Analysis of different energy conservation strategies on existing school buildings in a Pre-Alpine Region

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In this article we deal with the energy renovation of existing school buildings, one of the most relevant and current issue concerning Italian public buildings.

The necessity of a re-alignment with the European performance levels, achievable through a renovation of the school buildings stock, of which almost 90% is more than 30 years old, finds the two main obstacles in the lack of a full awareness of the current state of integrity of buildings and in the absence of an effective energy retrofit planning.

The aim of this study is to define the most promising renovation strategies applicable to all the school building in Lecco municipality, from both the economy and the energy point of view, through the devel-opment of an analysis method, repeatable and applicable to most realities, that allows optimizing and simplifying the energy analysis. The presented research is based on the classification and analysis of the study sample, consisting of 38 school buildings that differ in educational level, age of construction and typological design. The methodology developed allows dividing the sampled schools in homogeneous clusters, each one represented by a reference building, whose energy analysis makes it possible to define the best renovation strategy in terms of cost/benefit.

The results obtained provide replicable guidelines useful to the Public Administration in planning of energy retrofit interventions, in defining the total investment amounts and the consequent raising of necessary investments. Specifically the total investment would amount to D 62.971.530, with a calculated economic investment per student equal to D 5.060,0.

Keywords: School buildings renovation, Energy conservation measures, Energy consumption, Clusters

1. Introduction

For many years now the quality of the Italian school buildings has been in a state of emergency and it is far from many European countries quality standards; this issue is exasperated even more by the Public Administration lack of full knowledge on the matter of schools buildings conservation.

Nowadays the most complete and reliable research able to provide a representation, in broad terms and not in detail, of the current school buildings stock condition, is the report "Ecosistema Scuola" [1]; this is an annual survey on the school buildings quality, facilities and services that Legambiente has drawn up annually since 2000. This report submits an alarming picture about the 42,000 school buildings managed at the municipal and provincial levels, accommodating about 8 million students which represent over 15% of Italian population [2]: indeed more than 65% of schools were built before 1973, hence before Laws 373/1976 [3] and 64/1974 [4] became operative. In this scenario more than 39% of the buildings manifest an urgent need for maintenance and regulatory changes.

Furthermore, on taking into account the energy consumption, it emerges that the real situation is even more critical because about 90% of schools were built before the 1990's, and particularly before the coming to force of Law 10/1991 [5], which regulates the integration of energy saving measures and the use of renewable energies in buildings. The inadequacy and dated condition of the buildings, in conjunction with a greater environmental awareness, have led the Italian State to explore the issue and put forward sustainable restructuring interventions that are in line with the current European priorities. Moreover the international standard, in terms of energy efficiency in buildings [6], state the need to define strategies able to reach the Zero Energy Building target [7,8] for new and deep renovated building.

In this respect, the school building would represent an instance of successful sustainable architecture and would stand as a prime example of how the dual goal of preserving our cultural heritage, while promoting sustainable architecture, can be achieved.

The issue of this article is highly topical, as several studies demonstrate. Last year, in Austria the work of Stocker et al. [9]

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proposed a study about heating energy performance focusing on 8 different primary schools affected by particular climate conditions. The aim of their work regards cost-optimal building performance: they show that the best scenario is between a heating energy demand of 50–60 kWh/m^2 reach with different renovation strategies depending on building age and on energetic construction qualities. Similarly, Santamouris et al. [10] carried out energy audits on 238 Greek schools, characterized by an annual average total energy consumption amounting to 93 kWh/m^2. They prove that it is possible to reduce energy consumption by 20% with various energy-conservation strategies. The study of Trachte and De Herde [11], starting from the consideration that a lack of comfort has negative and scientifically proven consequences on pupils' concentration and learning, shows different energy efficient strategies for non-residential building. Also Dimoudi and Kosterala [12] focused on potential energy saving of school buildings in the climatic zone of Greece. They demonstrated, through simulation studies, that it is possible to reduce the heating consumption by 28,75% improving the insulation level. Sesana et al. developed and test a Methodology for Energy Efficient Building Refurbishment (MEEBR) on two case studies [13]. Another study was carried out by Desideri and Proietti [14] in order to calculate the energy consumption and the possible intervention to save energy in a school building stock located in Perugia, central Italy. The theme of improvement of energy performance in school building is assessed also by Dall'O' and Sarto [15]; starting from a study on 49 schools building located in the Lombardy region of Italy, they analysed cost-effectiveness building performance based on different energy retrofit scenarios. Their studies show that the excessive improvement of heating energy performance is not always the best economically advantageous solution. Butala and Novak [16], analysing a building stock of 24 school building in Slovenia, found that the heat loss in the sample was 89% higher than the recommended values. They assessed that the best cost-effective strategies, in 83% of the building stock, were through insulation of the envelope and replacement of windows. The energy renovation measure for existing building has been investigate also by Masera et al. [17] showing a set of innovative technologies for inner and outer envelope renovation. The importance of energy saving strategies and the improvement of energy performance in existing building is developed by the European Commission through the Commission Delegated Regulation (EU) n. 244/2012 [18]. The Commission proposes a comparative method to analyse the cost-effectiveness strategies for the existing building renovation by introducing a new instrument: a reference building. Its definition implies the study of a large amount of information, made possible by using the clustering analysis: a data mining technique that allows splitting the sample of buildings into small and homogeneous sub-groups. The analysis of each reference building, which is representative of its sub-group, allows extending the results to the other buildings in the cluster. This theme was carried out by many authors, such as Arambula Lara et al. [19], with the object of exploring a clustering method applied to a sample of 60 school buildings in the province of Treviso, North-East of Italy. They found out a few reference buildings representative of every cluster thus simplifying energy analysis. Similarly, Santamouris et al. [20], developing a clustering technique, selected 10 school buildings which were representative of a sample of 320 schools in Greece. They studied in detail the energy efficiency and the performance of the reference buildings proposing several scenarios in order to improve their energy behaviour. Some years later again in Greece, Gaitani et al. [21], starting from a sample of 1100 school buildings, which represents 33% of all secondary education schools, selected a typical building for each group, based on an energy classification, that they defined by means of clustering method.

The clustering method is a technique that can be used to analyse different types of buildings as demonstrated in many papers. For example, Petcharat et al. [22] applied this method to classify the energy performance of 36 case studies in Thailand. In another context, Heidarinejad et al. [23] used cluster analysis to examine simulated energy consumption of office buildings in USA. The main peculiarity of this work is that they apply the clustering on simulated buildings and not on real ones.

Through the achievement of a categorisation system and analysis of the current buildings integrity state, in order to create a knowledgeable database about the study sample, this work aims to define an analysis method, repeatable and applicable to different case studies. It allows the energy analysis to be optimized and simplified, with a view to determining the best renovation strategies applicable to every single school building, from both economy and energy point of view.

The final goal pursued is therefore to achieve a complete knowledge of the renovation strategies to be undertaken, of costs and benefits obtainable from each building, in order to carry out the most effective urban renovation planning.

The paper deals with the followings steps:

- Classification of the study sample through a mapping tool;
- Definition of the energy retrofit strategies, from both economy and performance point of view;
- Development of an analysis method, repeatable and applicable to most realities, in order to divide the sampled schools into more homogeneous and small groups, useful in terms of energy analysis;
- Determination of representative buildings for the purposes of optimizing and simplifying the energy analysis sample;
- Assessment of the most economically advantageous strategy for each cluster.

The proposed methodology can be extended to different context and to different building typology. Moreover, for each case, is necessary to know the type of building (eg. residential, tertiary or school building) and how they are occupied by the user in order to study the most promising renovation strategies. The proposed cataloguing form allow scheduling in a fast and homogenous way the geometrical and the qualitative characteristics of the buildings that represent the basis for the further retrofitting strategies analysis.

The main weak point is represented by a lacking of information regarding the building characteristics (drawing, energy certification, building technology etc.) from which derive the information for the building classification. The impact of work is definitely considerable if conducted using informatics' tools that share information in a single database accessible to a large scale of users.

Considering the information flow the following Fig. 1 shows the relation

2. The Italian local school building stock: analysis

2.1. General description

As of 1996 with the coming into force of Law 23/1996 [24], a special interest in the Italian school buildings stock began, which ensured a targeted planning of the interventions with the aim to achieve a better qualitative development.

Through the above mentioned law, the MIUR (Ministero della Istruzione Università e Ricerca) [25] (Ministry for University Education and Research) engaged in the realisation and the development of a National School Buildings Mapping upgrade; this computerised and cognitive tool would allow assessing the consistency, the condition and the availability of the existing school buildings stock on the national territory, in order to improve the effectiveness of the programming activities of maintenance and requalification.

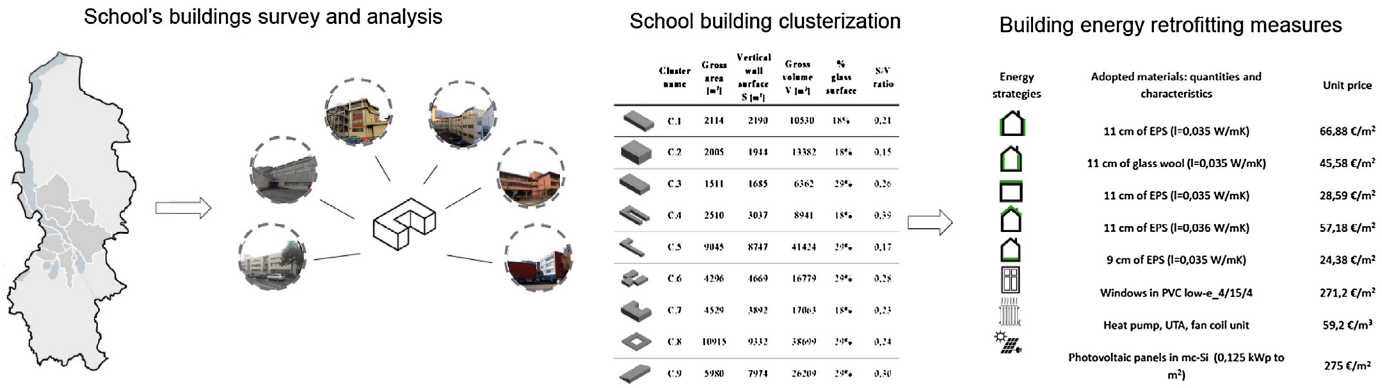


Fig. 1. Information flow between the different steps: from the survey to the retrofitting measures calculation.

Unfortunately, as it is often the case, the responsible Ministry did not define the guidelines for the application of the rules and the creation of the school buildings database was resumed a few years ago thanks to the reform "La Buona Scuola" [26] which introduced the first measures to face up to the school buildings emergency in Italy. However, to this date, a clear and comprehensive mapping of schools public properties continues to lack in support for Public Administrations and designers.

In the absence of this information, firstly, the present research work seeks to build an extendable investigative tool that could be repeated for most municipalities in addition to the region taken as a sample, in order to obtain a full understanding of the schools public properties (Fig. 1). The cataloguing form is aimed at evaluating the geometrical and quality characteristics of the building organism, and is accompanied by an implementable glossary as needed. The novelty of the approach consist of the systemic analysis of an high number of buildings with standardised method. Moreover the model can be implemented easily into app for a more quickly and real-time compiling.

The research sample consists of 38 school buildings belonging to Lecco municipality and of the 8 neighbouring municipalities of Lecco province. Out of the whole school buildings stock we considered only state schools, with the exception of universities and kindergartens, which differ significantly from primary, lower and upper secondary schools by type of services, logistics and structuring of teaching.

In order to achieve a complete picture of the current study sample condition, the data collected from the school buildings stock was revised in synthetic charts [Fig. 2]. The territorial survey results show that within the sample the building types fall into the block building type, as defined by Sole [27]; they are specifically divided into merged block (47%), linear block (40%), which are the most recurrent, a stepped block (8%) and internal court block (5%).

In relation to the buildings age, the analysis shows that 69% was completed before 1974, which is the year when the anti-seismic regulations came into force, while no new school buildings were erected from 1990 to this day; this last data is really symbolic if we consider that, after Law10/1991, the first binding legislation concerning the building energy performance was the D.Lgs. 192/2005 [22].

It should also be noted that there is a percentage of older buildings (16%), built between the second half of the nineteenth century and the first decades of the twentieth century, often bound by restrictions from the local Superintendence authority.

The results relating to the maintenance carried out to improve the school building energy performance (windows replacement, new plant installation and presence or absence of insulation in vertical or horizontal closures) show that 26% of the sample has not undergone any type of interventions since its construction, while 50% has only had one major intervention, which in most cases consisted of windows replaced with others characterized by better performance. However, 8% of the buildings underwent such maintenance as to gain a good energy performance.

Table 1
(1) CEER-Lecco data; (2) ref. D.G.R. 6480/2015.

	U-Value $U_{average}$ (1) [W/m^{2}K]	U-Value U_{limit} (2) [W/m^{2}K]
Basement	0,87	0,26
Roof	1,04	0,22
Window	3,36	1,40
Envelope	1,13	0,26

2.2. *Thermal resistance of building envelope*

The mapping of the school buildings stock returned a full picture of the current study sample condition in terms of legislation, construction characteristics and conservative conditions, but without going into detail on the energy performance. In order to cover the lack of this information and to gain a full knowledge of the study sample, mainly as regards the energy behaviour, reference was made to data provided by the CEER (Energy Land Registry of Regional Buildings) [29].

Through this IT service the Accreditation Body manages the storage and the computerized consultation of the APE (Energy Performance Certificate) in the Lombardy region: the database is continually updated and currently the certified buildings in Lecco province are more than 50.000.

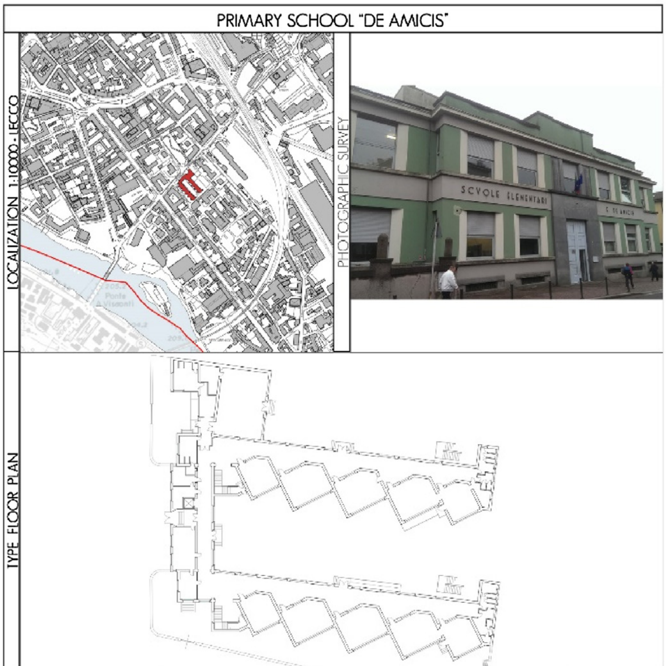
Upon available consultation, the low energy performances of the schools buildings park in Lecco is apparent: the primary energy demand (E_{pH}) for winter heating per year stands at 59.94 kWh/m^{3}year and the U-value averages of the building constituent elements as reported in Table 1.

3. Methodology and data analysis

3.1. *Definition of the energy strategies*

Acquiring a full knowledge of the school buildings sample, firstly, made it possible to define the energy strategies, aimed at classifying them through a single economical quantification, as well as by interventions typology, in order to establish a methodology that could constitute a simple tool both for quantification of the total expenditure and for a comparison of costs and benefits.

The energy strategies choice fell onto major interventions for the building envelope performance improvement, such as windows replacement and thermal insulation, besides plant system



CLASSIFICATION

Localization		*Morphology of the complex*	
Adress	Via Amendola 24, Lecco	Complex	NO
		N' buildings in the complex	1
		Outdoors service spaces	SPA1, SPA2, SPA5a
Latitude	45°51'23" N		
Longitude	9°24'14" E		
Altitude s.l.m.	214 m	Noise level	HIGH
Climatic zone	E		
Landscape-enviromental restriction	\		

ANALYSIS OF CONSTRUCTION

Technical data		*Evolution of the construction*	
Type of building	TE2b	Costruction age	1934 - 1937
Surface area [m²]	4562	Designer	Ing. Prandoni Arch. Loneve
Roof surface [m²]	1845		
Gross surface [m²]	3770	D. U. orig. se diversa dall'attuale	\
Gross surface available to students [m²]	3275	Measures	I1¹, I12²³
of which gym [m²]	275		
Gross volume above ground [m³]	14265		
Gross volume of basement [m³]	800	Energy efficiency class	N.D.
of which habitable [m³]	\	Architectural restriction (art.10 comma 1 D.lgs 22/04, n.42)	YES
Gross volume of gym [m³]	1240		
N' floors above ground	2		
N' basament floors	1		
N' students	195		
N' classrooms	10		
N' lesson class	10	*Preliminary regulatory control*	
N' special classrooms	4	Static testing	N.D.
N' laboratories	2	Presence of a emergency plan	YES
m² per student da DM 18/12/75	7.56	Presence of two fire escape by floor	YES
m² per student	16.79	Presence of windows fireproof	NO
Service areas	SSI3, SSI5, SSI7, SSI8, SSI9, SSI13a	Presence of at least a outside stairway or a anti-smoking stairway	YES
		Presence of architectonic barriers	NO
Connective	C1a, C2a, C4a	Antiseismic adjustment	NO

Notes
¹ 1998: makeover plants, part of the windows and locker rooms of the gym;
² 2000: adaptation of architectonic barriers (lift and outer slides);
³ 2011: rebuilding of the gym floor.

TECHNOLOGICAL ANALYSIS

Technological elements	*Main body*	*Conservation st.*	*Gym*	*Conservation st.*
Supporting structure	SP3a	2	SP3a	2
Vertical closures	CV5b	2	CV5	2
Horizontal closures	CO2b	1	CO4b	1
Vertical trasparent closures	CTV3a, CTV3b	2, 1	CTV3a	2
Horizontal trasparent closures	\	\	\	\
Obscuration typology	TO1, TO4	2	TO1, TO4	2
External surface finishes	FSE1b, FSE1d	2	FSE1b	2
Internal surface finishes	FSI1	1	FSI1	1
Flooring	PAV 2	1	PAV 4	1
Countertop	\¹	\	\	\
Technological services				
Heating typology	TR1b		TR1b	
Ventilation typology	TV1		TV1	
Lighting typology	TI1		TI1	

Notes
¹ Presence of sound-absorbing panels in refectory rooms.

Fig. 2. Example of a cataloguing form.

interventions, such as air conditioning replacement or photovoltaic plants installation.

To establish a unit price for each strategy, firstly it was necessary to identify and quantify the materials involved in each intervention; this also allowed defining the thermal performance achievable with individual energy retrofit interventions, with a view to determining the primary energy demand of the school buildings after the application of each strategy.

To attain that objective, we started from an essential assumption: the insulation material quantities were assessed based on those needed to achieve the U-value limits as imposed by the Lombardy Region with the 6480 Decree of 30 July 2015 [30] (in implementation of Law 90/2013 [31]), starting from medium energy performance for building element (CEER data) (Table 1); that Law transposes the European Directive 2010/31/UE, which aims at improving the number of nearly zero-energy buildings (NZEB, Near Zero Energy Building), in which, because of a very high energy performance due to the use of renewable energy, the energy demand is extremely low or almost zero.

In order to achieve these limit values by applying the energy strategies, different solutions for each interventions was defined. Specifically as regards the thermal insulation strategies we referred to the thermal properties of two materials among the most commonly used available: extruded polystyrene foam, or, in the specific case of internal vertical insulation, glass wool, both with thermal conductivity values l range of 0,035 and 0,036 W/mK.

According to the materials and the quantities calculated for each individual intervention, economic strategies quantification was carried out establishing a unit price parameter per m^2 or m^3.

The values were obtained by consulting the "Regione Lombardia, 2011" [32] and "Camera di Commercio di Milano, 2013" price lists, within sections of the completed works, therefore calculating, in addition to raw material costs, also expenditures related to labor, transport and assembly.

In Table 2 are summarized the main data for each energy strategy identified.

3.2. Building typology classification: the clustering

In order to simplify the sample analysis, characterized by a high number of data, and to optimize the process, aimed at defining the best cost-effective strategies, a typological classification based on objective parameters was considered necessary, so that it could be referred to for the study of any school building. Through the adoption of a data mining technique the sample was divided into homogeneous clusters, thereby allowing a large amount of buildings to be assembled into a small number of schools groups, which share typological and technological characteristics, as well as fuel

Table 2
Energy strategies.

Energy strategies		Adopted materials: quantities and characteristics	Unit price
	External insulation	11 cm of XPS (l = 0,035 W/mK)	66,88 €/m^2
	Internal insulation	11 cm of glass wool (l = 0,035 W/mK)	45,58 €/m^2
	Flat roof insulation	11 cm of XPS (l = 0,035 W/mK)	28,59 €/m^2
	Sloped roof insulation	11 cm of XPS (l = 0,036 W/mK)	57,18 €/m^2
	Basement insulation	9 cm of XPS (l = 0,035 W/mK)	24,38 €/m^2
	Windows replacement	Windows in PVC low-e_4/15/4	271,2 €/m^2
	New plant installation	Heat pump, UTA, fan coil unit	59,2 €/m^3
	PV installation	Photovoltaic panels in mc-Si (0,125 kWp to m^2)	275 €/m^2

consumption and similar energy behaviour. With a view to significantly reduce the number of schools having to specifically submit to energy analysis, it was firstly necessary to define which variables were the most suitable to characterize the sample in the classification construction

Based on the available data, the authors analysed the school buildings characteristics that come into play in energy performance, dividing them between fixed and variable benchmarks in function of the homogeneity within the sample.

The characteristics qualified as fixed would be equal for all typologies, whilst they would distinguish themselves for the variable ones. A benchmark was considered "fixed" if it was homogeneous in at least 80% of the sample; specifically, opaque and transparent vertical closures types belong to this category, respectively with the construction technology of bearing wall present in 89% of the sample and the technology of single or double-glazed without thermal break windows present in 80% of the total.

Also the internal ventilation type was considered as fixed, since natural ventilation was present in 87% of the buildings and winter heating, consisting of a radiator system flanked by a low-performance methane boiler, and the lack of summer cooling characterised in both cases 96% of the sample.

Finally even the lack of a thermal insulation layer in the building envelope was considered fixed, because it was homogeneous in 89% of the school sample.

Instead a benchmark was considered "variable" if it turned out to be uneven within the reference (Table 3): thereby three benchmarks were identified, from whose interpolation various clusters were defined.

The first variable benchmark turned out to be the building type, for which the classification sustained by Sole [27] was followed. The available types for the study sample of school buildings were found to be [Fig. 3a]:

- linear block;
- merged block at C or at L;
- internal court block;
- stepped block.

Subsequently, also the number of floors above ground was qualified as variable, distinguishing the school buildings of the sample in two categories [Fig. 3b]:

- low buildings with 1–2 floors;
- medium-high buildings with 3–4 floors.

Finally the last variable benchmark was found to be the percentage of transparent vertical surface on the vertical surface total, distinguishing two categories [Fig. 3c]:

- 18% of glass surface, which included most of the buildings with traditional fixtures; the percentage of the value used was the average between the derived values of every single school of this category, ranging between 13 and 23%;
- 29% of glass surface, which included most of the buildings with large ribbon windows: the percentage of the value used was the average between the derived values of every single school of this category, ranging between 24 and 34%.

The building type benchmark, which defines the building geometric shape, and the number of floors, can thus be referred to the S/V parameter (the ratio between envelope surface and volume defining the primary energy demand – E_{pH}) used primarily in energy study fields and in accordance with prescribed regulations. Between the buildings within the clusters a correlation is then obtained which does not depend directly on their geometric dimensions, but on the relationships among them. Different cluster types were generated by their interpolation which in the study sample case were found to be 9, as stated in Table 3.

3.3. *Representative buildings and its validation*

Once the clusters with which to classify the construction of the park study were defined, the next step was the quantification of the benefit in terms of primary energy demand reduction E_{pH}, obtained through the application of each identified energy strategy.

This has been possible through the use of a *representative building*, a fictitious model that is representative of the geometry and the energy behavior of the buildings belonging to the cluster: the use of an analysis tool as proposed by the European Commission with the Commission Delegated Regulation (EU) n. 244/2012 which contains a study on the efficiency of existing buildings.

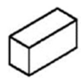
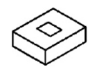
This building is "built" on the constituent data of each cluster: in particular on the number of floors, on the average values of the paved surface and on the vertical surface, both transparent and opaque.

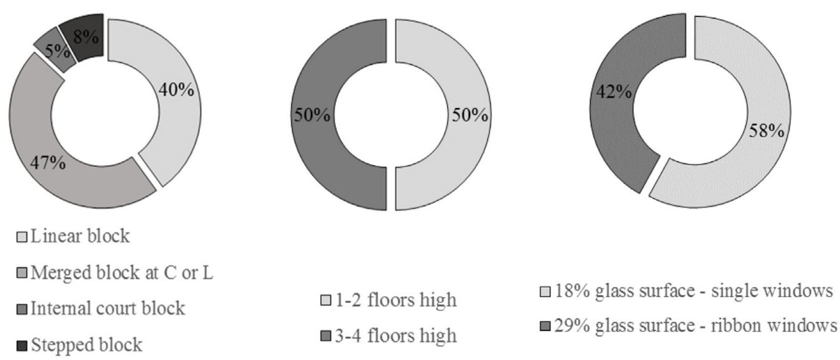
By the use of such data, it was actually possible to quantify the perimeter and the value of the average surface of a floor characterizing each cluster; interpolating such values with the cluster type made it possible to define a geometric shape to be given to the representative building of each cluster, capable of maintaining the average proportions of paved surface and dispersant surface.

In this way it was possible to obtain a fictitious building that represented each of the identified clusters.

The hypothesis sustained, that the energy analysis of the representative building could replace that of every single building belonging to the cluster, was verified considering the standard deviation for each clusters: after the identification of the representative building of each clusters, the related energy consumption was com-

Table 3
The reference buildings. () Number of the buildings in the cluster.

Clusters (N°)	Building Typology  Linear Block	 Merged Block at "C" or "L"	 Internal court block	 Stepped block	N° of Floor 1–2	3–4	% of glass surface Average 18% (13–23%)	Average 29 (24–34%)
C.1 (10)	X				X		X	
C.2 (4)	X					X	X	
C.3 (2)	X				X			X
C.4 (3)		X			X		X	
C.5 (8)		X				X		X
C.6 (1)		X			X			X
C.7 (5)		X				X	X	
C.8 (2)			X		X			X
C.9 (3)				X		X		X



a) b) c)

Fig. 3. Building variable parameters.

Table 4
Building performance data.

Building performance data	
Location	Lecco, Lombardy
Outside temperature	Max: 35 °C/Min: – 3 °C
Main use	Scholastic
Number of occupants (gross floor area per student)	9 m^2/student
Average consumption of electrical appliance	7,19 W/m^2
Average lighting power	10,66 W/m^2
Internal gains: metabolic heat input of the occupants (latent)	59 W/person
Internal gains: metabolic heat input of the occupants (sensible)	73 W/person
Internal gains: lighting heat input	12,92 W/m^2
Internal gains: heat input of electrical appliance (computers, printer etc.)	16,15 W/m^2
Air changes per person	8 L/s
Opening times for the school from Monday to Friday	from 8am to 6pm
Opening times for the school on Saturday	from 8am to 2pm
Opening times for the school on Sunday	closed

pared with those of the school buildings belonging to the same cluster.

Several dynamic building energy analysis using the Green Building Studio® software plug-in for Autodesk® Revit® BIM platform [33] were carried out in order to evaluate the energy consumption of each building. We simulated the building energy behavior according to the design benchmarks, which were considered to be the same for the all samples.

The design parameters defined for energy analyses are presented in Table 4.

The simulations carried out for all the clusters, concerned the buildings' current state, giving a primary energy demand value E_{pH} expressed in kWh/m^{2}year. The hypothesis would be verified in the case where values of E_{pH} and S/V of buildings and of representative building represented comparable results with an acceptable standard deviation.

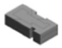
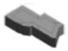
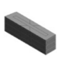
The obtained data verified the assumption: the E_{pH} values are comparable with each other, the maximum difference ranging from 13% for the cluster 7–2% for the cluster 8 with a standard deviation respectively equal to 7.2 and 2.4 (Table 5 shows the comprehensive results for each clusters). Although the quantities of surfaces and volumes for each building investigated were found to be very different, it should be noted how the S/V values appear constant for each cluster, confirming the truthfulness of the method undertaken. On confirmation of the suggested method validity, we defined each cluster representative reference building (Table 6).

4. Main results and discussion

4.1. Definition of the best cost-optimal renovation strategy

Energy consumption simulations were carried out for each reference buildings, relating both to the current state and to each energy strategy applied individually. The values of primary energy demand (E_{pH}) determined for each energy strategy were compared with the value obtained for the current state, in order to quantify the energy savings generated by every intervention and their value expressed as a percentage. The cost/benefit parameter was then defined, expressed in €/kWh year, as the ratio between the amount of savings on the total annual energy consumption and the overall

Table 5
Validation of the clusters.

Cluster 1	School name	Envelope S. S [m^2]	Gross V. V [m^3]	% glass surface	S/V	E_{pH} [kWh/m^2 /year]	% from R.B.	Standard deviation
	Middle school Papa Giovanni XXIII	2376	6838	19%	0,35	214	10	11.2
	Elementary school Via per Castello	1203	5854	18%	0,21	220	13	
	Elementary school N. Sauro	2417	7335	20%	0,33	201	3	
	Elementary school Fantasia	2868	11630	19%	0,25	213	10	
	Elementary school S. Stefano	4782	32214	17%	0,15	180	7	
	Elementary school A. Stoppani	2446	13626	19%	0,18	216	11	
	Elementary school F. Filzi	734	2097	15%	0,35	208	7	
	Elementary school S. Pellico	1185	3796	13%	0,31	204	5	
	Middle school Don G. Ticozzi	3667	20243	22%	0,18	200	3	
	Elementary school G. Rodari	662	1680	10%	0,39	217	12	
	Reference building	2190	10530	18%	0,21	194	/	
Cluster 2								
	Elementary school Pio IX	1386	11529	16%	0,12	206	8	7.1
	Elementary school G. Carducci	2052	12305	19%	0,17	204	7	
	Middle school via Nazionale	828	1120	14%	0,74	211	10	
	Elementary school A. Manzoni e Middle school B. Croce	4039	28576	21%	0,14	196	3	
	Reference building	1944	13382	18%	0,15	191	/	
Cluster 3								
	Elementary school T. Tarelli	1021	4077	31%	0,25	245	13	8.5
	Elementary school Don Milano	2254	8648	29%	0,26	228	5	
	Reference building	1685	6362	29%	0,26	216	/	

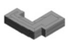
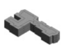
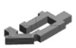
Cluster 4								
	Elementary school G. Marconi	1173	2556	16%	0,46	250	11	
	Elementary school G. Oberdan	2630	7964	18%	0,33	210	7	
	Elementary school E. De Amicis	6012	16305	22%	0,37	231	3	
	Reference building	3456	8941	18%	0,39	225	/	
Cluster 5	School name	Envelope S. S [m^2]	Gross V. V [m^3]	% glass surface	S/V	E_{pH} [kWh/m^2 /year]	% from R.B.	Standard deviation
	Middle school A. Stoppani	6594	26823	31%	0,25	203	12	11.7
	High school A. Fiocchi	8776	71379	31%	0,12	180	1	
	Elementary school E. Toti	3785	16726	25%	0,23	199	10	
	High school G. Bovara	7196	37974	29%	0,19	174	4	
	High school G. Bertacchi	8674	43548	29%	0,20	200	10	
	High school G. B. Grassi	8343	48233	28%	0,17	204	13	
	High school G. Parini	11273	71888	32%	0,16	182	1	
	Middle school L.B. Vassena	3904	14826	31%	0,26	205	13	
	Reference building	7240	41424	29%	0,17	181	/	
Cluster 6								
	Elementary and Middle school A. Moro	3991	16779	29%	0,24	247	1	/
	Reference building	4669	16779	29%	0,28	249	/	

Table 5 (*Continued*)

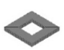
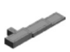
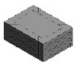
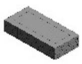
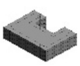
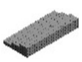
Cluster 7								
	High school A. Manzoni, and T. Grossi	7483	28415	18%	0,26	206	11	7.2
	Elementary school A. Diaz	3310	13704	23%	0,24	200	8	
	Elementary school C. Battisti	2431	9235	17%	0,26	209	13	
	Middle school A. Ponchielli	3970	18193	19%	0,22	207	12	
	Middle school A.Volta	4022	15768	20%	0,26	189	2	
	Reference building	3892	17063	18%	0,23	184	/	
Cluster 8								
	I.T.I. A. Badoni	15683	65791	31%	0,24	227	2	2.4
	Middle school P.G.XXIII	2982	11607	24%	0,26	224	1	
	Reference building	9333	38699	29%	0,24	221	/	
Cluster 9								
	Elementary school S. Pertini	6339	22686	34%	0,28	193	4	12.5
	High school M. Rosso	6046	37759	32%	0,16	206	3	
	Elementary school G. Leopardi	6266	18184	30%	0,34	226	13	
	Reference building	7974	26209	29%	0,30	200	/	

Table 6
The clusters.

	Cluster name	Gross area [m²]	Disper. surface S [m²]	Gross volume V [m³]	% glass surface	Aver. S/V
	C.1	2114	2190	10530	18%	0,21
	C.2	2005	1944	13382	18%	0,15
	C.3	1511	1685	6362	29%	0,26
	C.4	2510	3456	8941	18%	0,39
	C.5	9045	7240	41424	29%	0,17
	C.6	4296	4669	16779	29%	0,28
	C.7	4529	3892	17063	18%	0,23
	C.8	10915	9332	38699	29%	0,24
	C.9	5980	7974	26209	29%	0,30

intervention cost, determined by multiplying its extension by the unit costs.

As regards the quantification of the cost/benefit parameter, in the case of the internal insulation strategy applied to the vertical surfaces for buildings subject to architectural restrictions, a correction had to be made, in order to take into account the thermal bridge incidence generated by the use of this intervention.

In accordance with the provisions specified in Decree 6480 of 30 July 2015, the choice of method fell onto the analytical one, which is based on the use of reference abacus for the quantification of the thermal bridge incidence; specifically those provided by CENED [34] were used.

In order to evaluate this incidence, the calculation was carried out considering, among the buildings of the study sample, the primary school E. De Amicis, of which accurate geometric data were available; the percentage of incidence thus determined was used as reference value for all the clusters.

The application of an internal insulation in particular generates a thermal bridge formed by the junction of the exterior walls and the floors, whose beams are not thermally insulated.

The U_{value} (thermal transmittance measured in W/m^{2}K) of the thermal bridge is determined through the value of the linear thermal transmittance y_E (W/mK), referring to the external dimensions, which is obtainable by applying the following formula:

$$y_E = 0,934 - 0,037 \cdot U + (0,018/l_{eq})$$

Where U is the termal trasmittance (W/m^{2}K) of a building component and l_{eq} is defined as equivalent conductivity of a non-homogenous materials and is an assumption used to take into account the thermal bridge effect (W/mK). The ratio between this factor and the U value of the exterior wall allows quantifying the thermal bridge incidence generated by the use of the internal insulation strategy, which in this case was found to be 20% of the envelope thermal performance.

This value was thus used to increase the cost/benefit consequent result of the internal insulation strategy: applying it to all types in which buildings subject to architectural restrictions were present, a more realistic value was achieved.

The simulations results point out, for all clusters, the cost/benefit values achieved for each energy strategy (Table 7).

By their comparison, it was possible to identify the most promising strategy between those proposed.

Firstly it can be noted how, in all cluster typologies, the strategy that involves the best benefit in terms of reduction of E_{pH}, variable between 30 and 40%, appears to be the new plant installation – S4 (Fig. 4).

That is due to the type of intervention that plays a key role in school buildings, especially as regards the primary ventilation; indeed the high air changes values imposed by the UNI 10339 [35] legislation result in ventilation losses preponderance within the energy balance. Still in terms of primary energy reduction, the external insulation strategy – S1, is characterized by a constant value of E_{pH} reduction in all clusters amounting to approximately 20%, conversely the benefit generated by the strategy of windows replacement – S3 varies according to the percentage of glass surface. In actual fact, this value ranging between 7% in the clusters characterized by classic frames and 15% in those with ribbon windows.

Secondly, as regards the analysis of the cost/benefit benchmarks, we can deduct that the results previously identified may not be equally reflected in terms of best strategy. Actually, if as for primary energy demand reduction the new plant installation strategy was found to be the most advantageous, in economic terms and thus in regards to investment return, it was found to be the least profitable, due to the intervention high cost.

The obtained cost/benefit values comparison (Fig. 5) showed that the best strategy in terms of investment return proved to be the external insulation – S1 for all clusters, particularly for schools with a glass surface percentage reduced.

In conclusion, for clusters characterized by a high percentage of glass surface by a high percentage of glass surface (eg. C3; C5 and C6) the windows replacement intervention – S3 has a performance

Table 7
Results of the cost-benefit analysis.

Clusters	E_{pH} existing building [kWh/m^2/year]	Energy strategies	E_{pH} after renovation [kWh/m^2/year]	Energy consumption reduction [%]	Total price [€]	Cost-benefit [€/kWh year]	Architectural restriction (20% thermal bridge incidence) [€/kWh year]
C.1	194	External Insulation[a]	146	25%	125.121	**1,23**	1,47
		Windows replacement	180	7%	55.217	1,85	
		New plant installation	133	31%	536.251	4,16	
C.2	191	External Insulation[a]	151	21%	115.474	**1,45**	1,74
		Windows replacement	179	6%	63.332	2,58	
		New plant installation	137	28%	779.901	7,16	
C.3	216	External Insulation[a]	169	22%	84.121	**1,20**	1,43
		Windows replacement	187	14%	75.131	1,69	
		New plant installation	140	35%	357.242	3,11	
C.4	225	External Insulation[a]	158	30%	179.059	**1,07**	1,28
		Windows replacement	204	9%	119.133	2,30	
		New plant installation	142	37%	470.206	2,25	
C.5	181	External Insulation[a]	146	20%	375.756	**1,18**	1,41
		Windows replacement	158	13%	339.309	1,62	
		New plant installation	129	29%	2.004.046	4,23	
C.6	249	External Insulation[a]	195	21%	203.770	**0,89**	1,06
		Windows replacement	217	13%	198.269	1,46	
		New plant installation	128	49%	636.104	1,22	
C.7	184	External Insulation[a]	143	22%	236.362	**1,27**	1,53
		Windows replacement	171	7%	119.124	2,00	
		New plant installation	132	28%	938.770	3,96	
C.8	221	External Insulation[a]	178	20%	395.771	**0,84**	1,01
		Windows replacement	204	8%	306.897	1,65	
		New plant installation	128	42%	1.939.422	1,91	
C.9	200	External Insulation[a]	161	20%	323.382	**1,38**	1,65
		Windows replacement	179	11%	242.480	1,90	
		New plant installation	103	49%	1.434.692	2,47	

The bold valued represent the best cost-benefit strategy.
[a] Vertical and horizontal building envelope.

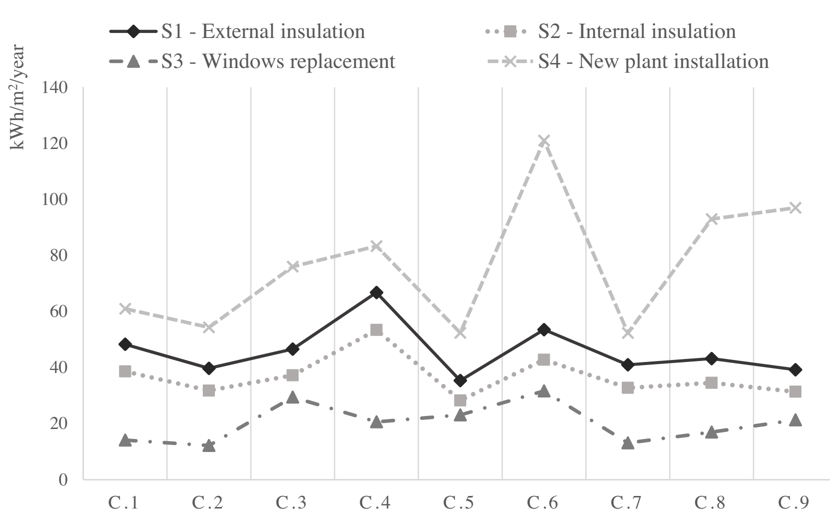


Fig. 4. Best strategy for E_{pH} reduction.

comparable with that of insulation strategy, especially in the case of restricted buildings with internal insulation applications.

The analysis result is corroborated by the fact that for the majority of schools in the study sample, the windows are one of the few elements subject to a requalification in time. Indeed, for this reason the benefit produced by their replacement is lower.

The use of innovative materials such as thermo-reflective insulations, in order to obtain benefits from the point of view of weights reduction or loss of inner space, would lead to an increase of the expenditure per m^2 to 30–35% more than with using traditional materials. In this case, there would be a different scenario (Fig. 6) where, for clusters characterized by a high glass surface percent-

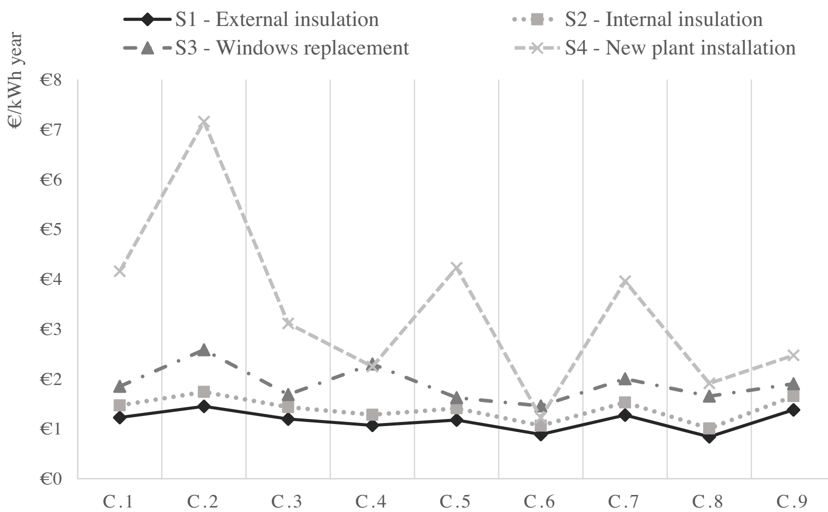


Fig. 5. Best strategy for cost-benefit.

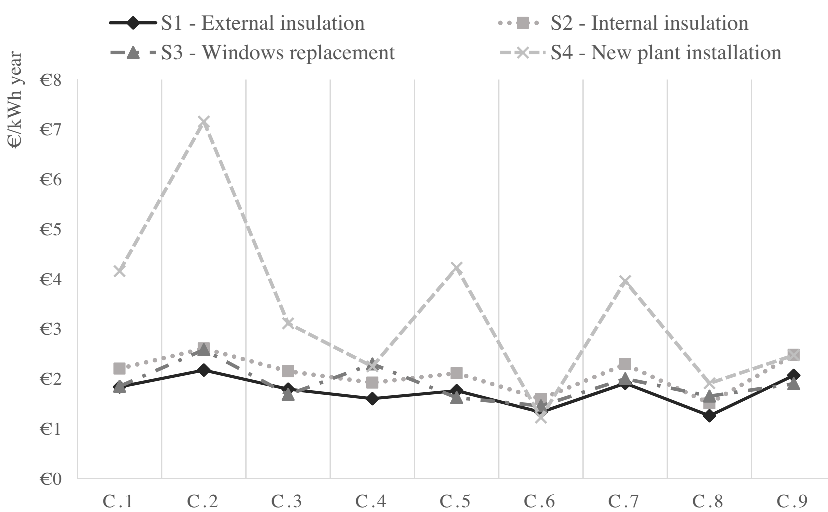


Fig. 6. Best strategy for cost-benefit_ scenario 2.

age, the replacement windows strategy of – S3 would emerge as the most profitable.

4.2. Cost for the whole municipality renovation

At the same time an economic study on the whole building stock was carried out, in order to estimate the predictable expenditure which the Public Administration will have to sustain in the coming years for the energy renovation of schools public properties.

With a view to obtain an overall investment value as reliable as possible, firstly we calculated the quantities involved in the energy requalification: starting thus from mapping sheets, carried out in order to classify the study sample, and from the information contained in them, the geometric quantities of the building-plant system were extrapolated for each school building. It was evident that, with the aim of obtaining a value as reliable as possible, the areas of the buildings, which had already undergone a redevelopment due to chosen energy strategies, were detracted from the final results.

The 38 analysed school buildings are characterised by a total gross area of 178.789 m^2, a total volume of 787.903 m^3 and a total vertical wall surface of 89.443 m^2. In addition the transparent vertical surface is 22.722 m^2, while the surface covering extends for 71.870 m^2, divided into 34.427 m^2 of flat roof and 37.433 m^2 of slanted roof. This distinction is particularly important for the quantification both of the thermal insulation intervention and of the photovoltaic plants installation; just concerning this last intervention, in order to define the potential performance of the system, the slanted roof area was further divided according to the sun exposure.

Through the multiplication of the derived geometric quantities for the prices of each energy strategy, the amount of the total expenditure and that of every single intervention were established, compared according to a percentage of incidence.

As regards the realisation of the photovoltaic plants we could also determine the return period of the investment for this energy strategy, as we were able to obtain the annual return plan. For this analysis we considered as project value of the photovoltaic plant an efficiency of 143,75 kWh/year per 1 m^2 of installed surface.

We attributed to the flat surface and to the slanted one oriented towards South a panel efficiency h equal to 1, while to the other slanted surfaces oriented towards East and West a low efficiency equal to h = 0,86, thereby achieving a value of energy production potential from FER (renewable energy sources), amounting to 4.445.152 kWh/year for the first and 2.104.344 kWh/year for the second ones. This means a related benefit to the territory condition due to the emission reduction of CO_2 of about 328 ton every year.

Table 8
Results of the cost-benefit analysis related to the number of students.

Cluster	Total investements [€]	N° of students	Energy strategies	Investment for each strategy [€]	Investments per student [€]	Total Investments per student [€]
C1	7.972.932	1.490	External Insulation*	1.019.978	685	5.351
			Windows replacement	427.947	287	
			Photovoltaic plants installation	2.198.020	1.475	
			New plant installation	4.326.987	2.904	
C2	3.687.608	685	External Insulation*	290.874	425	5.383
			Windows replacement	253.329	370	
			Photovoltaic plants installation	723.250	1.056	
			New plant installation	2.420.155	3.533	
C3	1.351.468	171	External Insulation*	127.787	747	7.903
			Windows replacement	150.261	879	
			Photovoltaic plants installation	320.100	1.872	
			New plant installation	753.320	4.405	
C4	2.740.165	492	External Insulation*	339.050	689	5.569
			Windows replacement	357.400	726	
			Photovoltaic plants installation	455.675	926	
			New plant installation	1.588.040	3.228	
C5	25.635.628	5.504	External Insulation*	2.463.538	448	4.658
			Windows replacement	1.593.476	290	
			Photovoltaic plants installation	6.075.850	1.104	
			New plant installation	15.502.763	2.817	
C6	582.762	311	External Insulation*	161.743	520	1.874
			Windows replacement	198.269	638	
			Photovoltaic plants installation	222.750	716	
			New plant installation	0	0	
C7	7.953.433	1.151	External Insulation*	811.714	705	6.910
			Windows replacement	595.621	517	
			Photovoltaic plants installation	1.495.450	1.299	
			New plant installation	5.050.648	4.388	
C8	5.529.486	1.405	External Insulation*	571.241	407	3.936
			Windows replacement	613.793	437	
			Photovoltaic plants installation	449.625	320	
			New plant installation	3.894.827	2.772	
C9	7.520.402	1.236	External Insulation*	891.668	721	6.084
			Windows replacement	727.439	589	
			Photovoltaic plants installation	1.244.100	1.007	
			New plant installation	4.657.196	3.768	

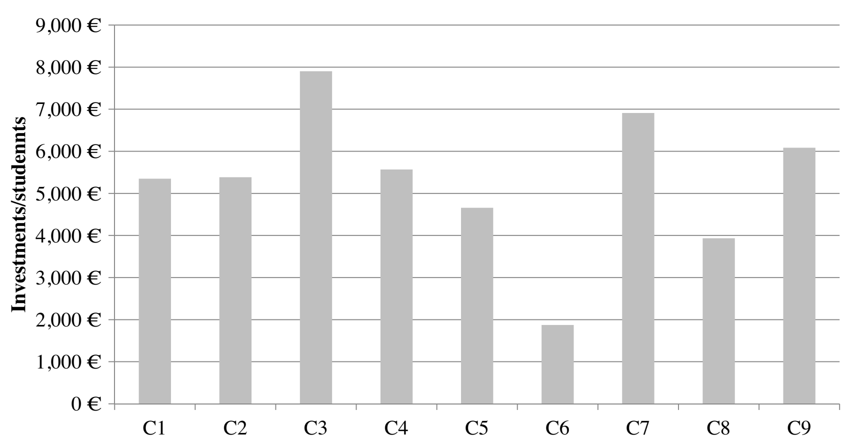


Fig. 7. The cost of the investments related to the number of students.

Finally, considering the current market price of electricity, we realized an investment return period of 12 years for the former and 14 years for the latter.

In order to have an other useful indicator for the decision making phase the cost of the energy renovation strategies has been divided by the number of student for each school building. The criteria is intended to give an uniform criteria independent from the geometrical and architectural status of the building and only related to the number of users. The results are shown in Table 8 and in Fig. 7.

5. Conclusion

As argued in the previous section the developed methodology represents an important state school buildings renovation tool,

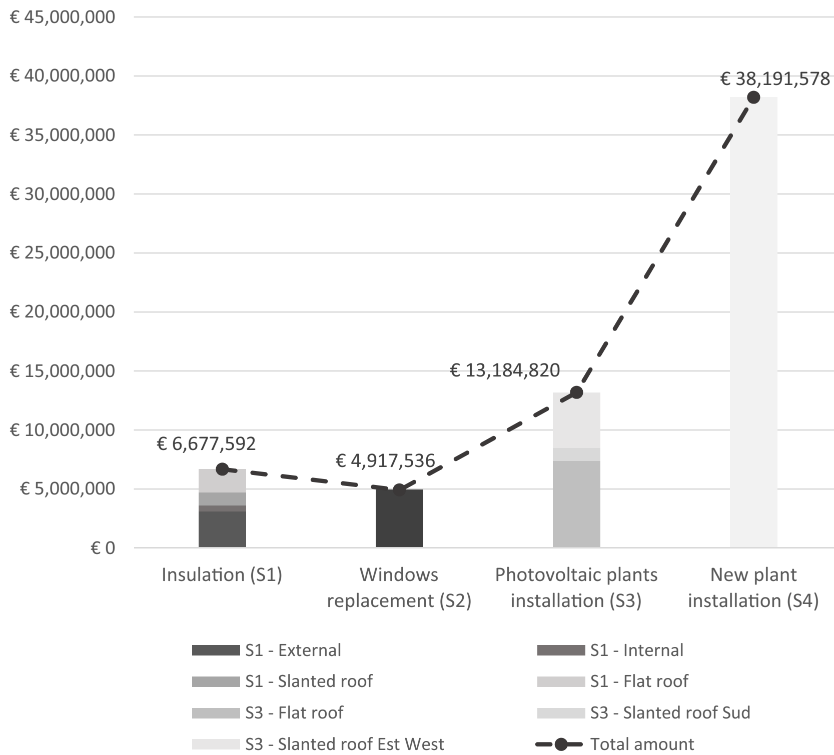


Fig. 8. The cost of the investment for the whole municipality renovation.

since it provides homogenous guidelines applicable to different contexts in view of the method replicability.

Through the method developed and applied to Lecco schools, it was possible to define the most promising energy strategy for each building, setting an extremely useful parameter in planning short-term investments to be allocated to the school buildings.

Since the Public Administration does not have the budget to allow the application of all the strategies to each school building, it becomes of paramount importance to know which strategy is the most advantageous from an investment return perspective, in order to plan the interventions priorities over time.

Applying firstly a more advantageous renovation strategy in terms of cost/benefit, compared to another, will result in savings leading to the availability, in a shorter time, of more money to be allocated to other strategies, in order to achieve a total retrofit of the building stock in the shortest possible time.

Finally, the breakthrough treatment allowed establishing the overall cost for the investment needed in the building stock renovation, which could be extremely advantageous to the Public Administration. Knowing the total necessary investment amounts to € 62.971.530,0 (Fig. 8) with the average expenditure per student estimated at € 5.060,0, would prove useful for long-term economic resource planning.

In the end the proposed method gives to the local school facility planners a uniform criteria for the description of the status of their school buildings. It should simplify the task of individual school evaluation and long-range planning. The proposed method can be computerized and integrated in a regional or national database, which may be available on line, with an up to date overview of the state of the art of the building stock. Starting from the building information collected in the database it is possible to analyze the impact of different energy efficient measures, analyze the single or overall investment and their impact on student's population.

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