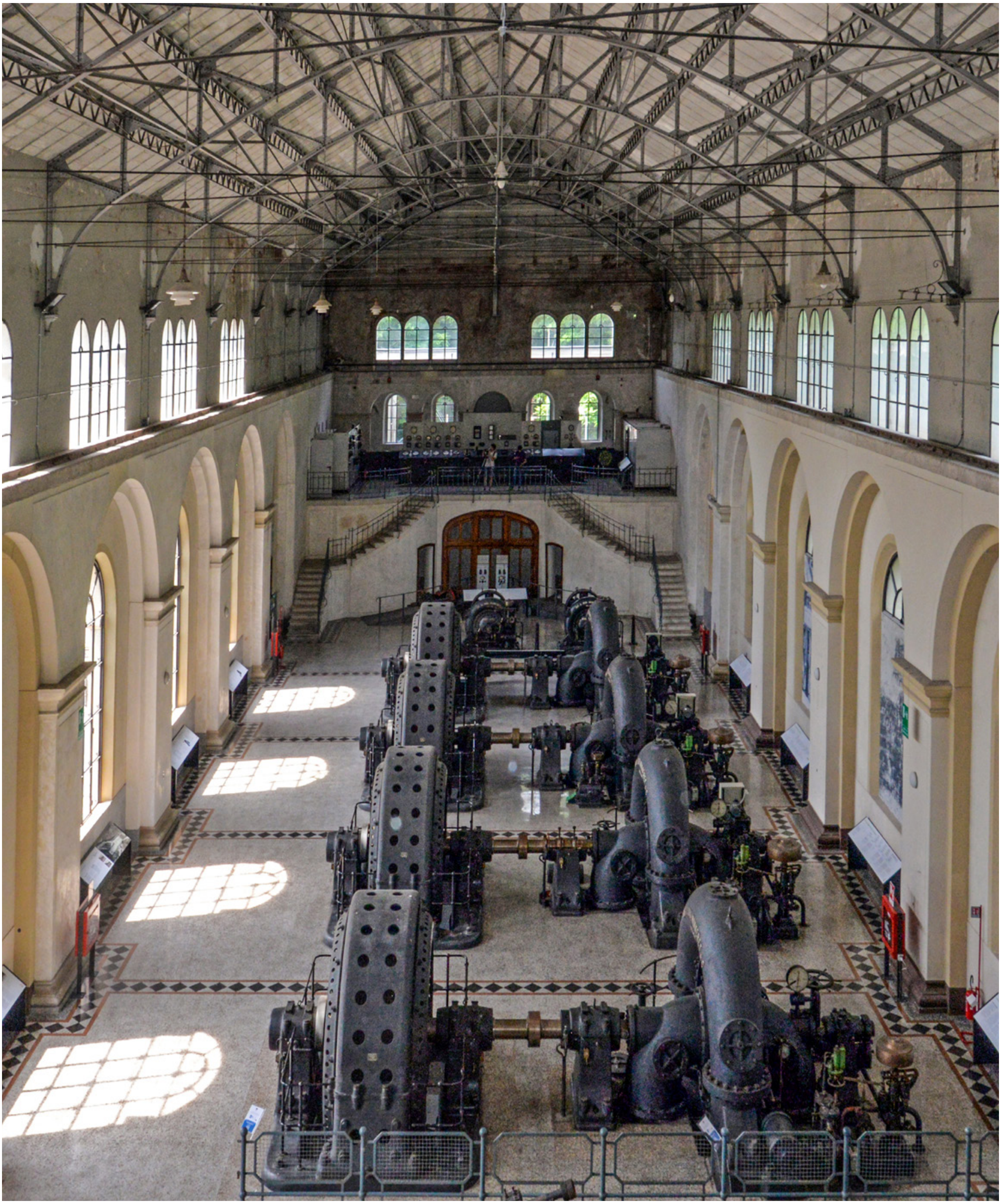

TEMA
Technologies
Engineering
Materials
Architecture

Journal Director: R. Gulli

e-ISSN 2421-4574

Vol. 7, No. 2 (2021)

Issue edited by Editor in Chief: R. Gulli

Cover illustration: Antonio Pitter power plant, interior view (Malnisio). © Francesco Chinellato, Livio Petriccione, 2019

Editorial Assistants: C. Mazzoli, D. Prati

TEMA
Technologies
Engineering
Materials
Architecture

e-ISSN 2421-4574
Vol. 7, No. 2 (2021)
Year 2021 (Issues per year: 2)

Editor in chief
Riccardo Gulli, Università di Bologna

Assistant Editors
Annarita Ferrante – Università di Bologna
Enrico Quagliarini – Università Politecnica delle Marche
Giuseppe Margani – Università degli Studi di Catania
Fabio Fatiguso – Università Politecnica di Bari
Rossano Albatici – Università di Trento

Special Editors
Luca Guardigli – Università di Bologna
Emanuele Zamperini – Università degli Studi di Firenze

Associated Editors
İhsan Engin Bal, Hanze University of Applied Sciences – Groningen
Antonio Becchi, Max Planck Institute – Berlin
Maurizio Brocato, Paris – Malaquais School of Architecture
Marco D'Orazio, Università Politecnica delle Marche
Enrico Dassori, Università di Genova
Vasco Peixoto de Freitas, Universidade do Porto – FEUP
Stefano Della Torre, Politecnico di Milano
Marina Fumo, Università di Napoli Federico II
José Luis Gonzalez, UPC – Barcellona
Francisco Javier Neila Gonzalez, UPM Madrid
Alberto Grimoldi, Politecnico di Milano
Antonella Guida, Università della Basilicata
Santiago Huerta, ETS – Madrid
Richard Hyde, University of Sydney
Tullia Iori, Università di Roma Tor Vergata
Raffaella Lione, Università di Messina
John Richard Littlewood, Cardiff School of Art & Design
Camilla Mileto, Universidad Politecnica de Valencia UPV – Valencia
Renato Morganti, Università dell'Aquila
Francesco Polverino, Università di Napoli Federico II
Antonello Sanna, Università di Cagliari
Matheos Santamouris, University of Athens
Enrico Sicignano, Università di Salerno
Claudio Varagnoli, Università di Pescara

Editorial Assistants
Cecilia Mazzoli, Università di Bologna
Davide Prati, Università di Bologna

Journal director
Riccardo Gulli, Università di Bologna

Scientific Society Partner:
Ar.Tec. Associazione Scientifica per la Promozione dei Rapporti tra Architettura e Tecniche per l'Edilizia
c/o DA - Dipartimento di Architettura, Università degli Studi di Bologna
Viale del Risorgimento, 2
40136 Bologna - Italy
Phone: +39 051 2093155
Email: info@artecweb.org - tema@artecweb.org

Media Partner:
Edicom Edizioni
Via I Maggio 117
34074 Monfalcone (GO) - Italy
Phone: +39 0481 484488

TEMA: Technologies Engineering Materials Architecture
Vol. 7, No. 2 (2021)
e-ISSN 2421-4574

DIGITAL MODELS FOR DECISION SUPPORT IN THE FIELD OF ENERGY IMPROVEMENT OF UNIVERSITY BUILDINGS

TEMA
Technologies Engineering Materials Architecture
e-ISSN 2421-4574
Vol. 7, No. 2 - (2021)

Cristina Cecchini, Marco Morandotti

DOI: 10.30682/tema0702h

Highlights

In this research, the opportunity of integrating GIS (Geographic Information System) and BIM (Building Information Modeling) is exploited to obtain a multi-scale spatial database capable of interfacing with innovative IT (Information Technology) methodologies to support decision-making in energy efficiency. The paper discusses the methodology and shows its application to a case study related to university buildings.

Abstract

According to the most recent provisions of the European Union, public buildings should play an exemplary role in sustainable development, adopting accelerated renovation rates aimed at improving their energy performance.
Within this category, university buildings are a case study of great interest to experiment with new approaches for energy refurbishment and sustainable management of architectural assets. The research presents a workflow that originates from easily available input data, to reach the definition of a multi-scale spatial database, founded on the synergy between GIS (Geographic Information System) and BIM (Building Information Modeling) and defined according to standard and shared data models. Tools of this kind are crucial for promoting efficient information management building assets, by organizing data into navigable three-dimensional models. In addition to the clear benefits associated with structured archiving, the provision of a relational database makes it possible to capitalize on the already available knowledge and to activate decision support tools for comparative assessment of transformation scenarios. In particular, the use of the cost-optimal methodology is proposed: it is a multi-criteria assessment aimed at identifying a set of optimal energy refurbishment solutions concerning energy consumption and management costs. The paper presents the methodological framework and examines its application at different scales, from the case of the University of Pavia real estate asset to the application to a single building complex.

Keywords

Public buildings, Multi-scale energy modelling, Energy-oriented management, Spatial relational database.

Cristina Cecchini*
DICAR - Dipartimento di Ingegneria Civile ed Edile, Università degli Studi di Pavia, Pavia (Italy)

Marco Morandotti
DICAR - Dipartimento di Ingegneria Civile ed Edile, Università degli Studi di Pavia, Pavia (Italy)

** Corresponding author:*
e-mail: cristina.cecchini01@universitadipavia.it

1. INTRODUCTION

The improvement of energy performances of public buildings is nowadays among the priorities in the policies for sustainable growth. Therefore, the activation of an accelerated renewal process for public buildings is encouraged by the European Union, entrusting the category with an exemplary role in its development framework. In this context, the built heritage of historic universities constitutes a case study of great interest for experimenting with new approaches aimed at energy efficiency. In fact, among public buildings, those devoted to educational use have the greatest impact in terms of floor area and energy needs [1]. Among them, university buildings represent particularly stimulating examples due to the large variety of construction periods, formal configurations and intended uses.

At present, university complexes are subject to two contrasting forces that direct their development scenarios: one internal, which pushes towards performance and regulatory adaptation in order to meet quickly increasing requirements of their users, and another external, which sees buildings as public goods, placing the interest of protection and enhancement before those of carrying out educational functions [2]. Because of this, intending to promote effective and sustainable management strategies, it may be useful to define a multidisciplinary method, based on three mutually influencing theoretical principles: functional adequacy, life cycle perspective and energy saving.

The research presents a methodology for organizing knowledge on university real estate assets with particular reference to the theme of energy behavior. As a result, a decision support system is defined upon the collected data, to achieve a preliminary evaluation of possible sustainable development options. The study will be organized in two consecutive parts: the definition of a spatial database designed to capitalize the information already acquired on university buildings and the implementation of the cost-optimal methodology for the comparative assessment of transformation scenarios in a life-cycle oriented perspective.

To test and validate the methodology, an application is presented on the case study of Palazzo San Felice, an architectural ensemble located in the historic center of Pavia and currently used by the University, which complex construction history dates back to the 10th century A.D.

2. METHODOLOGY

The research presented here focuses on the implementation of an integrated multi-scale methodology aimed at organizing knowledge on built heritage and supporting the decision-making phases for the improvement of energy performances. With this aim, it has been designed a workflow that makes joint use of GIS (Geographic Information System) and BIM (Building Information Modeling), which are integrated into a spatial database based on CityGML (City Geographic Markup Language) (Fig. 1). CityGML is an XML-based, open, and extensible standard promoted by the OGC (Open Geospatial Consortium) for modelling, storing, and exchanging spatial data. Its main purpose is to provide a shared definition of objects, attributes, and relationships for the characterization of three-dimensional city models. With this aim, the data model organizes the information by describing the entities according to four different domains (geometric, semantic, topological and appearance properties) and includes the possibility of multi-scale representation thanks to its definition in five Levels of Detail (LOD) [3].

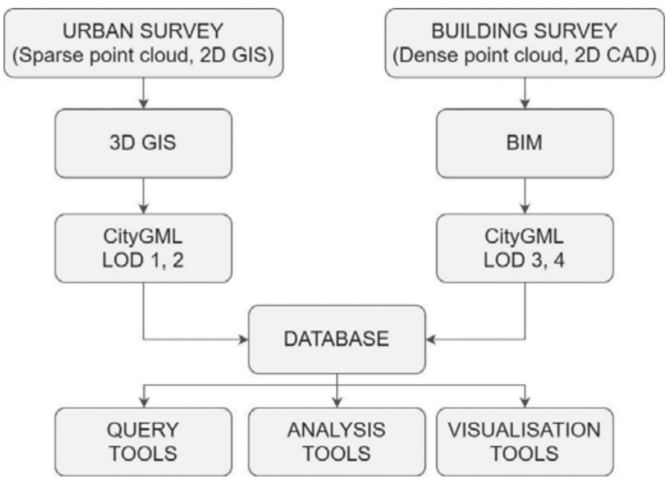

Fig. 1. *Proposed workflow for the definition of a multi-scale spatial database aimed at the management of technical information.*

CityGML is compliant with the ISO 19100 series of standards on geographic information, compatible with the European INSPIRE Directive [4] and suitable for interoperability with BIM thanks to the affinity of its semantic structure with IFC (Industry Foundation Classes), the open standard for Building Information Modeling. At present, the main fields of application of CityGML include urban planning, risk assessment and energy analysis, but some experiments have already been tested for its application to cultural heritage [5], although the opportunities in this field of investigation have not yet been adequately exploited. Since the standard was not originally designed to deal with built heritage, it is possible to identify some deficiencies of the scheme relating to this application. However, its extensibility feature allows the definition of thematic expansions (Application Domain Extension - ADE), which can be used to adapt the schema to specific knowledge domains [6].

2.1. DATABASE DEFINITION

To reach the definition of a multi-scale information database, it is crucial to acquire and harmonize input data at different scales. This is not trivial, since diverse representations of the built environment may reflect specific approaches in its analysis, which don't always ensure the compatibility of information. Moreover, to guarantee the repeatability and transferability of the tool in the European context, particular attention should be paid to the availability of input data in most of the Member States.

At the urban level, the main source of information used here consists of two data sets: two-dimensional vector cartography including the footprints of the buildings and a low-density point cloud derived from air LiDAR (Light Detection and Ranging) surveys. The combination of these two information layers, processed within GIS software, allows the reconstruction of three-dimensional city models at a low level of detail [7]. The 3D GIS thus created can be transformed into a CityGML model, thanks to the use of Visual Programming Language scripts (VPL). In this experience, the rough 3D GIS was manipulated with Safe FME, a powerful application for the conversion of data models, which allowed to recreate the semantic structure of CityGML [8]. Consistently with the amount of information considered at this stage, the CityGML model created from the three-dimensional GIS meets the requirements of the lowest Levels of Detail (LOD1 and LOD2), which are useful for contextualizing the area of interest.

To complete the information system with a detailed representation of the selected buildings, it is necessary to acquire more accurate data both in terms of geometry and information. With this aim, tools that are more concerned with the building scale, such as BIM authoring software, should be adopted. For the definition of the 3D models, traditional surveys (consisting of two-dimensional representations such as plans, sections, elevations, etc.) and digital surveys (composed of high-density point clouds, acquired with terrestrial LiDAR technology) were considered. With relation to non-graphical information, thermal and energy aspects related to the building envelopes were derived from Energy Performance Certifications (EPC) and Energy Audits, both strategic tools promoted by the European Union for improving energy efficiency in urban frameworks [9].

At the end of the modelling phase, once again the data need to be converted to CityGML. The task takes place again employing VPL, but the similarity between the schemes of IFC and CityGML allows a simpler procedure than in the previous case. A new CityGML model for each building is integrated into the broader one, constituting the LOD3 and LOD4. By doing this, the whole model is characterized by a loose representation of the context with punctual insights focused on the University built asset. This scheme is meant to support both large-scale urban analyses and more detailed investigations on specific buildings.

Within the CityGML, spatial and thematic information is stored and organized according to a shared data model. However, to ensure a wider application of the system, it is useful to transfer the content of the digital representation into a proper relational database. In this study, the open DBMS (DataBase Management System) PostgreSQL with the PostGIS plug-in for the management of spatial data was used. The logical scheme of the database consists of the CityGML structure itself plus an ADE specifically designed to support decision-making processes involving energy efficiency. With reference to already published

ADEs on energy behavior of buildings [10] and cultural heritage [11], the extension of the scheme implicates the addition of a set of attributes in the Building thematic module. Since the data structure of the CityGML model and that of the Database are identical, the information is in a one-to-one relationship and the data transfer can take place without the need for any further adaptation.

2.2. APPLICATION OF DECISION SUPPORT TOOLS

The provision of an organized database on university built assets makes it possible to deepen the understanding of buildings behavior and to simulate transformation scenarios, bringing clear advantages to the related building processes in terms of reproducibility of analysis and transparency of results. To clearly show an example of this, an already codified decision support procedure was implemented by linking the database to a calculation engine.

The cost-optimal methodology is a calculation process for the evaluation of the optimal levels of energy performances as a function of operating costs, introduced by the European Directive 2010/31/EU [12] and specified in the following Delegated Regulation (EU) No. 244/2012 [13]. It consists of the combination of two separate analyses, aimed at identifying groups of optimal development scenarios in a life-cycle perspective:

- an economic evaluation: estimation of the overall cost of energy management in the calculation period in terms of Net Present Value (NPV), as reported in the standard UNI EN 15459:2008. In the case of public buildings, the macroeconomic scenario is applied, by considering initial investments, energy costs, monetization of CO_2 emissions, all energy-related management costs (maintenance, replacement, disposal, and residual value of building components) and possible earnings deriving from the sale of on-site produced energy through renewable sources;
- an energy assessment: calculation of the global energy requirement, performed according to the scheme of the international standard UNI EN 15603:2008, with reference to UNI TS 11300 series for Italy. The energy consumption for each end-use (heating, cooling, domestic hot water, lighting, and ventilation) and energy source must be calculated, taking into account the efficiencies of the plant subsystems and the on-site production of energy from renewable sources.

The cost-optimal methodology was originally developed to estimate the optimal performance levels with relation to operating costs, with the aim of giving the Member States a calculation method to define their minimum energy requirements. However, it was soon transferred within the academic field to be used as a comparative assessment tool for the evaluation of building refurbishment scenarios. For the selection and composition of possible alternative design choices, the procedure implemented here refers to a best practice deriving from literature, which operates in two steps by identifying Energy Refurbishment Solutions (ERS) (Fig. 2a) to be aggregated in Energy Scenarios (ES) (Fig. 2b) [14]. In this approach, ERS are elementary technical solutions referred to individual building element classes (for instance, realization

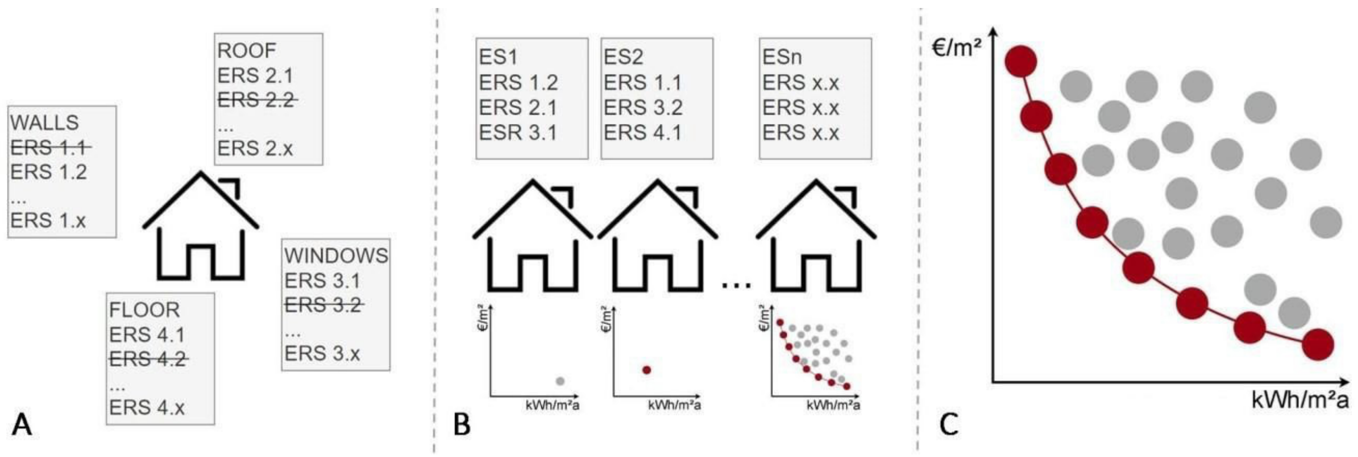

Fig. 2. *Three-phase implementation scheme of the cost-optimal methodology.*

of a thermal coat or substitution of existing windows), while ES are all the possible combinations of ERS, aggregated to create more complex case studies. The optimization process iterates the calculation for each scenario to identify pairs of values to be represented as points in the cartesian plane "Overall cost (€/m^2)/Energy requirement (kWh/m^{2}y)". The resulting graph allows the identification of the so-called Pareto Frontier, where the equally optimal solutions lie (Fig. 2c). Since no weights are given to the two criteria, the result does not lead to the univocal identification of an ideal scenario but, on the contrary, the graphical representation allows to appreciate a set of alternatives that cannot be further improved (non-dominant points), among which the stakeholders will be able to choose on the basis of wide range reasoning, activating the proper decision-making phase of the process.

In the proposed case study, the energy analysis prescribed by the cost-optimal methodology is shortened, limiting the calculation to the energy contribution necessary for heating in the winter season. The result is the ideal thermal energy requirement for heating Qh,nd (kWh), in which the heat exchange losses due to transmission (Qh,tr) and ventilation (Qh,ve) and the internal (Qint) and solar (Qsol) loads are calculated and weighted on the utilization factor (ηh,gn). The simplification does not concern methodological aspects and has been chosen to obtain comparable results with reference to the energy audits commissioned by the University of Pavia in 2016, which outcome is the calculation of the ideal thermal energy requirement for heating for all its buildings.

Within the interoperable process presented here, the extraction of the data for the development of the cost-optimal methodology takes place directly from the database using queries formulated in SQL (Structured Query Language). The resulting information matrices are then processed with the software Simulink Matlab, which is used for the computational phase.

3. CASE STUDY

Founded in 1361, the University of Pavia is the third oldest in Italy, and its history is closely intertwined with the events that shaped the city of Pavia over the centuries. The University owns and manages a vast and varied real estate portfolio, consisting of 230000 m^2 of built area divided between: 77000 m^2 of listed architectural assets located in the historic center, 60,000 m^2 built before 1940, and 85000 m^2 included in the most recent expansion area of the city [15].

The experimental phase starts from the definition of a database representing the historic center of Pavia using a CityGML LOD1 and LOD2 model, and subsequently deepens the knowledge of the University buildings located in the area (Fig. 3) [16].

Fig. 3. *The informative model of the historic centre of Pavia, with the University buildings highlighted.*

In this context, one of the most interesting buildings is Palazzo San Felice: a former monastic complex currently used by the Department of Economics and Business Sciences and the Department of Psychology. The history of the building is long and intricate [17] (Fig. 4a). The most remote traces date back to the 10th century A.D. and are still standing in some parts of the church. In medieval times, the structure of the monastic complex is not easily understandable, due to the lack of graphic documentation that lasted until the 17th century. However, it is known that at the end of the 15th century an important renovation involved the whole building, also leading to the construction of the porticoed cloister adjacent to the church. During the 18th century, the expansion continued with the construction of the refectory overlooking the eastern side of the cloister, while in the following century the complex extended towards the west, with a new wing that included an octagonal chapel dedicated to the Madonna. The religious history of the building ended in 1785, when the monastery was suppressed and, shortly after, the architect Leopoldo Pollack was commissioned to transform the complex into an orphanage. The works, completed in 1792, involved a huge enlargement of the building, which was enriched by two other cloisters expanding to the east. During the 19th century, several minor interventions followed one another until the restoration driven by the architect Emilio Aschieri, who removed most of the incoherent additions. In 1980 the University of Pavia acquired the complex, foreseeing to transfer here the Faculty of Economics. This change of ownership coincided with major renovations

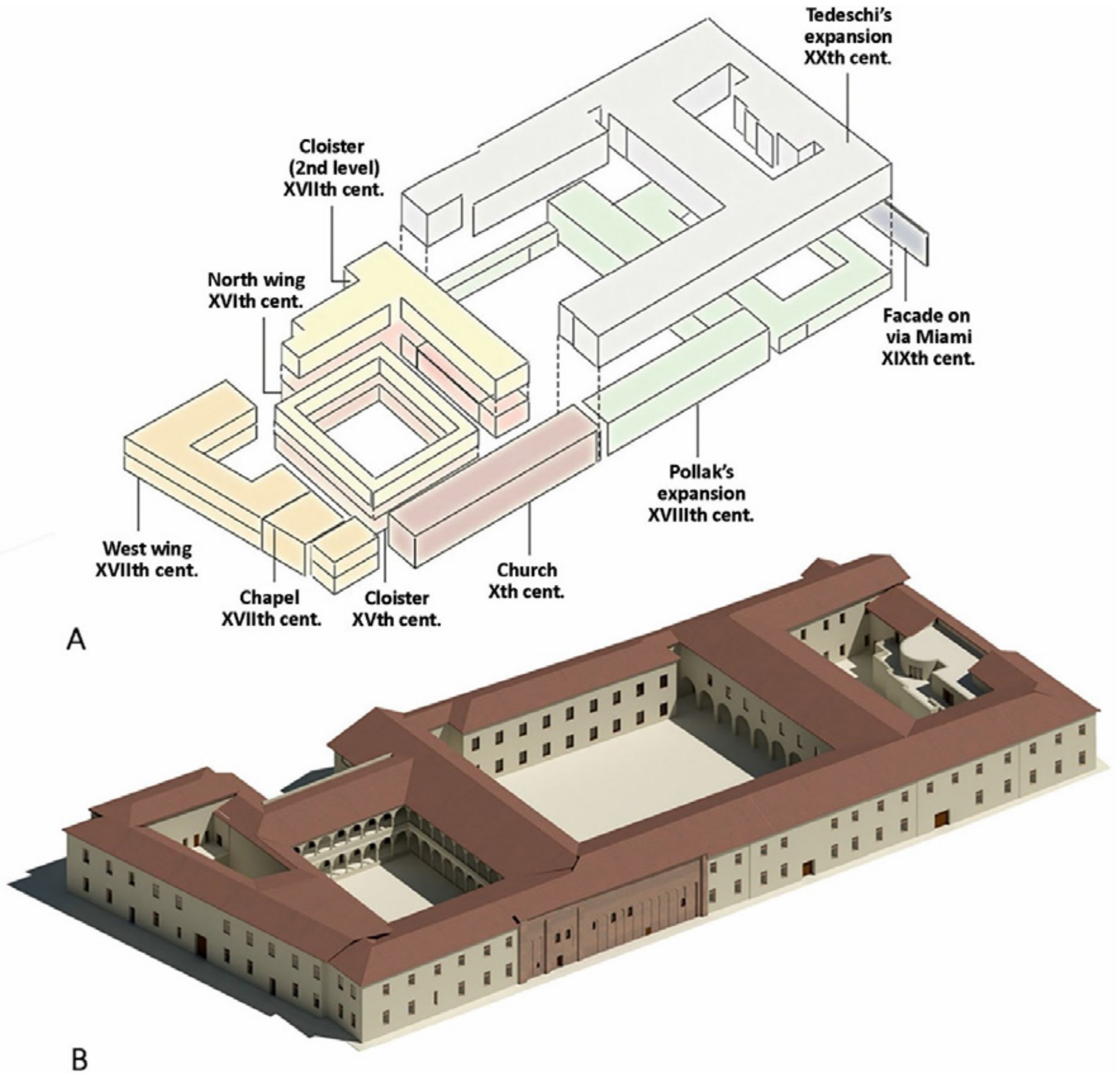

Fig. 4. *Volumetric representation of the construction phases (2018, Bolognesi, G. [17]) and axonometric view of the BIM model of Palazzo San Felice.*

led by architect Eugenio Gentili Tedeschi, which included the construction of a new level above the part previously built by Pollack.

For the application of the methodology, the building was modelled with Autodesk Revit 2018 (Fig. 4b), using different versions of surveys that have followed one another over the years. Thermal and energy characteristics were obtained from the energy audits commissioned by the University in 2016 and included in the model. From the technological point of view, the historical events that characterized the construction led to the generation of a heterogeneous complex. The structure is generally made up of non-insulated masonry with variable thicknesses, while the roof presents a wooden structure covered with tiles, built above a series of unheated attics. The ceilings are characterized by vaulted brick structures in the oldest parts and brick-concrete floors in the most recent portions. The transparent surfaces are mainly double-glazed wooden-framed with a minor presence of PVC- framed windows. For the energy calculation, the thermal characteristics shown in Table 1 were considered.

As specified by the workflow, the BIM model was converted into its CityGML LOD3 and LOD4 twin, and the information was transferred within the database. The input data for the activation of the cost-optimal procedure were extracted from the BIM and organized thanks to the definition of specific attributes identified with the ADE. The calculation parameters were largely derived from the report published by ENEA entitled "Development of the cost-optimal comparative methodology according to Directive 2010/31/EU", the main guidelines for the adaptation of the procedure to the Italian construction market [18]. In detail, the quantities shown in Table 2 are assumed.

The selection of the ERS deemed admissible on Palazzo San Felice was a particularly delicate operation, as it is a listed historical building, characterized by a complex stratification of construction phases. Among the scientific community the theme of transformability judgment is a debate still open, especially when applied to built heritage and, despite several methodological frameworks that have been tested [20], a standard approach

Dexcription	*Thickness [m]*	*Transmittance [W/m²K]*	*Superficial mass [kg]*	*Periodic transm. [W/m²K]*	*Attenuation factor [/]*
External walls	0.75	0.77	1200	0.006	0.008
Walls towards cold rooms	0.75	0.974	1484	0.007	0.007
Floors towards cold rooms	0.32	1.388	606	0.223	0.161
Inter-storey floors	0.32	1.395	606	0.222	0.159
Ceilings toward attic	0.32	1.695	592	0.395	0.233

Tab. 1. *Thermal characteristics of the technical elements of the envelope of Palazzo San Felice.*

Parameter	*Value*	*Source*
Calculation period	20 years	Report RdS/2013/144 [18]
Discount rate	3%	Report RdS/2013/144 [18]
Life span and operating costs of building components		Appendix A from EN 1549:2007
Unit cost of building components		Price list DEI "Recovery Renovation and Maintenance" (2018) [19].
Cost of natural gas	0.3265 €/m3	Economic conditions of the protected market published by ARERA (Autorità di Regolazione per Energia, Reti e Ambiente)
Annual growth rate of the cost of energy	2.8%	Processing from Report RdS/2013/144 [18]
Cost of CO2 emissions	29.95 €/ton	Processing from Report RdS/2013/144 [18]

Tab. 2. *Parameters assumed for the calculation in the cost-optimal methodology.*

ID	*Energy efficiency measure*	*Technical element*	*λ [W/mK]*	*s [m]*	*Fsh,gl [/]*	*Unit cost [€/m²]*
2.4	Thermal plaster	External walls	0.47	0.02	1	60.05
8.1	EPS insulation	Ceilings towardattic	0.033	0.03	1	16.83
8.2	XPS insulation	Ceilings towardattic	0.034	0.03	1	10.19
8.3	Fiberglass insulation	Ceilings towardattic	0.036	0.05	1	6.67
9.1	Polyurethane insulation	Flat roof	0.028	0.03	1	15.00
9.2	XPS insulation	Flat roof	0.034	0.03	1	10.88
9.3	Rock wool insulation	Flat roof	0.036	0.05	1	26.45
ID	*Energy efficiency measure*	*Technical element*	*Uw [W/m²K]*	*g [/]*	*ε [/]*	*Unit cost [€/m²]*
13.4	New double glazing windows	External window	2.8	0.8	0.85	598.77
13.5	New double glazing windows with low E treatment	External window	1.58	0.6	0.2	699.77

Tab. 3. *Main characteristics of the energy efficiency measures considered for Palazzo San Felice.*

hasn't been recognized yet. From an literature analysis, it is clear that the application of systematic procedures for the recognition of feasible interventions on cultural heritage entails risks, which are related to an excessive flattening of the peculiar characteristics of this kind of structures. Therefore, given that each historic building is unique, the safest approach seems to be a case-by-case evaluation supported by multidisciplinary examinations, including historical, technological, and structural assessments [21].

For the energy refurbishment of Palazzo San Felice, the investigation phase led to the selection of a limited number of measures, to be applied mainly to the most recent parts or to those elements that have already been modified over time, as reported in Table 3. The physical properties and the unit costs reported in the table come from the ERS catalogue presented in [18] as a reference for the Italian framework, with the foresight of updating the cost items according to a more recent price list [19].

4. RESULTS

Based on the input data, the calculation engine processes 95 Energy Scenarios, which are represented on the cartesian plane as shown in Figure 5. In the image, the green point (0) is the unaltered state, the red marks are the ERS (with the relative ID code) and the grey ones are the possible combinations of ERS in more complex ES. Despite there is a wide margin for energy improvement, it is easy to notice that, in the given calculation period, it is rare to reduce the energy management costs. This is generally due to high investment costs, whose payback time is longer than 20 years.

Deepening the analysis, by dividing the possible interventions according to the class of technical units to which they refer, we can observe that:

- where it is possible to apply a thermal plaster, the refurbishment of the facades (ERS 2.4) involves an increase of the operating cost, compared to a small improvement in energy behavior;
- the insulation of the last floor towards the unheated attics (ERS 8.1, 8.2, 8.3) generates an advantage both in terms of energy-saving and global cost. In particular, the use of rock wool panels seems to be the most

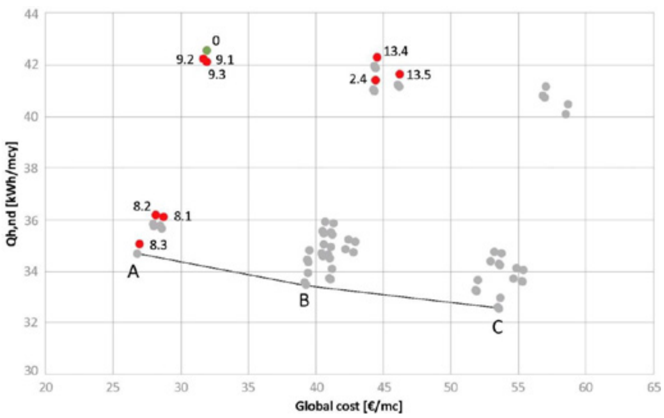

Fig. 5. *Global cost/energy requirement graph resulting from the application of the cost-optimal methodology to Palazzo San Felice.*

convenient solution, despite being associated with the highest unit cost;
- the insulation of the flat roof (ERS 9.1, 9.2, 9.3) produces an improvement in the performance of the building envelope, but the small available surface makes the effect barely significant;
- replacing the windows with more performing ones (ERS 13.4, 13.5) is an expensive measure with limited benefit, since the existing ones have already good thermal characteristics.

In the solution of the specific multi-criteria problem, the Pareto frontier identifies three distinct classes of results:

1. Best solutions in terms of costs: insulation of the last floor towards the attic with glass wool (ERS 8.3) and insulation of the flat roof with XPS panels (ERS 9.2).
2. Best cost/benefit balance: refurbishment of non-historic facades with the thermal plaster (ERS 2.4), insulation of the last floor towards the attics with fiberglass (ERS 8.3) and insulation of the flat roof with polyurethane panels (ERS 9.1).
3. Best solutions for energy saving: refurbishment of non-historic facades with thermal plaster (ERS 2.4), insulation of the last floor towards the attics with fiberglass (ERS 8.3), insulation of the flat roof with rock wool (ERS 9.3) and replacement of existing windows with new ones (ERS 13.4).

5. CONCLUSIONS

The research presents a workflow for the construction of a spatial database aimed at enhancing information management processes on architectural heritage, with a particular focus on the case of university assets. The organization of information according to a standard scheme allows the capitalization of the existing knowledge on the assets and facilitates the activation of decision support systems, useful for promoting sustainable management and development.

For the University of Pavia, the provision of a three-dimensional navigable platform collecting the energy-data available on its real estate asset is an important tool, which can be primarily used as a vehicle of communication both in the context of technical desks then for sharing information with final users. Similarly, the possibility of deepening the information content for some buildings and the application of cost/benefit assessments methods are precious, giving instruments capable of guiding building processes, ensuring repeatability of analyses and transparency of results. The experience on Palazzo San Felice provides evidence of the functioning of the proposed methodology and produces appreciable outputs, although the type of building does not allow to test a wide range of technical solutions. As a result, in relation to the two criteria assumed in the assessment, some groups of cost-effective strategies are identified and compared. This outcome constitutes an important element for the development of an effective decision-making process, in which a wider set of quantitative and qualitative parameters should be considered with the aim of representing all the values involved.

Future developments on this research intend to extend the investigation to other buildings of the University of Pavia, with the aim of evaluating the effects of the applications to highly heterogeneous architectural complexes. Furthermore, the inclusion of the characteristics of HVAC (Heating, Ventilation and Air Conditioning) systems in the calculation is envisaged. In fact, this aspect is seen as a determining factor for the estimation of the overall behavior of the building, which can provide interesting results especially when the admissible interventions on the envelope are limited, as in the case of cultural heritage.

6. REFERENCES

[1] Radulov L, Kaloyanov N, Petran H (2014) D2. 1 report on the preliminary assessment of public building stock. http://www.republiczeb.org/filelibrary/WP2/D2-1Public-Building-Stock-final.pdf

[2] Morandotti M (2017) Resilience and memory. Notes for an approach to the sustainable transformability of immovable Cultural Heritage. In: Besana D [RICH*] reuse and improvement of cultural heritage. Aracne, Roma, pp 55–74

[3] Kolbe TH, Gröger G Plümer L (2005) CityGML: Interoperable access to 3D city models. Geo-information for disaster management: 586–593

[4] European Parliament "Directive 2007/2/EC of the European Parliament and of the Council of 14 March 2007 establishing an Infrastructure for Spatial Information in the European Community (INSPIRE)", OJ L 108:1–14, 2007

[5] Gröger G, Plümer L (2012) CityGML–Interoperable semantic 3D city models. ISPRS Journal of Photogrammetry and Remote Sensing 71:12–33

[6] Biljecki F, Kumar K, Nagel C (2018) CityGML application domain extension (ADE): overview of developments. Open Geospatial Data, Software and Standards 3:13

[7] Macay Moreia JM, Nex F, Agugiaro G, Remondino F, Lim NJ (2013) From DSM to 3D building models: a quantitative evaluation. ISPRS-International Archives of the Photogrammetry. Remote Sensing and Spatial Information Sciences 1:213–219

[8] Cecchini C (2019) From data to 3D digital archive: a GIS-BIM spatial database for the historical centre of Pavia (Italy). Journal of Information Technology in Construction (ITcon) 24:459–471

[9] BPIE. Energy Performance Certificates across the EU (2014) http://bpie.eu/wp-content/uploads/2015/10/Energy-Performance-Certificates-EPC-across-the-EU.-A-mapping-of-national-approaches-2014.pdf

[10] Agugiaro G, Benner J, Cipriano P, Nouvel R (2018) The Energy Application Domain Extension for CityGML: enhancing interoperability for urban energy simulations. Open Geospatial Data, Software and Standards 3(1): 2

[11] Noardo F (2018) Architectural heritage semantic 3D documentation in multi-scale standard maps. In Journal of Cultural Heritage 32:156–165

[12] European Parliament "Directive 2010/31/EU of the European Parliament on the Energy Performance of Buildings" Official Journal of the European Union, L153 13–35, 2010

[13] European Commission "Delegated Regulation (UE) N. 244/2012", OJ L 81, 18–36, 2012

[14] Guazzi G, Bellazzi A, Meroni I, Magrini A (2017) Refurbishment design through cost-optimal methodology: The case study of a social housing in the northern Italy. International Journal of Heat and Technology 35: S1 336–44

[15] Magrini A, Gobbi L, d'Ambrosio FR (2016) Energy audit of public buildings: the energy consumption of a University with modern and historical buildings. Some results. Energy Procedia 101:169–75

[16] Cecchini C, Magrini A, Gobbi L. (2019) A 3d platform for energy data visualization of building assets. IOP Conference Series: Earth and Environmental Science 296: 1

[17] Bolognesi G (2018) Palazzo San Felice: progetto di riqualificazione e studio dell'accessibilità. Master thesis in Building Engineering-Architecture

[18] Corrado V, Ballarini I, Ottati I, Paduos S (2013) Sviluppo della metodologia comparativa cost-optimal secondo Direttiva 2010/31/UE. Report RdS/2013/144

[19] DEI - Tipografia del Genio Civile (2018) Prezzario Recupero, Ristrutturazione, Manutenzione – october 2018

[20] Lidelöw S, Örn T, Luciani A, Rizzo A (2019) Energy-efficiency measures for heritage buildings: a literature review. Sustainable cities and society 45:231–242

[21] Mazzarella L (2015) Energy retrofit of historic and existing buildings. The legislative and regulatory point of view. Energy and Buildings 95:23–31