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Support Decision Tool for Sustainable Energy Requalification the Existing Residential Building Stock. The Case Study of Trevignano Romano

Fabrizio Cumo [1], Federica Giustini [1], Elisa Pennacchia [2,*] and Carlo Romeo [3]

[1] Interdepartmental Center for Territory, Building, Conservation and Environment, Sapienza University of Rome, Via A. Gramsci, 53-00197 Rome, Italy; fabrizio.cumo@uniroma1.it (F.C.); federica.giustini@uniroma1.it (F.G.)
[2] Department of Planning Design and Technology of Architecture, Sapienza University of Rome, Via Flaminia, 72-00197 Rome, Italy
[3] ENEA, Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Via Anguillarese, 301-00123 Rome, Italy; carlo.romeo@enea.it
* Correspondence: elisa.pennacchia@uniroma1.it

Abstract: The control and improvement of energy-environmental quality in buildings are responsible for almost 40% of the emissions related to energy and processes, and are essential to achieve the commitment of the Paris Agreement and the Sustainable Development Goals (SDGs) United Nations (UN). This paper provides a support tool to planners and administrators of the territory for the identification of interventions aimed at the energy requalification of the existing Italian building heritage, mainly for residential use. The purpose of this tool is to reduce energy consumption by intervening on the building envelope with specific solutions that are identified through a matrix resulting from the study. In the first part of the study, an analysis was carried out on various factors such as the existing residential building, the building and construction types and the materials of the envelope typical of each construction period, which are critical for energy efficiency issues. In the second part of the study, the analysis of the state of the art of the insulating materials existing on the international and national market was carried out, in order to standardize the efficiency interventions of the building envelope. By exploiting the potential of the proposed matrix, and integrating it with Geographic Information System (GIS) technology, it would be possible to create a database containing information regarding the characteristics of the building envelope of the residential building stock and to identify a set of insulation interventions more suited to each specific case near Rome, Italy.

Keywords: energy requalification; building envelope; sustainable development and planning; standardized interventions of requalification; Geographic Information System

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1. Introduction

Climate change is a major global phenomenon today. In recent decades, attention to the environment has grown more and more, in particular to global warming, which has caused enormous quantities of greenhouse gas emissions released into the atmosphere, deriving from anthropogenic activities that question natural balances. The environmental issue is closely linked to the energy issue, the way in which energy is produced, distributed and consumed. According to the IPCC (Intergovernmental Panel on Climate Change), the energy supply sector is the largest contributor to greenhouse gas emissions [1], which is one of the issues that must be addressed and solved in the short term to limit the damage caused to ecosystem and human health.

Global residential energy demand has steadily increased over the past decades [2].

The Global Status Report for Buildings and Construction 2019 highlights the importance of decarbonizing the building and construction sector to achieve the Paris Agreement commitment and the United Nations (UN) Sustainable Developments Goals (SDGs);

as these are responsible for nearly 40% of energy and related emissions process, taking climate action in buildings and constructions is among the most cost-effective method [3]. These data highlight the need to identify new strategies to make the construction sector more sustainable. Two-thirds (about 65%) of the European building stock was built before 1980; around 97% of the EU buildings need to be refurbished to reach the 2050 decarbonization target, but only 0.4–1.2% are updated every year [4].

In the Green Deal, Europe defines the improvement of the energy efficiency of buildings as the key to achieving the ambitious goal of eliminating carbon emissions by 2050. [5]. The EU Directives implementing the energy and climate package therefore promote an energy policy aimed at decarbonizing the economy in order to achieve the goal of climate neutrality by 2050.

Energy efficiency is an effective tool for implementing this policy and addressing the recent challenges of climate change due to the scarcity of resources, emissions of climate-altering gases and dependence on energy imports, mainly from non-renewable sources.

The term energy efficiency generically refers to the ability of a physical system to obtain a certain result using the least amount of energy compared to other less efficient systems, increasing its performance and consequently obtaining energy savings, lower costs and significant environmental benefits. The energy requalification of buildings and the rational use of energy in all phases of the construction process are key interventions in the latest international policy documents aimed at decarbonizing real estate assets by 2050, with intermediate stages in 2030 and 2040. For example, the European Directive 2018/844, which replaces the previous Directive 2010/31/EU on the energy performance of buildings and the Directive 2012/27/EU on energy efficiency, obliges Member States to develop long-term national strategies to promote the energy renovation of residential, non-residential, private and public buildings. The aim is to reduce emissions in the EU by 80–85% compared to 1990 levels, by promoting the transformation of existing buildings into nearly zero energy buildings (NZEB) [6]. The thermal performance of buildings determines the amount of energy used for heating and cooling buildings, which profoundly affects energy efficiency. Far and Far [7] state that the use of sustainable design principles and the effective use of building materials can play a crucial role in improving the thermal performance of new and existing buildings.

Several research activities have focused on the evaluation of the energy consumptions of existing buildings stock. Paraschiv et al. [8] highlighted that most of the energy saving potential, and therefore a possible reduction of greenhouse gas emissions is the thermal renovation of existing buildings, which require thermal efficiency improvements in order to reduce the heating needs of the building. According to the data for 2018 reported in [9], the residential sector accounted for 26.1% of final energy consumption, or 16.6% of gross inland energy consumption in the European Union. In particular, the main energy consumption in EU households is for heating their homes (63.6%) and space cooling (0.4%).

The energy performance of the entire building depends mainly on the efficiency of the envelope, which establishes the boundary between indoor and outdoor environments [10]. In particular, 50% of a building's total energy consumption for general use is dissipated through its envelope [11]. As clarified by Poel et al., [12] given the very low renovation rate of the building stock, the refurbishment of existing buildings can be a good solution to improve the environmental performance of the building sector. Numerous researches conducted in the field of energy efficiency have started from the study of the characteristics and conditions of the existing heterogeneous building stock, considering only stationary thermal transmittance values, in order to identify methodologies for evaluating the energy performance of the building stock, such as EPIQR [13], IFORE [14], SUSREF [15], TABULA [16] and others [17,18]. These renovation research projects do not assess the environmental sustainability of the proposed energy efficiency interventions. In recent years, social housing societies in Europe have presented and implemented many retrofitting projects. For example, various initiatives are currently underway in the Netherlands to explore the financial and energy bill consequences of insulating terraced houses up to Passivhaus Standards, and renewable energy technologies for domestic hot water and space heating. Garufi et al. [19] developed a decision support tool for sustainable renovation projects in the Dutch housing corporations, applicable to all building complexes with same archetype (terraced houses 1945–1965). This tool is intended to provide an estimate of the total investment and operating cost applicable in large scale projects involving terraced and non-residential houses.

Understanding the energy performance of existing buildings in an urban cell, an entire neighborhood or an entire municipality is very important for sustainable energy planning strategies aimed at accelerating the energy renewal process.

O' et al. [20] and Moghadam et al. [21] developed a methodology based on the use of tools in a Geographic Information System (GIS) platform, which allows a complete and low-cost picture of the energy performance of buildings. These methodologies are mainly based on the information that is already available on the building stock from data collection and literature (e.g., energy auditors, municipality technical department, web and others), which is subsequently transferred to the GIS.

That said, the recent literature on the subject has strongly focused on the performance of the components of the building envelope that degrades due to environmental conditions over time, and on the enormous potential for energy savings even with basic energy retrofit actions. The use of a GIS platform is limited to monitoring the energy consumption of buildings, but does not offer any indication on improvement measures to be implemented for each building [22].

In this paper, the authors propose and describe their tool to immediately identify the most suitable standardized insulated solutions for the building envelope, according to the age of construction, the building type and the construction type of the existing building in the Italian territory.

The solutions were chosen considering the entire production chain (design, production of components, assembly, installation, evaluation of energy, environmental, seismic and economic performance), in order to reduce the environmental impacts during the execution, management/maintenance and future disposal as much as possible.

The proposed methodology also provides for the georeferencing of existing building envelope types and related interventions to improve efficiency through a GIS platform. This system is proposed to facilitate compliance with the obligation to improve the energy performance of buildings imposed by current legislation. The methodology was developed by the research center of Sapienza University of Rome—CITERA, as part of the "Research of the Electricity System" program with ENEA and the Ministry of Economic Development on "Improving the energy efficiency of production processes and management of the built environment". In the end, from the literature review, it emerged how that most methodology concerning the energy efficiency of buildings did not include a study of insulation materials to make the production chain more efficient.

For that reason, the authors believe that their contribution to the knowledge in this topic consists of: the development of an abacus of standardized envelope modules as the basis of an industrial production process for Deep Renovation interventions in the national residential building stock; a tool for identifying the most effective insulation solution for each existing building; an integration of the solutions identified through the tool in the GIS platform to the geolocation of the improvement interventions to be carried out on the existing building heritage; and to record the interventions already carried out.

2. Materials and Methods

Improving the energy performance of production and management processes in the built environment by developing a catalogue of standard construction layouts for insulation systems to be applied to the vertical opaque envelope of existing buildings is the aim of the research.

An outline of the methodology developed to obtain a tool for the identification of the efficiency solution for the existing building envelope, is shown in Figure 1.

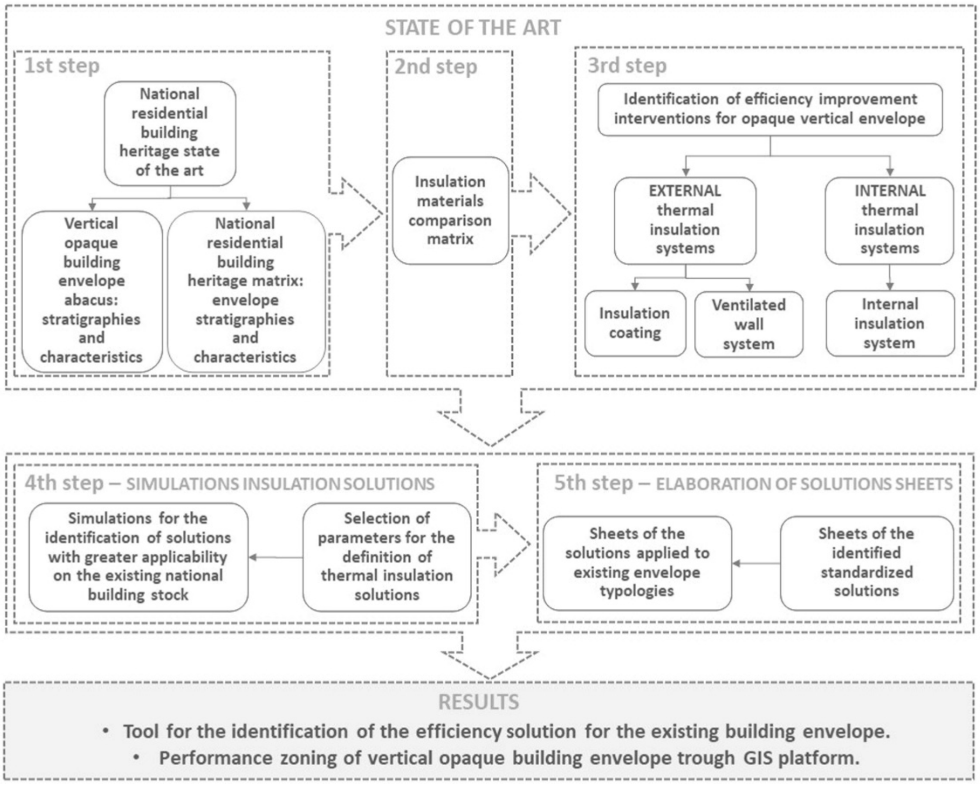


Figure 1. Research methodology flow chart.

The methodological approach is based on the search for the information needed to identify a range of main representative features to recognize such a rich national residential housing stock. In this context, the research aims to identify a set of buildings according to parameters considered relevant for the classification and to allow a subsequent identification of standardized interventions of deep sustainable redevelopment of the envelope system:

- Climatic area
- Seismic area
- Class of construction age
- Building type
- Construction type
- Layers and characteristics of the building envelope

2.1. State of the Art of the National Residential Building Stock

The investigation of the state of the art has made it possible to identify the most widespread construction types, and recognize the construction types that need to be upgraded in terms of energy efficiency, as made before any energy consumption regulations. The Italian territory is divided into six climatic areas, from A to F, according to D.P.R. no.412/1993, based on the number of degrees day (HDD—EN ISO 15927-6:2007). A comparison between the day degrees of each municipality present in each Italian region clearly shows a prevalence of climate zone E. The seismic areas of each Italian municipality have been analyzed using the classification updated in January 2019 by the Civil Protection Department [23]. This classification has the purpose of establishing the best interventions for both the reduction of seismic risk and the energy requalification of the national residential building envelope. 44% of the national territory is characterized by a high seismic risk, according to the seismic classification of the Italian municipalities of the Civil Protection (Seismic Zone 1 or Seismic Zone 2), mainly in the Center and South of the Italian peninsula.

The national residential building stock has been classified according to the age of construction into eight classes; these have been identified in connection with significant historical events and with the emanation of energy regulations that affected the use of building types and construction techniques:

- Class 1: until 1900
- Class 2: from 1901 to 1920
- Class 3: from 1921 to 1945
- Class 4: from 1946 to 1960
- Class 5: from 1961 to 1975
- Class 6: from 1976 to 1990
- Class 7: from 1991 to 2005
- Class 8: after 2005

According to ISTAT data, the national residential building stock is 14,515,795 units, of which 12,187,698 are buildings or residential building complexes (about 84%). More than half of the residential buildings, about 60%, were built after World War II until the 1990s, 15% before 1919, 14% after 1990 and 11% between 1919 and 1945. Most of the residential building stock was built before the first energy saving law No. 373 of 1976. More than 25% of the buildings constructed before this law record annual consumption from a minimum of 160 kWh/m^2 per year to more than 220 kWh/m^2 per year. [24]. As far as building types are concerned, there are two main types: isolated and aggregated. The first type includes the building organizations with prevalent residential use located within an urban context, usually situated in a marginal position with respect to the historical center, provided with a surrounding green area of different dimensions. The single-family housing development has been transformed over time into the minimum associable unit of the multi-family residential building, complex and significant in size. The residential building heritage can be classified into seven main types of buildings: isolated building single-family or duplex; multi-family linear; tower; terraced; with balcony access; Palazzina; or block building [25]. The prevalence of single-family buildings characterized by one or two floors above ground is clearly revealed by the analysis of the latest data published by the National Institute of Statistics. Construction techniques remained almost completely the same for several centuries, until the beginning of the 20th century, when there was a transformation in terms of the use of materials and construction systems thanks to the industrialization process.

In order to define the main construction systems, the classification, provided for by Law no. 64 of 2 February 1974, "Measures for constructions with special requirements for seismic zones" in Article 54, was used, which lists them as follows:

- masonry structure
- framed structure made of normal or prestressed reinforced concrete, steel or combined systems of the above-mentioned materials
- load-bearing panel structure
- timber structure

According to the 15th population and housing Italian census of 2011, load-bearing masonry is the most widespread type of construction, with an average of 57%, compared to 29% for reinforced concrete and 13% for other materials. The regions with the highest percentage of buildings made of load-bearing masonry are Molise, Sardinia and Tuscany, with percentages of around 70%, followed by Friuli-Venezia Giulia, Lombardy and Sicily with 50%. There are no substantial differences between the northern and southern Italian regions. The largest number of residential buildings made of reinforced concrete between 1946 and 1960 was in Lombardy (61,608), followed by Sicily (33,855) and Piedmont (32,054). The largest number of residential buildings built with a type of construction other than load-bearing masonry and reinforced concrete before 1918 was in Piedmont (19,362) and Lombardy (16,504). Knowledge of the different building types and masonry textures plays a fundamental role in defining the interventions for energy requalification of residential buildings, especially for historical buildings.

2.2. *Opaque Building Envelope Type Abacus*

A bibliographical investigation has been carried out into architectural technology, which revealed a very wide and heterogeneous stratigraphy used in residential buildings all over Italy.

A selection of the most representative ones has been carried out, which can be referred to a series of other similar stratigraphies, for the most significant parameters considered within this research for the energetic performance of the envelope package, thickness and transmittance. An abacus of the types of opaque building envelope packages emerged from the selection, reflecting the national residential building stock, according to the period of greatest diffusion, in order to facilitate the following identification of standardized energy requalification interventions. For example, with regard to most of the older masonry made with the use of natural materials, there is a wide variation related to the type of manufacturing, to the aggregation of the elements, to the historical period and to the geographical location [26]. The stratigraphies of these historical masonry are almost all related to stone masonry, since with regard to this research, the evaluation and comparison parameter used for the classification of the building envelope is the energy performance, the transmittance which, in this case, depends mainly on the thickness of the wall itself. The selection of the most representative stratigraphies and construction age classes was also made basing it on an existing internationally recognized research, the TABULA project, funded by the European Programme Intelligent Energy Europe (2009–2012) [16].

The building envelope types have been divided according to their position and function within the building system into:

- Roof (R)
- External Wall (EW)
- Floor (F)

A progressive numeric code has been assigned to each of them according to a chronological and typological order. In the abacus for each stratigraphy, it has been reported: the period in which it was most widespread; the total thickness; the description and thickness of each component numbered; and the energetic performance parameter in winter and summer regimes (Table 2).

The stratigraphies of the upper horizontal envelope selected are 12, while those of the vertical envelope are 28 and those of the lower horizontal envelope are 14.

The periodic and stationary transmittance values of each type of building envelope closure have been assessed.

The study carried out makes it possible to highlight the main cases on which *Deep Renovation*'s interventions should be focused on and to identify the best solutions to be adopted, both on the national and international market, linked to the concept of off-site construction according to the different characteristics of existing degraded buildings.

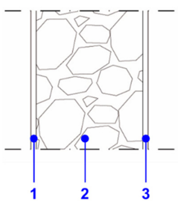
An example of Deep Renovation intervention is the replacement of the existing façade with a pre-fabricated sunspace in framed buildings. A comparison was made between the limit value of transmittance required by the regulations (Ecobonus Requirements Decree GU 05/10/2020) and that of walls (Table 1); a deviation from the limit value of up to 0.5 was deemed acceptable.

Table 1. The transmittance limit values required by the Ecobonus Requirements Decree GU 05/10/2020 (calculation according to UNI EN ISO 6946).

UNI EN ISO 6946	
Climate zone A e B	≤0.38
Climate zone C	≤0.30
Climate zone D	≤0.26
Climate zone E	≤0.23
Climate zone F	≤0.22

The following table shows the performance level of the wall according to climate zones, indicated by the letters A to F according to D.P.R. no.412/1993, red when the deviation from the standard transmittance value is greater than or equal to 0.5 and orange if it is smaller (Table 2). The other tables of the abacus are shown in Supplement 1.

Table 2. Extract from the abacus of building envelope types.

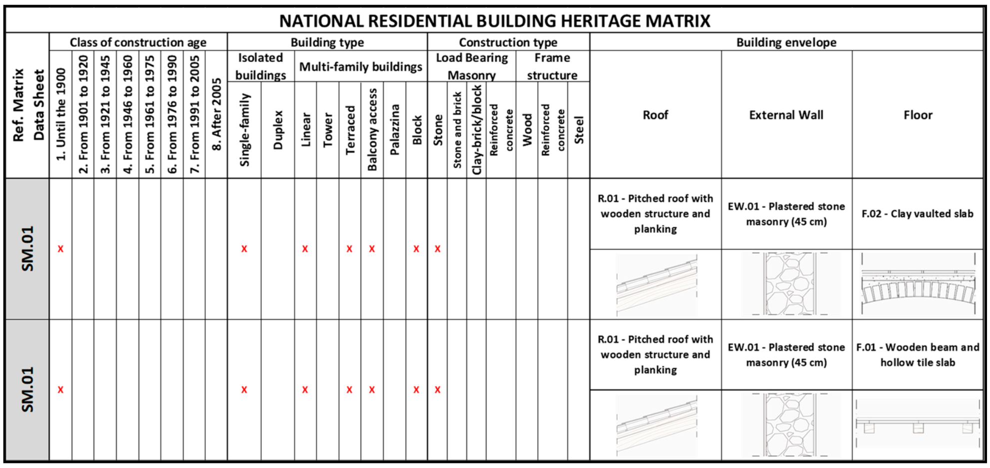
<table>
<tr><th>Construction Year Class</th><th colspan="3" rowspan="2">EW.01—Plastered Stone Masonry</th></tr>
<tr><th>Until 1920</th></tr>
<tr><th>Stratigraphy</th><th colspan="2">Thermal Performance</th><th>Level of Performance</th></tr>
<tr><td rowspan="7">

1. Exterior plaster: 2 cm
2. Stone: 41 cm
3. Interior plaster: 2 cm
Total thickness: 45 cm</td><td>Winter</td><td>Thermal transmittance (U) = 2.40 W/m^{2}K</td><td rowspan="2">A–B</td></tr>
<tr><td rowspan="6">Summer</td><td>Periodic thermal transmittance (Yie) = 0.362 W/m^{2}K</td></tr>
<tr><td>Internal areal heat capacity (Cip) = 77.6 kJ/m^{2}K</td><td>C</td></tr>
<tr><td>Thermal phase shift (Φ) (h) = 11.23</td><td>D</td></tr>
<tr><td>Attenuation factor (fa) = 0.142</td><td>E</td></tr>
<tr><td>Surface mass (Ms) = 1089 kg/m^2</td><td>F</td></tr>
</table>

The Thermal Transmittance is expressed in W/m^{2}K. The measure unit indicates watts of energy that are lost across one square meter of surface for a temperature difference of one degree Kelvin.

2.3. National Residential Building Heritage Matrix

A matrix of buildings, mainly for residential use, was drawn up, summarizing the results of the preliminary study of the state of the art (the main source of data used is National Statistical Institute—ISTAT), starting from the selection proposed in the abacus and in the data sheets where the possible building configurations that can be found within the national heritage have been outlined. The configurations shown are defined by the features that can commonly be found in buildings of the respective class of construction age, building type and construction type. The lines that make up the matrix represent the configurations of the envelope, characterized by a certain type of upper horizontal closure, vertical closure and lower horizontal closure (which can then be against the ground or towards an external space, such as on pilotis), relating to the class of construction age, building type and construction type most widespread. The order of the different configurations follows the evolution of construction techniques in chronological order. The configurations present in the matrix are 346 (only an extract is given due to the length of the text in Figure 2). At the end of the analysis of the state of the art of the national residential building patrimony, once the relative matrix has been set up, some data sheets representative of the designer's way of using the matrix were created. The National Residential Building Stock Matrix was elaborated by the authors, in the program for "Research of the Electricity System" in cooperation with ENEA on the project "Energy efficiency of industrial products and processes", 2019–2020.



NATIONAL RESIDENTIAL BUILDING HERITAGE MATRIX																										
Ref. Matrix Data Sheet	Class of construction age								Building type								Construction type							Building envelope		
									Isolated buildings		Multi-family buildings						Load Bearing Masonry				Frame structure					
	1. Until the 1900	2. From 1901 to 1920	3. From 1921 to 1945	4. From 1946 to 1960	5. From 1961 to 1975	6. From 1976 to 1990	7. From 1991 to 2005	8. After 2005	Single-family	Duplex	Linear	Tower	Terraced	Balcony access	Palazzina	Block	Stone	Stone and brick	Clay-brick/block	Reinforced concrete	Wood	Reinforced concrete	Steel	Roof	External Wall	Floor
SM.01	x								x		x		x	x		x	x							R.01 - Pitched roof with wooden structure and planking	EW.01 - Plastered stone masonry (45 cm)	F.02 - Clay vaulted slab
SM.01	x								x		x		x	x		x	x							R.01 - Pitched roof with wooden structure and planking	EW.01 - Plastered stone masonry (45 cm)	F.01 - Wooden beam and hollow tile slab

Figure 2. Extract from the National residential building stock matrix.

2.4. Building Envelope Configuration Data Sheets

A series of data sheets have been elaborated basing on the abacus to provide a summary of the different configurations (and combinations) of the characteristics of the building envelope components belonging to the main residential building categories. A detailed study on the individual case histories is offered in the overview of building and construction types according to the class of construction age, also allowing a quick evaluation of the energy performance (the thermal performance in stationary and dynamic regimes, calculation according to UNI EN ISO 6946) of the individual components by both experienced technicians and simple users. After selecting the building that could be involved in the renovation, the operator can identify the case history that best matches the case by using the data sheets. In this way, in order to carry out a qualitative evaluation of the possible interventions for the redevelopment of the building envelope, it will be possible to set out from a reference baseline, knowing its components and performance qualities. Especially in the case of existing buildings for which there are only a few indications, it will still be possible to base on some data references in order to quickly provide an early qualitative assessment of the energy performance of the building. There are 125 total sheets (The 125 sheets are in the report elaborated by the authors, in the program for "Research of the Electricity System" in cooperation with ENEA on project "Energy efficiency of industrial products and processes", 2019–2020).

2.5. Insulation Material Comparison Matrix

The regulations concerning the buildings' energy efficiency focus on the performance characteristics of thermal insulating materials, also in compliance with the principles introduced by the circular economy. This has led to the introduction on the market of different types of high-performance materials, which can be differentiated into four macro categories regarding their origin: natural organic insulation; natural inorganic insulation; synthetic organic insulation; or synthetic inorganic insulation [27,28]. The choice of the type of insulation depends on many considerations, which in addition to the satisfaction thermal comfort respecting the limits imposed by the reference standards, also concern the geographical location and orientation of the building under intervention and the environmental impact indicators. Another fundamental aspect for the selection of the insulation material is related to the prefabrication and therefore to the way the product is installed, which should allow a quick and dry application, in order to reduce the work site time, the environmental impacts associated with it and the possibility of future reuse. The building industry is the world's largest consumer of raw materials [29]. Therefore, the entire methodological approach is based on the principles of circular economics right from the design phase. The use of industrial processes of technologies and products is preferred, thinking from the very beginning about their use at the end of their life, having characteristics that will allow their disassembly or restructuring [30].

Priority is given to the modularity, versatility and adaptability of the product, and to the replacement of virgin raw materials with secondary raw materials coming from being recycled/reused, which preserves their qualities.

Through the key of circular economy, it is consequently possible to reduce the environmental impact of building interventions by preferring dry or mixed construction techniques, prefabricated components and materials from recycling, renewable and recyclable or reusable processes [31].

A matrix has been developed to compare the various types of insulation materials present on the national and international market for the following identification of the most suitable insulation system based on the features of the building to be energetically improved.

In order to allow a comparison between the numerous varieties of insulation materials, parameters relating to insulation capacities in winter and summer regime, environmental impact and direction for use were selected [32] (the table of the comparison of insulation materials is in Supplement 2).

After comparing the energy and environmental performance values, the selected insulation materials are: wood fiber among the natural organic insulators, rock wool and aerogel among the synthetic inorganic insulators, synthetic organic insulators include expanded polyurethane and expanded polystyrene.

The different types of insulation materials identified have been associated with the main insulation solutions: insulation coating; ventilated wall system; and internal insulation system.

The development of a methodology in which the performance of insulation scenarios is precalculated using an energy performance certificate software, can direct the production chain towards more efficient and environmentally sustainable standardized solutions.

Simulations with different insulation thicknesses were carried out on each type of wall of the abacus, for six standardized insulation solutions (simulations can be found at the end of the text as a Supplement 2 of the paper). Simulations have been carried out to identify the thicknesses of the selected insulating materials that allow the greatest application on the existing walls in all climate zones (Figure 3).

Through this study, it was possible to assess the percentage of applicability of insulation solutions on the national building stock according to climatic zones. The standardized insulation solutions, their characteristics and their applicability are shown in Table 3.

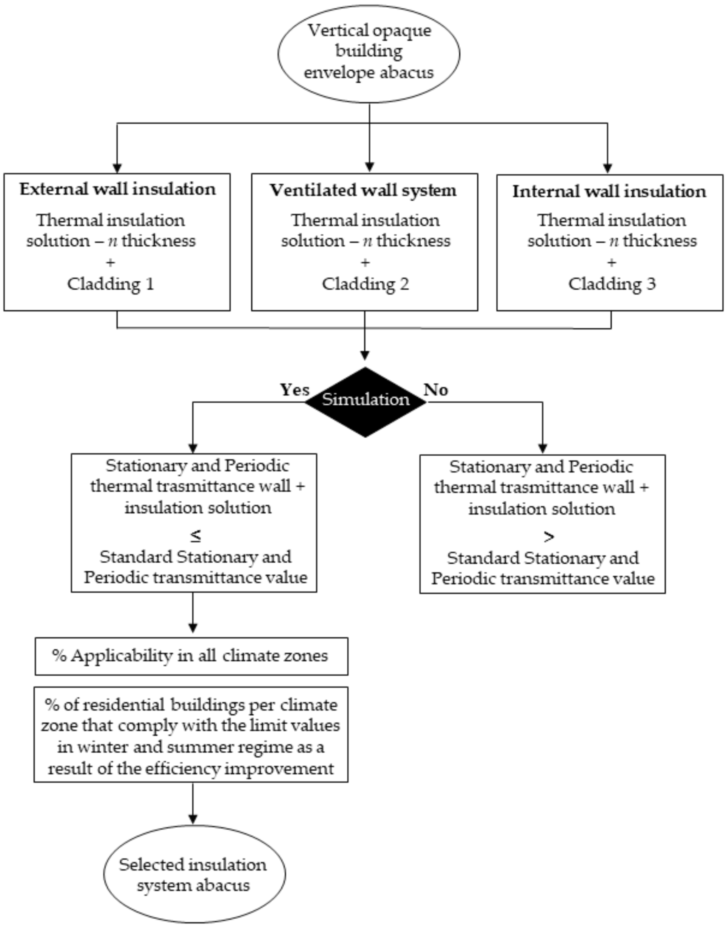


Figure 3. Flow chart of the methodology to identify standardized insulation solutions.

Table 3. Selected insulation systems abacus.

External thermal insulation systems	Insulation coating	**EIS.01** Synthetic inorganic **Rock wool**	• Semi-rigid rock wool insulation panel 0.12 m (λ = 0.032); • Calcium silicate slab 0.012 m (λ = 0.039); • Render/cladding 0.005 m (λ = 0.7)	% applicability in all climate zones: Winter regime: 91% Summer regime: 100%
		EIS.02 Natural organic **Wood fiber**	• Semi-rigid wood fiber insulation panel 0.14 m (λ = 0.04); • Cement mortar 0.005 m (λ = 0.9); • Render/cladding 0.015 m (λ = 0.9)	% applicability in all climate zones Winter regime: 81% Summer regime: 100%
	Ventilated wall system	**VWS.01** Synthetic organic **Rigid expanded polyurethane**	• Semi-rigid wood fiber insulation panel 0.08 m (λ = 0.022); • Air gap 0.04 m (λ = 0.25); • Facing panel 0.02 m (λ = 1.3)	% applicability in all climate zones Winter regime: 91% Summer regime: 100%
		VWS.02 Synthetic inorganic **Rock wool**	• Semi-rigid rock wool insulation panel 0.12 m (λ = 0.032); • Calcium silicate slab 0.012 m (λ = 0.039); • Air gap 0.04 m (λ = 0.25); • Facing panel 0.02 m (λ = 1.3)	% applicability in all climate zones Winter regime: 93% Summer regime: 100%

Table 3. *Cont.*

Internal thermal insulation systems	Interior insulation system	**IIS.01** Synthetic inorganic **Aerogel**	• Semi-rigid aerogel insulation panel 0.05 m (λ = 0.015); • Gypsum plasterboard 0.012 m (λ = 0.7); • Render/cladding 0.005 m (λ = 0.7)	% applicability in all climate zones Winter regime: 75% Summer regime: 97%
		IIS.02 Synthetic organic **Extruded polystyrene (XPS)**	• Semi-rigid extruded polystyrene (XPS) insulation panel 0.10 m (λ = 0.031); • Gypsum plasterboard 0.013 m (λ = 0.21) • Render/cladding 0.005 m (λ = 0.7)	% applicability in all climate zones Winter regime: 73% Summer regime: 97%

3. Results

The research has led to the development of a tool to identify the insulation solution best suited to the characteristics of the wall, building and climate zone.

Below the design per tool's menu is described in Figure 4, with the required inputs per step and outputs. In the Menu, the user is invited to go through three categories of selection: context data; general building data; and additional details.

INPUTS

1. SELECT *Context data* (Region -> Province -> Municipality) ⟶ Climatic zone
2. SELECT *General building data* (Period of construction -> Building type -> Construction typology -> Existing external Wall)
3. OPTIONAL SELECTION *Additional details* (Insulation position -> Cladding typology -> Price range)

OUTPUTS

- INSULATION SOLUTION SYSTEM
- PERFORMANCE ACHIEVED AFTER THE INTERVENTION

Figure 4. The steps involved in the tool.

The first category regards geographical localization and allows to select Region, Province and Municipality. The tool automatically determines the climate zone. General building data allows to select, through a drop-down menu, the *period of construction* (until 1900; from 1901 to 1920; from 1921 to 1945; from 1946 to 1960; from 1961 to 1975; from 1976 to 1990; from 1991 to 2005; or after 2005), the *building type* (isolated buildings: single family or duplex; multifamily buildings: linear; tower; terraced; balcony access; palazzina; or block), the *construction typology* (load-bearing masonry: stone, stone and brick, clay-brick/block or reinforced concrete; frame structure: wood, reinforced concrete or steel). There is also the possibility to choose further details: *insulation position* (External or internal thermal insulation system); *cladding typology* (plaster, facing panel); or *price range* (<150.00 €/m^2; >150.00 €/m^2). After the selection of the various parameters, the tool indicates the most suitable solution for the building to be treated, providing the technical data sheet containing the characteristics of the insulation system applied to the existing wall (wall and insulation system stratigraphy, performance in winter and summer regime and interstitial condensation verification).

The acquired information has been used for the realization of a GIS [33]; it is organized according to different layers, in order to be able to individually process the different categories of information collected. The layers developed regards *general building data* and the *level of performance.* The program can be questioned, and it also allows to simulate interventions based on the results obtained through the data entered by the technician. Once the data have been simulated, the program shows the various solutions of suitable type of insulation to have a better energy efficiency for each building.

With the use of a GIS software, it is possible to create an archive of general information such as the age of construction, type of construction and level of performance of each building in the studied area. This archive leads to the creation of a map that shows the status of the real estate assets of the area. The collection of this information allows the user to interrogate each building, and the program shows all the results that it has in its archive.

Therefore, it has been created a tool with all the information of each building that allows the user to interact with the characteristics of the building, and also have the technical sheet of the best simulation solution.

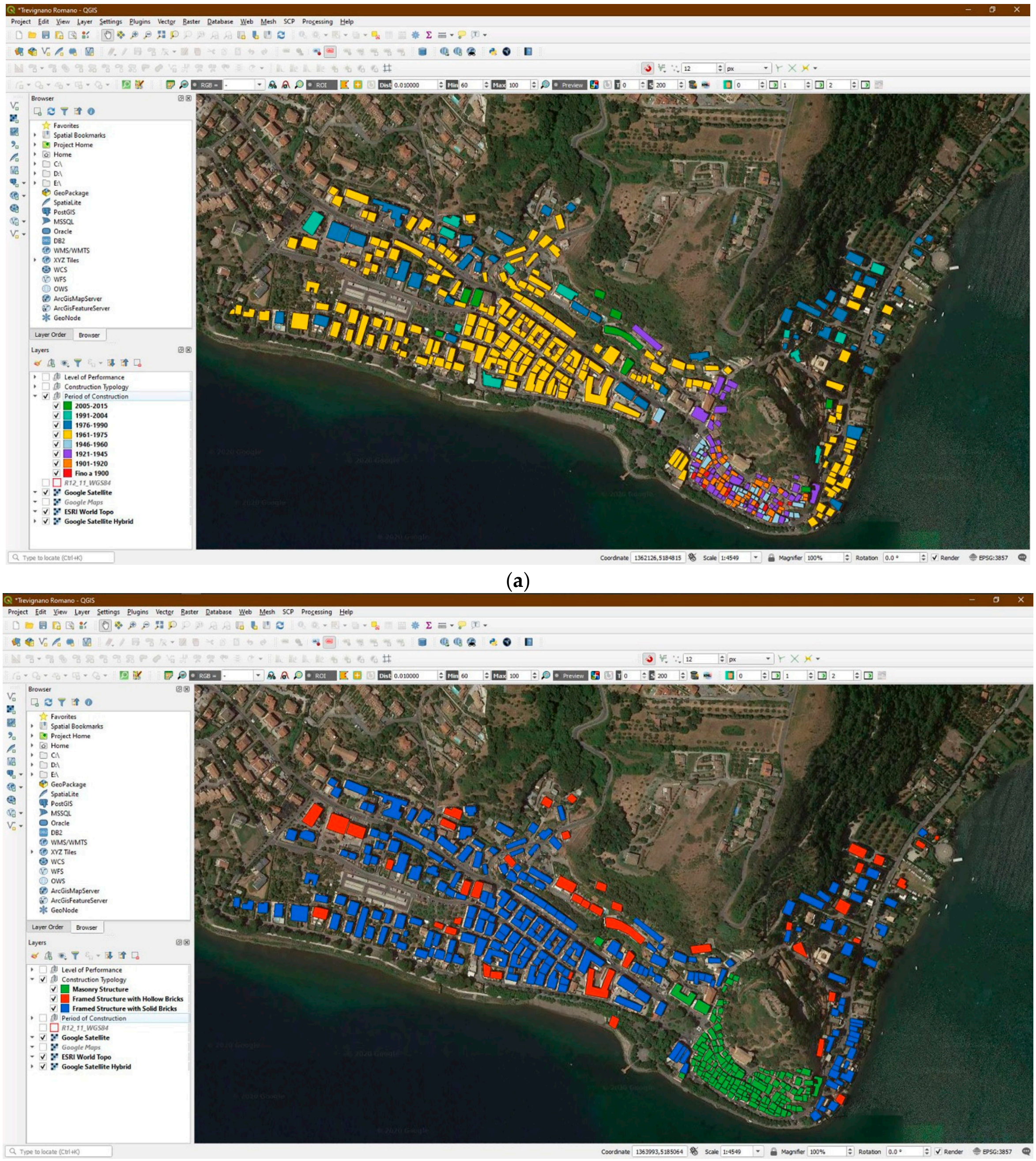
The platform development is based on open software, which aims to be an interoperable and flexible tool for administrator of the territory and for planners. Performance zoning of a vertical opaque building envelope through the GIS platform allows the administrators of the territory to view the actual state of performance of the building heritage, plan improvements and record the interventions carried out.

4. Case Study: Trevignano Romano A Small Town Near Rome, Italy

The methodology described has been applied and verified in the small town of Trevignano Romano, of about 6000 inhabitants, in the Lazio region, about 30 kilometers from Rome. Trevignano is part of the Regional Natural Park of the Bracciano-Martignano lake complex. There are 878 buildings in this city, 844 of which are residential buildings. The study was carried out in the old town center of the municipality and on a part of the lake promenade, since it is a particularly significant area for the purpose of this research.

The classification of the current state of the existing buildings was carried out by cross-referencing data from high-resolution satellite orthophotos, the municipal administration, ISTAT data and on-site surveys. The visual inspection, supported by the matrix of the national residential building heritage, has made it possible to identify the time of construction, the types of buildings and the characteristics of the building envelope. Almost 70% of the residential building heritage of the area investigated in Trevignano Romano was built between 1976 and 1990, and consists mainly of masonry buildings in the historical center and reinforced concrete with solid brick infill, and in a smaller number, of perforated bricks in the rest of the area examined (Figure 5).

The GIS has therefore made it possible to locate the different buildings in space, linking them to specific alphanumeric attributes saved in the relational database (Archive), and to manage them as "information layers" (Layers) that identify their spatial relations. Each building has been associated with a data sheet containing the information described above to guide the designers' choices towards the most suitable and sustainable energy efficiency systems (Figure 6) [34].



(**a**)

(**b**)

Figure 5. Extract from the Geographic Information System (GIS). (**a**) Class of construction age; (**b**) Construction type.

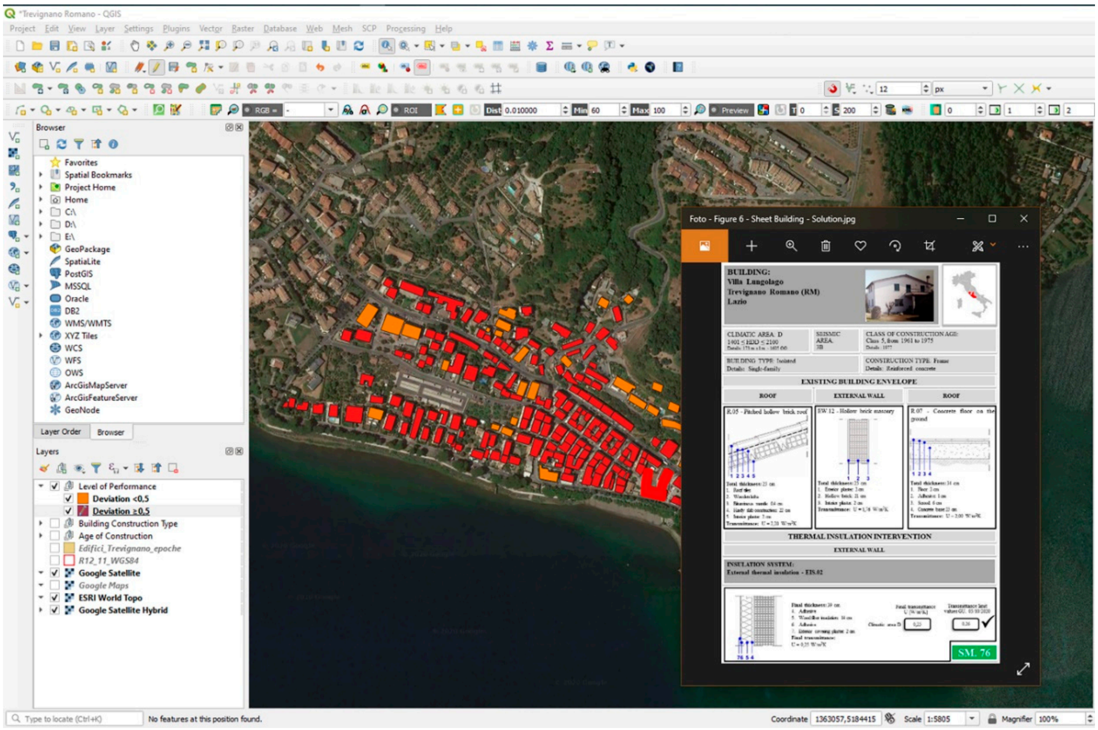


Figure 6. Example of a building data sheet with the insulation solution suggested and final performance.

5. Conclusions and Future Developments

With a view to reducing environmental impacts related to the construction industry, which strongly influence global warming due to greenhouse gas emissions caused by the excessive use of air conditioning systems, the residential construction sector will face major challenges in the coming years and decades addressing these issues.

The proposed methodology aims to support sustainable planning of interventions to improve the energy efficiency of production processes and management of the built environment. The methodology currently applied to external walls can also be applied to roofs and floors and to plant systems from the perspective of Deep Renovation.

With a view to applying the digitization to building and urban regeneration, as a future development, a Building Information Modeling (BIM) tool could be created to automatically identify the improvement interventions for the specific case study to be energy-efficient according to the climate. For building retrofit projects, the integration of BIM and GIS supports decision-making. Putting as-is geometric BIM data and other necessary data into GIS, it becomes possible to create a pre-retrofit simulation model to perform building data and corresponding insulation solutions for existing building [35].

This development leads to an important design and process innovation for territorial information systems playing a fundamental role in addressing the development of built environment, providing both the congruity information management in GIS environment and the information produced through BIM processes [36].

Supplementary Materials: The following are available online at https://www.mdpi.com/1996-1073/14/1/74/s1, Supplement 1, Abacus of building envelope types; Supplement 2, Comparison of insulation materials; Supplement 3, Simulations with different insulation thicknesses.

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