Evaluation of the Cost-Optimal Method Applied to Existing Schools Considering PV System Optimization

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Abstract: In Italy in 2020, only 15.5% of school building heritage was retrofitted from an energy and environmental point of view. In this paper, the cost-optimal method was applied to two different school buildings belonging to the same Italian cold climate zone but characterized by different structural and technological solutions. The research aims at defining the cost-effective redevelopment solution among several ones proposed to apply to this building type. At the same time, this paper provides a critical analysis of the methodology applied, highlighting deficiencies related to a not proper evaluation of environmentally friendly retrofitting measures. In a cost-effective context, the main results show that the intervention on the heating system is more convenient than the retrofitting of the envelope. The energy saving is equal to about 35% for both considered schools. Among the different proposed requalification configurations, the adoption of PV (photovoltaic) electric generation is included. In this regard, an optimization procedure was implemented in a generative design environment to maximize energy production with reference to different design parameters. As a result, a solution with south oriented PV modules with a tilt angle of 42° and arranged in 0.7 m spaced rows proved to be the most effective.

1. Introduction

According to the Global Status Report REN21 [1], building energy need represents 33% of global energy demand and only a share less than 15% is satisfied by renewables. In total, 77% of the whole energy demand for buildings is related to heating, cooling, and domestic hot water (DHW) while the remaining 23% accounts for electricity needs such as lighting, equipment, and appliances [1]. In line with the previous report, the European Commission's 2020 report "A renovation wave for Europe" [2] highlights that buildings are currently responsible for 40% of final energy consumption and 36% of greenhouse gas emissions (GHG) into the atmosphere.

In accordance with ENEA (Italian National Agency for New Technologies, Energy and Sustainable Economic Development), in Italy in 2018 the primary energy demand is equal to about 160 Mtep, satisfied for most by fossil fuel, even if the percentage covered by renewables increased in the past 2 years up to about 20% [3]. A total of 40% of the Italian primary energy demand is required for civilian use (Source: Eurostat) [3] and the residential sector shows energy consumption in line with the European average. On the contrary for non-residential buildings, Italy's energy demand is, by far, higher than the European one (source: EU Building Stock Observatory) [4].

Issues about energy consumption and environmental impact highlighted by this critical overview are mainly related to the age of the building stock, most of which was built in absence of specific energy and emissions regulations [5,6]. Furthermore, the European Commission admits that 75% of the current building stock is affected by several energy and environmental deficiencies and 80% of the existing building heritage will still be present by 2050 [2].

For this reason, in accordance with the SDGs (Sustainable Development Goals) of ONU (United Nations), the European Member States have signed the European Green Deal [7] highlighting the building sector as a key point of this agreement. In this perspective, one of the goals directly addresses the annual renovation rate of the building stock, prescribing an improvement from the current 0.4% up to 1.2% [3]. Usually, high initial investment costs and raised payback periods make the integrated redevelopment (architectural, environmental, and energy) of a building difficult to achieve and very often retrofitting measures simply concern a single building element (e.g., the substitution of the lighting system). However, an integrated approach for existing building redevelopment also considering energy and environmental sustainability is mandatory to achieve a carbon-free economy by 2050, as called for in the Paris Agreement of 2015 [8]. Moreover, existing building heritage retrofitting is necessary to reach the goals set for 2030 (reduction of GHG emissions of 55% with respect to 90s level, increase in energy efficiency up to 32.5%, use of renewables up to 40% to satisfy the energy needs) as well (2030 climate and energy framework) [9].

In this context, a critical building stock is the one represented by education buildings. Italian existing schools are characterized by architectural, energy, and environmental critical issues since 63% of them were built before 1974 (23% before 1940) when no requirements dealing with energy and GHG emissions were considered in the design phase [5]. Obviously, this building stock requires urgent retrofitting to meet European current goals concerning energy savings and reduction of the environmental impact of buildings but also to guarantee proper wellbeing to students and teachers. The Italian school sector energy demand accounts for 1 Mtoe/year [10] and 73% of the whole energy needs is for kindergartens and primary and secondary schools. According to Legambiente's report [5] of 2020, only 15.5% of the total existing schools in Italy was energy retrofitted and an even lower percentage (nowadays only 5.5%) was classified as energy efficiency class A following the Italian energy label criteria (global energy performance index for non-renewables $EP_{gl,nren} > 0.8\ EP_{gl,nren,rif,standard\ (2019/21)}$ reference building global energy performance index for non-renewable) [11]. In Italy, 0.8% of newly constructed buildings in the last 5 years were meant for hosting schools; moreover, demolition and reconstruction of buildings is not always the most suitable solution because of the required time, the initial investments, and the environmental impact [12]. There are many studies in the literature about existing schools' energy retrofitting, proposing different measures to reduce primary energy demand and operational costs [13] or initial investments for different interventions [14]. Moreover, other researchers aimed at redeveloping existing buildings to meet the Nearly Zero Energy Building (nZEB) standard [15–17], also through an integrated approach [18], 3-liter building standard [19] or plus energy level [20]. For instance, Salvalai et al. [14] tried to define, with an energy and economical approach, the most suitable and cost-effective redevelopment measures for facilities (clusters) representative of different school building types in Italy. Many authors pointed out that renewing the artificial lighting systems and managing solar shading systems can significantly reduce the primary energy demand of a school building. Other research stressed that it is fundamental to implement an energy management system to decide which schools should be redeveloped [21]. Furthermore, considering the Mediterranean climate, Gamarra et al. [22] proposed different energy strategies for the retrofitting of two schools located in Madrid. The aim of the research was minimizing both the global warming potential and the energy consumption through the implementation of renewables and the optimization of energy use. This was obtained through the increase in cooling and lighting system efficiency. Otherwise, Marrone et al. [23] firstly performed a cluster analysis to individuate the representative school building types between 80 different schools located in central Italy and secondly, they identified the best energy retrofit measure for each one of them. They suggested envelope insulation, energy service upgrade, and renewables implementation to obtain 80% of heating energy saving. On the other hand, Pagliano et al. [24] considered a child center located in Milan and they want to define some energy redevelopment strategies to guarantee the proper thermal comfort of the occupants also in future decades considering climate change and the in-

crease in external air temperature. They state that it is fundamental to take into account the introduction of passive cooling strategies combined with the refurbishment of the external envelope. According to the previous study also Heracleous et al. [25] analyzed educational buildings in Cyprus considering the current climate change. They want to individuate the proper energy redevelopment measures (mainly passive measures and heat recovery for ventilation) to guarantee the occupants thermal comfort minimizing heating demand and avoiding overheating in summer. Alternatively, Lakhdari et al. [26] used genetic algorithms to propose a classroom design to ensure proper thermal and lighting internal conditions by guaranteeing low energy consumption. They concluded that an optimization of the external envelope parameters (such as window-to-wall ratio or solar shading system) during the preliminary design phase ensures good comfort and energy performance.

Within the context outlined so far, the research presented in the paper proposes the application of the cost-optimal methodology to evaluate retrofitting interventions to be applied on several educational buildings. This study aims at supporting the decision-making process of designers involved in energy improvements of school facilities, preliminarily estimating the costs of different kinds of measures and their energy savings.

The paper deals with the analysis of two different school buildings located in Florence (cold climate zone) to define cost-effective energy and environmental redeveloping measures. Since the studied facilities are characterized by two different structural and technological solutions, both widely spread in Italy for schools built in the 70–90 s period, the chosen interventions could be implemented on a larger building stock. One of these buildings was chosen also because it was constructed by the same company with the same structural and technological solution of another school that was previously studied [27]. Therefore, it is possible to make comparisons between the main results obtained [27].

It is worth noticing that in the literature there is a lack of research applying a cost-optimal method to school building type. Thus, this work wants to focus on a wide building stock not often analyzed but affected by several energy issues. By adopting a cost-optimal approach, a series of cost-effective measures can be identified to produce relevant improvement in energy performance keeping the initial investments within an affordable level. This aspect is particularly significant in this case since these interventions are funded by public administrations that have to deal with limited budgets. The methodology was not only merely applied, but the results obtained were also critically discussed in order to highlight the weaknesses of the cost-optimal method itself. Moreover, an entire section of the paper deals with the optimization of PV modules distribution to maximize energy production that has no precedent in literature about schools. In the paper, at first the state of the art about cost-optimal methodology for different building types will be shown; secondly the methodology used for the research will be explained in detail, then the main results of the performed cost-optimal analysis will be illustrated and discussed, and finally conclusions will be delineated with some outlook for future research.

2. State of the Art

The cost-optimal procedure is a comparative method proposed for the first time directly by the European Directive 2010/31/EU [28], known as EPBD recast, and the delegated Regulation 244/2012 [29] and later updated by the last European Directive 2018/844/EU [30]. This cost-optimality methodology enables to define the requalification measures for both new constructions and existing ones aiming at both energy and economic sustainability. Therefore, performing this kind of analysis, the designer can outline the redevelopment interventions that minimize energy consumption maintaining an affordable cost for the owners. The upgrading intervention alternatives are related in the same graph to both primary energy demand (kWh/m^{2}a) and global cost (EUR/m^2). The whole cost includes initial investments and operational, servicing, substitution, energy, and disposal costs [31]. Obviously, it is possible to consider both single energy measures and combinations of different redevelopment interventions.

Several studies about cost-optimal methodology applied to different buildings typologies (residential and non-residential intended use) can be found in the literature [32]. Many authors performed cost-optimal analysis in the case of residential constructions, which is indeed the most studied building type with this kind of approach. For instance, Tadeu et al. [33,34] used the cost-optimality methodology to study the existing residential building stock in Portugal. They proposed a simplified cost-optimal methodology to compare the energy resources for four possible systems to satisfy energy needs for DHW and heating. The solution coupling a gas water heater and heat pump proved to be the best to minimize primary energy consumption, but in a cost-effective perspective the gas water heater and the gas boiler had to be preferred for DHW and heating system, respectively. As a final result, acting on the energy system was assessed to have a greater impact than implementing passive measures, such as insulation of both facades and roofs or the substitution of windows with better ones. Moreover, such a result confirms other previous research findings for Italy [35]. On the other hand, Panagoutidou et al. [36], introducing environmental impact evaluations as well, tested the combination between active and passive measures affirming that the external envelope insulation and the installation of a heat pump can reduce greenhouse emissions by about 60%. A further decrease up to 96% can be achieved introducing a coupled PV system.

However, the residential intended use is not the only studied to find out the cost-effective solution for energy and environmental retrofitting. In the literature there are some studies concerning offices [37], hotels [38], shopping malls [39], and some cases of industrial buildings [40]. Vujnovic et al. [41] performed a cost-optimal methodology to evaluate a newly built hotel in Croatia. They took into account the costs of energy, systems, and installation, considering also internal comfort conditions to avoid systems oversizing and consequent reductions in their efficiency.

In line with the previous study, the cost-optimal methodology was used by other authors also during the design phase to obtain efficient and environmentally friendly newly constructed buildings. For instance, Congedo et al. [42] concluded that for a new office building located in a warm climate it was essential to install a heat pump integrated with solar collectors and PV panels to meet both the cost-effective and the nZEB standard. Considering the same intended use, Niemela et al. [37] applied the cost-optimal methodology to evaluate retrofitting measures for office buildings built in the 70s and 80s. They proposed a ground-source heat pump for both heating and cooling purposes as cost-optimal measure to guarantee proper internal thermal conditions and low CO_2 emissions.

Moving up to a larger scale, other studies point out that is essential to consider the urban level and not only a single building type. Luzuriaga et al. [43] proposed a cost-optimal assessment to be applied at urban scale to provide a tool supporting public administrations in the decision-making processes. By this way, long-term strategies for the management and the redevelopment of existing residential building stocks could be effectively improved. They considered a combination of both passive and active measures applied to 17 different types of residential buildings, selected as representative of the housing heritage. They stated that an external insulation layer of 0.7–0.8 m can reduce the heating primary energy demand by about 19–47%, depending on the characteristics of the building considered. Moreover, the combination of the external insulation layer and the use of solar collectors for DHW covering about 60% of production proved to be the cost-effective solution in this case. Following the previous study, Yazdanie et al. [44] proposed a renovation of existing building stocks to reduce energy demand and CO_2 emissions at urban scale. Adopting cost-effective solutions in a long-term perspective of carbon-neutrality was considered by the authors a key point to ensure sustainable urban energy planning strategies with the same approach, research by Carpino et al. [45] addressed the widespread Italian social housing building stock to promote an urban sustainable growth. They pointed out that for these kinds of facilities, often old and outdated, it was necessary to intervene on the building system and to integrate renewables for both cold and warm climates to have a cost-effective solution and a decrease in net thermal energy. Moreover,

external envelope retrofitting was also needed to comply with the nZEB requirement. Some authors tried to analyze different kinds of refurbishment measures applied to different building types [32,46].

Some of them highlighted a significant gap between the cost-effective measures and the ones needed to reach the nZEB status. Baldoni et al. [47] pointed out that such a difference can be related to the variability of the economic parameters used in the analysis, while Becchio et al. [48] concluded that the nZEB solution is far from being the cost-effective one. However, Salem et al. [49] stated that the nZEB retrofitting solution and cost effective one differs by about 30%. In this regard, Soares dos Reis [50] proposed to update the cost-optimal evaluation introducing environmental impact and quality indicators remarking that sustainability must be ensured in a multidisciplinary perspective and not from a merely economic point of view.

Other studies performed a similar analysis in different climate conditions. Paduos et al. [51] stated that the refurbishment of the existing building stock complying with the nZEB standards (considering the nZEB definition of several European Member State) is possible only with very high initial investment costs. Consequently, retrofitting measures allowing to ensure a zero-energy demand for buildings are not always the cost-effective ones. D'Agostino et al. [52] pointed out a methodology to define the cost-effective solution to reach nZEB standard energy savings (beyond 90%) considering 14 different locations in Europe: for colder climate zones, envelope retrofitting is fundamental while for hotter climates the lighting system renovation is needed to obtain zero energy consumption. The energy system redevelopment and its integration with renewables are crucial to ensure zero energy consumption and low environmental impact. Finally, Ferrara et al. [53] demonstrate that energy redevelopment interventions can produce a dual benefit, making buildings more efficient and, at the same time, most resilient to climate change.

Looking at the European target of a carbon-free economy by 2050, many authors agree that it is fundamental to include the greenhouse gas emissions in the cost-optimal methodology. For instance, Chastas et al. [54] proposed a first attempt to introduce the embodied impact in the EPBD recast in the cost-optimal methodology. They performed a sensitivity analysis considering climatic, design, and economic parameters and they highlight an increase in global costs in a range between 0.90% and 2.40%. At the same time, Asdrubali et al. [55] affirmed that it is necessary to consider the energy and environmental payback period in the analysis of cost optimal to obtain both the cost-effective measures and the nZEB standard.

Other research in the literature pointed out that achieving the nZEB status for existing building is impossible recurring only to passive redevelopment measures, but system retrofitting is essential. For instance, Galimshina et al. [56] performed a multi-objective optimization considering all the possible uncertainties of LCA (Life Cycle Analysis) and LCCA (Life Cycle Cost Analysis), mainly related to building operation phase and materials production. They found out that to minimize both GHG and annual costs, the replacement of the existing gas boiler for the heating system is needed. For the authors, the best solution is a biomass (wood) boiler compared to an air–water heat pump. Amer et al. [57] as well performed a multi-objectives optimization looking for the zero-energy and cost-optimal solution for the construction of a roof stacking. They pointed out that this could be an effective solution to build new residential facilities without constructing new buildings. The goal of the performed analysis was to minimize the global cost and the energy demand assisting in the decision-making process for this kind of intervention. Moreover, for completeness, they considered the increase in weight for the construction from a structural point of view.

Finally, studies applying a cost optimal method to school buildings [13,58,59] are not very common in the literature since, as already mentioned, the residential type is the most studied building type. For instance, regarding school buildings, Bonomolo et al. [60] proposed the cost-optimal approach to evaluate the cost-effective measure for the renovation of the artificial lighting system of two existing school buildings, since this

measure proved to be the most effective and sustainable retrofitting intervention. Stocker et al. [61] proposed this kind of method applied to eight schools in the Alps, considering different solutions for external walls with different thicknesses of insulation and several alternatives of heat generators to minimize heating energy needs. They stated that the substitution of the existing heating system can ensure the best trade-off solution between investment costs and primary energy demand reduction. Alternatively, Moazzen et al. [62] aimed at implementing the life cycle assessment for school building type also taking into account the occupants' thermal comfort, the nZEB standard, and the cost-optimal method to define the redevelopment measures to be used. They considered different technological solutions for the external envelope and three climate zones. For some climatic conditions, the increase in occupants comfort level can be reached for both nZEB and cost-optimal retrofitting scenario. Finally, Congedo et al. [63] applied the cost-optimal method to a kindergarten and a nursery school situated in Italy. The cost-effective solutions proposed by the authors, always including heat pump and renewables coupling, permit to reduce the primary energy demand and the gas emissions by 85% and about 83%, respectively.

3. Method

The research followed a method made up by four phases, following the same procedural steps adopted in a previous similar work by the research group concerning [27] the same building type:

Phase 1

At first, two different case study representatives of the Italian existing school buildings heritage are individuated. The facilities chosen are characterized by two of the most recurrent technological and structural solutions adopted in the period 70–90s, with a reinforced concrete load bearing structure and a prefabricated one, respectively. Both schools are located in Florence, in climate zone D [64] with 1821 heating degree-day. The city has a temperate and sub-coastal climate with moderately cold winter and 2–3 months with an average temperature < 10 °C and hot summer with 3–4 months with an average temperature > 20 °C. The heating period is within 15 November and 15 April.

A more detailed description of the two buildings analyzed will be provided in Section 3.1 Case studies. The differences registered in the construction technique are also reflected in the different approach to be applied for energy retrofitting measures. For the first building, the redevelopment proposed is based on the addition of layers to the existing external envelope, while for the other also disassembly and replacement of the current prefabricated panels is considered.

Phase 2

In a second stage, a detailed analysis of the case studies is performed to define their energy performance and, consequently, the environmental one. Energy simulations are performed using Energy Plus software [65] with Design Builder [66] as a graphical interface. Heating, cooling, artificial lighting, and domestic hot water were considered for the estimation of primary energy demand because they are the most important contributions to the energy balance of school buildings. As concerns the energy simulation set up, the real geometry of the two existing schools is imported in Design Builder starting from a Building Information Model (BIM) of the current condition previously realized in Revit software [67]. In the energy analysis model, each thermal zone is individuated according to its intended use (Figure 1). Further, for each functional unit the following design parameters are defined: (i) occupancy (persons/m^2) according to Appendix A of UNI 10339 [68] (UNI Italian National Agency of Unification), (ii) minimum air flow rate according to the same standard with reference to the type of functional unit (vol/h or m^3/s person), (iii) heating and cooling setpoint during the activity period and the attenuation temperature (°C) for the rest of the day depending on the thermal zone in accordance to UNI/TS 11300-1 [69] (TS technical specification), (iv) internal gains according to the same legislation [69], (v) domestic hot water need depending on the number of students in accordance to UNI/TS 11300-2 [70], and (vi) the openings hours according to the real school time table. Dynamic

energy simulations were performed in hourly time steps considering a simple Heating, Ventilation and Air Conditioning (HVAC) system and choosing the proper energy vector and the right efficiency for the system.
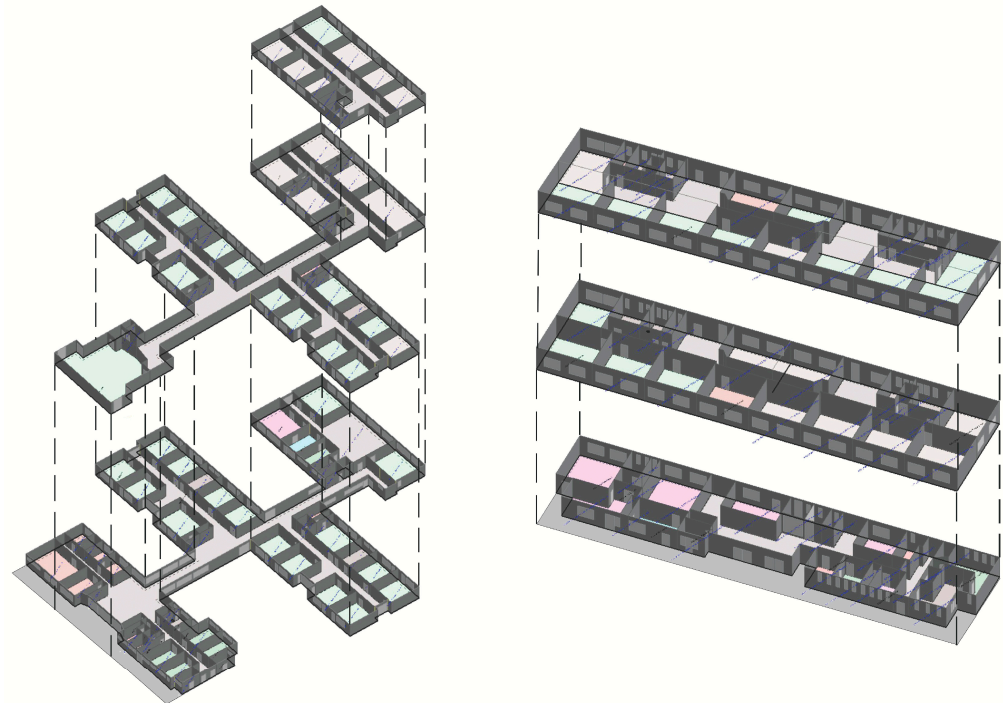

Figure 1. Design builder models for both Poliziano (on the left) and Rodari (on the right) school with the indication of the different thermal zones considered for the analysis.

Phase 3

To integrate energy production from renewable sources, the installation of photovoltaic panels is proposed among the other retrofitting measures for both the case studies. A photovoltaic system with PV modules of 1×2 m with a power peak of 500 Wp was considered. While in the Rodari school their distribution is substantially obliged due to the roof geometry, the Poliziano case study is chosen to test an optimization method to guarantee the maximum exploitation of rooftop solar technical potential. Starting from the BIM model, parametric modelling and generative design tools are implemented to point out the optimized PV array geometry. Nowadays, these techniques are emerging trends in the Architecture Engineering and Construction (AEC) sector and can assist designers in the decision-making process. The extreme flexibility of these tools, often relying on algorithms autonomously set up by the designers, makes them suitable for different subjects of interest and final goals. They ensure the automatic generation of different solutions exploiting the computational resources of computers to produce several alternatives otherwise not considerable with traditional calculations. Two different approaches are currently adopted for the evaluation of the generated alternatives. The first one, related to said optimization procedures, is based on the maximization or minimization of one or more fitness functions set by the designer and is autonomously carried out by the computer until convergence according to the optimization algorithm [71]. The second method is represented by the design optioneering approach, that allows the exploration of the various design options obtainable from a given set of parameters but without pre-set target values for the outputs of interest [72]. This latter possibility was tested by the research group in a previous study [73] concerning the choice of materials for envelope components based on multicriteria considerations including sustainability aspects. In this regard, several applications of optimization methods can be found in the literature [74]. For instance, studies are performed regarding envelope components [75] as well as lighting conditions

and systems [76]. To satisfy sustainability goals, other authors focus their research on the search of the optimized design of form and facade of buildings [77], recurring to Mc Neal's Grasshopper plugins. Generative design algorithms can indeed be coupled with environmental simulation platforms allowing rapid comparisons and more conscious design choices. In the research here presented, the tools illustrated until now are used to evaluate the most effective distribution of PV modules to be installed on the roof of Poliziano school aiming at maximizing the total incident radiation and, consequently, energy production. The method is summarized in Figure 2 and combines the use of Revit, Grasshopper for Revit [78], and a series of related plugins for environmental analysis, optimization, and design optioneering procedures.
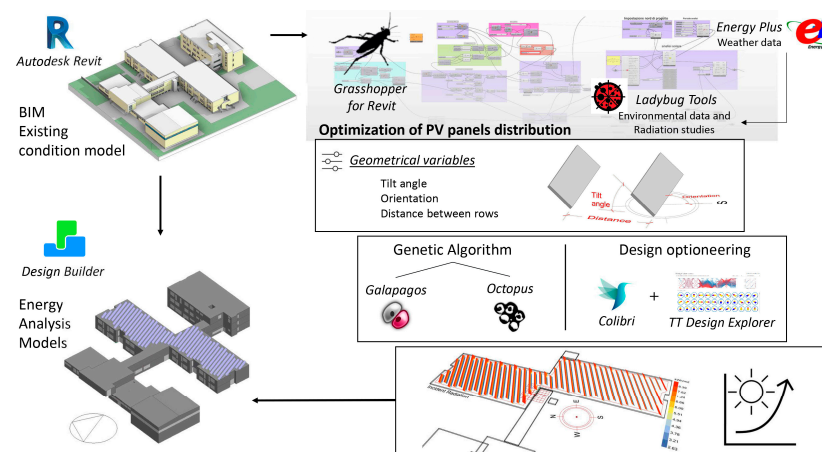
Figure 2. Optimization of PV panels workflow: starting from the BIM model of the building, realized with Revit, an optimization procedure is set in Grasshopper thanks to an interoperable plugin. The model is analyzed to select the roof of interest and surfaces casting shadows. In Grasshopper, the geometry of a single panel and the one of the arrays are generated and the radiation analysis is set through the Ladybug plugin with reference to Energy Plus weather data. Once the geometrical variables are selected, a single objective optimization is performed with Galapagos, while Octopus is used for multifactorial analysis. Results are validated with a design optioneering procedure implementing Colibri plugin and TT DesignExplorer. A Design Builder analysis was finally run coupling the building geometry extracted from the BIM model and modeling PV modules according to the optimized distribution.

Starting from the BIM model in Revit, Grasshopper is used to produce an original algorithm in visual programming language (VPL) for the automatic generation and evaluation of different configurations for the PV panels array. This procedure is implemented with reference to the wider roofing surface available, whose geometry is selected directly from the BIM model. Module dimensions can be set according to manufacturer technical sheets in terms of width and length and are assumed as fixed. The input variables chosen for the optimization are the tilt angle of the panels, the orientation of the array and the distance between consecutive rows. For each of the parameters listed before, a range of variability is assigned. For the tilt angle, configurations considered start from a minimum of 0° to reach a maximum value of 60° with increments of 2°. Orientation is assumed to vary from 0° to 360° (2° increment), while the maximum distance between rows is set to 2.2 m starting from 0.7 m (0.1 m increment). This minimum boundary is introduced to ensure adequate maintenance operations and for the same reason panels are not foreseen in a perimeter band all over the roof. As for the radiation analysis, climatic data are obtained by the EnergyPlus database available online and implemented in the algorithm through the Ladybug plugin, the same used for environmental simulation too. The reliability of this tool is certified by other authors [79] comparing the result obtained with the ones provided by fully integrated climatic simulation engines. The radiation analysis is carried out considering a period from 1 to 6 January with 6 hourly timesteps to enhance energy production in

the most adverse conditions. Moreover, considering a short time interval prevents from excessively time-consuming operations. The search for the optimized solution is initially undertaken using the genetic algorithm of the Galapagos plugin. Based on natural selection processes, this kind of algorithm proceeds until convergence starting from an initial set of possible configurations and applying combination and random mutation to reach the optimized solution. To validate the result obtained and ensure reliability to the whole process, various alternative solutions are explored with a design optioneering approach. The Colibri plugin [80] is used to generate the configurations while the online viewer DesignExplorer by Thornton Tomasetti [81] allows to effectively compare and filter them. Once the solution of interest is pointed out, the analysis is deepened considering a different distribution of PV modules. Instead of single rows of panels, a configuration with collectors paired on their top edge is considered since it proved to be the most effective according to the result of previous research [82]. In this case, a multi-objective evolutionary optimization is processed thanks to the Octopus plugin for Grasshopper [83] based on SPEA-2 and HypE algorithms from ETH Zurich. The total incident radiation and the number of panels installed are selected as outputs of interest and the pareto front of non-dominated solutions is generated by the optimization tool. By this way, the best trade off configurations, able to maximize energy production with the lowest number of panels installed, can be assessed. Comparing the incident radiation obtainable with the same collectors of the first optimized geometry, it is then possible to choose the most cost-effective array. The preferred panels geometry is finally reinstated in the Design Builder energy analysis model to assess hourly energy production.

Phase 4

At the final stage, the cost-optimal methodology is applied to analyze and compare the different retrofitting measures proposed and to individuate the most cost-effective ones from an energy and economic point of view. The most recurrent energy and environmental redevelopment measures for this building type were already individuated in literature as a result of a previous study [84] and so some of them are applied to these two representative case studies to comply with Italian standard energy requirements. In the following tables (Tables 1 and 2), the redevelopment proposed for the cost-optimal analysis is listed for both schools. The tables show redevelopment measures considered individually and some combination of them addressing both external envelope and system. Among the retrofitting measures related to the external envelope redevelopment, some foresee the insertion of an insulation layer (made of mineral wool or wood fiber) for both external wall and roof to meet the half of the minimum thermal transmittance. As it concerns systems retrofitting, three different kinds of solutions are proposed: firstly, the substitution of the existing gas boiler (efficiency equal to 50%) with a new one characterized by an efficiency of 90%, secondly the substitution of the existing halogen lamps with LED (Lighting Emitted Diode; efficiency equal to 120 lm/W), and finally the substitution of the existing gas boiler with an air-to-air heat pump (COP (Coefficient of Performance) equal to 3.8 and EER (Energy Efficiency Ratio) equal to 3.5). This last measure was evaluated in two different scenarios: at first considering the building connected to the public electricity grid and later taking into account the integration of photovoltaic system on the roof in order to maximize the electricity production on site. The choice is in this case to install as many panels as possible to produce a surplus of electrical energy, since Italian schools are expected to be plus energy buildings as many European ones. The modules for the photovoltaic system are characterized by an efficiency of 21.3% and a peak power of 500 Wp.

Table 1. Different upgrade measures and their combinations considered in the cost-optimal analysis for Poliziano school. In the table, P stands for Poliziano, EW means external wall, RF roof floor, Syst stands for system, N for new, U means the thermal transmittance, COP means the coefficient of performance, EER stands for energy efficiency ratio, and LENI stands for Lighting Energy Numeric Indicator.

Abbreviation	Upgrade Measure Description	Parameter
P_EW_N1.1	Addition of rock wool external insulation and advanced ventilated facade characterized by half of the thermal transmittance of the reference building [1]	$U_{external-wall}$ (W/m²K)
P_EW_N3.1	The same of P_EW_N1.1 but with wood fiber insulation	$U_{external-wall}$ (W/m²K)
P_EW_N4.1	The same of EW_N3.1 but with ETICS external finishing	$U_{external-wall}$ (W/m²K)
P_EW_N5	Addition of insulation layer by blowing with urea resin to fill the internal air gap	$U_{external-wall}$ (W/m²K)
P_RF_N1 + P_RF_N2	Insulation and waterproofing of roof stratigraphy with external finishing with gravel	$U_{roof-floor}$ (W/m²K)
P_RF_N1.1 + P_RF_N2.1	Insulation and waterproofing of roof stratigraphy with technological solution of green roof	$U_{roof-floor}$ (W/m²K)
P_W_N1	Substitution of all windows in the whole building (glazing + frame)	U_{window} (W/m²K)
P_Syst_1	Substitution of gas boiler with condensing one characterized by a performance equal to 90%	COP heating
P_Syst_2	Substitution of artificial lighting system with one more efficient (LED) (120 lm/W)	LENI (kWh/m²a)
P_Syst_3	Substitution of the existent gas boiler with a heat pump for heating and cooling (public electricity distribution) characterized by COP = 3.8 and EER = 3.5 + fancoils	COP heating
P_Syst_3.1	Substitution of the existent gas boiler with a heat pump for heating and cooling characterized by COP = 3.8 and EER = 3.5 + fancoils and photovoltaic system to produce energy with renewables	COP heating—CO_2 emissions

Combinations of upgrade measures		
P_1	P_RF_N1 + P_RF_N2 + P_EW_N5 + P_W1	-
P_2	P_RF_N1 + P_RF_N2 + P_EW_N3.1 + P_W1	-
P_3	P_Syst 1 + P_RF_N1 + P_RF_N2 + P_EW_N5 + P_W1	-
P_4	P_Syst 2 + P_RF_N1 + P_RF_N2 + P_EW_N5 + P_W1	-
P_5	P_Syst 3 + P_RF_N1 + P_RF_N2 + P_EW_N5 + P_W1	-
P_6	P_Syst 1 + P_RF_N1 + P_RF_N2 + P_EW_N4.1 + P_W1	-
P_7	P_Syst 2 + P_RF_N1 + P_RF_N2 + P_EW_N4.1 + P_W1	-
P_8	P_Syst 3 + P_RF_N1 + P_RF_N2 + P_EW_N4.1 + P_W1	-
P_9	P_Syst 3.1 + Syst 2 + P_RF_N1 + P_RF_N2 + P_EW_N4.1 + P_W1	-
P_10	P_Syst 3.1 + Syst 2 + P_RF_N1 + P_RF_N2 + P_EW_N5 + P_W1	-

[1] *"Reference building is a building that is identical in geometry in terms of geometry (volumes, floor area, surfaces of construction elements and elements and components), orientation, spatial location, intended use and boundary situation, and having thermal characteristics and energy parameters predetermined in accordance with this* [11]*"*.

The different technological solutions proposed are detailed in Tables A8–A16 and Tables A21–A28 in Appendix A for Poliziano and Rodari school, respectively.

In a cost-optimal analysis both financial and macroeconomic scenarios have to be considered as recommended by the European Directive [28] and thus the global cost was calculated using the following equation (Equation (1)) according to the UNI EN 15459: 2018 [85]:

$$C_G(\tau) = C_I + \sum_j \left[\sum_{i=1}^{\tau} (C_{a,i}(j) * R_d(i) + C_{c,i}(j)) - V_{f,r}(j) \right], \tag{1}$$

where $C_G(\tau)$ is the global cost referred to the first year $\tau = 0$, C_I means the initial investment costs, $Ca_{,i}(j)$ stands for the annual cost for the year i for the component j, $R_d(i)$ is the discount factor for the year i for the component j, $V_{(f,r)}(j)$ means the residual value of the component j

at the end of the calculation time, and $C_{(c,i)}(j)$ is the cost of CO_2 emissions that is considered only for the macroeconomic scenario.

Table 2. Different upgrade measures and combinations of them for cost-optimal analysis applied to Rodari school. In the table, R stands for Rodari, EW means external wall, RF roof floor, Syst stands for system, N for new, U means the thermal transmittance, COP means the coefficient of performance, EER stands for energy efficiency ratio, and LENI stands for Lighting Energy Numeric Indicator.

Abbreviation	Upgrade Measure Description	Parameter
R_EW_N1	Substitution of the external envelope with aerated concrete for load-bearing functional layer, rock wool insulation, and advanced ventilated facade (thermal transmittance equal to the reference building)	$U_{external\text{-}wall}$ (W/m^{2}K)
R_EW_N1.1	The same of R_EW_N1 but characterized by half of the thermal transmittance	$U_{external\text{-}wall}$ (W/m^{2}K)
R_EW_N2.1	Substitution of external envelope with dry solution with rock wool insulation and gypsum fiber panel as external finishing (characterized by half of the thermal transmittance with respect to reference building)	$U_{external\text{-}wall}$ (W/m^{2}K)
R_EW _N3	The same of R_EW_N1.1 but with wood fiber insulation	$U_{external\text{-}wall}$ (W/m^{2}K)
R_EW _N3.1	The same of R_EW_N2.1 but with wood fiber insulation	$U_{external\text{-}wall}$ (W/m^{2}K)
R_EW_N3.2	The same of R_EW_N3 but with ETICS (External Thermal Insulation Composite System) external finishing	$U_{external\text{-}wall}$ (W/m^{2}K)
R_RF_N1	Insulation and waterproofing of roof stratigraphy with external finishing with gravel	$U_{roof\text{-}floor}$ (W/m^{2}K)
R_RF_N2	Insulation and waterproofing of roof stratigraphy with technological solution of green roof	$U_{roof\text{-}floor}$ (W/m^{2}K)
R_Syst_1	Substitution of gas boiler with condensing one characterized by a performance equal to 90%	COP heating
R_Syst_2	Substitution of artificial lighting system with one more efficient (LED) (120 lm/W)	LENI (kWh/m^{2}a)
R_Syst_3	Substitution of the existent gas boiler with a heat pump for heating and cooling (public electricity distribution) characterized by COP = 3.8 and EER = 3.5 + fancoils	COP heating
R_Syst_3.1	Substitution of the existent gas boiler with a heat pump for heating and cooling characterized by COP = 3.8 and EER = 3.5 and photovoltaic system to produce energy with renewables	COP heating—CO_2 emissions
Combinations of upgrade measures		
R_1	R_EW_N3.2 + RF_N1	-
R_2	R_EW_N3.2 + RF_N1 + Syst_1	-
R_3	R_EW_N3.2 + RF_N1 + Syst_2	-
R_4	R_EW _N3.1 + RF_N1 + Syst_1	-
R_5	R_EW_N3.1 + RF_N1 + Syst_2	-
R_6	R_EW_N3.2 + RF_N1 + Syst_3	-
R_7	R_EW_N3.1 + RF_N1 + Syst_3	-
R_8	R_EW_N3.2 + RF_N1 + Syst_3.1 + Syst_2	-

As in [27], the initial investment cost for materials was calculated recurring to Italian region price list [86], DEI price list of 2018 [87] and, in case of no available information, referring to producer's websites and references in the literature [45]. The cost of labor is included in the cost of components according to most of the price lists; when not available, the price of a specialized labor is considered for the calculation. As it concerns the period for the cost-optimality methodology, it is assumed equal to 30 years. For all the measures and components characterized by a shorter service life, the costs for maintenance and substitution have to be considered (Table 3). The annual servicing cost is calculated as a percentage of the initial investment cost as required by Annex D of regulation EN 15459:2018 (EN Comité Européen de Normalisation) [85]. On the other hand, the substitution cost is equal to the initial price of the element properly modified referring to the discount rate for

the corresponding year. Finally, the disposal cost was not considered because in this case it is irrelevant compared to the others.

Table 3. Maintenance and replacement costs for the building elements characterized by a lower service life span than the 30 years considered for cost-optimal analysis. Data in the table refers to Poliziano school. The same was done for the other building (Rodari school). The references for the following cost are [45,85–87].

Building Element	Maintenance Cost	Service Life	Replacement Cost
Windows	782.41 EUR/year	30	-
Inverter	18.49 EUR/year	10	EUR 1848.42
Heat generator (boiler)	309.46 EUR/year	20	EUR 1542
Heat generator (heat pump) + fancoils	3.2 EUR/m^{2}year	20	80.1 EUR/m^2
Photovoltaic system	2.92 EUR/module year	25	585 EUR/module

The cost of energy for building operational phase is set according to ARERA (Authority of Regulation for energy grid and environment) and it is included as well. As mentioned before, both financial and macroeconomic scenarios are considered for completeness; in the first one VAT (Value Added Tax) and excise duties are considered, while in the latter the cost of CO_2 emissions was included, and the previous factors are not. As stated by the aforementioned regulation [72], the cost of the emissions is equal to 20 EUR/tCO_2 within 2025, 25 EUR/tCO_2 within 2030, and 25 EUR/tCO_2 after 2030. To calculate the CO_2 emissions related to energy consumption, the conversion factors for each energy vector provided by ISPRA (Institute for Environmental Protection and Environmental Research) report 317/2020 [88] are used. Discounting factors are equal to 4% and 5% for financial scenario and 3% and 4% for the macroeconomic one.

3.1. Case Studies

Poliziano school is a secondary school located in Florence designed and built by "Baldassoni Adolfo e figlio s.r.l." company in 1976 in a construction site of about 13,200 m^2. The building is organized into three different volumes, connected through a large horizontal connection, with a load-bearing structure with reinforced concrete pillars and beams. The school is characterized by a very complex and articulated geometry and the total surface is about 4700 m^2 with a volume equal to about 17,300 m^3. As it is possible to observe in Figure 3, the central block and the east-oriented one are characterized by the presence of most of the classrooms and laboratories. As expected, the functional area dedicated to the teaching activities covers about 33% of the whole school surface. In the school there is also an auditorium and a gym that are used also for extracurricular activities. The load-bearing structure is made of reinforced concrete. This facility underwent an energy retrofitting in recent years with the addition of a polystyrene insulation layer for the redevelopment of the external walls. By the way, this intervention involved only a portion of the building that hosts part of the home base [89]. With respect to the technological solutions used in this building (Tables A1–A7, Appendix A), the ground floor is made of two different types of slab (brick slab or predalles one) depending on the building block, the external walls are constituted by a double layer of bricks with an internal cavity, except for the retrofitted building portion where they are made of expanded clay blocks and external insulation layer in EPS material. The roof floor is composed by a brick slab with external finishing made of waterproof sheet. Finally with respect to the windows, they are characterized by a wooden frame and a single glazing 5 mm thick. Except for the external wall of the retrofitted block, all the technological solutions do not meet the minimum requirements of the Italian energy standard, as demonstrated in Tables A1–A7 (Appendix A). It must be specified that, for this school, the requalification of the gym is not considered.

Figure 3. Aerial view (**top left**), main entrance and internal courtyard (**bottom left**), and plan of the standard floor of Poliziano school with the indications of the main functional units.

Rodari school, built in the first half of the 70s by Fratelli Bortolaso Company of Verona, is located in Florence and it is characterized by a metal load-bearing structure with external walls made of insulated precast reinforced concrete panels. The use of such modular structures for school buildings was quite common in Italy during the 60s and 70s, when prefabrication techniques spread significantly. The building, hosting a primary school and a kindergarten, has a linear geometry and it develops over three floors (Figure 4). The different functional units are organized along a horizontal connection on both sides. The total surface of the school building is about 790 m² and the area of the gym is equal to 360 m² for a total volume of the building of about 13,100 m³. Canteens, kitchen, locker rooms, reception. and toilets are located on the ground floor. First and second floors host the home base with classrooms and laboratories for kindergarten and elementary school, respectively. In this case also the gym was considered in the redevelopment since it is characterized by the same structural and technological solutions of the main building. As regards technological solutions, the ground floor is characterized by a brick slab with wood internal finishing, the external walls are made of vibrated and reinforced concrete conglomerate panels of 0.03 m thick that also presents an insulation layer in resin foam. The roof floor is constituted by a precast reinforced concrete slab and an insulation layer in resin foam. In this case, windows and glazing have not been redeveloped yet and so their retrofitting is not considered in this study. As for Poliziano school, all the technological solutions do not meet with the minimum thermal Italian standard requirements, as reported in Tables A17–A20 (Appendix A).
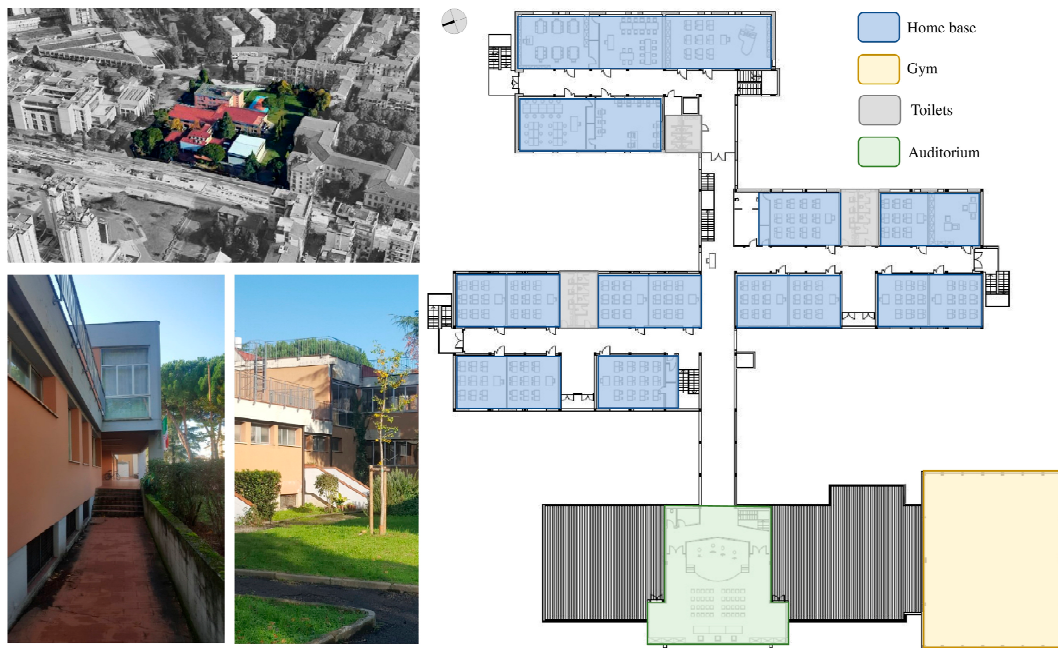
Figure 4. Aerial view (**top left**), main entrance and internal courtyard (**top right**), and plan of the standard floor of Rodari school with the indications of the main functional units.

In both schools. the heating system is made of a gas boiler (efficiency was considered equal to 50%) for heat generation and in each functional units and radiators are installed. There is not a cooling system and natural ventilation for the internal space was considered.

4. Results and Discussion

As for the optimization of PV modules distributions, results will be discussed considering the different procedures and tools implemented. Starting from the optimization in the case of a single row-distribution, a PV array south oriented with rows spaced by 0.7 m and panels with a tilt angle of 42° proved to be the most suitable geometry according to the Galapagos solver (Figure 5). This solution, emerging as the optimum solution after 53 iterations, can ensure a maximum solar incident radiation of 4442.30 kWh.

This geometry was validated applying a design optioneering procedure. Thanks to the open-source interactive visualization platform DesignExplorer (Figure 6), it was possible to filter the 5016 solutions generated according to the preferred output of interest. Restricting the range of incident radiation values to admit only the highest performance, the same values of tilt angle, orientation, and rows distance previously obtained were retrieved in the columns collecting input variable parameters. Immediate visual feedback is associated to each of the geometries along with the graphical representation of the radiation analysis. The results are freely accessible online simply using the following link (http://tt-acm.github.io/DesignExplorer/?ID=BL_3ncyykm, accessed on 7 November 2021).

As anticipated in the previous section, a configuration with paired PV panels was also evaluated. At first, an optimization analysis with Galapagos was carried out. In Figure 7 the two best distribution for paired and single panels, respectively, are compared: the former, with south-west orientation and 60° tilt angle, allows higher energy production but requires the installation of more modules.
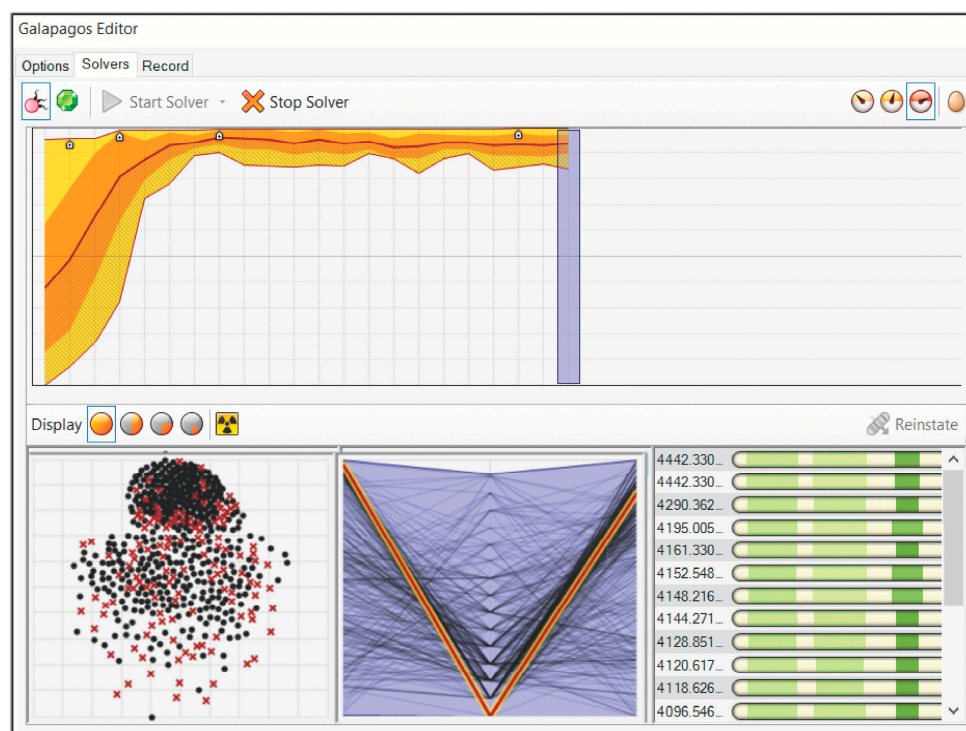
Figure 5. Galapagos optimization results. At the top of the figure, the graph about the solutions convergence is presented. At the bottom, the comparison between solutions with a scatter plot graph and the optimized solution in a parallel coordinate plot are presented.
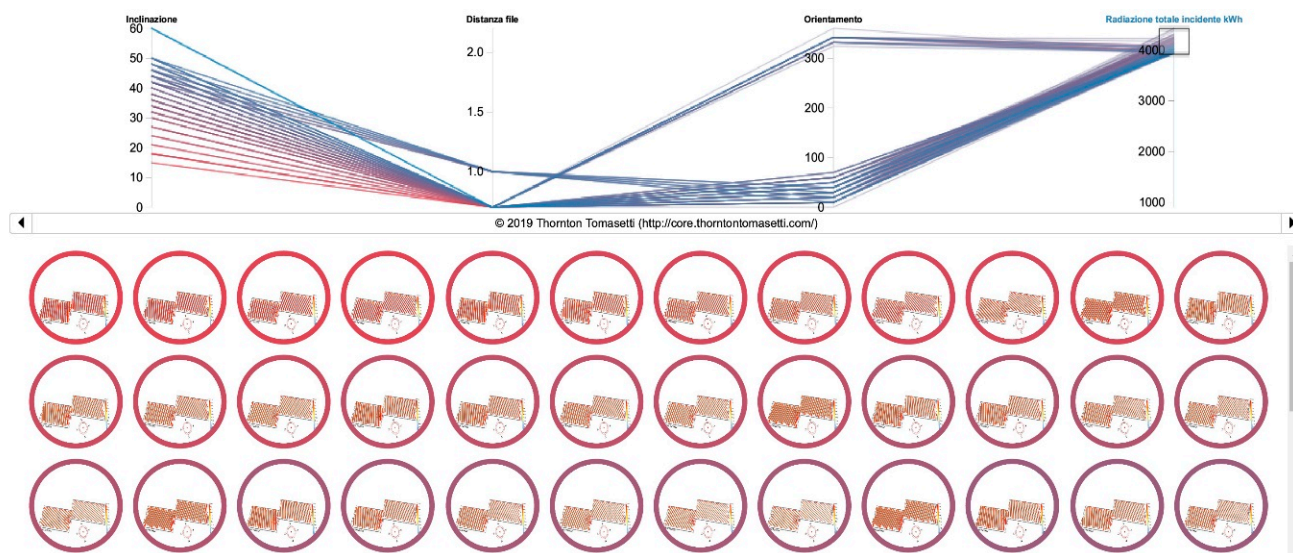
Figure 6. DesignExplorer interface for the visualization and filtering of solutions (filters in the case are the following: tilt angle, rows distance, orientation, and solar incident radiation).

Paired panels configuration		Single panels configuration	
4943.093 kWh Incident Radiation		**4442.305 kWh** Incident Radiation	
Orientation: *64°* Tilt angle: *60°* Rows distance: *0.7 m*	***511*** PV modules	Orientation: *4°* Tilt angle: *42°* Rows distance: *0.7 m*	***305*** PV modules
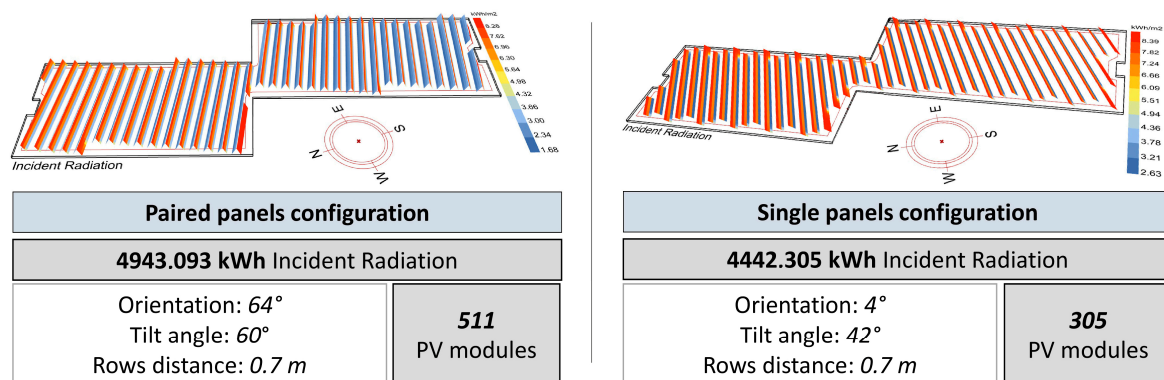
Figure 7. Comparison between the two different configurations of PV panels installed on the roof to find the optimal solution for modules to maximize the electrical energy production.

A multi-objective optimization was then performed with Octopus to assess the maximum radiation achievable with the same number of panels. The results of this process are plotted in a two-dimension graph (Figure 8) relating the amount of PV modules and the incident radiation (kWh). Red dots are part of the so called "Pareto front" that collects all the best trade-off combinations. According to this simulation, by installing 305 panels the incident radiation is limited to 4442.305 kWh.
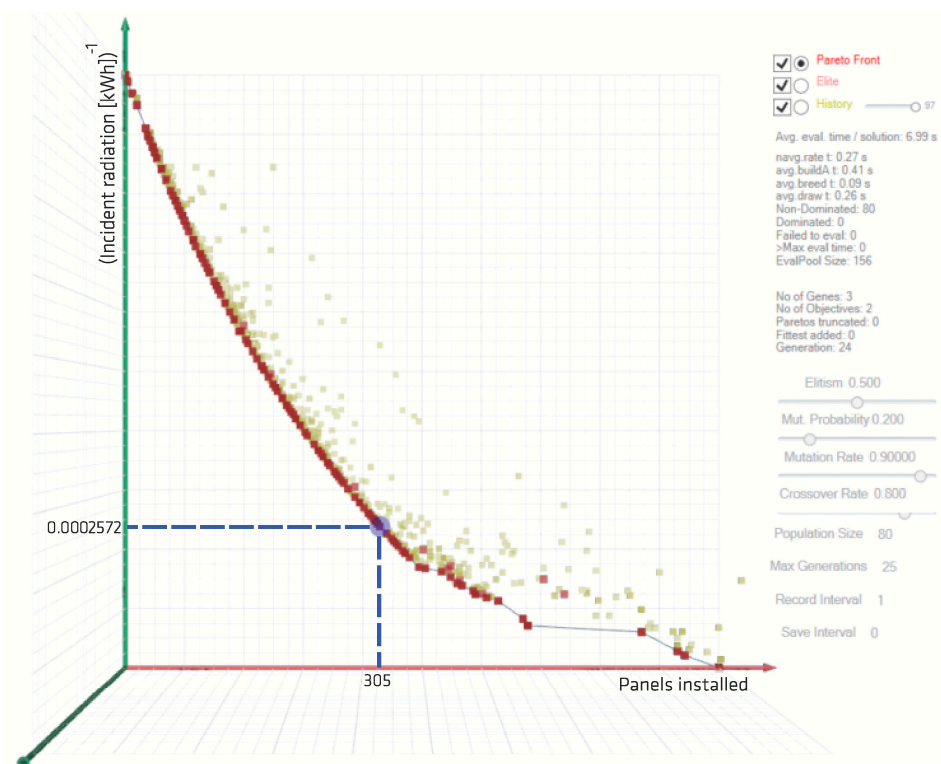
Figure 8. Octopus optimization results displaying the Pareto front. In the graph, the number of installed panels is reported on the X-axis while the Y-axis collects the values for incident radiation. Since the algorithm works by minimizing the output of interest, this latter value was considered reversed. The Pareto front collects the non-dominated solutions: the red dots express the maximum radiation achievable with a fixed number of panels.

Considering this evidence, this latter configuration was discarded, and thus the PV distribution suggested by Galapagos for the single row configuration was adopted.

As far as the cost-optimality method concerns, Figure 9 shows the results related to the financial scenario for the "Rodari" school with a discount factor equal to 4% considering only the single redevelopment measures (Table 2).
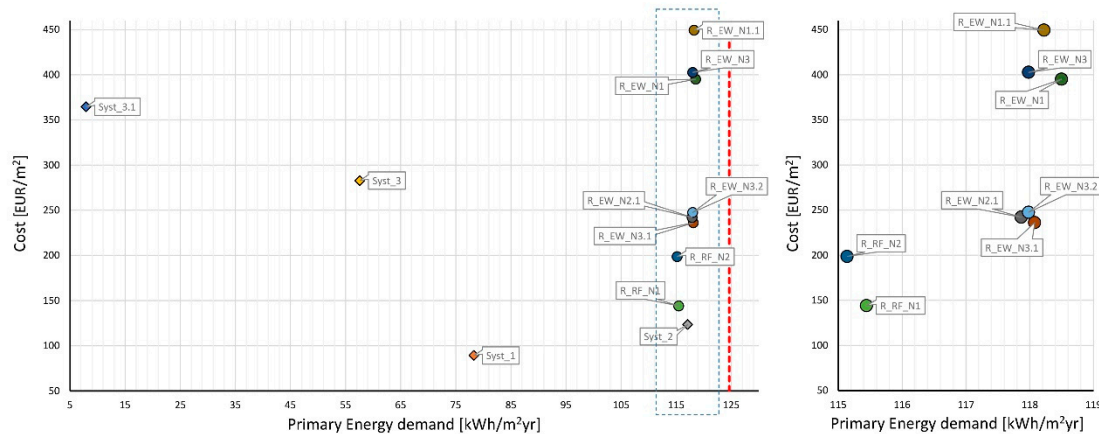
Figure 9. Cost-optimality method results for financial scenario for the single redevelopment measures and discount factor equal to 4% for Rodari school. The red line in the graph shows the primary energy consumption for existing building. On the right the enlargement of the first graph with the retrofitting measures for the external envelope is shown.

Firstly, the graph highlights that all the retrofitting measures proposed for the external envelope for both external wall and roof floor are comparable in terms of primary energy demand. The optimum solution, that ensures a decrease in primary energy demand of about 7.6%, is the one with the redevelopment of the roof floor with insulation and gravel finishing (R_F_N1). Regardless, comparing this strategy with other interventions addressing the external envelope, a difference of about 3.5 kWh/m^{2}yr is registered. With respect to the cost parameter, a more significant difference between the technological solutions suggested for external walls is highlighted: adopting a ventilated facade as external finishing leads to higher costs because of metal substructures and external cladding materials. By contrast, technological solutions implementing ETICS (using both rock wool and wood fiber insulation) involve the lowest cost ensuring the same energy performance. Regardless, the dry technological solution R_EW_N3.1, resulting in a slight decrease in primary energy demand of about 5.2% mainly related to energy needs for heating, proves to be the optimum one. Moreover, this technological solution is preferrable also because it requires lower time for construction with consequent economic savings. The difference between prices of ETICS and dry solution is related to the cost of the external plaster, more expensive than plasterboard panels. Moreover, acting on the roof components adopting solution R_F_N1 emerges as the cheapest strategy: its global cost, equal to about 150 EUR/m^2, is by far the lowest especially if compared to the most expensive technological solution that is characterized by an annual cost of about 450 EUR/m^2.

Focusing on interventions involving systems, the optimum solution is the substitution of the gas boiler with one characterized by a higher value of COP (Syst_1). This solution also represents the cost effective one among the single redevelopment measures for the financial scenario assuming a discount factor equal to 4%. This intervention permits to decrease the primary energy demand by 37.1% with a limited initial investment cost. Such a result requires further reflections about the cost-optimal methodology itself. The solution Syst_3.1, featuring an air-to-air heat pump coupled with a PV system to produce electrical energy, proves to be the most environmentally friendly one but, at the same time, is economically unprofitable because of the significant initial investment cost. In this case, adopting an optimized configuration of PV panels to enhance energy production, it is possible to guarantee about 76 kWh/m^{2}yr of surplus electrical energy, avoiding 64tCO$_2$/yr

of CO_2 emissions in the atmosphere. Energy in excess can be introduced in public electrical energy grids to be exploited by other buildings in the district.

Finally, it is worth noticing that primary energy demand can be decreased by 6.1% by simply renovating the existing artificial lighting system introducing LED lamps. If compared to interventions on the external envelope, this solution can ensure higher energy savings with a lower initial investment cost. Such a result is in line with the ones obtained in previous research; in that case [27], where the substitution of the artificial lighting system was assessed as the cost-effective solution [27].

The graph in Figure 10 illustrates the results related to the financial scenario as well but considering also several different combinations of the previous retrofitting measures (Table 2).
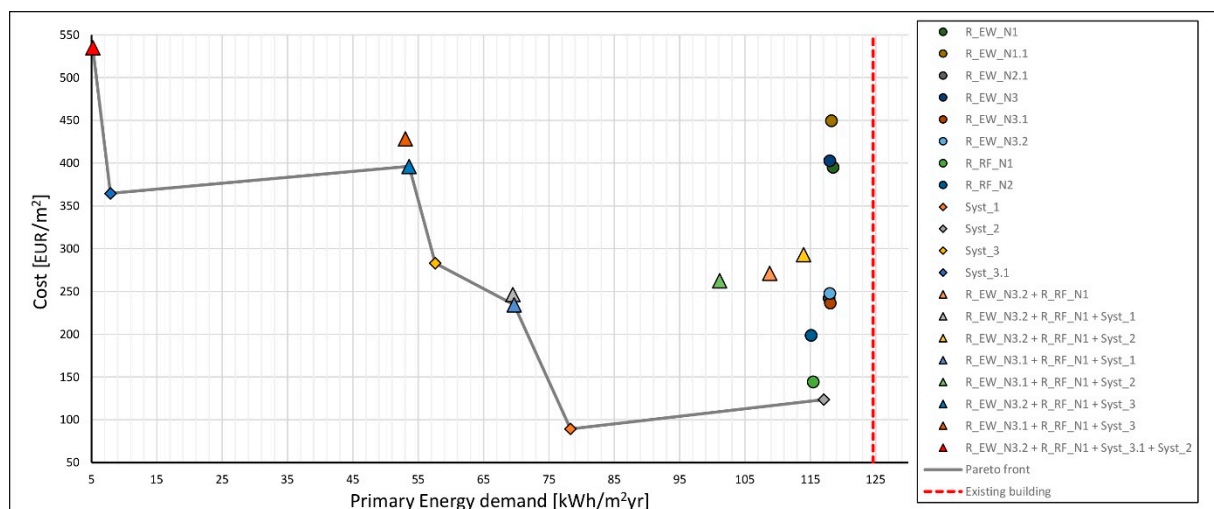
Figure 10. Cost-optimality method results for financial scenario (discount factor equal to 4%) for both single redevelopment measures and their combinations for Rodari school. The red line in the graph shows the primary energy consumption for the existing building.

Considering only the different combinations, the optimum one is the R_EW_N3.1 + R_RF_N1 + Syst_1 that includes the dry solution for the redevelopment of external walls, the retrofitting of the roof floor, and the replacement of the gas boiler. However, as clearly emerging from the graph, the solution with the simple substitution of the existing gas boiler with a new more efficient one is still the cost-effective one for the Rodari school with a cost of 89 EUR/m^2. It is important to notice that also in this case this intervention (Syst_1) is preferrable in terms of cost and primary energy demand, but it does not allow to meet the nZEB or low-carbon standards.

This cost-optimality approach is useful to individuate the proper energy retrofitting compromise considering both initial investment cost and the advantages achieved in terms of energy saving. Moreover, other parameters crucial for the nZEB requirements considered in the current European policy cannot be easily included in the method. For instance, the environmental impact or the surplus energy production cannot be properly quantified or translated into real costs or advantages. However, this methodology can be surely used for all those schools that need urgent energy requalification without having significant funds available.

With respect to the European goal of a carbon-free economy by 2050, the solution R_EW_N3.2 + R_NF_N1 + Syst_3.1 + Syst_2 should be the most effective retrofitting measure for this school. In this case, the use of an air-to-air heat pump integrated with renewables allows to meet the nZEB standard and considerably reduces CO_2 emissions. However, this solution is not emerging as the eligible one because of its very high initial investment cost (like a heat pump and PV system), obviously not suitable within a cost-optimal perspective.

The surplus energy production could be assessed considering the macroeconomic scenario as shown in the graph in Figure 11, where the configuration Syst_3.1 On grid is introduced. In this case, an evaluation of the surplus electrical energy powered by the photovoltaic system on the roof was calculated also considering the hourly simultaneity of the energy production and building needs. Consequently, in the global cost formula the annual operational cost is decreased by the amount of energy fed into the grid applying a sell price of electrical energy of about 0.07 EUR/kWh. As a result, a sensible reduction of the global cost of about 30% was registered making the introduction of an air-to-air heat pump and renewables integration more cost-effective than some external envelope retrofitting measures. In Appendix B, Figures A5 and A6 show the summary of the results for the financial and macroeconomic scenario for a discount rate equal to 4%; for completeness, Figures A7 and A8 synthesize the results for financial scenario with a discount rate equal to 5% and for the macroeconomic one with a discount rate equal to 3%.

Figure 11. Cost-optimality method results for the macroeconomic scenario for both single redevelopment measures and their combinations and discount factor equal to 4% for Rodari school. The red line in the graph shows the primary energy consumption for the existing building.

Moving on to the Poliziano school building, as it results from the graph in Figure 12 related to the financial scenario, the cost-effective retrofitting measure is once again the configuration with the substitution of the existing gas boiler with a new and more efficient one (Syst_1). In this case, a reduction in primary energy demand by 32% with respect to the current energy performance of the school can be achieved. Additionally, for this school, the solution including a heat pump and PV system is characterized by the highest initial investment cost and so it is the less cost-effective one. This result confirms the weakness of the methodology, that does not properly consider environmental parameters and benefits. With respect to the redevelopment of the external envelope, the insufflation of the insulation materials in the existent air cavity (P_EW_N5) is the most convenient in terms of both energy performance and economic investment. While the adoption of an external insulation layer (P_EW_N4.1), comparable for energy performance and cost, requires scaffolding, this kind of measure is less invasive and could be realized during the summer closing period.
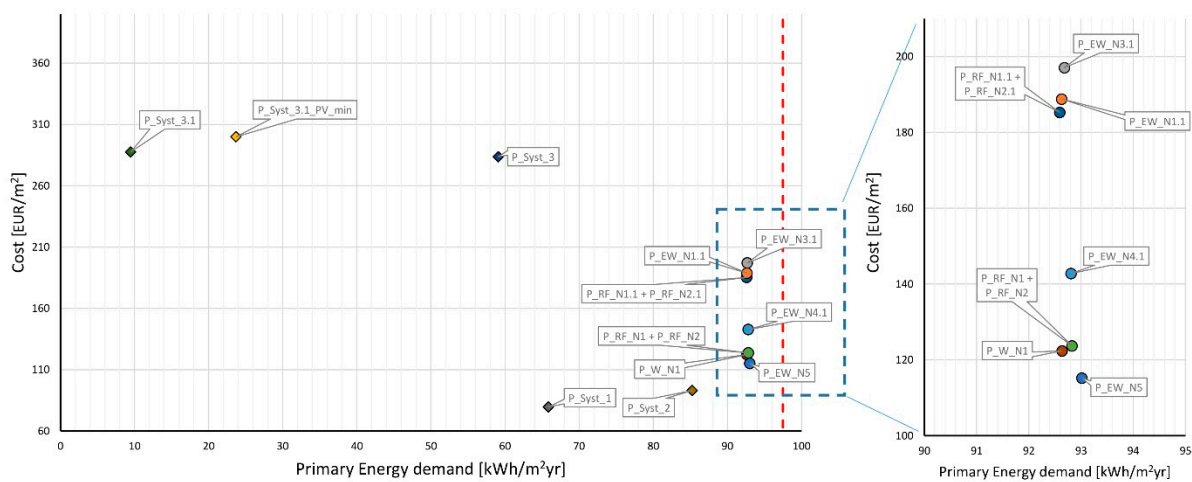
Figure 12. Cost-optimality method results for the financial scenario for the single redevelopment measures and discount factor equal to 4% for Poliziano school. The red line in the graph shows the primary energy consumption for existing building. On the right the enlargement of the first graph with the retrofitting measures for the external envelope is shown.

Figure 13 shows the graph illustrating the result for the financial scenario considering the several combinations as well. As for Rodari school, also in this case the configuration Syst_1 is still the cost-effective one. Regarding systems, it is worth noticing that in the case of Poliziano school another configuration with the minimum PV panels required by the Italian standard was considered (Syst_3.1_PV_min) to make a comparison with the optimized configuration that maximizes electrical energy production, such as explained before. As pointed out in the same graph (Figure 13), comparing the retrofitting measures with a heat pump and the minimum (Syst_3.1_PV_min) and maximum (Syst_3.1) surface of PV panels, the maximization of the PV surface has to be preferred because of the reduced annual energy costs and mostly because of the very high residual value at the end of the building life. Regardless, the results slightly change when considering also the redevelopment of an artificial lighting system. The introduction of the LED system affects the value of the annual energy expense and the solution with the minimum surface of the photovoltaic system enables to save altogether about 20 EUR/m^2.
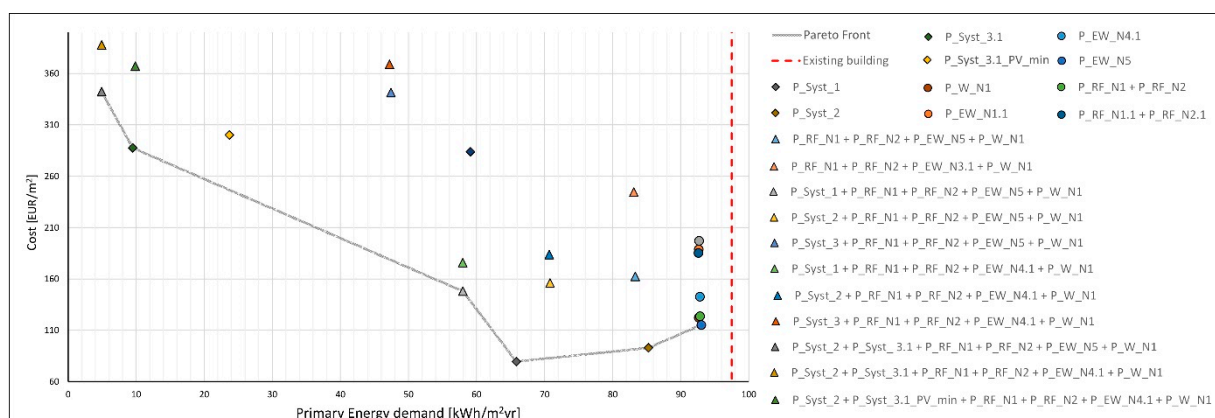
Figure 13. Cost-optimality method results for the financial scenario for both single redevelopment measures and their combinations and discount factor equal to 4% for Poliziano school. The red line in the graph shows the primary energy consumption for the existing building.

Finally, Figure 14 shows the results obtained within a macroeconomic perspective and taking into account both the CO_2 emissions related to the surplus energy production and the economic advantages. As expected, the configuration with the minimum surface of the

PV panels does not allow an extra-production of electrical energy (1 kWh/m^{2}yr), while recurring to the optimized modules distribution it is possible to obtain a surplus of about 128 kWh/m^{2}yr and a corresponding saving of 217 tCO$_2$/yr of emissions.
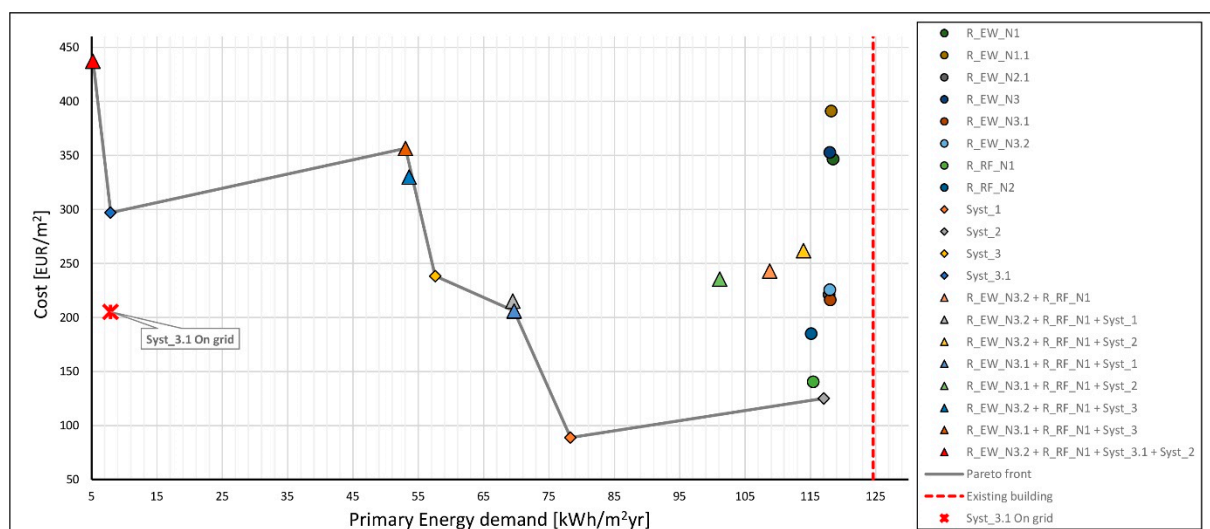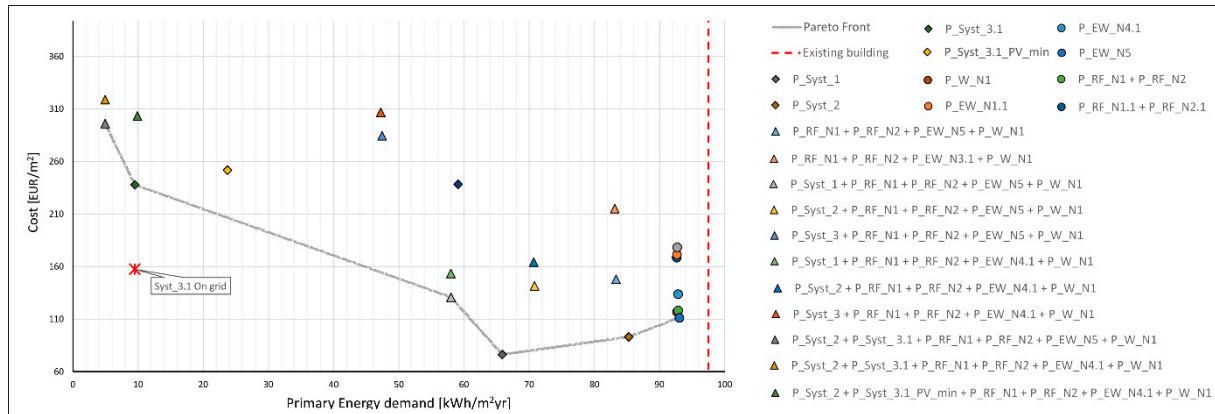

Figure 14. Cost-optimality method results for the financial scenario for both single redevelopment measures and their combinations and discount factor equal to 4% for Poliziano school. The red line in the graph shows the primary energy consumption for the existing building.

Comparing the results illustrated until now with the findings of other previous research, interesting considerations can be formulated even if only a few similar studies dealing with educational buildings can be retrieved in the literature. The lack of an adequate evaluation of environmental parameters was registered also by other authors such as Becchio et al. [40] or Stocker et al. [61]. In the cited works, they agree about the opportunity of a redefinition of the criteria adopted for the selection of the solution to be preferred in order to include an environmental impact quantification. According to the current framework of the methodology, acting on systems proves to be more cost-effective than developing envelope components. The same conclusion can be found in a work from Carpino et al. [45] dealing with social housing facilities, where interventions addressing systems are highlighted as mandatory for effective retrofitting. By contrast, in the case of a school building, replacing the current lighting system with LED technology was indicated by Bonomolo et al. [60] as the most cost-effective solution. For both the schools analyzed, only the renovation of the heating gas boiler proves to be better than the installation of LED systems from an economic point of view, thus confirming the great potential impact of this measure.

For completeness, the graph in Figure 15 shows the monthly energy production with the optimized PV system installed on the roof, the energy needs of the school building, and the net energy balance. For all the quantities illustrated in the graph the simultaneity between energy production and needs is considered. For both January and December, the school electrical energy needs are covered for 34% and 22% by energy from public grid, respectively. In August, the PV system produces the highest quantity of surplus electrical energy. The results for the financial and macroeconomic scenario for a discount rate equal to 4% are summarized in Figures A1 and A2 of Appendix B, respectively; for completeness, Figures A3 and A4 illustrate the findings for the financial scenario with a discount rate equal to 5% and for the macroeconomic one with a discount rate equal to 3%.

Furthermore, Figure 16 shows the hourly energy demand of the building compared to the energy produced by the PV system over a representative week in March. The graph stresses that at the beginning of the day, when the heating setpoint temperature must be reached, PV panels alone cannot satisfy the energy needs.
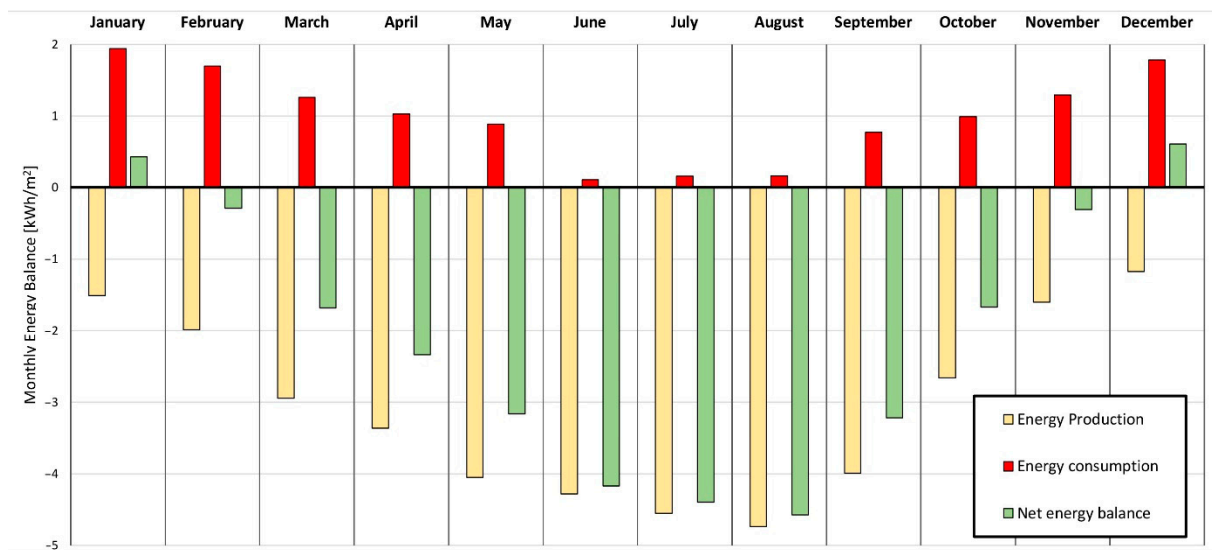
Figure 15. Energy balance (kWh/m^{2}yr) for Poliziano school for each month considering the optimized configuration. In the graph, the energy production of the PV panels (yellow), the energy consumption of the building (red), and the net energy balance (green) are illustrated. A positive value of the net energy balance means that the building needs electrical energy from grid, while a negative value means a surplus electrical energy production that could be fed into the public grid.
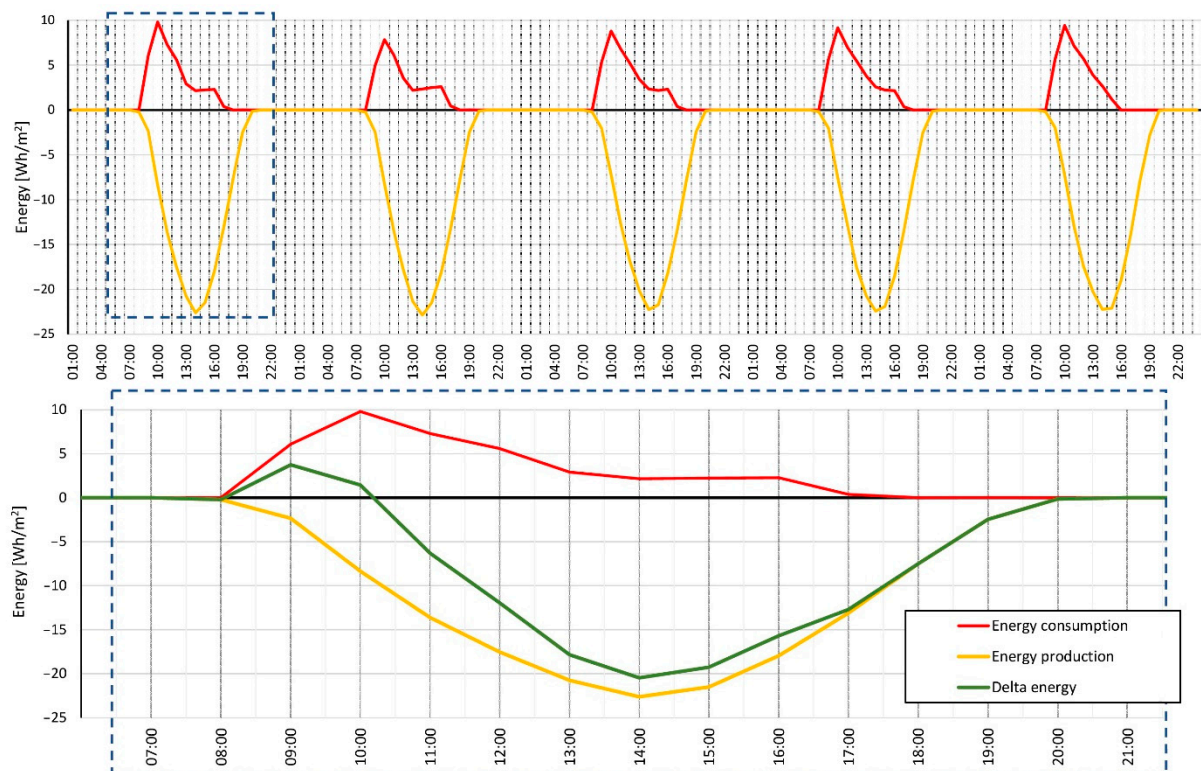
Figure 16. Hourly energy consumption of the building (red), PV energy production (yellow), and the difference between them (green) for a school week in March (14th–18th) and on the bottom the enlargement of the first day of the week is presented to stress the amount of the electrical energy from the public grid. The simultaneity of needs and PV production can be seen.

5. Conclusions

In conclusion, with regard to the optimization of PV modules distribution, the configuration with orientation 4° with respect the building's axis north–south, row distance equal to 0.70 m, and tilt angle equal to 42° emerges as the one that maximizes the incident solar radiation and therefore the electrical energy production. In the paper, several optimization strategies for PV panels configuration were analyzed to validate the different results obtained. The choice of the method for the optimization depends on the final goal of the analysis itself. For instance, the multi-objectives optimization allows more comprehensive considerations because it affects and involves a wider range of design parameters. While the optimization procedures rely on generation and evaluation of the alternatives carried out autonomously by computer, the Design Optioneering method assigns to the machine only the first operation, since it does not require in advance the definition of any fitness function. By this way, the designer can have a greater control on the results and the selection of the preferred solutions to be used. In this case, to exclude ineligible configurations, filters can be also applied to the input variables, whose range of variability must be by contrast necessarily defined in the initial phase of optimization procedures. The used tools allow to perform reliable, accurate, and less time-consuming simulations directly in the BIM environment without recurring to external simulation software.

As far as cost-optimal analysis concerns, the results illustrated in the paper show that the substitution of the existing condensing boiler with a more efficient one (Syst_1) is the cost-effective solution for both analyzed schools. Therefore, in this case as well, according to literature, it is more convenient to intervene on the existing system rather than on the external envelope, even if the latter does not meet the Italian minimum energy requirements. It is worth noticing that the applied cost-optimality method is not the most proper and precise methodology to evaluate also environmentally friendly retrofitting solutions including for instance active strategies to produce electrical energy. In fact, the configuration with the use of an air-to-air heat pump and PV panels installed on the roof it is not the cost-effective one even if it allows to produce a surplus of electrical energy completely preventing CO_2 emissions. Indeed, the cost-optimal methodology is a cost-oriented method and so all the proposed retrofitting solutions affected by high initial investment costs are penalized. In the European context of reaching a carbon-free economy by 2050, this method should be updated to take adequately into account also environmental parameters and the surplus energy production. This because it is impossible to meet the European goals without considering the redevelopment of the existing heritage and the use of active integrated strategies to produce energy. Moreover, this method is still appropriate to enhance low-cost retrofitting measures to be applied on buildings that need an urgent energy requalification. This work could be developed in the future proposing the improvement of the cost-optimal methodology applied to schools with some indicators about the environmental impact. By this way, the actual weaknesses of the method could be overcome leading to a more comprehensive evaluation and avoiding the excessive penalization of all those measures that can ensure a better environmental performance but require a higher initial investment cost. For instance, future redevelopment measures to be considered in the cost-optimal analysis for schools could be different kinds of renewables and batteries for electrical energy storage.

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Appendix A

Existing technological solution stratigraphy for the external envelope of Poliziano school.

Table A1. Existing ground floor stratigraphy (P_GF_E1).

Technological Solution	Layer	T (m)	λ (W/mK)	R (m²K/W)
Ground floor type 1–P_GF_E1	Brick slab	0.23	-	0.32
	Screed	0.05	1.40	-
	Stone finishing	0.02	1.47	-
Thermal transmittance (W/m²K)				1.71

Table A2. Existing ground floor stratigraphy (P_GF_E2).

Technological Solution	Layer	T (m)	λ (W/mK)	R (m²K/W)
Ground floor type 2–P_GF_E2	Predalles slab	0.30	-	0.75
	Waterproof sheet	0.005	0.10	-
	Screed	0.05	1.10	-
	Internal finishing	0.01	0.90	-
Thermal transmittance (W/m²K)				0.93

Table A3. Existing external wall stratigraphy (P_EW_E1).

Technological Solution	Layer	T (m)	λ (W/mK)	R (m²K/W)
External wall–P_EW_E1	External plaster	0.015	0.81	-
	Lightweight brick	0.80	0.43	-
	Air gap	0.05	-	0.17
	Brick	0.15	0.96	-
	Internal plaster	0.015	0.70	-
Thermal transmittance (W/m²K)				1.671

Table A4. Existing external wall stratigraphy (P_EW_E2) for the retrofitted block.

Technological Solution	Layer	T (m)	λ (W/mK)	R (m²K/W)
External wall–P_EW_E2	External plaster	0.015	0.81	-
	EPS	0.10	-	0.18
	Expanded clay blocks	0.30	0.21	-
	Internal plaster	0.015	0.70	-
Thermal transmittance (W/m²K)				0.29

Table A5. Existing roof floor stratigraphy (P_RF_E1).

Technological Solution	Layer	T (m)	λ (W/mK)	R (m²K/W)
Roof floor–P_RF_E1	Waterproof sheet	0.005	0.10	-
	Screed	0.1	0.12	-
	Brick slab	0.23	-	0.32
	Internal plaster	0.01	0.70	-
Thermal transmittance (W/m²K)				0.73

Table A6. Existing roof floor stratigraphy (P_RF_E2).

Technological Solution	Layer	T (m)	λ (W/mK)	R (m²K/W)
Roof floor–P_RF_E2	Asbestos	0.008	0.80	-
	Air gap	0.10	-	0.08
	Waterproof sheet	0.005	0.10	-
	Screed	0.10	0.12	-
	Predalles slab	0.30	-	0.75
Thermal transmittance (W/m²K)				0.73

Table A7. Existing windows characteristics (P_W_E1).

Technological Solution	Existing Windows Description
Windows–P_W_E1	The existing windows are characterized by a wooden frame and a single glazing (5 mm thick) with thermal transmittance that does not meet the Italian requirements

Proposed retrofitting measures for the external envelope for Poliziano school.

Table A8. Possible upgrade measure of external wall stratigraphy (P_EW_N1.1) with the advance screen façade as external finishing and the thermal transmittance equal to the half of the reference building.

Technological Solution	Layer	T (m)	λ (W/mK)	R (m²K/W)
External wall–P_EW_N1.1	Advance screen facade	-	-	-
	Rock wool insulation	0.12	0.035	-
	Lightweight brick	0.80	0.43	-
	Air gap	0.05	-	0.17
	Brick	0.15	0.96	-
	Internal plaster	0.015	0.70	-
	Rock wool insulation	0.06	0.035	-
	Gypsum fiber panel	0.015	0.30	-
	Gypsum fiber panel	0.015	0.30	-
	Thermal transmittance (W/m²K)			0.168
	Periodic thermal transmittance (W/m²K)			0.002
	Surface mass (kg/m²)			479

Table A9. Possible upgrade measure of external wall stratigraphy (P_EW_N3.1) with the same technological solution of P_EW_N1.1 but with wood fiber insulation.

Technological Solution	Layer	T (m)	λ (W/mK)	R (m²K/W)
External wall–P_EW_N3.1	Advance screen facade	-	-	-
	Wood fiber insulation	0.12	0.037	-
	Lightweight brick	0.80	0.43	-
	Air gap	0.05	-	0.17
	Brick	0.15	0.96	-
	Internal plaster	0.015	0.70	-
	Rock wool insulation	0.06	0.035	-
	Gypsum fiber panel	0.015	0.30	-
	Gypsum fiber panel	0.015	0.30	-
	Thermal transmittance (W/m²K)			0.173
	Periodic thermal transmittance (W/m²K)			0.002
	Surface mass (kg/m²)			491

Table A10. Possible upgrade measure of external wall stratigraphy (P_EW_N4.1) with ETICS technological solution as external finishing and insulation material made of wood fiber.

Technological Solution	Layer	T (m)	λ (W/mK)	R (m²K/W)
External wall–P_EW_N4.1	External plaster	0.015	0.810	-
	Wood fiber insulation	0.12	0.037	-
	Lightweight brick	0.80	0.43	-
	Air gap	0.05	-	0.17
	Brick	0.15	0.96	-
	Internal plaster	0.015	0.70	-
	Rock wool insulation	0.06	0.035	-
	Gypsum fiber panel	0.015	0.30	-
	Gypsum fiber panel	0.015	0.30	-
	Thermal transmittance (W/m²K)			0.172
	Periodic thermal transmittance (W/m²K)			0.002
	Surface mass (kg/m²)			512

Table A11. Possible upgrade measure of external wall stratigraphy (P_EW_N5) with the insufflation of urea resin to fill the air gap.

Technological Solution	Layer	T (m)	λ (W/mK)	R (m^{2}K/W)
	External plaster	0.015	0.810	-
	Lightweight brick	0.80	0.43	-
	Urea resin	0.05	0.031	-
External wall–P_EW_N5	Brick	0.15	0.96	-
	Internal plaster	0.015	0.70	-
	Rock wool insulation	0.06	0.035	-
	Gypsum fiber panel	0.015	0.30	-
	Gypsum fiber panel	0.015	0.30	-
	Thermal transmittance (W/m^{2}K)			0.172
	Periodic thermal transmittance (W/m^{2}K)			0.002
	Surface mass (kg/m^2)			512

Table A12. Possible redevelopment measure for roof floor with gravel as the finishing layer (P_RF_N1).

Technological Solution	Layer	T (m)	λ (W/mK)	R (m^{2}K/W)
	Gravel	0.05	-	-
	Waterproof sheet	0.005	0.10	-
Roof floor–P_RF_N1	Wood fiber	0.10	0.037	-
	Vapor barrier	0.0005	0.4	-
	Screed	0.1	0.12	-
	Brick slab	0.23	-	0.32
	Internal plaster	0.01	0.70	-
	Thermal transmittance (W/m^{2}K)			0.248

Table A13. Possible redevelopment measure for roof floor with gravel as the finishing layer (P_RF_N2).

Technological Solution	Layer	T (m)	λ (W/mK)	R (m^{2}K/W)
	Gravel	0.05	-	-
	Waterproof sheet	0.005	0.10	-
Roof floor–P_RF_N2	Wood fiber	0.08	0.037	-
	Vapor barrier	0.0005	0.4	-
	Screed	0.10	0.12	-
	Predalles slab	0.30	-	0.75
	Thermal transmittance (W/m^{2}K)			0.256

Table A14. Possible redevelopment measure for roof floor with green roof as the finishing layer (P_RF_N1.1).

Technological Solution	Layer	T (m)	λ (W/mK)	R (m^{2}K/W)
	Earth	0.12	-	0.3
	Filter layer	0.001	-	-
	Accumulation layer (EPS)	0.04	-	0.71
	Waterproof sheet	0.005	0.10	-
Roof floor–P_RF_N1.1	Wood fiber	0.06	0.037	-
	Vapor barrier	0.0005	0.4	-
	Screed	0.10	0.12	-
	Brick slab	0.23	-	0.32
	Internal plaster	0.01	0.70	-
	Thermal transmittance (W/m^{2}K)			0.253

Table A15. Possible redevelopment measure for roof floor with green roof as the finishing layer (P_RF_N2.1).

Technological Solution	Layer	T (m)	λ (W/mK)	R (m²K/W)
	Earth	0.12	-	0.3
	Filter layer	0.001	-	-
	Accumulation layer (EPS)	0.04	-	0.71
Roof floor–P_RF_N2.1	Waterproof sheet	0.005	0.10	-
	Wood fiber	0.08	0.037	-
	Vapor barrier	0.0005	0.4	-
	Screed	0.10	0.12	-
	Predalles slab	0.30	-	0.75
	Thermal transmittance (W/m²K)			0.256

Table A16. Upgrade measure for existing windows (P_W_N1).

Technological Solution	Upgrade Measure for Existing Windows
Windows–P_W_N1	The new glazing is type AGC 66.2A(16AR)44.2A with solar factor equal to 31% and U = 1 W/m²K and window frame with thermal break

Existing technological solution stratigraphy for the external envelope of Rodari school.

Table A17. Existing ground floor stratigraphy (R_GF_E1).

Technological Solution	Layer	T (m)	λ (W/mK)	R (m²K/W)
	Brick slab	0.06	-	0.14
Ground floor type 1–R_GF_E1	Screed	0.05	1.910	-
	Wood finishing	0.02	0.15	-
	Thermal transmittance (W/m²K)			0.22

Table A18. Existing external wall stratigraphy (R_EW_E1).

Technological Solution	Layer	T (m)	λ (W/mK)	R (m²K/W)
	Vibrated and reinforced concrete conglomerate panel	0.03	1.91	-
External wall (prefabricated panel)–R_EW_E1	Air cavity	0.10	-	0.15
	Resin foam	0.04	0.032	
	Aluminum sheet	-	-	-
	Gypsum laminate	0.018	0.21	
	Thermal transmittance (W/m²K)			1.671
	Periodic thermal transmittance (W/m²K)			0.57
	Time shift (h)			1.90

Table A19. Existing roof floor stratigraphy (R_RF_E1).

Technological Solution	Layer	T (m)	λ (W/mK)	R (m²K/W)
	Waterproof sheet	0.003	0.5	-
Roof floor–R_RF_E1	Resin foam	0.03	0.032	-
	Precast reinforced concrete slab	0.03	1.91	-
	Thermal transmittance (W/m²K)			0.912

Table A20. Existing windows characteristics (R_W_E1).

Technological Solution	Existing Windows Description
Roof floor–R_RF_E1	The glazing is characterized by solar factor equal to 31% and U = 1 W/m²K.

Proposed retrofitting measures for the external envelope for Rodari school.

Table A21. Possible redevelopment measure for external wall (R_EW_N1) with the same transmittance of the reference building.

Technological Solution	Layer	T (m)	λ (W/mK)	R (m²K/W)
External wall–R_EW_N1	Advance screen facade	0.06	-	-
	Air cavity	0.05	-	-
	Aerated concrete	0.00005	0.07	-
	Gypsum fiber panel	0.14	0.3	-
	Gypsum fiber panel	0.04	0.3	-
	Thermal transmittance (W/m²K)			0.22
	Periodic thermal transmittance (W/m²K)			0.042
	Time shift (h)			13.37

Table A22. Possible redevelopment measure for external wall characterized by the half value of the thermal transmittance of the reference building (R_EW_N1.1).

Technological Solution	Layer	T (m)	λ (W/mK)	R (m²K/W)
External wall–R_EW_N1.1	Advance screen facade	-	-	-
	Air cavity	-	-	-
	Rock wool	0.04	0.035	-
	Aerated concrete	0.30	0.07	-
	Gypsum fiber panel	0.015	0.3	-
	Gypsum fiber panel	0.015	0.3	-
	Thermal transmittance (W/m²K)			0.175
	Periodic thermal transmittance (W/m²K)			0.019
	Time shift (h)			15.30

Table A23. Possible redevelopment measure for external wall with dry solution (rock wool insulation) characterized by the half value of the thermal transmittance of the reference building (R_EW_N2.1).

Technological Solution	Layer	T (m)	λ (W/mK)	R (m²K/W)
External wall–R_EW_N2.1	Cement board	0.013	0.13	-
	Vapor barrier	0.0002	0.38	-
	Rock wool	0.20	0.035	-
	Gypsum panel	0.015	0.21	-
	Rock wool	0.04	0.035	-
	Gypsum fiber panel	0.015	0.3	-
	Gypsum fiber panel	0.015	0.3	-
	Thermal transmittance (W/m²K)			0.137
	Periodic thermal transmittance (W/m²K)			0.092
	Time shift (h)			6.44

Table A24. Possible redevelopment measure for external wall characterized by the half value of the thermal transmittance of the reference building with advanced screen facade as external finishing (R_EW_N3).

Technological Solution	Layer	T (m)	λ (W/mK)	R (m²K/W)
External wall–R_EW_N3	Advance screen facade	-	-	-
	Air cavity	-	-	-
	Wood Fiber	0.04	0.035	-
	Aerated concrete	0.30	0.07	-
	Gypsum fiber panel	0.015	0.3	-
	Gypsum fiber panel	0.015	0.3	-
	Thermal transmittance (W/m²K)			0.177
	Periodic thermal transmittance (W/m²K)			0.019
	Time shift (h)			15.83

Table A25. Possible redevelopment measure for external wall with dry solution (wood fiber insulation) characterized by the half value of the thermal transmittance of the reference building (R_EW_N3.1).

Technological Solution	Layer	T (m)	λ (W/mK)	R (m²K/W)
External wall–R_EW_N3.1	Cement board	0.013	0.13	-
	Vapor barrier	0.0002	0.38	-
	Rock wool	0.014	0.035	-
	Gypsum panel	0.015	0.21	-
	Rock wool	0.04	0.035	-
	Gypsum fiber panel	0.015	0.3	-
	Gypsum fiber panel	0.015	0.3	-
	Thermal transmittance (W/m²K)			0.186
	Periodic thermal transmittance (W/m²K)			0.083
	Time shift (h)			8.72

Table A26. Possible redevelopment measure for external wall characterized by the half value of the thermal transmittance of the reference building with ETICS as external finishing (R_EW_N3.2).

Technological Solution	Layer	T (m)	λ (W/mK)	R (m²K/W)
External wall–R_EW_N3.2	External plaster	0.03	0.43	-
	Wood fiber	0.04	0.034	-
	Aerated concrete	0.30	0.07	-
	Gypsum fiber panel	0.015	0.3	-
	Gypsum fiber panel	0.015	0.3	-
	Thermal transmittance (W/m²K)			0.177
	Periodic thermal transmittance (W/m²K)			0.019
	Time shift (h)			15.83

Table A27. Possible redevelopment measure for roof floor with gravel as the finishing layer (R_RF_N1).

Technological Solution	Layer	T (m)	λ (W/mK)	R (m²K/W)
Roof floor–R_RF_N1	Gravel	0.05	-	-
	Waterproof sheet	0.003	0.5	-
	Wood fiber	0.14	0.037	-
	Vapor barrier	0.0005	0.4	-
	Precast reinforced concrete slab	0.03	1.91	-
	Thermal transmittance (W/m²K)			0.253

Table A28. Possible redevelopment measure for roof floor with green roof as the finishing layer (R_RF_N2).

Technological Solution	Layer	T (m)	λ (W/mK)	R (m²K/W)
Roof floor–R_RF_N2	Earth	0.12	-	0.3
	Filter layer	0.001	-	-
	Accumulation layer (EPS)	0.04	-	0.71
	Waterproof sheet	0.003	0.5	-
	Wood fiber	0.10	0.037	-
	Vapor barrier	0.0005	0.4	-
	Precast reinforced concrete slab	0.03	1.91	-
	Thermal transmittance (W/m²K)			0.253

Appendix B

SOLUTION	Initial Investment Costs [EUR]	Substitution costs [EUR]	Annual costs [EUR/yr]				Annual costs over the reference period [EUR/m²yr]	Residual value [EUR]	Global cost [EUR/m2]	Primary Energy demand [kWh/m²yr]		
			Heating	Electricity	Maint.	Total				Gas	Electricity	Total
Existing building	-	-	16813	10387	-	27001	-	-	-	72.62	24.87	97.49
P_EW_N1.1	439721.95	-	15512	10387	-	25900	447'859	-	188.85	67.75	24.87	92.63
P_EW_N3.1	478372.86	-	15525	10387	-	25912	448'069	-	197.12	67.81	24.87	92.68
P_EW_N4.1	222592.29	-	15553	10387	-	25940	448'562	-	142.80	67.93	24.87	92.81
P_EW_N5	92272.47	-	15600	10387	-	25987	449'372	-	115.24	68.14	24.87	93.01
P_RF_N1 + P_RF_N2	132938.20	-	15557	10387	-	25944	448'625	-	123.74	67.95	24.87	92.82
P_RF_N1.1 + P_RF_N2.1	422010.85	-	15504	10387	77	25968	449'039	-	185.33	67.72	24.87	92.59
P_W_N1	110814.41	-	15514	10387	955	26856	464'394	-	122.38	67.76	24.87	92.63
P_Syst_1	18876.84	8615.14	9454	10387	378	20218	349'616	2910.04	79.62	40.98	24.87	65.85
P_Syst_2	64529.61	-	17272	4289	-	21562	372'845	-	93.06	75.53	9.72	85.25
P_Syst_3	459293.40	2099615.51	-	24155	18372	42527	735'373	70804.36	283.72	-	59.09	59.09
P_Syst_3.1	679227.58	293823.70	-	9606	19483	29089	503'002	124495.84	287.57	-	9.48	9.48
P_Syst_3.1_PV_min	530064.28	237870.04	-	23468	18737	42205	729'814	87703.98	300.01	-	23.71	23.71
P_RF_N1 + P_RF_N2 + P_EW_N5 + P_W_N1	336025.07	-	13405	10387	955	24747	427'922	-	162.54	58.44	24.87	83.31
P_RF_N1 + P_RF_N2 + P_EW_N3.1 + P_W_N1	722125.47	-	13358	10387	955	24700	427'109	-	244.52	58.23	24.87	83.11
P_Syst_1 + P_RF_N1 + P_RF_N2 + P_EW_N5 + P_W_N1	363517.06	8615.14	7672	10387	1332	19391	335'315	2910.04	148.07	33.10	24.87	57.98
P_Syst_2 + P_RF_N1 + P_RF_N2 + P_EW_N5 + P_W_N1	400554.68	-	13999	4289	955	19243	332'745	-	156.02	61.06	9.72	70.78
P_Syst_3 + P_RF_N1 + P_RF_N2 + P_EW_N5 + P_W_N1	1004933.99	2099615.51	-	19458	19326	38784	670'658	70804.36	341.44	-	47.42	47.42
P_Syst_1 + P_RF_N1 + P_RF_N2 + P_EW_N4.1 + P_W_N1	493836.88	8615.14	7670	10387	1332	19389	335'277	2910.04	175.79	33.09	24.87	57.97
P_Syst_2 + P_RF_N1 + P_RF_N2 + P_EW_N4.1 + P_W_N1	530874.50	-	13972	4289	955	19216	332'279	-	183.65	60.94	9.72	70.66
P_Syst_3 + P_RF_N1 + P_RF_N2 + P_EW_N4.1 + P_W_N1	1135253.80	2099615.51	-	19374	19326	38700	669'206	70804.36	368.86	-	47.21	47.21
P_Syst_2 + P_Syst_3.1 + P_RF_N1 + P_RF_N2 + P_EW_N5 + P_W_N1	1373605.96	293823.70	-	5160	20437	25597	442'633	124495.84	359.95	-	4.91	4.91
P_Syst_2 + P_Syst_3.1 + P_RF_N1 + P_RF_N2 + P_EW_N4.1 + P_W_N1	1503925.78	293823.70	-	5166	20437	25603	442'730	124495.84	387.69	-	4.92	4.92
P_Syst_2 + P_Syst_3.1_PV_min + P_RF_N1 + P_RF_N2 + P_EW_N4.1 + P_W_N	1298808.82	237870.04	-	10012	18737	28749	513'631	87703.98	366.97	-	9.89	9.89

Figure A1. Summary table of cost-optimal methodology for financial scenario with discount rate equal to 4% for Poliziano school.

SOLUTION	Initial Investment Costs [EUR]	Substitution costs [EUR]	Annual costs [EUR/yr]				Annual costs over the reference period [EUR/m²yr]	Residual value [EUR]	Global cost [EUR/m2]	Primary Energy demand [kWh/m²yr]		
			Heating	Electricity	Maint.	Total				Gas	Electricity	Total
Existing building	-	-	16'613	10'387	-	27'001	-	-	-	72.62	24.87	97.49
P_EW_N1.1	439'721.95	0.00	15'512	10'387	-	25'900	398'142	0.00	188.85	67.75	24.87	92.63
P_EW_N3.1	478'372.86	0.00	15'525	10'387	-	25'912	398'329	0.00	186.53	67.81	24.87	92.68
P_EW_N4.1	222'592.29	0.00	15'553	10'387	-	25'940	398'767	0.00	132.20	67.93	24.87	92.81
P_EW_N5	92'272.47	0.00	15'600	10'387	-	25'987	399'487	0.00	104.63	68.14	24.87	93.01
P_RF_N1 + P_RF_N2	132'938.20	0.00	15'557	10'387	-	25'944	398'823	0.00	113.14	67.95	24.87	92.82
P_RF_N1.1 + P_RF_N2.1	422'010.85	0.00	15'504	10'387	77	25'968	399'192	0.00	174.72	67.72	24.87	92.59
P_W_N1	110'814.41	0.00	15'514	10'387	955	26'856	412'842	0.00	111.42	67.76	24.87	92.63
P_Syst_1	188'876.84	7'114.48	9'454	10'387	378	20'218	310'805	2183.84	71.19	40.98	24.87	65.85
P_Syst_2	64'529.61	0.00	17'272	4'289	-	21'562	331'455	0.00	84.25	75.53	9.72	85.25
P_Syst_3	459'293.40	173'102.85	-	24'155	18372	42'527	653'739	70'304.36	262.34	-	59.09	59.09
P_Syst_3.1	679'227.58	239'618.85	-	9'606	19483	29'089	447'164	124'495.84	270.76	-	9.48	9.48
P_Syst_3.1_PV_min	530'064.28	195'570.52	-	23'488	18737	42'205	648'798	65'317.37	278.43	-	23.71	23.71
P_RF_N1 + P_RF_N2 + P_EW_N5 + P_W_N1	336'925.07	0.00	13'405	10'387	955	24'747	380'418	0.00	152.43	58.44	24.87	83.31
P_RF_N1 + P_RF_N2 + P_EW_N3.1 + P_W_N1	722'125.47	0.00	13'358	10'387	955	24'700	379'696	0.00	234.43	58.23	24.87	83.11
P_Syst_1 + P_RF_N1 + P_RF_N2 + P_EW_N5 + P_W_N1	362'016.40	7'114.48	7'672	10'387	1332	19'391	298'092	2183.84	139.98	33.10	24.87	57.98
P_Syst_2 + P_RF_N1 + P_RF_N2 + P_EW_N5 + P_W_N1	400'554.68	0.00	13'999	4'289	955	19'243	295'807	0.00	148.16	61.06	9.72	70.78
P_Syst_3 + P_RF_N1 + P_RF_N2 + P_EW_N5 + P_W_N1	968'421.33	173'102.85	-	19'458	19326	38'784	596'209	70'304.36	321.59	-	47.42	47.42
P_Syst_1 + P_RF_N1 + P_RF_N2 + P_EW_N4.1 + P_W_N1	492'336.21	7'114.48	7'670	10'387	1332	19'389	298'058	2183.84	167.70	33.09	24.87	57.97
P_Syst_2 + P_RF_N1 + P_RF_N2 + P_EW_N4.1 + P_W_N1	530'874.50	0.00	13'972	4'289	955	19'216	295'393	0.00	175.80	60.94	9.72	70.66
P_Syst_3 + P_RF_N1 + P_RF_N2 + P_EW_N4.1 + P_W_N1	1'098'741.14	173'102.85	-	19'374	19326	38'700	594'917	70'304.36	349.05	-	47.21	47.21
P_Syst_2 + P_Syst_3.1 + P_RF_N1 + P_RF_N2 + P_EW_N5 + P_W_N1	1'319'401.11	239'618.85	-	5'160	20437	25'597	393'496	93'427.78	344.57	-	4.91	4.91
P_Syst_2 + P_Syst_3.1 + P_RF_N1 + P_RF_N2 + P_EW_N4.1 + P_W_N1	1'449'720.93	239'618.85	-	5'166	20437	25'603	442'730	93'427.78	382.77	-	4.92	4.92
P_Syst_2 + P_Syst_3.1_PV_min + P_RF_N1 + P_RF_N2 + P_EW_N4.1 + P_W_N	1'256'509.30	195'570.52	-	10'012	18737	28'749	456'613	65'317.37	350.49	-	9.89	9.89

Figure A2. Summary table of cost-optimal methodology for financial scenario with discount rate equal to 5% for Poliziano school.

SOLUTION	Initial Investment Costs [EUR]	Substitution costs [EUR]	Annual costs [EUR/yr]				Annual costs over the reference period [EUR/m²yr]	CO₂ emissions costs [EUR]	Residual value [EUR]	Global cost [EUR/m²]	Primary Energy demand [kWh/m²yr]		
			Heating	Electricity	Maint.	Total					Gas	Electricity	Total
Existing building	-	-	12'981.29	7'910.30	-	20'891.59	-	105'476.95	-	-	72.62	24.87	97.49
P_EW_N1.1	360'427.83	0.00	12'121.47	7'910.30	0.00	20'031.76	392'631.42	99'895.36	0.00	181.48	67.75	24.87	92.63
P_EW_N3.1	392'108.90	0.00	12'130.94	7'910.30	0.00	20'041.24	392'817.12	99'956.86	0.00	188.27	67.81	24.87	92.68
P_EW_N4.1	182'452.69	0.00	12'153.22	7'910.30	0.00	20'063.51	393'263.72	100'101.46	0.00	143.79	67.93	24.87	92.81
P_EW_N5	75'633.17	0.00	12'189.81	7'910.30	0.00	20'100.10	393'970.90	100'338.99	0.00	121.26	68.14	24.87	93.01
P_RF_N1 + P_RF_N2	108'965.74	0.00	12'156.08	7'910.30	0.00	20'066.38	393'309.87	100'120.06	0.00	128.17	67.95	24.87	92.82
P_RF_N1.1 + P_RF_N2.1	345'910.53	0.00	12'115.02	7'910.30	62.73	20'088.04	393'734.51	99'853.48	0.00	178.62	67.72	24.87	92.59
P_W_N1	90'831.48	0.00	12'122.81	7'910.30	782.41	20'815.52	407'993.34	99'904.10	0.00	127.39	67.76	24.87	92.63
P_Syst_1	15'472.82	8'566.93	7'389.76	7'910.30	309.46	15'609.51	305'963.30	69'179.36	2'385.28	84.25	40.98	24.87	65.85
P_Syst_2	52'893.12	0.00	13'495.84	3'279.87	0.00	16'775.71	328'811.34	95'308.44	0.00	101.49	75.53	9.72	85.25
P_Syst_3	376'470.00	208'442.31	0.00	18'364.67	15'058.80	33'423.47	655'114.70	52'673.36	58'036.36	258.54	0.00	59.09	59.09
P_Syst_3.1	556'743.92	296'058.56	0.00	7'317.01	15'969.41	23'286.42	456'424.17	20'443.16	102'045.77	253.90	0.00	9.48	9.48
P_Syst_3.1_PV_min	434'478.92	237'664.11	0.00	17'843.32	15'358.09	33'201.41	650'762.35	51'152.41	96'060.07	271.91	0.00	23.71	23.71
P_RF_N1 + P_RF_N2 + P_EW_N5 + P_W_N1	275'430.39	0.00	10'475.82	7'910.30	782.41	19'168.33	375'707.71	89'211.33	0.00	157.52	58.44	24.87	83.31
P_RF_N1 + P_RF_N2 + P_EW_N3.1 + P_W_N1	591'906.12	0.00	10'438.90	7'910.30	782.41	19'131.61	374'987.91	88'972.94	0.00	224.65	58.23	24.87	83.11
P_Syst_1 + P_RF_N1 + P_RF_N2 + P_EW_N5 + P_W_N1	299'470.13	8'566.93	5'998.43	7'910.30	1'091.86	15'000.59	294'018.12	60'147.50	2'385.28	138.39	33.10	24.87	57.98
P_Syst_2 + P_RF_N1 + P_RF_N2 + P_EW_N5 + P_W_N1	328'323.51	0.00	10'939.39	3'279.87	782.41	15'001.67	294'039.30	78'713.17	0.00	149.17	61.06	9.72	70.78
P_Syst_3 + P_RF_N1 + P_RF_N2 + P_EW_N5 + P_W_N1	860'342.70	208'442.31	0.00	14'798.04	15'841.21	30'639.25	600'542.85	42'268.17	58'036.36	303.32	0.00	47.42	47.42
P_Syst_1 + P_RF_N1 + P_RF_N2 + P_EW_N4.1 + P_W_N1	406'289.66	8'566.93	5'996.70	7'910.30	1'091.86	14'998.86	293'984.30	60'136.30	2'385.28	161.11	33.09	24.87	57.97
P_Syst_2 + P_RF_N1 + P_RF_N2 + P_EW_N4.1 + P_W_N1	435'143.03	0.00	10'918.36	3'279.87	782.41	14'980.64	293'627.06	78'576.64	0.00	171.78	60.94	9.72	70.66
P_Syst_3 + P_RF_N1 + P_RF_N2 + P_EW_N4.1 + P_W_N1	967'162.22	208'442.31	0.00	14'734.26	15'841.21	30'575.47	599'292.64	42'082.09	58'036.36	325.74	0.00	47.21	47.21
P_Syst_2 + P_Syst_3.1 + P_RF_N1 + P_RF_N2 + P_EW_N5 + P_W_N1	1'181'125.98	296'058.56	0.00	3'941.20	16'751.82	20'693.02	405'592.28	10'594.63	136'357.32	310.84	0.00	4.91	4.91
P_Syst_3.1 + P_RF_N1 + P_RF_N2 + P_EW_N4.1 + P_W_N1	1'287'945.51	296'058.56	0.00	3'945.49	16'751.82	20'697.31	405'676.42	10'607.15	136'357.32	333.59	0.00	4.92	4.92
P_Syst_2 + P_Syst_3.1_PV_min + P_RF_N1 + P_RF_N2 + P_EW_N4.1 + P_W_N1	1'107'286.06	237'664.11	0.00	7'625.26	16'140.50	23'765.78	465'819.80	21'342.51	96'060.07	318.81	0.00	9.89	9.89

Figure A3. Summary table of cost-optimal methodology for macroeconomic scenario with discount rate equal to 3% for Poliziano school.

SOLUTION	Initial Investment Costs [EUR]	Substitution costs [EUR]	Annual costs [EUR/yr]				Annual costs over the reference period [EUR/m²·yr]	CO_2 emissions costs [EUR]	Residual value [EUR]	Global cost [EUR/m²]	Primary Energy demand [kWh/m²·yr]		
			Heating	Electricity	Maint.	Total					Gas	Electricity	Total
Existing building	-	-	12'981.29	7'910.30	-	20'891.59		1'054'476.95			72.62	24.87	97.49
P_EW_N1.1	360'427.83	0.00	12'121.47	7'910.30	0.00	20'031.76	346'389.93	99'895.36	0.00	171.64	67.75	24.87	92.63
P_EW_N3.1	392'108.90	0.00	12'130.94	7'910.30	0.00	20'041.24	346'553.76	99'956.86	0.00	178.43	67.81	24.87	92.68
P_EW_N4.1	182'452.69	0.00	12'153.22	7'910.30	0.00	20'063.51	346'938.94	100'101.46	0.00	133.93	67.93	24.87	92.81
P_EW_N5	75'633.17	0.00	12'189.81	7'910.30	0.00	20'100.10	347'571.66	100'338.99	0.00	111.39	68.14	24.87	93.01
P_RF_N1 + P_RF_N2	108'965.74	0.00	12'155.08	7'910.30	0.00	20'066.38	346'988.48	100'120.06	0.00	118.31	67.95	24.87	92.82
P_RF_N1.1 + P_RF_N2.1	345'910.53	0.00	12'115.02	7'910.30	62.73	20'088.04	347'363.11	99'853.48	0.00	168.75	67.72	24.87	92.59
P_W_N1	90'831.48	0.00	12'122.81	7'910.30	782.41	20'815.52	359'942.63	99'904.10	0.00	117.17	67.76	24.87	92.63
P_Syst_1	15'472.82	7'061.59	7'389.76	7'910.30	309.46	15'609.51	269'920.18	69'179.36	2'385.28	76.44	40.98	24.87	65.85
P_Syst_2	52'893.12	0.00	13'495.84	3'279.87	0.00	16'775.71	290'086.16	95'308.44	0.00	93.25	75.53	9.72	85.25
P_Syst_3	376'470.00	171'815.99	0.00	18'364.67	15'058.80	33'423.47	577'959.70	52'673.36	58'036.36	238.49	-	59.09	59.09
P_Syst_3.1	556'743.92	240'839.10	0.00	7'317.01	15'969.41	23'286.42	402'569.60	20'445.16	102'045.77	238.01	-	9.48	9.48
P_Syst_3.1_PV_min	434'478.92	194'975.44	0.00	17'843.32	15'358.09	33'201.41	574'119.94	51'152.41	71'888.51	251.67	-	23.71	23.71
P_RF_N1 + P_RF_N2 + P_EW_N5 + P_W_N1	275'430.39	0.00	10'475.62	7'910.30	782.41	19'168.33	331'459.39	89'211.33	0.00	148.11	58.44	24.87	83.31
P_RF_N1 + P_RF_N2 + P_EW_N3.1 + P_W_N1	591'906.12	0.00	10'438.90	7'910.30	782.41	19'131.61	330'824.36	88'972.94	0.00	215.26	58.23	24.87	83.11
P_Syst_1 + P_RF_N1 + P_RF_N2 + P_EW_N5 + P_W_N1	297'964.80	7'061.59	5'998.43	7'910.30	1'091.86	15'000.59	259'390.65	60'147.50	2'385.28	130.88	33.10	24.87	57.98
P_Syst_2 + P_RF_N1 + P_RF_N2 + P_EW_N5 + P_W_N1	328'323.51	0.00	10'939.39	3'279.87	782.41	15'001.67	259'409.33	78'713.17	0.00	141.80	61.06	9.72	70.78
P_Syst_3 + P_RF_N1 + P_RF_N2 + P_EW_N5 + P_W_N1	823'716.38	171'815.99	0.00	14'798.04	15'841.21	30'639.25	529'314.95	42'268.17	58'036.36	284.63	-	47.42	47.42
P_Syst_1 + P_RF_N1 + P_RF_N2 + P_EW_N4.1 + P_W_N1	404'784.32	7'061.59	5'996.70	7'910.30	1'091.86	14'998.86	259'360.81	60'136.30	2'385.28	153.59	33.09	24.87	57.97
P_Syst_2 + P_RF_N1 + P_RF_N2 + P_EW_N4.1 + P_W_N1	435'143.03	0.00	10'918.36	3'279.87	782.41	14'980.64	259'045.64	78'576.64	0.00	164.42	60.94	9.72	70.66
P_Syst_3 + P_RF_N1 + P_RF_N2 + P_EW_N4.1 + P_W_N1	930'535.90	171'815.99	0.00	14'734.26	15'841.21	30'575.47	528'711.99	42'082.09	58'036.36	307.08	-	47.21	47.21
P_Syst_2 + P_Syst_3.1 + P_RF_N1 + P_RF_N2 + P_EW_N5 + P_W_N1	1'125'906.52	240'839.10	0.00	3'941.20	16'751.82	20'693.02	357'824.35	10'594.63	102'045.77	296.23	-	4.91	4.91
P_Syst_2 + P_Syst_3.1 + P_RF_N1 + P_RF_N2 + P_EW_N4.1 + P_W_N1	1'232'726.65	240'839.10	0.00	3'945.49	16'751.82	20'697.31	357'898.58	10'607.15	102'045.77	318.98	-	4.92	4.92
P_Syst_2 + P_Syst_3.1_PV_min + P_RF_N1 + P_RF_N2 + P_EW_N4.1 + P_W_N1	1'064'597.39	194'975.44	0.00	7'625.28	16'140.50	23'765.78	410'958.68	21'342.51	71'888.51	303.19	-	9.89	9.89

Figure A4. Summary table of cost-optimal methodology for macroeconomic scenario with discount rate equal to 4% for Poliziano school.

SOLUTION	Initial Investment Costs [EUR]	Substitution costs [EUR]	Annual costs [EUR/yr]				Annual costs over the reference period [EUR/m²yr]	Residual value [EUR]	Global cost [EUR/m2]	Primary Energy demand [kWh/m²yr]		
			Heating	Electricity	Maint.	Total				Gas	Electricity	Total
Existing building	-	-	11'922	4'455	-	16'377	283'193.06	-		104.34	20.28	124.62
Syst_1	10'377	4'736	6683	4'455	208	11'346	196'190.28	1'600	89.30	58.00	20.28	78.28
Syst_2	38'196	-	12'289	2'285	-	14'574	252'010.10	-	123.58	107.58	9.49	117.07
Syst_3	229'490	104'736	-	11'956	9'180	21'135	365'473.86	35'378	282.88	0.00	57.58	57.58
Syst_3.1	495'815	206'346	-	4'225	10'500	14'725	254'618.55	100'512	364.62	0.00	7.91	7.91
R_RF_N1	73'346	-	10'884	4'455	-	15'340	265'251.26	-	144.18	95.16	20.28	115.44
R_RF_N2	201'214	-	10'850	4'455	36	15'341	265'279.49	-	198.64	94.86	20.28	115.14
R_EW_N3.1	284'240	-	11'182	4'455	-	15'637	270'403.88	-	236.18	97.80	20.28	118.08
R_EW_N2.1	298'689	-	11'158	4'455	-	15'614	269'993.32	-	242.16	97.59	20.28	117.87
R_EW_N1.1	784'502	-	11'199	4'455	-	15'654	270'691.28	-	449.32	97.94	20.28	118.22
R_EW_N3	675'391	-	11'172	4'455	-	15'627	270'219.13	-	402.66	97.70	20.28	117.98
R_EW_N1	656'607	-	11'230	4'455	-	15'685	271'225.02	-	395.09	98.22	20.28	118.50
R_EW_N3.2	311'301	-	11'172	4'455	-	15'627	270'219.13	-	247.62	97.70	20.28	117.98
R_EW_N3.2 + R_RF_N1	384'647	-	10'130	4'455	-	14'586	252'215.75	-	271.19	88.49	20.28	108.77
R_EW_N3.2 + R_RF_N1 + Syst_1	399'760	4'736	5'688	4'455	208	10'351	178'987.51	1'600	246.44	49.20	20.28	69.48
R_EW_N3.2 + R_RF_N1 + Syst_2	422'843	-	10'488	4'864	-	15'352	265'462.51	-	293.10	91.65	22.31	113.97
R_EW_N3.1 + R_RF_N1 + Syst_1	372'699	4'736	5'708	4'455	208	10'371	179'336.49	1'600	234.39	49.38	20.28	69.66
R_EW_N3.1 + R_RF_N1 + Syst_2	395'781	-	10'488	2'280	-	12'768	220'784.42	-	262.55	91.65	9.46	101.12
R_EW_N3.2 + R_RF_N1 + Syst_3	614'137	104'736	-	11'153	9'180	20'333	351'590.84	35'378	396.16	0.00	53.59	53.59
R_EW_N3.1 + R_RF_N1 + Syst_3	691'812	104'736	-	11'041	9'180	20'221	349'655.63	35'378	428.42	0.00	53.03	53.03
R_EW_N3.2 + R_RF_N1 + Syst_3.1 + Syst_2	1'125'004	206'346	-	2'912	10'500	13'412	231'926.12	100'512	535.01	0.00	5.21	5.21

Figure A5. Summary table of cost-optimal methodology for financial scenario with discount rate equal to 4% for Rodari school.

SOLUTION	Initial Investment Costs [EUR]	Substitution costs [EUR]	Annual costs [EUR/yr]				Annual costs over the reference period [EUR/m²yr]	Residual value [EUR]	Global cost [EUR/m2]	Primary Energy demand [kWh/m²/yr]		
			Heating	Electricity	Maint.	Total				Gas	Electricity	Total
Existing building	-	-	11'922	4'455	-	16'377	-	-		104.34	20.28	124.62
Syst_1	10'377	3'911	6'683	4'455	208	11'346	174'411.27	1'201	79.84	58.00	20.28	78.28
Syst_2	38'196	-	12'289	2'285	-	14'574	224'034.55	-	111.66	107.58	9.49	117.07
Syst_3	229'490	86'492	-	11'956	9'180	21'135	324'902.74	26'549	261.60	0.00	57.58	57.58
Syst_3.1	495'815	166'708	-	4'225	10'500	14'725	226'353.44	75429	346.38	0.00	7.91	7.91
R_RF_N1	73'346	-	10'884	4'455	-	15'340	235'805.82	-	131.64	95.16	20.28	115.44
R_RF_N2	201'214	-	10'850	4'455	36	15'341	235'830.91	-	186.10	94.86	20.28	115.14
R_EW_N3.1	284'240	-	11'182	4'455	-	15'637	240'386.45	-	223.40	97.80	20.28	118.08
R_EW_N2.1	298'689	-	11'158	4'455	-	15'614	240'021.46	-	229.39	97.59	20.28	117.87
R_EW_N1.1	784'502	-	11'199	4'455	-	15'654	240'641.94	-	436.53	97.94	20.28	118.22
R_EW_N3	675'391	-	11'172	4'455	-	15'627	240'222.20	-	389.89	97.70	20.28	117.98
R_EW_N1	656'607	-	11'230	4'455	-	15'685	241'116.43	-	382.27	98.22	20.28	118.50
R_EW_N3.2	311'301	-	11'172	4'455	-	15'627	240'222.20	-	234.85	97.70	20.28	117.98
R_EW_N3.2 + R_RF_N1	384'647	-	10'130	4'455	-	14'586	224'217.37	-	259.27	88.49	20.28	108.77
R_EW_N3.2 + R_RF_N1 + Syst_1	398'935	3'911	5'688	4'455	208	10'351	159'118.17	1'201	237.63	49.20	20.28	69.48
R_EW_N3.2 + R_RF_N1 + Syst_2	422'843	-	10'488	4'864	-	15'352	235'993.61	-	280.55	91.65	22.31	113.97
R_EW_N3.1 + R_RF_N1 + Syst_1	371'874	3'911	5'708	4'455	208	10'371	159'428.41	1'201	225.73	49.38	20.28	69.66
R_EW_N3.1 + R_RF_N1 + Syst_2	395'781	-	10'488	2'280	-	12'768	196'275.22	-	252.11	91.65	9.46	101.12
R_EW_N3.2 + R_RF_N1 + Syst_3	614'137	86'492	-	11'153	9'180	20'333	312'560.87	26'549	383.30	0.00	53.59	53.59
R_EW_N3.1 + R_RF_N1 + Syst_3	673'568	86'492	-	11'041	9'180	20'221	310'840.49	26'549	407.88	0.00	53.03	53.03
R_EW_N3.2 + R_RF_N1 + Syst_3.1 + Syst_2	1'085'365	166'708	-	2'912	10'500	13'412	206'180.09	75429	517.85	0.00	5.21	5.21

Figure A6. Summary table of cost-optimal methodology for financial scenario with discount rate equal to 5% for Rodari school.

SOLUTION	Initial Investment Costs [EUR]	Substitution costs [EUR]	Annual costs [EUR/yr]				Annual costs over the reference period [EUR/m²/yr]	CO₂ emissions costs [EUR]	Residual value [EUR]	Global cost [EUR/m²]	Primary Energy demand [kWh/m²/yr]		
			Heating	Electricity	Maint.	Total					Gas	Electricity	Total
Existing building	-	-	9'315	3'406	-	12'721.05	249'338.18	68'837.40	-		104.34	20.28	124.62
Syst_1	10'377.38	5745.70	5'224	3'406	208	8'837.26	173'214.12	42'278.36	2'137.67	97.72	58.00	20.28	78.28
Syst_2	31'308.06	-	9'602	1'758	-	11'359.64	222'654.00	65'889.57	-	136.20	107.58	9.49	117.07
Syst_3	188'106.84	104'150.20	102	9'101	7524	16'728.06	327'877.29	25'648.68	38'748.76	258.49	0.00	57.58	57.58
Syst_3.1	406'405.76	209'927.39	-	3'231	8607	11'837.28	232'015.85	8'522.00	110'088.39	318.00	0.00	7.91	7.91
R_RF_N1	60'119.45	-	8'505	3'406	-	11'910.75	233'456.04	63'577.35	-	152.08	95.16	20.28	115.44
R_RF_N2	164'929.46	-	8'478	3'406	30	11'913.43	233'508.40	63'402.82	-	196.66	94.86	20.28	115.14
R_EW_N3.1	232'983.55	-	8'738	3'406	-	12'143.46	238'017.16	65'087.96	-	228.28	97.80	20.28	118.08
R_EW_N2.1	244'826.79	-	8'719	3'406	-	12'124.92	237'653.72	64'967.59	-	233.12	97.59	20.28	117.87
R_EW_N1.1	643'034.67	-	8'751	3'406	-	12'156.44	238'271.57	65'172.21	-	403.03	97.94	20.28	118.22
R_EW_N3	553'598.83	-	8'729	3'406	-	12'135.12	237'853.61	65'033.79	-	364.71	97.70	20.28	117.98
R_EW_N1	538'202.62	-	8'775	3'406	-	12'180.54	238'744.03	65'328.69	-	358.66	98.22	20.28	118.50
R_EW_N3.2	255'164.73	-	8'729	3'406	-	12'135.12	237'853.61	65'033.79	-	237.63	97.70	20.28	117.98
R_EW_N3.2 + R_RF_N1	315'284.17	-	7'916	3'406	-	11'322.04	-	59'755.69	-	254.20	88.49	20.28	108.77
R_EW_N3.2 + R_RF_N1 + Syst_1	331'407.26	5745.70	4'447	3'406	208	8'060.34	-	37'234.98	2'137.67	223.34	49.20	20.28	69.48
R_EW_N3.2 + R_RF_N1 + Syst_2	346'592.23	-	8'195	3'716	-	11'911.46	233'469.93	62'472.66	-	273.61	91.65	22.31	113.97
R_EW_N3.1 + R_RF_N1 + Syst_1	309'226.08	5745.70	4'463	3'406	208	8'076.10	158'295.08	37'337.29	2'137.67	214.07	49.38	20.28	69.66
R_EW_N3.1 + R_RF_N1 + Syst_2	324'411.05	-	8'195	1'754	-	9'949.52	195'014.98	56'748.93	-	245.35	91.65	9.46	101.12
R_EW_N3.2 + R_RF_N1 + Syst_3	503'391.01	104'150.20	-	8'492	7524	16'015.95	-	23'870.12	38'748.76	341.69	0.00	53.59	53.59
R_EW_N3.1 + R_RF_N1 + Syst_3	585'360.03	104'150.20	-	8'407	7524	15'930.97	312'254.09	23'622.20	38'748.76	375.78	0.00	53.03	53.03
R_EW_N3.2 + R_RF_N1 + Syst_3.1 + Syst_2	962'925.39	209'927.39	-	2'234	8607	10'840.79	212'484.21	5'614.86	110'088.39	456.03	0.00	5.21	5.21

Figure A7. Summary table of cost-optimal methodology for macroeconomic scenario with discount rate equal to 3% for Rodari school.

SOLUTION	Initial Investment Costs [EUR]	Substitution costs [EUR]	Annual costs [EUR/yr] Heating	Electricity	Maint.	Total	Annual costs over the reference period [EUR/m²yr]	CO_2 emissions costs [EUR]	Residual value [EUR]	Global cost [EUR/m²]	Primary Energy demand [kWh/m²yr] Gas	Electricity	Total
Existing building	-	-	9'315	3'406	-	12'721	219'972.81	68'837.40	-		104.34	20.28	124.62
Syst_1	10'377.38	4736.10	5'224	3'406	208	8'837	152'814.12	42'278.36	1599.77	88.83	58.00	20.28	78.28
Syst_2	31'308.06	-	9'602	1'758	-	11'360	196'431.31	65'889.57	-	125.03	107.58	9.49	117.07
Syst_3	188'106.84	85'849.51	102	9'101	7'524	16'728	289'262.11	25'648.68	28'998.43	238.40	0.00	57.58	57.58
Syst_3.1	406'405.76	169'136.43	-	3'231	8'607	11'837	204'690.58	8'522.00	82'386.89	300.79	0.00	7.91	7.91
R_RF_N1	60'119.45		8'505	3'406	-	11'911	205'961.16	63'577.35	-	140.38	95.16	20.28	115.44
R_RF_N2	164'929.46		8'478	3'406	30	11'913	206'007.35	63'402.82	-	184.95	94.86	20.28	115.14
R_EW_N3.1	232'983.55		8'738	3'406	-	12'143	209'985.10	65'087.96	-	216.34	97.80	20.28	118.08
R_EW_N2.1	244'826.79		8'719	3'406	-	12'125	209'664.47	64'967.59	-	221.20	97.59	20.28	117.87
R_EW_N1.1	643'034.67		8'751	3'406	-	12'156	210'209.54	65'172.21	-	391.08	97.94	20.28	118.22
R_EW_N3	553'598.83		8'729	3'406	-	12'135	209'840.82	65'033.79	-	352.78	97.70	20.28	117.98
R_EW_N1	538'202.62		8'775	3'406	-	12'181	210'626.37	65'328.69	-	346.69	98.22	20.28	118.50
R_EW_N3.2	255'164.73		8'729	3'406	-	12'135	209'840.82	65'033.79	-	225.70	97.70	20.28	117.98
R_EW_N3.2 + R_RF_N1	315'284.17		7'916	3'406	-	11'322		59'755.69	-	243.07	88.49	20.28	108.77
R_EW_N3.2 + R_RF_N1 + Syst_1	330'397.66	4736.10	4'447	3'406	208	8'060		37'234.98	1599.77	215.22	49.20	20.28	69.48
R_EW_N3.2 + R_RF_N1 + Syst_2	346'592.23	-	8'195	3'716	-	11'911	205'973.42	62'472.66	-	261.90	91.65	22.31	113.97
R_EW_N3.1 + R_RF_N1 + Syst_1	308'216.47	4736.10	4'463	3'406	208	8'076	139'652.15	37'337.29	1599.77	205.93	49.38	20.28	69.66
R_EW_N3.1 + R_RF_N1 + Syst_2	324'411.05	-	8'195	1'754	-	9'950	172'047.43	56'748.93	-	235.57	91.65	9.46	101.12
R_EW_N3.2 + R_RF_N1 + Syst_3	503'391.01	85'849.51	-	8'492	7'524	16'016		23'870.12	28'998.43	330.10	0.00	53.59	53.59
R_EW_N3.1 + R_RF_N1 + Syst_3	567'059.34	85'849.51	-	8'407	7'524	15'931	275'478.91	23'622.20	28'998.43	356.48	0.00	53.03	53.03
R_EW_N3.2 + R_RF_N1 + Syst_3.1 + Syst_2	922'134.42	169'136.43	-	2'234	8'607	10'841	187'459.25	5'614.86	82'386.89	439.80	0.00	5.21	5.21

Figure A8. Summary table of cost-optimal methodology for macroeconomic scenario with discount rate equal to 4% for Rodari school.

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