be transferred to a wide number of historical cities in the EU hosting historical universities.


**Figure 3.** The 3D model of the historical center of Pavia and its university buildings (in red).

Input data for the definition of the three-dimensional model of the city center of Pavia were derived from the following sources [23]:

- Spatial data (urban level): two-dimensional GIS cartography provided by the Territorial Information System (SIT—Sistema Informativo Territoriale) of the Municipality of Pavia and digital point cloud resulting from a LiDAR (Light Detection And Ranging) survey campaign of 2008–2009 conducted by the Italian Ministry of the Environment (Ministero dell'Ambiente e della Tutela del Territorio e del Mare);
- Spatial data (building level): two-dimensional documents (plans, sections and elevations) provided by the university technical office;
- Energy data (urban level): EPC data collected from the regional open database (CENED, Certificazione ENergetica degli EDifici—Building Energy Certification authority of the Lombardy region);
- Energy data (building level): energy bills (thermal and electrical) provided by the university technical office and energy audits commissioned by the university in 2016 for the assessment of its built asset.

### *3.1. Geolocation of EPCs for the Historical Centre of Pavia*

As a first step of the multiscale analysis, the city center was considered, in order to understand the energy context in which the building stock of the University of Pavia is. This is fundamental for the purpose of performing wide range evaluations, which are able to consider multiple aspects that mutually affect the city and its buildings. With this aim, a 3D navigable model was realized meeting the specification of the lowest Levels of Detail of CityGML (LOD1 and LOD2). Thanks to the implementation of CityGML ER_ADE, it was possible to include within the model the information related to EPCs, collected from the regional open database (CENED, Certificazione ENergetica degli EDifici—Building Energy Certification authority of Lombardy region). As energy performance certificates are usually issued for each building unit, it was necessary to define a method aimed at their aggregation with relation to the 3D building entities. With reference to the attributes defined in the Application Domain Extension, "heated area", "heated volume", "annual thermal energy" and "annual electrical energy" were added, and "EPC class" was assigned on the basis of a weighted average on the involved surfaces.

The result was published in the Cesium Ion online platform, where all the data can be visualized after the predisposition of a web app programmed in JavaScript. A screenshot taken from the app is visible in Figure 4. The data analysis made it possible to comprehend the built environment which surrounds the university buildings. The historical center of the city is mainly composed by historical buildings, characterized by low energy performance. According to the CENED database, most of the buildings subjected to energy certification were built during the 19th century, and their behavior could be better than expected, due to the big thermal inertia associated with thick brick walls. Few buildings, heterogeneously distributed, reach high EPC classes, due to recent interventions.

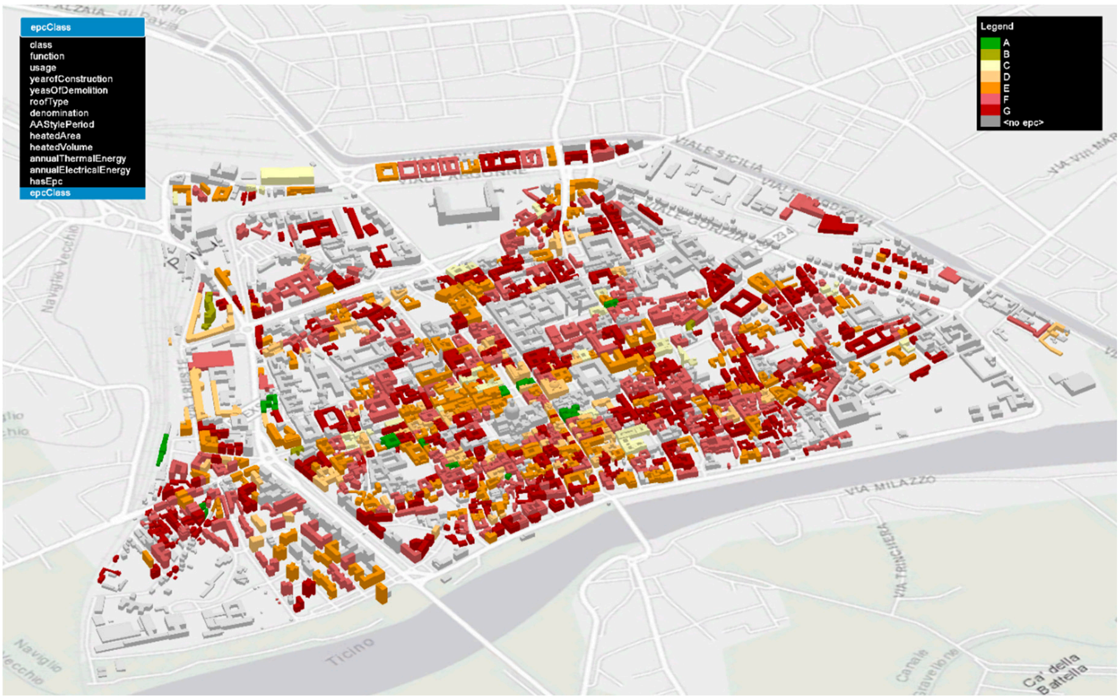
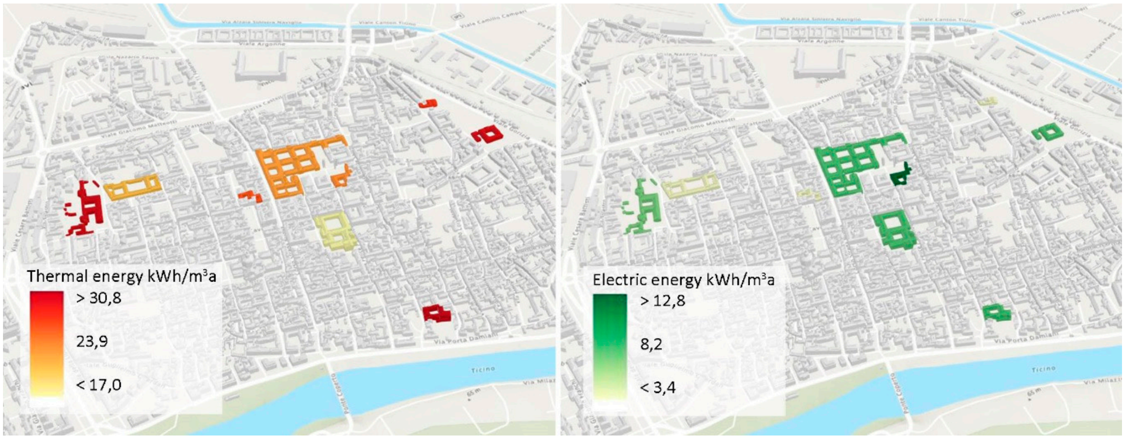



**Figure 4.** A screenshot from the web app. Different building colors represent energy classes, from class A (green) to class G (red), while the models left in light gray are those for which the data on EPC class was not available.

### 3.2. Energy Demand of Public Historic Buildings

Moving to a higher level of detail, the nine building complexes owned by the university were investigated. At this stage, the main aim of the tool was improvement of the communicability of huge amounts of data, with the prospect of capitalizing and disseminating the information collected by the university technical office. The attention was focused on thermal and electrical energy needs, in order to identify the critical issues of the building stock. To this aim, the monthly data collected from 2011 to 2017 were mapped within the 3D GIS, while it was chosen to store only the average annual value in the CityGML model. Moreover, a set of thermal properties regarding the building envelope and some information on the HVAC system were collected from the energy audits (2016). The combination of numerical data with the geometries constituting the building asset model can be very precious because it makes it possible to perform integrated analyses to highlight the energy behavior of buildings with relation to their structural and geometric properties.

To ensure visibility and data access, a web application was developed making use of the ArcGIS Online platform, provided by ESRI. Some graphic outputs are shown in Figure 5, where thermal and electric energy demands are displayed per heated volumetric unit. The global vision makes it possible to find out where it could pay more to intervene and how. As can be observed from the graphic outputs, in fact, three buildings have the worst energy performance, and there is a building clearly responsible for higher electrical energy consumption.

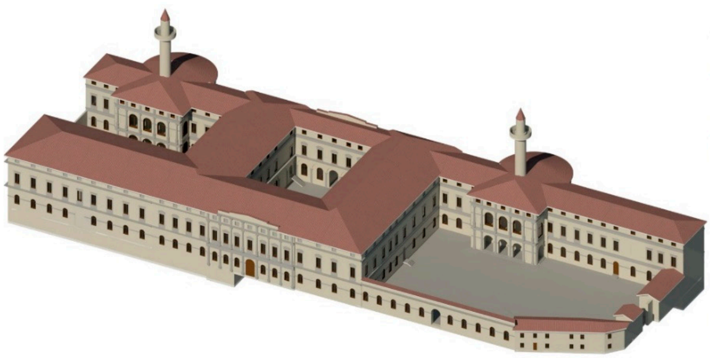



(**a**) (**b**)

**Figure 5.** Possible outputs from the web app. Thermal energy needs (**a**) and electrical needs (**b**) per volume unit are displayed with color scales.

## 3.3. Energy Assessment of Single Buildings

At the subsequent stage, a deeper level of information was associated with single buildings, as is here shown for the Palazzo Botta Adorno (Figure 6a). The complex, built as a noble residence starting from the 18th century and transferred to the University in 1885, is actually under restoration to become a university museum. At this stage, the aim was to organize all the energy-related information already available on the building with the referred geometries, within the relational database, and to design some summary sheets (Figures 6b and 7b). For this application, the required input data are more detailed with respect to the ones seen until now; therefore, it is necessary to involve building information modeling to reach the highest levels of detail provided by CityGML.



(**a**)

| BUILDING | VALUE |
|---|---|
| class | schools, education, research |
| function | residential building |
| usage | college or university |
| yearOfConstruction | 1702 |
| yearOfDemolition | |
| roofType | hipped roof |
| measuredHeight | 15.75 [m] |
| storeysAboveGround | 3 |
| storeysBelowGround | 1 |
| storeysHeightsAboveGroung | 15.75 [m] |
| storeysHeightsBelowGroung | 3.80 [m] |
| denomination | Palazzo Botta Adorno |
| AATStylePeriod | Neoclassical |
| heatedArea | 4659 [m²] |
| heatedVolume | 24818.44 [m³] |
| annualThermalEnergy | 751953.05 [kWh] |
| annualElectricalEnergy | 174959.67 [kWh] |

(**b**)

**Figure 6.** Axonometric view of the BIM model of Palazzo Botta Adorno (**a**) and summary sheet example (**b**).

| BUILDING COMPONENTS | VALUE |
|---|---|
| BSArea | 3.56 [m²] |
| BSThickness | NA |
| hasAuthor | No |
| timeOfBeginningExistence | 1804 |
| timeOfEndingExistence | |
| ifcElementType | ifcWindow |
| deterioration | |
| isThermalBoundary | Yes |
| transmittanceU | 4.83 [W/m²K] |
| emissivityE | 0.84 |
| absorptionCoefficientA | NA |
| αFin | 0 [°] |
| αHor | 0 [°] |
| αOv | 0 [°] |
| boundaryCondition | External |
| exposition | E |
| solarFactorG | 0.75 |

(**a**) (**b**)

**Figure 7.** Axonometric view of a building component (**a**) and summary sheet example (**b**).

With this operation, the information included in the EPCs and in the energy audits became geolocated and directly referred to the building entities, providing better accessibility of data. Furthermore, the data categories, accepted by the CityGML scheme as enriched with the ER_ADE, allow showing all the energy information, giving the opportunity to perform detailed calculations.

## 4. Discussion

On the basis of the outlined approach and its applications, some methodological considerations may be highlighted in order to drive the knowledge and transformation processes in relation to public historic buildings. At least three main reasons determine the strong relevance of building infrastructure management: (a) the symbolic value of the buildings involved, seen as a tangible demonstration of their relevance; (b) the ever-accelerating transformation of users' requirements, which make it necessary to exploit adequate technical solutions and financial resources (moreover, when existing buildings are relevant historical monuments, accessibility, safety, security, and energy efficiency and comfort require an integrated approach in order to satisfy users while preserving the original values of existing historical buildings); (c) the ever-enlarging amount of new activities that may take place in university spaces, always more frequently not traditional ones like teaching and research, generates a completely new set of activities, and, consequently, requirements to be satisfied.

For this kind of building, with the aim of developing a sustainable management approach, a deep and integrated knowledge of the constructions and their energy behavior is the starting point to achieve effective decision-making [36]. Therefore, a holistic method should be developed, which takes in account a wide spectrum of different and related aspects concerning restoration, valorization, energy efficiency and management of historical heritage from a sustainability perspective. Neither a strictly preservative approach, neglecting each opportunity for reuse of or public benefit from the building, nor the opposite perspective of extensive economic exploitation of the building itself seems to be sustainable from a mid-term perspective. On the contrary, an effective strategy for sustainable restoration of cultural heritage shall consider: (a) functional compatibility evaluation between the expected use and the historical building itself; (b) long-term sustainability, via the minimization of conservation actions trough a comprehensive monitoring strategy, which is aimed at planned preservation of the cultural heritage; (c) performance optimization of the building envelope, from the perspective of energy efficiency increase.

In the outlined context, the case of university buildings in historic centers is particularly interesting. Among public buildings, in fact, the largest portion are educational buildings, which are also the most significant in terms of energy need [37]. University buildings are extremely interesting, because they are strongly differentiated according to the period of construction, the architectural form, user profiles and their connected uses (classrooms, libraries, offices, conference rooms, laboratories, bars, refectories, gyms). Moreover, universities in Europe have often developed in close connection with the cities which host them, becoming an important part of the cultural heritage of the counties.

University building stocks constitute a stimulating test field in order to assess decision-making aimed at enhancement processes. This is particularly true in the cases of historical universities, which are characterized by significant architectural heritage in close contact with the urban landscape and are subjected to pressures that mix conservative and transformative interests. Two opposite forces can generate interest in the transformation of the university's historical assets. The first, internal, strives for performative and legislative adaption in order to satisfy contemporary teaching needs. The other, coming from the outside, is linked to external potential stakeholders, which are not necessarily interested in the educational use, but can represent other policies of enhancement of the heritage [38]. This complex framework generates a proper challenge in order to understand which alternative is preferable with a view to sustainable enhancement.

A coherent long-term strategy which takes into consideration all of these three actions may achieve an improvement of the global efficiency of university settlements in historical contexts, which may be considered a strategic asset of the university from at least four different perspectives: (a) it is a cultural asset, as a huge number of these buildings have historical value and are submitted to specific national conservation rules; (b) it is a social asset, as it is the physical space where all the categories of university users spend their time, and their level of functional adequacy and conservation influences the evaluation of the perceived quality of the users; (c) it is a financial asset, due to the huge amount of financial resources required for ordinary maintenance, for energy-related costs, and for the relevance of restoration expenses required for specific projects (it is possible to determine at least three integrated actions to optimize the huge amount of financial resources usually required for this kind of building management policy: (i) reduction of energy consumption by means both of energy retrofitting and more effective plant maintenance; (ii) improvement of cost/effectiveness ratio of ordinary maintenance procedures and interventions; and (iii) development of an integrated information system oriented to predictive and continuous conservation procedures); (d) it may be considered as a scientific asset, if historical real estate properties are seen as open-air laboratories for advanced research in the field of building technologies.

The present research fits into this methodological framework by proposing an applicative tool able to offer a multi-disciplinary knowledge base aimed at supporting visualization and communication of energy-related data and to stimulate informed decision-making. As already mentioned, in the recent past, both academic studies and European projects have tried to give a general answer to the specific problem of energy and performance improvement of historic buildings, some of them deepening the case of public [39] or university buildings [36]. However, effort to find a standardized and repeatable methodology for assessing and enhancing the efficiency of the built heritage often clashes with the characteristic of uniqueness that distinguishes this kind of building. In this sense, the challenge of the presented work was to identify the delicate equilibrium that should guide the design of the applicative tools, to make them effective when applied to the huge variety of public historic buildings. Despite their important value, previous studies established methodologies with two main drawbacks: they are either too broad to describe the assortment of heritage buildings—in this case, the desire to be universal causes a loss of specificity, as happens when reference buildings are substituted for real ones—or too specific to be comprehensive—as in the case of those studies that try to extract general methodologies, starting from single case studies and moving forward through bottom-up approaches.

In contrast, with the aim of defining a repeatable approach suitable for many use cases, the present research takes advantage of shared and widely diffused input data sets, data models and languages in all stages of its development, achieving a multi-scale methodology that can be exploited both for broad and detailed analyses. The choice of referring to standard information structures, in fact, limits to the minimum the subjectivity and ensures full reusability of the connected tools.

## 5. Conclusions

This research presents an innovative workflow able to integrate GIS and BIM with the final aim of defining a multi-scale database for the visualization and analysis of the energy behavior of buildings within historic contexts. It gives an easy-to-use tool to administrations to manage a wide variety of multi-disciplinary and multi-scale information in a single platform, ensuring data integrity and consistency. Moreover, it can be used to collect and present in a simple way the most complex information that characterizes public historic buildings, since they are subject to specific regulatory requirements and more complex management. The methodological advantages are:

- A multi-scalar approach, due to mutual influence between the urban contexts and the buildings within the theme of energy efficiency;
- Inclusiveness, because from a community perspective it is useful to design tools able to communicate energy related issues to both technical and final users.

Along with the presentation of the operative workflow supported by a series of IT tools, a methodological framework is presented, with the idea that synergy between theory and practice can lead to major advantages.

In order to highlight the benefits of the process, a case study of the built heritage owned by the University of Pavia was considered. The availability of a complete data set within a structured database demonstrates the data access and analysis possibilities. Three possible outputs are presented: the geolocation of the EPCs (Energy Performance Certificates) within historical centers, the visualization of the thermal and electrical demands of the buildings in specific stocks, and the summary sheet use, referred to single buildings and their components. The outcomes demonstrate the strength of the approach, since it is proved that working on a central data source ensures the consistency of the results, regardless of the heterogeneity of the analysis to be performed.

In future works, the intention is to expand the database by including detailed models (CityGML LOD 3 and 4) of all the buildings owned by the University of Pavia, and to provide the technical office with a complete informative tool on the built asset it manages. Moreover, a thematic integration is also desirable. The whole system, in fact, is planned to work as a modular structure, able to attach to the central database different modules regarding various knowledge domains. In this idea, new units supported by the respective ADEs could represent information with a relation to other fields of facility management (cleaning and security services, risk management, etc.) or sustainability (mobility, waste management, etc.).

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