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EDeSSOpt - Energy Demand and Supply Simultaneous Optimization for cost-optimized design: application to a multi-family building

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Abstract

In the context of European efforts to reduce energy consumption and CO_2 emissions in the building sector, the second recast of the Energy Performance of Buildings Directive promotes the acceleration of the energy renovation of European building stock. To do this, a cost optimization is necessary to find the best combination of energy efficiency measures which minimize the global cost during the entire life-cycle of the building, as suggested in the first recast of the same Directive. Since a great number of combinations must be analyzed, an automated procedure is necessary to reduce the calculation time. In this work, an iterative input-output process is set, thanks to the coupling of a dynamic energy simulation software (TRNSYS) and a generic optimization software (GenOpt). The cost optimization is applied to a new social housing construction – a multi-family building located in Northern Italy. The methodology that was adopted allows the simultaneous optimization of both the building energy demand (building envelope) and the building energy supply (technical systems and renewable sources). Results are compared with those obtained using a more widespread sequential approach whose purpose is firstly the optimization of one of these two factors, and subsequently the optimization of the other one. This study has demonstrated that an integrated approach allows a larger number of possible combinations of energy efficiency measures to be explored with respect to the sequential approach.

Keywords: simulation-based optimization; integrated optimization; social housing; EPBD second recast 2018; global cost; nearly zero energy buildings.

1. Introduction

1.1 Background

The building sector has been identified as one of the key fields in which action is needed in order to achieve the 20/20/20 targets regarding emission reductions, energy saving and use of renewables that European Member States have jointly set [1], given the important role of buildings in terms of energy consumption (around 40%) and CO_2 emissions (around 36%) of the annual European energy expenditure and greenhouse gas emissions [2]. The first recast of the Directive on the Energy Performance of Buildings (EPBD) sets the frameworks and boundaries to achieve the established objectives [3], imposing the adoption of cost-effective measures to improve the energy performance of buildings, in order to fulfil the 2020 NZEB (Nearly Zero Energy Building) target [1]. Furthermore, the recent recast of the EPBD (EU 2018/844) encourages stronger policies within the roadmap to 2050 to reduce greenhouse gas emissions of the European building stock by 80-95% compared to 1990. In this Directive, it is recommended that innovative strategies for improving energy efficiency in buildings are not limited to the building envelope, but also include all the components of technical systems, ensuring both technical and economic feasibility.

In fact, in recent years, many promising technologies have emerged that are able to move the energy performance of new buildings towards the Zero Energy target, but the economic feasibility of these improvements is yet to be demonstrated and constitutes the main barrier to their massive implementation. In order to combine energy and financial targets, the EPBD recast has introduced the so-called cost-optimal methodology framework that has been widely applied by European Member States to set the minimum performance requirements and by the scientific community, in order to advance in the NZEB design and optimization [4].

Under this framework, within a NZEB design process, different energy efficiency measures related to the building energy supply and demand, including renewable sources, should be evaluated in various combinations with the aim of finding the cost-optimal NZEB design solutions that are able to minimize the global cost while reducing the non-renewable energy demand of buildings and the related CO_2 emissions [5]. Given the great number of involved design variables, the cost-effective NZEB design results in a complex optimization problem, where the objective function is the so-called Global Cost function.

The design variables involved in the NZEB design can be grouped in three sets: one related to the building envelope and geometry, another related to energy systems and the last to renewable sources. When trying to combine the three together, optimization may become very laborious and time consuming. That is why traditional approaches [6] to building design optimization are structured around consecutive and different steps, where the optimization process is performed considering only one or two set of design variables at a time. These are the steps constituting such sequential approach to NZEB design:

(1) minimize the energy need through “passive” measures (related to envelope);

(2) based on the optimized energy need resulting from step 1, minimize the energy consumption through “active” measures (related to energy systems);

(3) based on the optimized energy consumption resulting from step 2, optimize the use of renewable energy sources (RES).

However, this approach does not allow a proper consideration of the mutual relationships between the parameters affecting the energy demand and the others impacting the energy supply, as the latter are optimized over a fixed configuration of previously optimized “passive” parameter, thus limiting the exploration of the entire NZEB design space.

Because the strict interdependence between passive measures, active measures and RES implementation has been demonstrated [7], it is clear that an integrated approach considering both the building and systems design variables may lead to very different outcomes when compared to the sequential approach. An integrated approach allows exploring the entire design space within the same optimization run, without “prioritizing” passive or active measures. Using this method all the design variables can be optimized in their mutual relationships with the others, leading to design solutions that could not emerge within the sequential approach and therefore to better results in terms of minimization of the objective function.

In this context, simulation-based optimization constitutes the most advanced tool to explore such a wide design space while maintaining the calculation accurate and manageable, especially for projects characterized by high complexity, such as for multi-family buildings design.

The multi-family building typology represents the most widespread construction in residential areas in Italy: in big cities 85% of families live in multi-family buildings and the percentage is about 70% in their suburban areas and in smaller cities [8]. Moreover, multi-family buildings are the most common type of social housing constructions [9], so the improvement of their energy performance can decrease the risk of energy poverty for low-income households [10]. Therefore, in the Italian context, it is important to investigate the NZEB design problem for this building typology, both in terms of methods and results.

1.2 Literature review

The popularity of simulation-based optimization methods applied to building design has increased in the last years [11]. In particular, there is evidence that the introduction of the cost-optimal methodology has led the research community to significant advancements in simulation-based optimization techniques to be applied to energy-efficient building design [4].

Many studies applying such methods are mainly focused on the energy demand, aiming at optimizing the passive design of new building envelopes at different scales, from enclosures [12] to high-rise buildings [13] to districts [14], from both the energy performance and the costs points of view [15]. Indeed, some of the most recent studies have concentrated on the optimization of one particular element of the building envelope, such as its façade [16] and windows [17]. Other recent studies focus on cost-optimal building envelope renovation for a hospitals [18] or schools [19], based on tailored optimization tools [20] and effects that renovations have on thermal comfort and indoor air quality [21] and on greenhouse gas emissions [22].

Other studies are related to the optimization of systems design for energy supply [23], some studies can be found on residential buildings [24], or non-residential buildings [25] as commercial buildings [26]. Ascione et al. [27] investigate how to maximize the efficiency of an earth to air heat exchanger specifically designed for the Mediterranean climate, Wei et al. [28] optimizes the performance of HVAC systems by means of evolutionary algorithms, while other studies focus on the optimization of ventilation systems [29]. Wang et al. [30] deal with a complex optimization problem aimed at finding the best design alternative for ground source heat pump systems with integrated photovoltaic thermal collectors. Lately, simulation-based optimization methods have also been used for optimization problems related to the integration of renewable sources in buildings, such as [31], [32] and [33], which focus on optimization of renewable energy sources for residential applications.

With respect to applications in residential buildings, simulation-based methods applied to multi-family buildings design are less present in literature with respect to those optimizing a single-family house, but some cases can be found. Concerning single-objective optimization in the Italian context, Ascione et al. [34] hypothesize energy retrofit measures including building envelope and energy system parameters, but not solar renewable sources, as do Penna et al. [35]. Instead, the analysis of only renewable sources can be found in [36] [37] [38]. In Europe, a similar study on multi-family buildings was performed in Portugal: building envelope and energy systems efficiency measures were also considered in this case [39].

Examples of sequential multi-step optimization methods can also be found for multi-family buildings: in Finland, Niemela et al. [40] used this approach to perform many simulations, for a fixed energy systems, in order to study the behavior of the building envelope and renewable sources parameters. In Italy, Zacà et al. [41] hypothesize several energy efficiency measures for a multi-family building including the building envelope, energy systems and renewable sources. For the energy simulation, the software ProCasaClima was used, but the optimization process was carried out manually without using an optimization tool.

The above cited studies rely on sequential approaches, either focusing only on energy demand or supply, either considering energy demand and supply in different steps. In this work the potential of an integrated optimization of energy demand and supply will be demonstrated.

1.3 Objectives – aim of the present study

Based on previous considerations, the aim of the present work is to investigate the possibilities offered using simulation-based optimization methods for the integrated optimization of a multi-family building in the Italian context, towards the NZEB objective.

This work aims to highlight the results achievable by adopting an integrated approach that provides the simultaneous optimization of energy demand and supply, determined by the optimal combination of parameters related to the building envelope, the energy systems and the renewable sources. Moreover, since it has been demonstrated that the optimal solution is highly sensitive to the problem uncertainty, such as simulation accuracy [42], cost estimations and financial assumptions [43], it is necessary to find easy-to-use methods to perform robustness analysis on the results while maintaining the calculation manageable.

Based on the aforementioned considerations, the objectives of this study can be summarized as follows:

- identification and definition of the energy efficiency measures related to envelope, systems and RES applied to the multi-family building design problem;
- setup of an EDeSSOpt (Energy Demand and Supply Simultaneous Optimization) framework for the solution of the problem;
- identification of the design solutions that lead to the lowest global cost for the multi-family building typology in the Italian context;
- analysis of the solution stability and the algorithm efficiency through the study of the optimal solution neighborhood;
- comparison between results obtained from the integrated approach and those obtained using a traditional sequential approach.

In this work, TRNSYS as the building dynamic simulation programme and GenOpt as the optimization engine have been coupled in order to create a framework able to support the integrated and cost-effective NZEB design.

2. The EDeSSOpt methodology

The methodology framework proposed in this study consists in the simultaneous assessment and optimization of both the energy demand and supply, that is the main novelty with respect to the state of the art.

It is expected that this approach, if compared to more traditional operative procedures, is particularly suitable when it is necessary to analyze and optimize with a careful balance between conflicting requirements (i.e. heating and cooling). In fact, an optimization process structured into two/three consecutive phases, can lead to a situation where a reduction for a certain energy demand (i.e. heating energy) may cause, at the same time, an increase of energy demand for other uses, thus frustrating positive effects on the overall energy consumption of the building.

Through the proposed EDeSSOpt (Energy Demand and Supply Simultaneous Optimization) method, it is possible, for example, to determine whether it is more convenient to increase the thermal insulation layer of the building envelope rather than the option of using electricity produced by PV panels, based on the minimization of costs calculated over the medium-long term.

The main phases of the *EDeSSOpt method* are described in the following sections. Here below some preliminary definitions for correct interpretation of these sections.

- Optimization: the procedure by means of which one tries to find the best possible values for a set of variables (decision variables) of a system, while satisfying various constraints [44], in order to maximize or minimize a certain system output (objective function);
- Decision parameter: also known as design variable, optimization variable or optimization parameter, denote a component of the system that is able to affect system performance, expressed by the optimization objective function, through the variation of its value (see def. parameter value);
- Environment parameters: create the scenario in which the optimization is performed;
- Parameter value: one of the alternatives that have been defined for that specific parameter in a range of variation. Such value may directly represent a physical property (e.g. thickness of a layer, thermal transmittance of a glass) or it may be the name of the alternatives (e.g. the decision variable "heating system" has two values: value "1" refers to a gas condensing boiler, value "2" refers to a heat pump);
- Design option (solution): a combination of parameter values (one value for each decision parameter);

- Design space: the set of all the possible design options, depending on the set of decision parameters and the range of parameter values;
- Objective function: the optimization objective, which is computed as a function of the set of parameter values (see section 2.2.2).

2.1 Pre-processing phase

Input parameters for a generic system optimization can be divided in two categories: environment parameters and decision parameters, as shown in Figure 1.

In case of building optimization problems, environment parameters usually include hourly or annual profiles of weather conditions, market characteristics such as cost evolution of materials and technologies or energy prices and available technologies in the project location. Although these parameters may have a great impact on system performance, these cannot be controlled by the system designer, but they must be considered as boundary conditions that create the scenario in which the optimization is performed.

Decision parameters constitute the main input to the system to be optimized, shaping the features of the optimization problem itself. The decision parameters related to the building envelope (defined as "passive" parameters) mostly affect the building performance in terms of passive reduction of energy needs. They may refer to the construction of the opaque envelope, in terms of material and thickness of each layer and/or or wall packages alternatives, and to the type and dimension of window packages (glass ad frame). The so-called "active parameters" instead, are related to the energy system and RES, thus affecting the building energy performance from the supply side.

All the decision parameters should be selected according to their availability on the market and should be optimized to the order of their variability on the market [45].

For instance, the range of variation associated with the insulation thickness of opaque components can generally vary with a step of 1-2 cm, considering the construction feasibility and the linked energy enhancements. Similar considerations apply to the selection of window types, as it is necessary to consider the standard (and marketed) dimension of modular glass panels in addition to the correspondent visual and thermal properties that cannot be optimized as independent one from each other. Concerning technical systems, under the same assumptions, multiple alternatives can be assessed estimating the investment, maintenance and replacement costs as well as related energy costs.

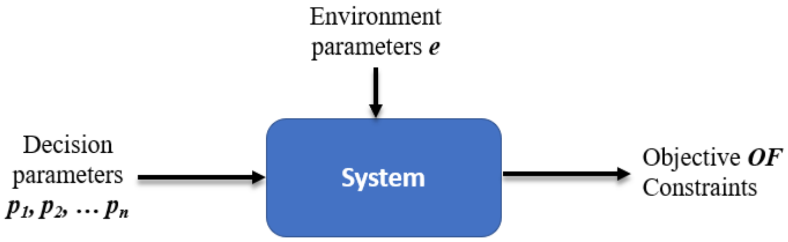


Figure 1: Inputs and outputs for a system optimization.

2.1.1 Modelling framework

The EDeSSOpt method is a simulation-based optimization method (SBOM); this require a coupling between a dynamic energy simulation tool (TRNSYS) and an optimization tool (GenOpt).

In order that the design optimization is automated, the building dynamic energy model itself has to be properly designed since the beginning of the model conception, so that the model components (the "types "in TRNSYS) are ready to be controlled by decision parameters and therefore linked to the optimizer.

If the passive decision parameters are quite easy to set up (e.g. insulation thickness can be inputed by just changing one value in the model input file), it is not easy to implement a single model which considers more than one technical systems configurations. This is the reason why in most studies concerning simulation-based optimization methods applied to NZEB design a sequential approach is adopted rather than an integrated one [6].

In fact, technical systems are often composed of multiple types (generator, pipes, terminals, controllers,...) working together. Designing a model that is ready to properly simulate either an air to air heat pump or a gas boiler with radiators within the same optimization run entails creating a control center. Such center has to be able, based on the decision parameter values selected by the optimization algorithm at each iteration, to switch on or off the all types and settings related to the one or the other system.

The proposed method has been set up thanks to the modular structure offered by the TRNSYS® simulation software and its possibility to define a large set of boolean variables within its environment and is represented in Figure 2.

First of all, it is necessary to define how many options k_i for each technical system must be included during the optimization process. It is important to remark that there is usually one set of k_i options for each energy use or RES, as there may be different design options for both the heating and the cooling systems, as well as for the solar thermal or PV system. Each k_i is included in the range of variation of the value of one active decision parameter (see section 2.1.2).

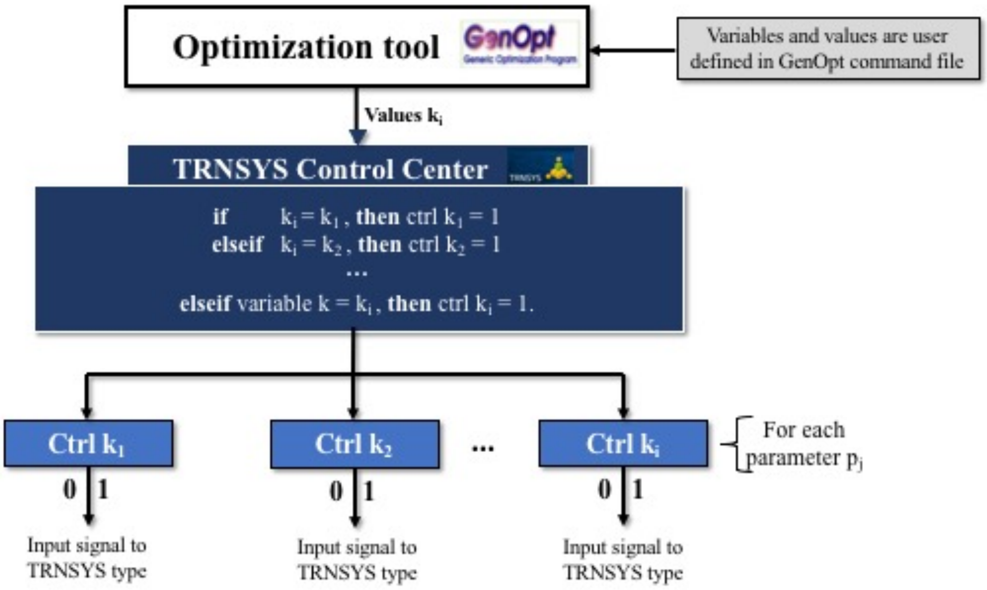


Figure 2: Definition of boolean variables during the pre-processing phase.

As shown in Figure 2, the optimization tool is the first control, which sends parameter values k_i to the control center of TRNSYS at the beginning of each simulation. Here, several boolean statements are defined: these strings read values sent by the optimization tool and give back a value equal to 0 or 1. Then, the control center sends these values to system components: if a component (e.g. a boiler) receives an input value equal to zero, it will be switched-off and viceversa, together with all the types linked to that component. In this way, all the possible configurations of the plant are included in the same model, but, at each simulation, only one configuration is functioning depending on the values assumed by these discrete control variables.

2.1.2 Optimization problem

The total set of possible design options is the n-dimensional space defined by the **P** set of n user-defined decision parameters p_j. The set **P** includes both the subset of parameters related to building envelope and the one related to energy systems and renewable sources. As mentioned in section 2.1.1, $k_i(p_j)$ indicates a value assumed by the decision parameter p_j in a design solution S. S_{OPT} indicates the set of parameters values k_{OPT} assigned to each decision parameter p_j in the optimal solution. Since each p_j corresponds to a real feature of the building, it is necessary to define a range of variation for each parameter value in order to avoid non-feasible configurations of the building. Each range of variation has a lower bound $k_{i,min}$ and an upper bound $k_{i,max}$ among which the value k_i of decision parameter p_j can vary during the optimization process.

Considering that each decision parameter p can influence the objective function OF, the optimization problem can be formulated as follows:

Find $S_{OPT}=\{k_{OPT}(p_j)\}$ $\quad \forall j \in \{1, 2, 3, \dots , n\}$

such that minimize $OF = f(\mathbf{P})$

where

$\mathbf{P} = \{p_1, p_2,\dots, p_j, \dots , p_n\} \subset \mathbb{Q}^n$

subject to

$k_{i,min}(p_j) \leq k_{OPT}(p_j) \leq k_{i,max}(p_j) \qquad \forall j \in \{1, 2, 3, \dots , n\}, \forall i \in \{i_{min}, \dots, i, \dots , i_{max}\}$

where the objective function OF is the global cost function.

2.2 Optimization phase

2.2.1 Optimization algorithm

The optimization is the core-phase of the entire process. In this work, the GenOpt®software was used, since it is a numerical optimization software by means of which it is possible to minimize an objective function calculated by an external simulation software (TRNSYS). However, other similar tools may be used within the same methodology.

Prior to this, it is essential to declare the optimization variables (using the proper syntax required by the software itself) together with their variability range. In addition to this, in order to succeed in the optimization, it is fundamental to choose the most suitable optimization algorithm among those available in the GenOpt environment. Some of them better deal with problems in the continuous domain whereas others are more suited to discrete variable problems. Since, as it has already been said, the present study deals with the optimization of building constructive elements and systems, the investigation of variables in the continuous space is impossible because the market offers only some measures and dimensions, thus handling discrete values.

In light of this consideration, the Particle Swarm Optimization (PSO) algorithm [46] was selected, given its robustness and efficiency in converging towards the global minimum [47]

[7]. PSO algorithm is a population-based evolutionary heuristic search method. Briefly, this algorithm evaluates starting solutions (to an optimization problem) and, based on the obtained objective function values, by recombining the set of parameter values and introducing elements of disorder is able to generate new solutions in an attempt to converge towards optimal results, according to a specified selection logic [45].

As a result of that, the process of optimization can be graphically summarized in Figure 3. For each iteration, GenOpt assigns a set of values *k* to decision parameters *p*, to be entered to TRNSYS, which performs the energy simulation and calculates the value of the objective function. Based on the so-calculated value of the objective function and the selected optimization algorithm, the optimization software then selects another set of values to be assigned to variables, in order to perform a further simulation and objective function calculation. This iterative cycle ends when the stopping criterion is met. GenOpt then registers the value assumed by each of the optimization variables at each run together with the correspondent objective function value.

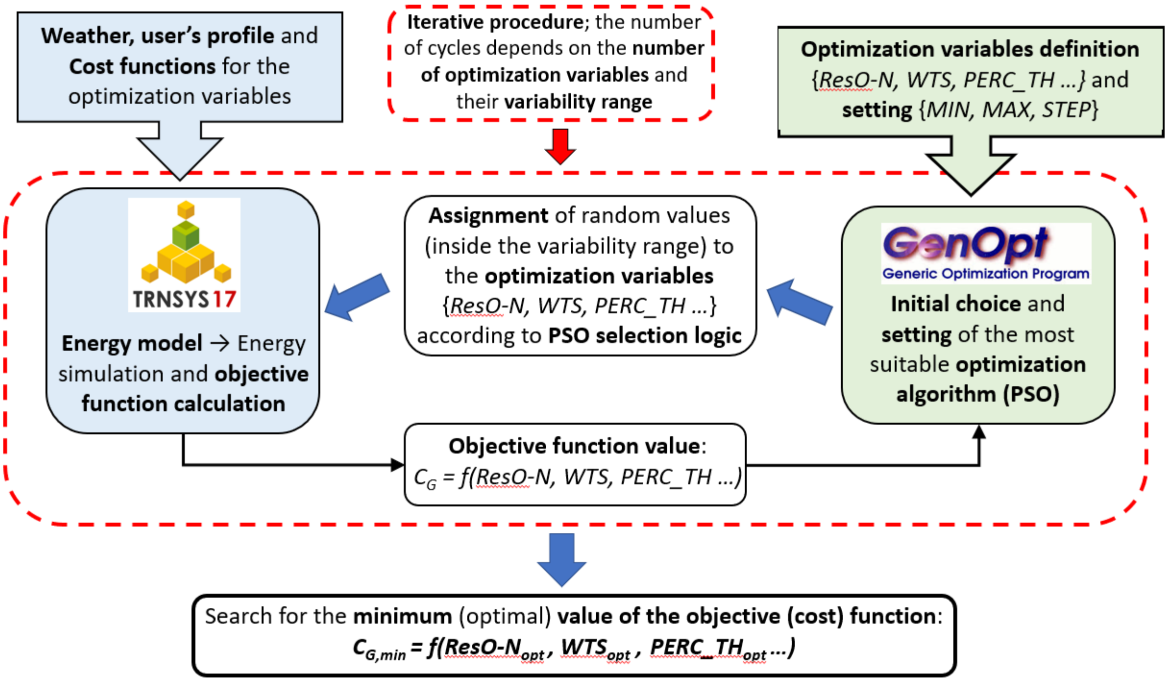


Figure 3: EDeSSOpt methodology framework.

2.2.2 Objective functions

2.2.2.1 Financial - Global cost function

The global cost function is the primary objective function of this study. It is calculated according to the European Standard EN 15459 [48], published by CEN (European Committee for Standardization). This is a standard method which allows energy systems inside buildings to be analyzed from the financial point of view. Equation (1) reports the general form of the global cost function: it includes investment cost CI of each energy-related component *j* of the building systems and annual costs C_a needed for their correct operation, maintenance and replacement during the calculation period τ, assumed to be equal to 30 years. The negative term of the equation indicates the possibility to have a residual economic value of a component at the end of the calculation period.

$$C_G(\tau) = \sum_j [CI(j) + \sum_{i=1}^{\tau} \left(C_a(j) * R_d(i)\right) - V_{f,\tau}(j)] \tag{1}$$

The discount rate $R_d(i)$ is used to refer replacement costs to the starting year of calculation. If annual costs must be considered for all the years of the calculation period, as in the case of the running costs for energy or maintenance costs, it is possible to multiply the annual cost for the present value factor f_{pv}. Definitions of the discount rate and of the present value factor are the same used in [7].

2.2.2.2 Secondary functions

In addition to the global cost function, whose minimization is the first goal of the study, some energy objective functions can be calculated at each simulation to measure the energy performances of the building. The net annual heating demand $Q_{H,nd}$ and net annual cooling demand $Q_{C,nd}$ vary according to the building parameters considered in each simulation; these values are extracted directly from TRNSYS simulations. These four indices are expressed in kWh per square meter of net floor area. The domestic hot water demand $Q_{DHW,nd}$ and the electrical demand $Q_{El,nd}$ are fixed and calculated according to Standards [49] and [50], respectively.

Moreover, the primary energy consumed by the building is calculated using conversion factors defined in the Italian standard [51]; both the total primary energy EP_{tot} and the non-renewable primary energy EP_{nren} are calculated and expressed in kWh/m^2, as for the previous indices.

2.3 Post-processing phase

The post-processing phase ends the optimization process. At this stage of the procedure, it is necessary to analyze the space of solutions obtained by means of the energy simulation model and identify the optimal configuration of the building and systems.

The output file contains, for each design option that is explored during the optimization process, the value of the objective function, the related set of decision parameters and the values of other secondary functions defined by the user. Within the purpose of this study, these functions could be the heating and cooling demand deriving from that specified design parameters combination or relative consumption of primary energy.

Besides the optimal point, also the neighborhood of the optimal solution is analyzed, according to the principle that, within a building design problem, the exploration of the design space is as much important as finding the optimal solution. The study of the optimum neighborhood should be performed aiming at

1. looking for possible solutions that are close to the optimum value of the primary objective function and have at the same time better values of the secondary functions with respect those of the optimal one (i.e. slightly higher global cost, but lower primary energy consumption);
2. checking the behavior of the algorithm and monitoring the robustness of the resulted optimal solution.

To identify the optimum neighborhood, a threshold percentage can be fixed in order to consider only design options in a limited range of variation of the objective function value.

3. Application to a multi-family building

3.1 The case study building

The case study building is a residential complex located in Cremona, in Lombardia region. It was built in 2014 and it is a social housing construction, a new habitation type that is expanding in the last few years which has the goal to guarantee residential benefits and social integration at relative low cost.

The complex is composed of five buildings (Figure 4) which includes 98 apartments for a total of approximately 7950 m^2 of net floor area. The part analyzed in this study is the South portion of the complex (from here on defined only as “building”), composed by building number 1 and number 2. This part includes 35 apartments for a total of 2460 m^2 of net floor area and 6600 m^3 of gross volume heated. The study of this building is interesting because it has a large façade facing South which allows to maximize solar gains during the cold season and reduce them in summer thanks to external projections. Moreover, the South oriented pitched roof is optimal for the installation of solar renewable sources; the available area is almost 400 m^2.

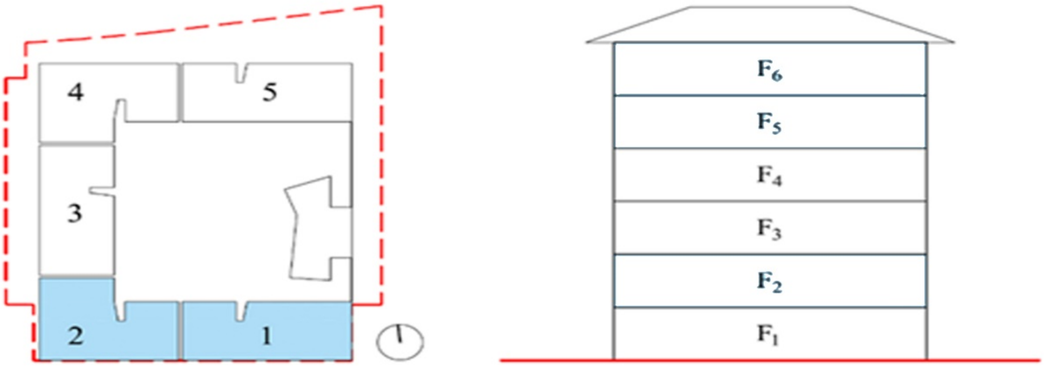


Figure 4: Disposition of buildings in the residential complex and section of the analyzed part.

The building has six floors: at the first floor (F1) there are commercial activities and meeting places, while the other floors (F2-F6) are for residential use, except for a part of the sixth floor that is used as non-heated storage space. Floors plans are reported in Figure 5-7.

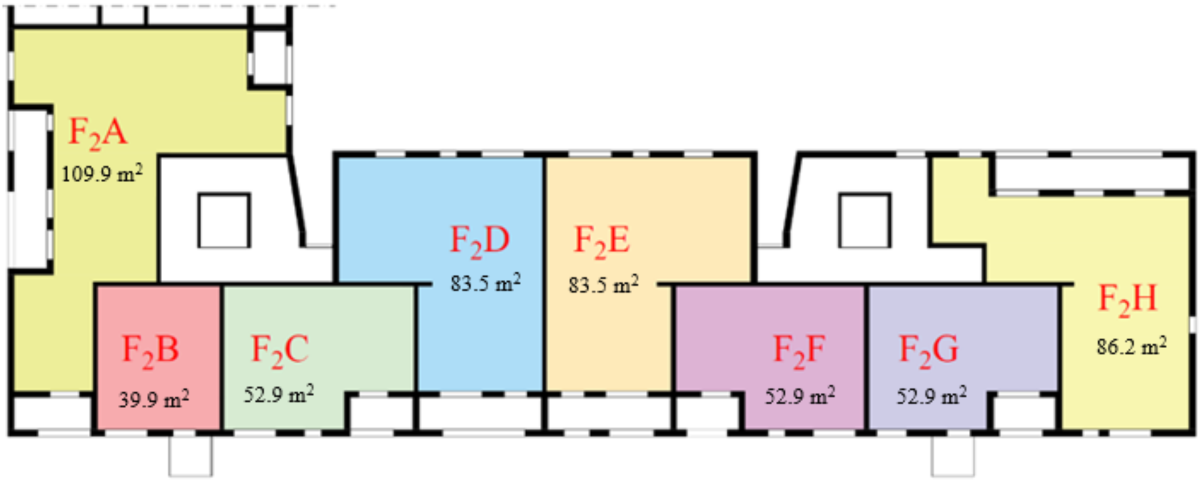


Figure 5: Plan of floors F2 to F4.

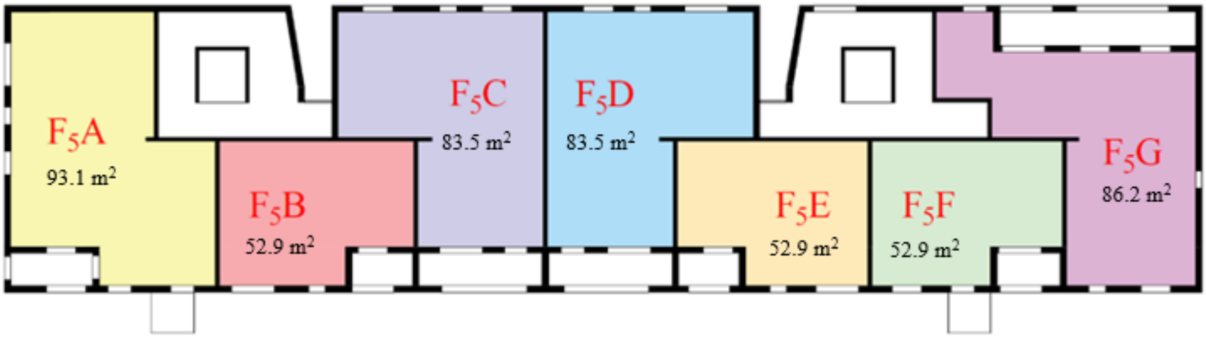


Figure 6: Plan of floor F5.

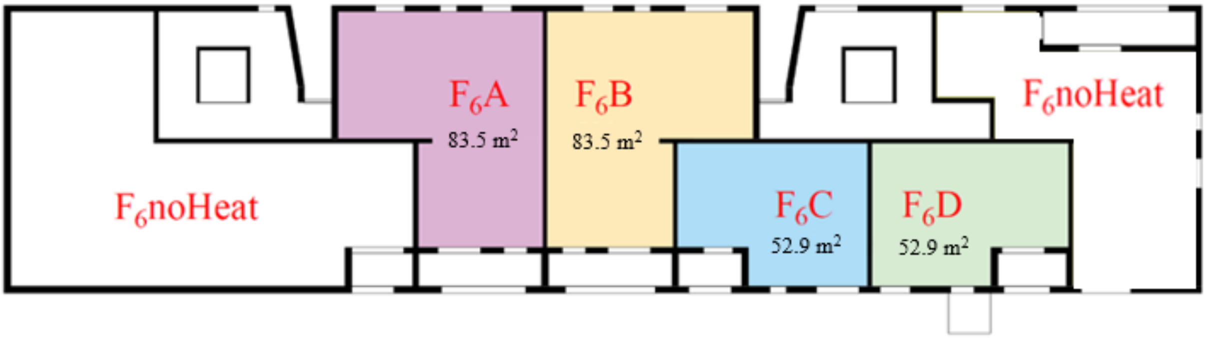


Figure 7: Plan of floor F6.

In the current design configuration, the opaque envelope of the building is made of reinforced concrete and bricks with external insulation (U=0.26 W/m^{2}K). Transparent components are characterized by low-e double pane windows with metal frame (U_W=1.45 W/m^{2}K, g-value=0.59, data obtained from manufacturer).

The heating and domestic hot water demands are satisfied by the district heating network of the city, whereas cooling equipment are not designed. A mechanical ventilation system with heat recovery (efficiency 50%) is installed in the building. Renewable sources were not included in the current design of the building.

Under the described design configuration, the net heating energy demand is equal to 23.02 kWh/m^2 (calculated using a dynamic simulation tool considering a set point temperature equal to 20°C). Even if cooling equipment are not present in the building, the net cooling energy demand is calculated using TRNSYS and it is equal to 12.11 kWh/m^2. The domestic hot water demand and the electricity demand for lighting, calculated with standards [49] and [50], are 18.9 kWh/m^2 and 22.74 kWh/m^2, respectively.

According to the energy performance certificate, based on Italian regulation [52], the current building design is classified under class A1.

In this study different configurations of the building envelope, technical system and renewable sources are proposed, whereas the mechanical ventilation system is not an objective of optimization. To do this, the possibility to redesign both the building envelope and the energy systems is hypothesized, in order to find which is the best configuration that minimize the global cost of the building in a lifespan of several years and verify if the proposed methodology is effective to find potential solutions leading to improve the performance of the current design.

The process is structured around three optimization runs:

1) The first run concerns building envelope optimization (passive parameters). In this phase, energy systems are fixed and those indicated in DM 26/06/2015 [52] for the Italian reference building are considered.
2) The second run concerns energy systems and RES optimization (active parameters). In this phase, the optimal building envelope obtained from the previous simulation is fixed.
3) The third run concerns the integrated optimization of both the building envelope and the energy systems, following the EDeSSOpt methodology.

This allows the results obtained by EDeSSOpt to be compared to those obtained by a sequential approach.

The simulation time for the so-created building energy model is 256 s (Intel® Core™ i7-4770 – 3.4 GHz, 8 MB cache, 4 core - HD 4600), eight simulation runs can be performed in parallel. The computation time depends on the number of simulations performed within the same optimization run until the maximum number of generations is reached. According to the results of the study on the PSO algorithm performance reported in [45], the number of particles was set to 20 and the number of generation was set to 100, leading to 2000 iterations for each optimization run. However, within the same optimization run, the algorithm may lead to the same design option in different iterations. The different design spaces in which the optimization is conducted in the three runs led to a different number of analyzed design options and a related computation time of 5 h 14’ for the first run (582 simulations), 4 h 21’ for the second run (486 simulations), 15 h 51’ for the third run (1795 simulations).

3.2 Decision parameters

As mentioned, passive parameters are referred to opaque and transparent components of the building envelope. Some parameters refer to the thickness of insulation of the roof (ResR), of the external walls (ResO-N for walls facing North and ResO-EWS for other orientations) and of the floor of the first level (Res2), as shown in Table 1. Note that the insulation thickness is expressed with the unit of measure of the thermal resistance ($(m^2K)/W$), considering that the has a thermal conductivity of the insulation material is 0.033 W/(mK) for the roof and 0.035 W/(mK) for external walls.

For transparent components, five types of windows are considered, as reported in Table 2. Three decision parameters control the type of windows in different orientation: North (WTN), South (WTS) or East/West (WTEW). Another parameter (WFactor) considers the possibility to reduce or increment glazing areas by a quote of ±20% with respect to current design. Percentages of the window area reduction factor are calculated in order to maintain adequate values of the daylight factor in ambient.

Table 1: Opaque envelope variables.

Parameter	Insulation thickness [cm]	Step [cm]	Res min [(m^{2}K)/W]	Res max [(m^{2}K)/W]
ResR	4-20	2	1.212	6.061
Res2	4-20	2	1.143	5.714
ResO-N	4-20	2	1.143	5.714
ResO-EWS	4-20	2	1.143	5.714

Table 2: Transparent envelope variables (data from TRNSYS library and [53]).

Variable	Window type	Description	Composition	U_W [W/(m^{2}K)]	g-value
WTN WTS WTEW	1	Double glazing, w/o Argon	4/16/4	2.83	0.755
	2	Double glazing, low-E, with Argon	4/15/4	1.1	0.609
	3	Double glazing, low-E and solar control, with Argon	6/16/6	1.29	0.333
	4	Triple glazing, low-E and solar control, with Argon	6/12/4/12/4	0.7	0.294
	5	Triple glazing, low-E, with Argon	4/16/4/16/4	0.7	0.501

Active decision parameters (Table 3) include the choice of generators (T-Gen), terminals (T-Ter), auxiliary heaters for domestic hot water (T-Aux), photovoltaic panels type (T-PV), dimension of water storage (Dim-WS) and quantity of renewable sources installed in the building (Perc-PV for photovoltaic system and Perc-TH for solar thermal system). These last two variables indicate the percentage of available roof area occupied by the photovoltaic system and the solar thermal system respectively.

The control network represented in Figure 8 is used for active parameters commanded by a boolean statement. Moreover, string controls are written in order to avoid non-optimal combinations between generators and terminals; for example, the coupling between heat pump and radiators is discarded because it would not be implemented in the reality due to its low efficiency. Other parameters, controlling the size of water storage (Dim-WS) and the percentage of roof area that is covered by PV and thermal solar collectors (Perc-PV and Perc-TH) are defined as discrete variables varying within a defined range. In case the parameter values assigned by the algorithm to the percentage of renewable sources exceeds 100% of the available roof area (the sum of the value of Perc-PV and the value of Perc-TH is greater than 100%), quantities are scaled down preserving their ratio. It is important to underline that the model is structured so that the choice of terminals installed in ambient influences the fluid operating temperatures of the energy generators, so that it is possible to model the operation and the performance of generators as a function of heating and cooling terminals.

Table 3: Technical system variables.

Component	Value	Description
T-Gen	1	Water source heat pump (HP)
	2	Traditional boiler (TB) + Air cooled chiller (ACC)
	3	Condensing boiler (CB) + Air cooled chiller (ACC)
	4	Traditional boiler (TB) + Water cooled chiller (WCC)
	5	Condensing boiler (CB) + Water cooled chiller (WCC)
T-Ter	1	Radiators
	2	Fan-coils
	3	Radiant panels
T-Aux	1	Gas
	2	Electric
T-PV	1	Polycrystalline
	2	Monocrystalline
	Interval	Step
Perc-PV	0-100%	5%
Perc-TH	0-100%	5%
Dim-WS	50-100 l/m^2	25 l/m^2

Figure 8: Control network for variables of technical system controlled by boolean statements.

In summary, given the entire defined set of decision parameters, the optimization problem has a 15-dimensional design space that is composed of $3 \cdot 10^{11}$ different design options. This underlines the importance of using an optimization algorithm to explore the design space and drive the search towards the optimum neighborhood.

3.3 Financial assumptions

As mentioned, the global cost objective function includes investment, maintenance and replacement costs of all the components involved in simulations [48]. For envelope components, only the initial investment cost is considered because we can assume they work for the entire life of the building. On the contrary, maintenance and replacement costs must be taken into account when we consider components of the technical system. According to Standard EN 15459 [48], annual maintenance costs are calculated as a percentage of investment cost of components. Replacement costs are calculated based on the investment cost depending on the component lifetime, which is set as defined in the same Standard.

Since at each iteration design parameters assume different values and consequently investment costs change, initial investment costs are evaluated through functions having a decision parameter involved in simulations as independent variable. These cost functions were built according to the price list of the city of Milan for year 2017 [53] and comprehend both the supply and the installation of components.

Concerning cost functions related to the transparent envelope, the windows area is the independent variable; costs per unit of area are reported in Table 4.

Table 4: Costs of transparent envelope components [53]

Window type	Description	Cost [€/m^2]
1	4/16/4 Double glazing, w/o Argon	166.60
2	4/15/4 Double glazing, low-E, with Argon	179.85
3	6/16/6 Double glazing, low-E and solar control, with Argon	220.81
4	6/12/4/12/4 Triple glazing, low-E and solar control, with Argon	266.41
5	4/16/4/16/4 Triple glazing, low-E, with Argon	217.19

For opaque envelope, thermal resistance of insulation layers is used as independent variable to define corresponding cost functions. Eq. (2) refers to external walls (ResO) and eq. (3) to the roof (ResR).

$$C_{ResO} = 4.97 * ResO + 3.36 \ [€/m^2] \tag{2}$$

$$C_{ResR} = 5.775 * ResR + 2.6 \ [€/m^2] \tag{3}$$

Cost functions of technical system components were created as shown in Figure 9, representing cost function for chillers considered in simulations: points indicate prices available on the price list, lines are the linear interpolation of these points and equations are the real functions considered in calculations of the global cost function.

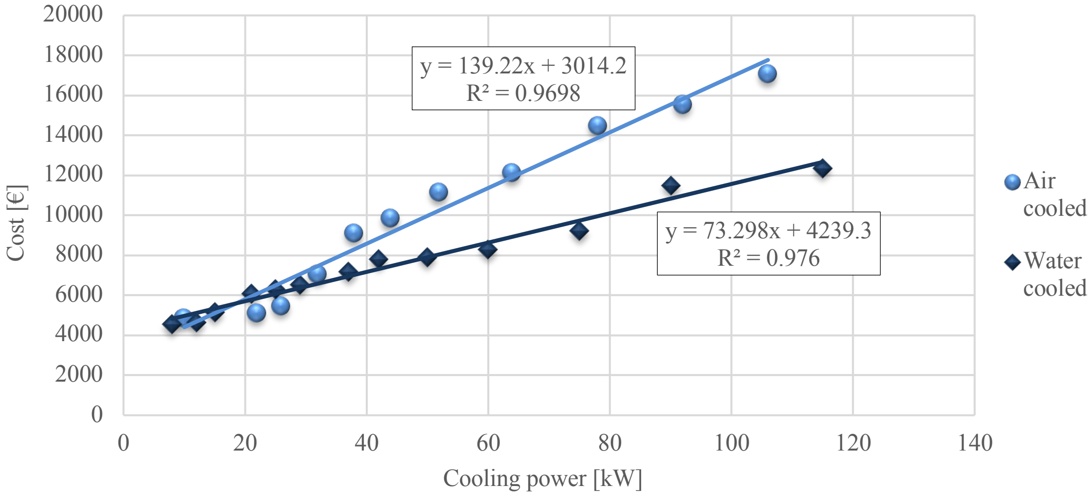


Figure 9: Examples of cost functions for air-cooled and water-cooled chillers.

The same procedure has been followed to build cost functions of other generators of thermal or cooling energy: the thermal capacity P_{th} has been used as independent variable for traditional ($C_{b,t}$ - eq. (4)) and condensing ($C_{b,c}$ - eq. (5)) boiler, whereas cooling capacity P_f has been used for the heat pump (C_{hp} - eq. (6).

$$C_{b,t} = 17.283 * P_{th} + 1282.2 \ \ [€] \tag{4}$$

$$C_{b,c} = 43.515 * P_{th} + 2634 \ \ [€] \tag{5}$$

$$C_{hp} = 579.21 * {P_f}^{0.6535} \ \ [€] \tag{6}$$

For solar thermal collectors, the occupied area is used as independent variable, considering a cost of 520.4 € per square meter of collector installed. The solar thermal system includes also a thermal storage: its cost is calculated as a function of its volume (parameter V_{ts}) expressed in liters, as reported in equation (7) for a thermal storage with a single heat exchanger and in equation (8) for one with two heat exchangers.

$$C_{ts,1hx} = 1.18 * V_{ts} + 1266.7 \ \ [€] \tag{7}$$

$$C_{ts,2hx} = 1.76 * V_{ts} + 1579.8 \ \ [€] \tag{8}$$

The cost of the photovoltaic panels depends on the peak power (P_{max}) of the entire system. Considering that the area of a single module was set to 1.63 m^2 and its peak power was set to 310 W, the cost function of a monocrystalline PV module can be computed as follows:

- 3163.9 €/kWp if $1 \leq P_{max} \leq 6$ [kWp]
- 2760.6 €/kWp if $7 \leq P_{max} \leq 20$ [kWp]
- 2271.5 €/kWp if $21 \leq P_{max} \leq 50$ [kWp]
- 2016.3 €/kWp if $P_{max} > 50$ [kWp]

Based on the analysis of the PV Italian market, the cost of polycrystalline modules is considered to be equal to the 90% of the monocrystalline one [53].

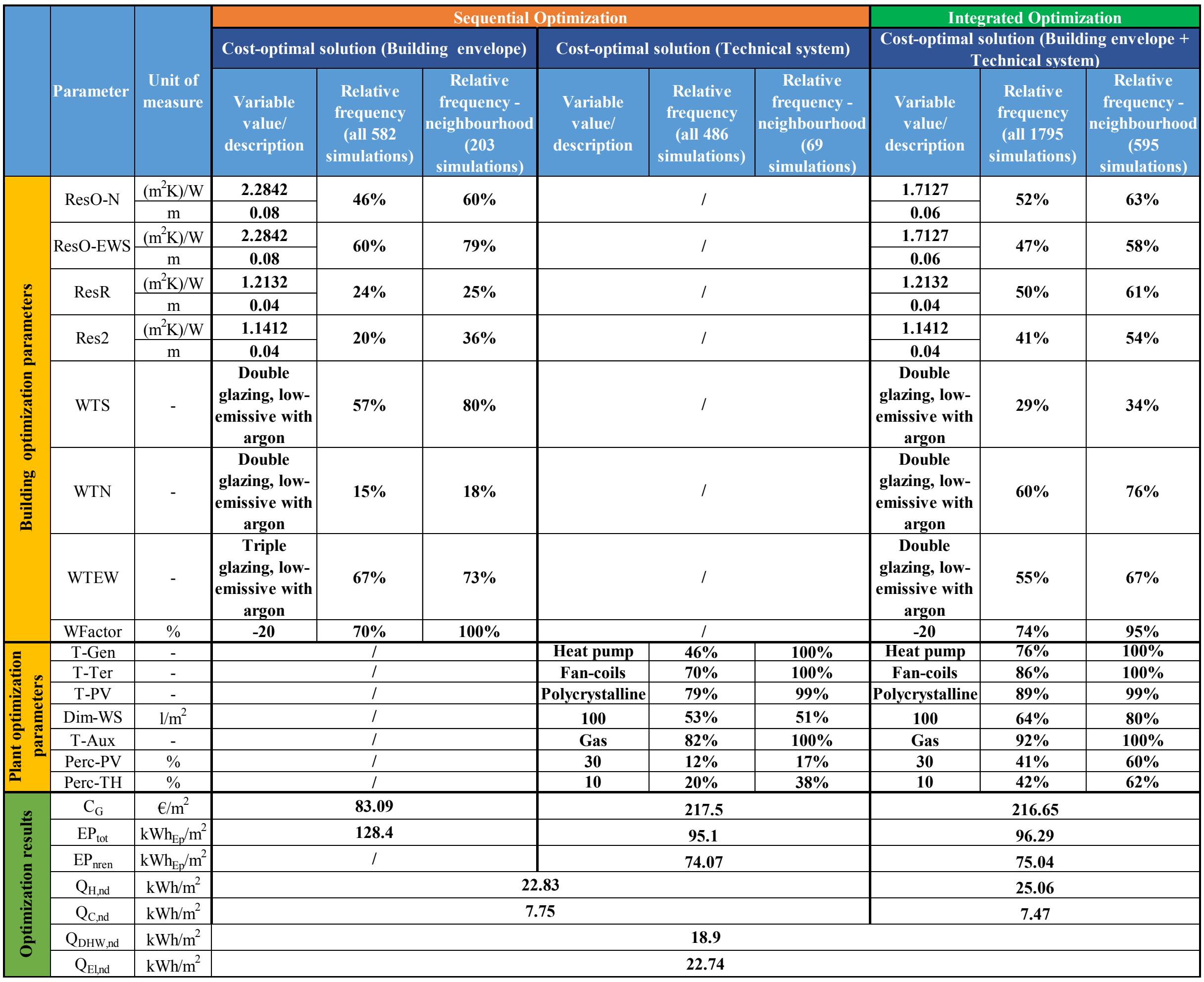
To complete the calculation of the global cost, energy costs have to be calculated. For both the natural gas and electricity energy vectors, prices suggested by the Italian authority ARERA have been used [54]. The cost of a standard cubic meter of natural gas was assumed to be equal to 0.6716 €/Smc and the cost of electric energy to 0.1888 €/kWh (mean constant value). Moreover, prices of electricity produced by photovoltaic panels and sold to the grid are considered; monthly values suggested by the Italian authority GSE have been used (max 0.084 €/kWh in January – min 0.039 €/kWh in June).

4. Results and discussion

In this section, results of optimization runs are presented, both for the sequential approach (sections 4.1 and 4.2) and for the integrated approach (section 4.3).

An overview on the results of the three simulations are presented in Figure 10. In the first column of each vertical section (named "variable value/description), parameter values corresponding to the optimal solution are reported. The percentages reported in the second and third columns of each section indicate the occurrence frequency of the optimal value within the set of design options that were analyzed throughout the optimization run. The first refers to the entire set of design options that were simulated in the optimization process, indicating the occurrence frequency of that parameter value, the second is referred to all simulations in the neighborhood of the optimal solution, indicating the occurrence frequency of that parameter value in design options that are close to the optimum. These values give an idea of the robustness of the solution: in fact, the higher occurrence frequency, the higher robustness of that optimal values, given that the algorithm considers that value as very important to reach the optimum region and that the parameter value occurs in the greatest part of the design options included in the optimum neighborhood.

Values of the primary objective function (global cost function) and values of secondary energy functions corresponding to the optimal design solution are reported in the last rows of the figure (horizontal section called "optimization results").



	Parameter	Unit of measure	Sequential Optimization						Integrated Optimization		
			Cost-optimal solution (Building envelope)			Cost-optimal solution (Technical system)			Cost-optimal solution (Building envelope + Technical system)		
			Variable value/ description	Relative frequency (all 582 simulations)	Relative frequency - neighbourhood (203 simulations)	Variable value/ description	Relative frequency (all 486 simulations)	Relative frequency - neighbourhood (69 simulations)	Variable value/ description	Relative frequency (all 1795 simulations)	Relative frequency - neighbourhood (595 simulations)
Building optimization parameters	ResO-N	$(m^2K)/W$	2.2842	46%	60%	/			1.7127	52%	63%
		m	0.08						0.06		
	ResO-EWS	$(m^2K)/W$	2.2842	60%	79%	/			1.7127	47%	58%
		m	0.08						0.06		
	ResR	$(m^2K)/W$	1.2132	24%	25%	/			1.2132	50%	61%
		m	0.04						0.04		
	Res2	$(m^2K)/W$	1.1412	20%	36%	/			1.1412	41%	54%
		m	0.04						0.04		
	WTS	-	Double glazing, low-emissive with argon	57%	80%	/			Double glazing, low-emissive with argon	29%	34%
	WTN	-	Double glazing, low-emissive with argon	15%	18%	/			Double glazing, low-emissive with argon	60%	76%
	WTEW	-	Triple glazing, low-emissive with argon	67%	73%	/			Double glazing, low-emissive with argon	55%	67%
	WFactor	%	-20	70%	100%	/			-20	74%	95%
Plant optimization parameters	T-Gen	-	/			Heat pump	46%	100%	Heat pump	76%	100%
	T-Ter	-	/			Fan-coils	70%	100%	Fan-coils	86%	100%
	T-PV	-	/			Polycrystalline	79%	99%	Polycrystalline	89%	99%
	Dim-WS	l/m^2	/			100	53%	51%	100	64%	80%
	T-Aux	-	/			Gas	82%	100%	Gas	92%	100%
	Perc-PV	%	/			30	12%	17%	30	41%	60%
	Perc-TH	%	/			10	20%	38%	10	42%	62%
Optimization results	C_G	$€/m^2$	83.09			217.5			216.65		
	EP_{tot}	kWh_{Ep}/m^2	128.4			95.1			96.29		
	EP_{nren}	kWh_{Ep}/m^2	/			74.07			75.04		
	$Q_{H,nd}$	kWh/m^2	22.83						25.06		
	$Q_{C,nd}$	kWh/m^2	7.75						7.47		
	$Q_{DHW,nd}$	kWh/m^2	18.9								
	$Q_{El,nd}$	kWh/m^2	22.74								

Figure 10: Results of sequential and integrated optimization: global cost (C_G, Eq. (1)), total and non-renewable primary energy demand (EP_{tot} and EP_{nren}, respectively), net energy demand for heating ($Q_{H,nd}$), cooling ($Q_{C,nd}$), DHW ($Q_{DHW,nd}$) and electricity ($Q_{El,nd}$ – see section 2.2.2.2). For a correct interpretation of building optimization parameters see tables 1 and 2, for plant optimization parameters see table 3.

4.1 Sequential approach, first step: building envelope optimization

The first section of Figure 10 refers to the building envelope optimization. Results show that the adequate insulation of external vertical walls is more important than insulating horizontal surfaces such as the roof. This is because in a multi-family building the vertical walls have a much larger area than horizontal ones with respect to a single-family house, and the heat transfer through those walls have a greater impact on heating and cooling demand of the building.

Anyway, the optimal solution is far from a super-insulated envelope because this would increase the cooling demand more than the benefit obtained by the further heating demand reduction.

Concerning transparent components, double glazing windows are the optimal solutions for North and South orientations, whereas triple glazing windows are selected for East and West orientations. Also in this case, the global cost is minimized without the most efficient components. Triple glazing windows are selected for East and West orientations because this glazing area is much smaller than the one facing South and North, meaning that the higher cost of these windows slightly influences the total global cost while effectively improving the energy performance. The optimal window area reduction factor results to be equal to -20%.

In this optimal configuration, the net heating energy demand $Q_{H,nd}$ and the net cooling energy demand $Q_{C,nd}$ are equal to 22.83 kWh/m^2 and 7.75 kWh/m^2 respectively; these values are 1% and 36% lower than those of the initial configuration of the building, demonstrating that it is possible to further reduce the energy demand while reducing global cost. The corresponding consumption in terms of primary energy is very high because at this stage technical systems have not yet been modeled and references values of generators efficiencies are used to compute EP_{tot}.

The cost optimal cloud representing all the design options explored by the optimization algorithm is reported in Figure 11. Each point of the cloud corresponds to a different design option generated by a different combination of parameter values. In addition to the point with the minimum global cost (green dot), also the extreme points representing the maximum value of global cost and points with minimum and maximum values of total primary energy consumption are highlighted. Blue points represent design options located in the 3.5% neighborhood of the optimum. Within the optimum neighborhood, it is possible to find solutions to design a building that is more efficient from energy point of view with a small increase of global cost.

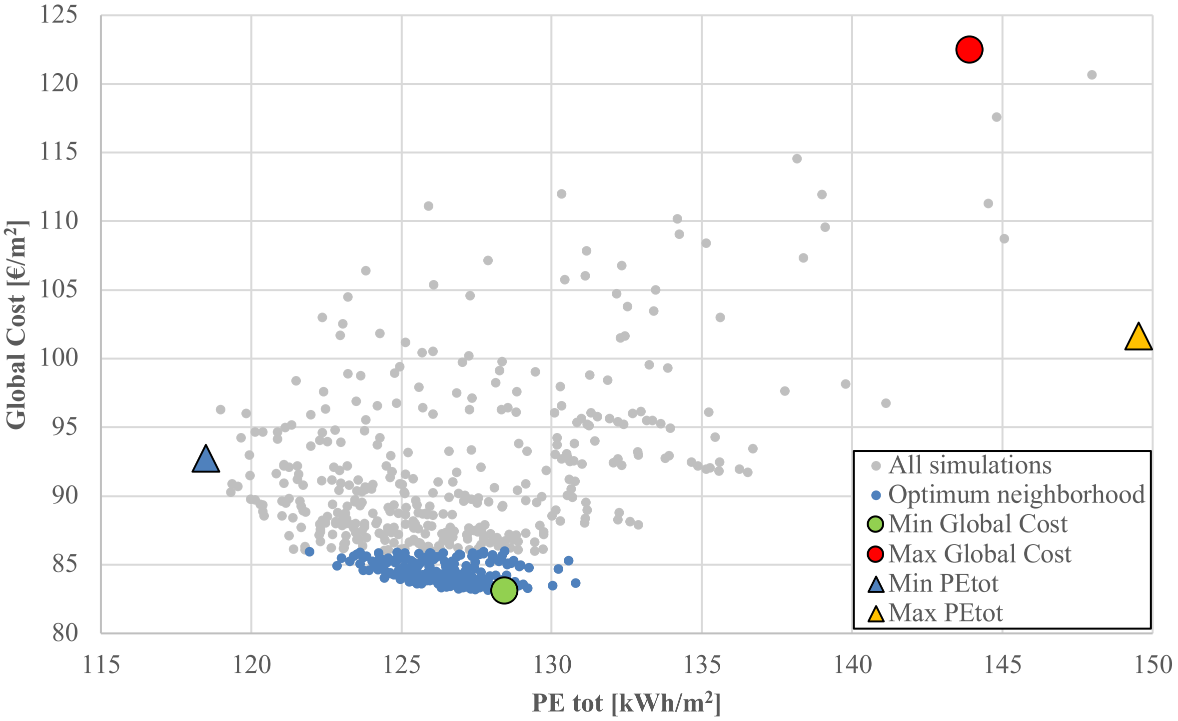


Figure 11: Cost optimal cloud: sequential approach - building envelope optimization.

Each point of the cost optimal cloud corresponds to a colored profile represented in Figure 12. This is a diagram which has the decision parameters of the optimization problem as polar axes; for axes regarding the insulation thicknesses, the minimum and the maximum points correspond to the minimum and maximum value that those variables can assume (4-20 cm). Transparent component axes are ordered considering an increasing energy performance of windows (1=single glazing; 5=triple glazing); finally, the window factor axis is normally ordered from the minimum to the maximum value that this variable can assume.

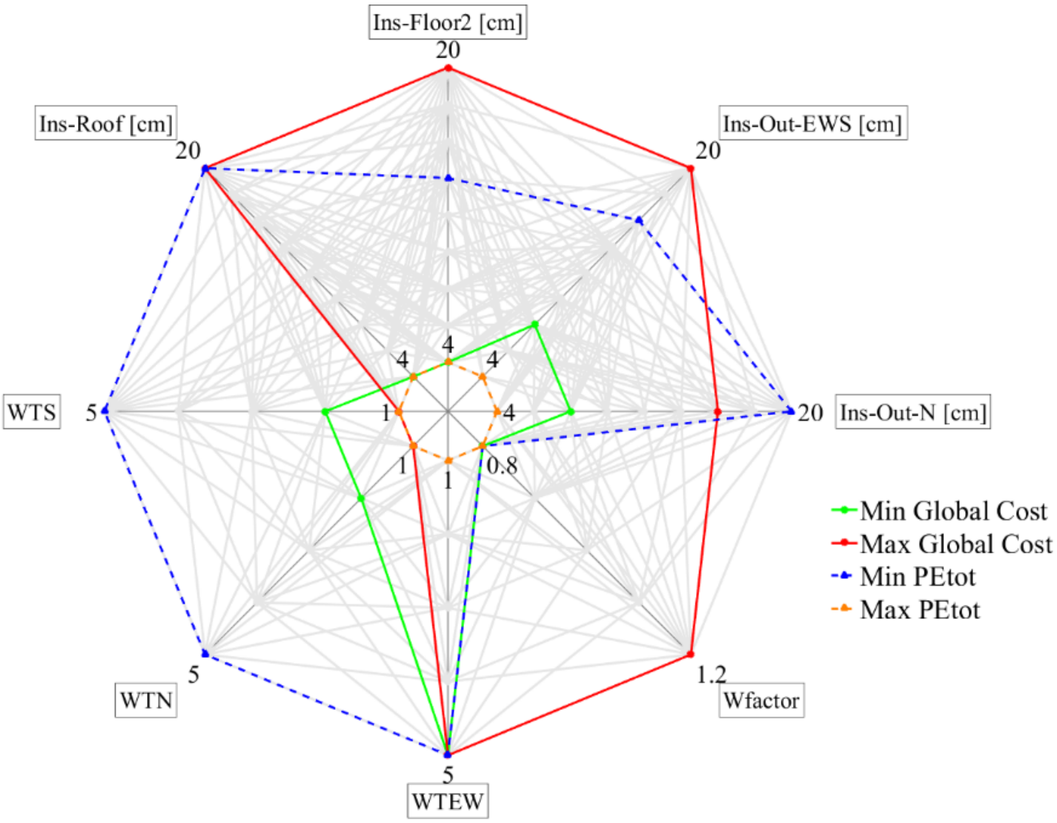


Figure 12: Building envelope configurations in notable points of the cost optimal cloud – building envelope optimization.

Each profile of the graph corresponds to a different design option explored by the optimization algorithm. In this way it is possible to represent all the parameter values that are related to each point in Figure 11. Thanks to the combined analysis of Figure 11 and Figure 12, it is possible to note that a design options with high performing opaque envelope (red configuration) or high performing transparent envelope (blue configuration) increases the global cost. However, the best performance is reached by design options including a high-performing transparent envelope. Moreover, design options represented by the orange and red points (very low performing envelope) highly increase both primary energy consumption and global cost with respect the optimum region.

A similar diagram is shown in Figure 13, where all design options in the optimum neighborhood are highlighted with blue lines. Percentage values reported next to the parameter name indicates the occurrence frequency of optimal parameter values within the optimum neighborhood, indicating the "stability" of each design variable. It is shown that for some parameters, like the insulation of vertical external walls, the occurrence frequency is very high, meaning that, whatever is the design of the other components, this optimal parameter value is very "robust" and a different design of this component would cause to fall outside the optimum neighborhood.

In other cases, as for the insulation of the second level floor, the percentage is very low, which is a sign that the algorithm has explored in the same way many possible values for that parameter without exiting the optimum region. To better understand this concept, Figure 14 and Figure 15 are the representations of a stable and not-stable variable; in the first case (Figure 14) there is a clear peak in correspondence of the optimum value (red dotted line), whereas in the second case (Figure 15) the optimum value has not the highest frequency of occurrence within the optimum neighborhood and other values can cause nearly-optimal solutions.

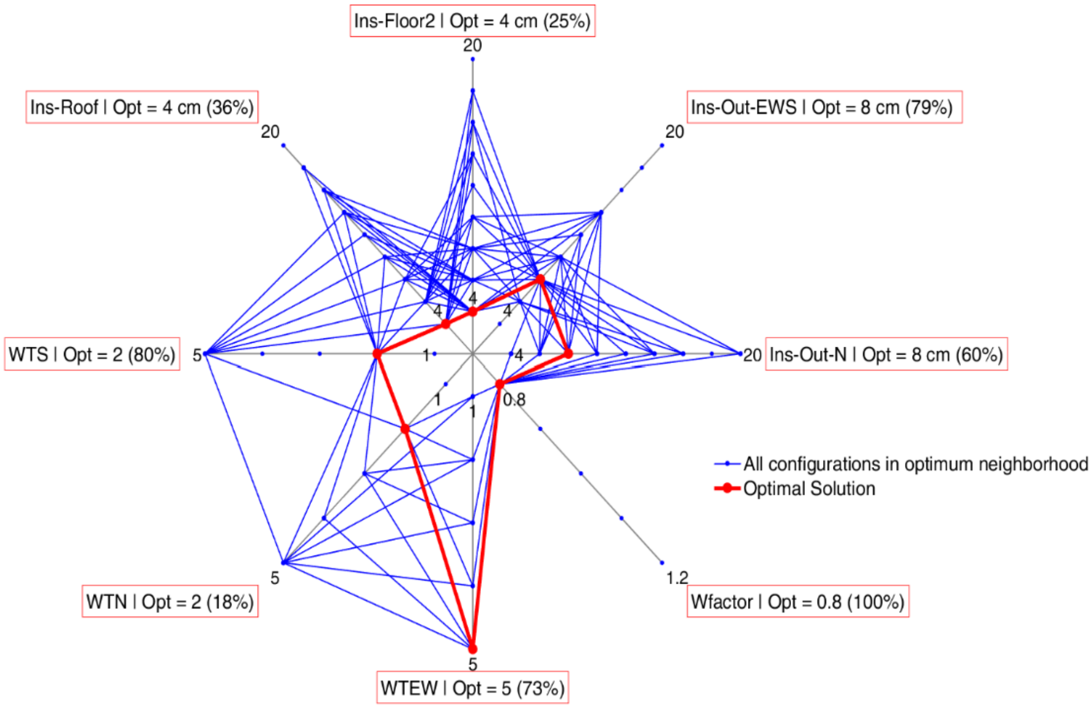


Figure 13: Building envelope configurations in the optimum neighborhood – building envelope optimization.

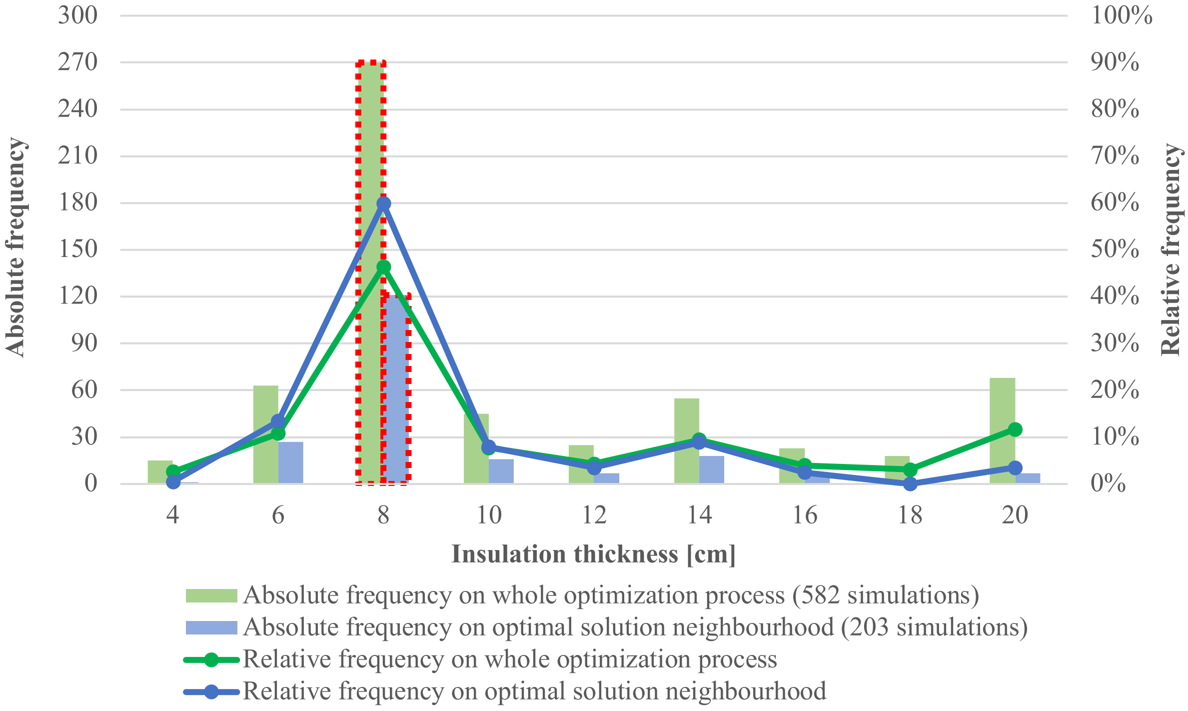


Figure 14: Example of stable variable: insulation of external walls facing North – building envelope optimization.

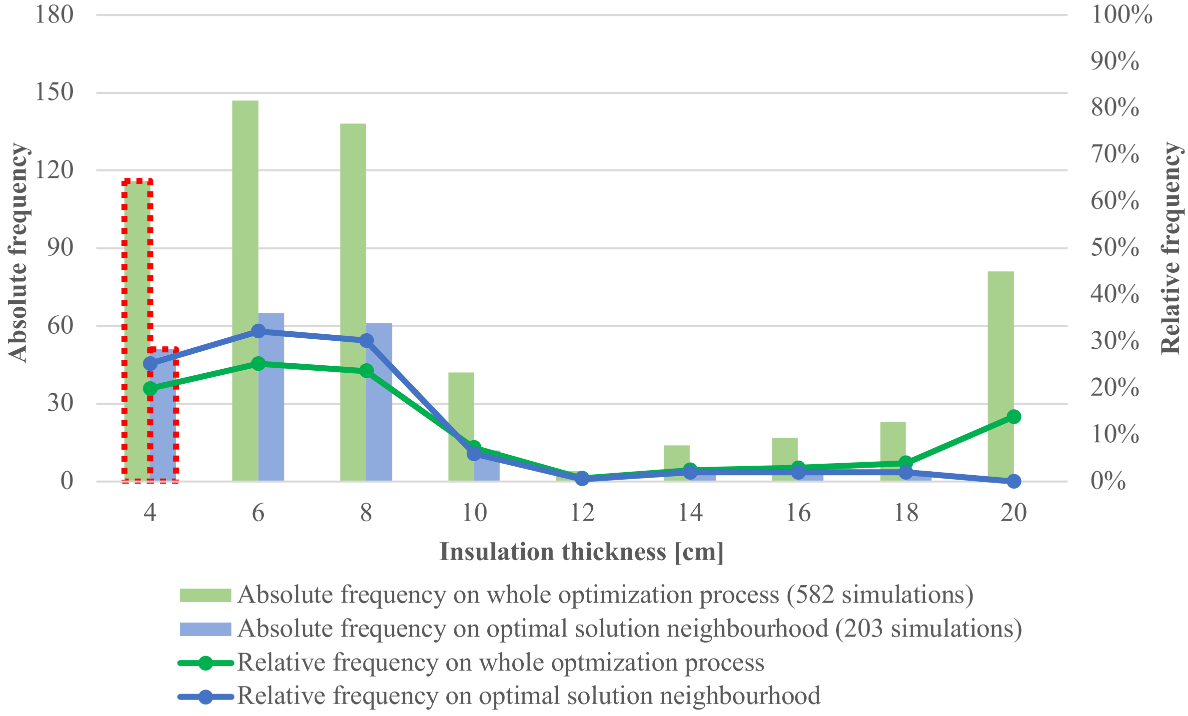


Figure 15: Example of non-stable variable: insulation of the floor of F2 – building envelope optimization.

4.2 Sequential approach, second step: technical system optimization

Results of the second step of sequential approach are reported in the columns denoted by "Cost-optimal solutions – technical systems" in Figure 10. The optimal solution includes the heat pump as generator of heating and cooling energy and fan-coils as terminals installed in ambient. 30% of roof area is covered by polycrystalline photovoltaic panels and 10% by solar thermal collectors, connected to a high-capacity water thermal storage of 100 liters per square meter. Finally, the domestic hot water heating demand is satisfied by a gas auxiliary heater in addition to solar thermal system. This configuration leads to a total primary energy consumption of 95 kWh/m^2. This value is lower with respect the one found at previous building envelope optimization stage, due to the exploitation of solar renewable sources and the utilization of more energy efficient generators in comparison with those of the reference building.

The corresponding cost optimal cloud is represented in red in Figure 16, together with the one of the integrated simulation (green dots) that is introduced later in section 4.3. This red cloud takes into account also the cost of the optimal building envelope deriving from the previous optimization stage.

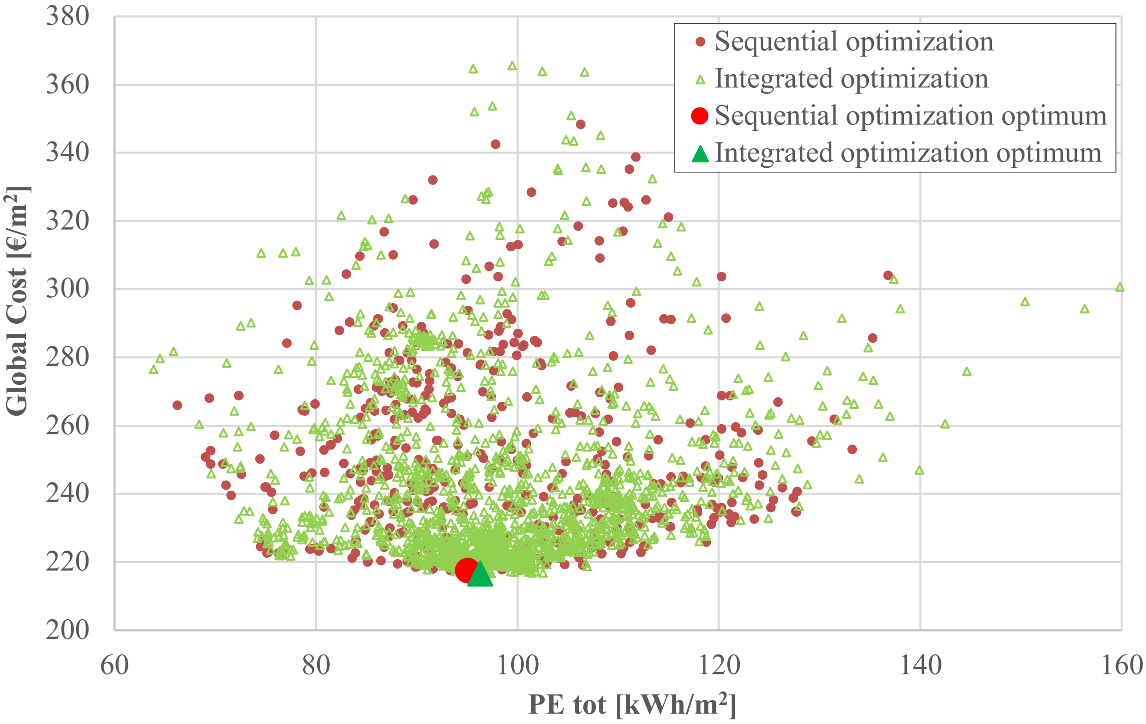


Figure 16: Sequential approach vs integrated approach cost optimal clouds.

The study of the stability of the optimal solution, as can be seen from percentages reported in Figure 10, leads to an important result. In the neighborhood of the cost optimal point all the solutions have the same configuration of generators, terminals and auxiliary heaters. Variables with lower occurrence frequency are those related to the quantities of solar renewable sources. Therefore, it may be interesting to study the influence of such variables on the global cost function. To this regard, starting from the simulation data, variation of the global cost as a function of percentages of roof area occupied by photovoltaic panels and solar thermal collectors is reported in Figure 17. Since, for each point of the plane of Figure 17, many design options can exist depending on values of all the other decision parameters, only the design option leading to the minimum global cost was considered for each point to interpolate the surface of Figure 17. Red points indicate the optimum neighborhood and the yellow one the minimum of the global cost function. The surface is lower when there is a low [14]percentage of solar thermal and a percentage of photovoltaic between 20% and 50%. This demonstrates that the maximization of renewable sources installed is not advantageous yet, if the goal is to minimize the global cost in the current Italian market. Moreover, the photovoltaic system has a greater impact on the global cost reduction in comparison to the solar thermal system.

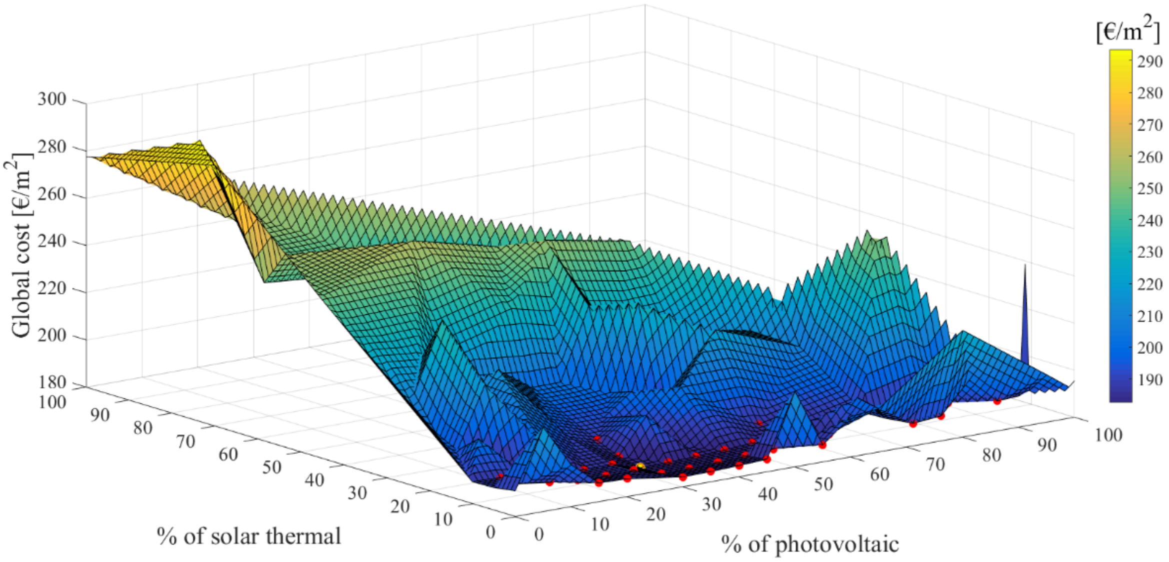


Figure 17: Global cost surface as a function of areas occupied by renewable sources – technical system optimization.

4.3 Integrated optimization

The last section of the table in Figure 10 reports results for the integrated optimization. It is important to note that the optimized values of active decision parameters are the same of the sequential optimization. Contrarily, building envelope parameters are slightly changed: insulation of external walls is decreased, as well as the performance of windows facing East and West. As we can see from Figure 16, the main consequence is that the global cost of the integrated simulation (green cloud) is lower than the one calculated as the sum of the two single simulations (red cloud). On the other hand, the total primary energy consumption is slightly increased from 95.1 to 96.29 kWh/m^2 because of the worst performance of the building envelope. The same reason explains the increasing of the net heating demand from 22.83 to 25.06 kWh/m^2 and the decreasing of the net cooling demand from 7.75 to 7.47 kWh/m^2.

It is therefore necessary to discuss what is the best solution for real design implementation. Firstly, it depends on the main target: as the main objective of the cost-effective NZEB design is the minimization of the global cost, the result of the integrated simulation should be implemented, whereas the choice will fall on the other solution if a little global cost increase can be accepted ton reach lower primary energy consumption.

Anyway, from the study of the optimum neighborhood of the integrated simulation, design options with both global cost and primary energy consumption lower than the one of the sequential approach can be found. In Figure 18 all the design options in the neighborhood of the minimum global cost are represented by blue lines; in addition to the building envelope parameters, as reported in Figure 12 and in Figure 13, also percentages of renewable sources installed are reported. Other parameters concerning the technical system are voluntarily omitted from the figure because they are characterized by a frequency of occurrence equal or near to 100%; it means that they are very stable in the neighborhood of the optimal solution. The red line in Figure 18 indicates the configuration with minimum global cost; as told before, this solution leads to a little increase of primary energy consumptions with respect to the sequential approach. Instead, three design options that have a slightly higher global cost, but still lower than the minimum of the sequential approach (217.50 €/m^2), and also with lower primary energy consumption are represented by yellow lines (in Figure 18 these are called “excellent solutions”). These solutions clearly underline the importance of an integrated approach: they cannot be explored in a sequential approach that uses a fixed configuration of the building envelope.

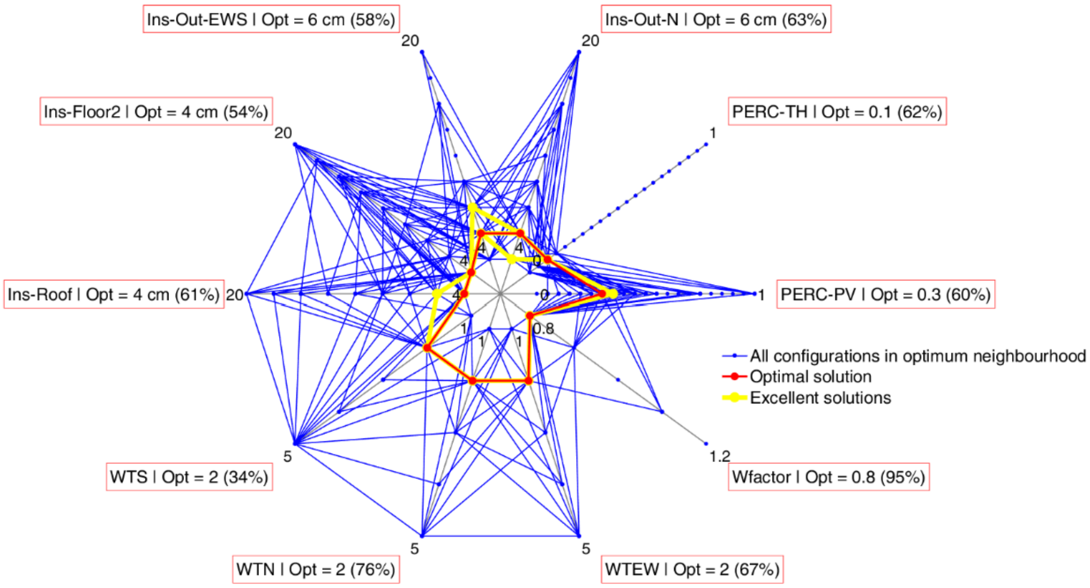


Figure 18: Building envelope and renewable sources configurations in optimum neighborhood – integrated optimization.

In general, the study of the optimal solution stability gives good results for both active and passive components of the building. In particular, parameters related to the technical system have a value of "robustness" equal or near to 100% and, despite the parameters related to renewable sources have lower values of occurrence frequency, their stability is still higher with respect to those obtained by the sequential approach. Variables concerning passive components of the building envelope have good values of relative frequency in the optimum neighborhood, but they are more fluctuating. This means that there are several configurations of the building envelope that, when associated to the same technical system, have a good value of the global cost. This cannot be explored with a sequential simulation where the building envelope has to be optimized considering a fictitious reference system.

4.4 Sensitivity analysis

To deal with the uncertainty in the study assumptions and therefore in results, a sensitivity analysis was performed by varying both decision and environment input parameters.

Figure 19 reports the analysis of the variation of the value of each decision parameter from its minimum ($p_{i,\,min}$) to the maximum ($p_{i,max}$) of its variation range, while the other parameters are fixed to the optimal value resulting from the integrated optimization (optimal parameter values reported in Figure 10). The parameter values are reported on the x-axis, while the relative variation of the objective function with respect to the optimal solution, laying on the 0% line, are reported on the y-axis. The variation of the total and non-renewable primary energy consumptions is also reported. It is shown that non-optimal values of envelope-related decision parameters may lead the global cost objective function to little increase, in most cases less than 3.5%, therefore leading to solutions below the optimum neighborhood threshold (indicated by the red line in Figure 19). Also, the variations in terms of primary energy consumptions are negligible. This confirms the importance of studying the mutual relationships between the design variables and of combining different energy efficiency measures to reach higher performance.

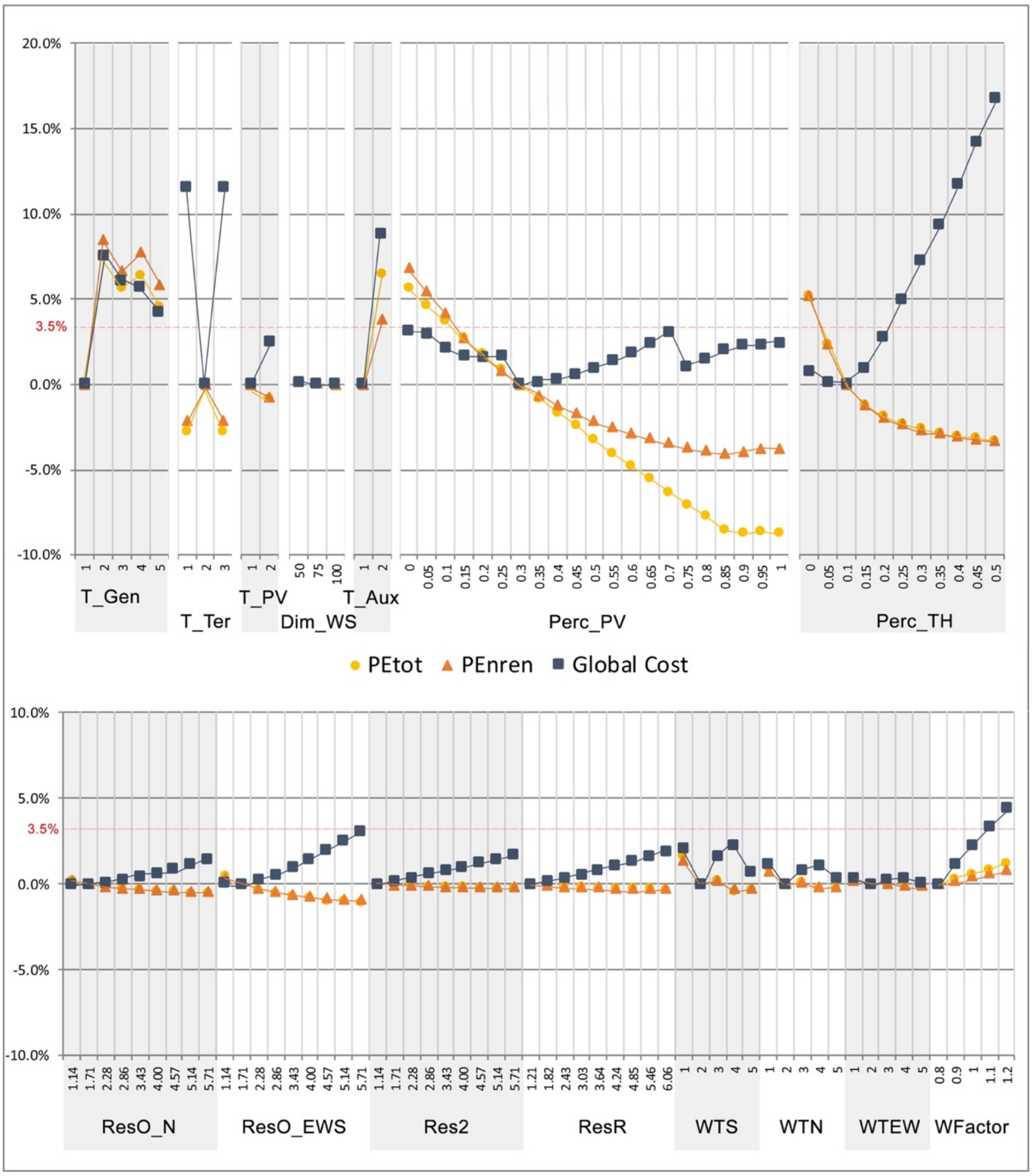


Figure 19: Sensitivity analysis: effect of the variation of each parameter (active parameters above, passive parameters below) on the global cost objective function and on primary energy consumptions. The red lines indicates the optimum neighborhood threshold.

The global cost objective function is more sensitive to the variation of active decision parameters, leading to increase the global cost value by more than 10% for a non-optimal type of system terminals (T_Ter) and by more than 15% for a non-optimal percentage of roof area covered by solar thermal system (Perc_TH). With regard to the primary energy consumptions, it is shown that they increases due to variation of some parameters (such as the type of generator T_Gen or auxiliary T_Aux), while in some cases (as for parameters related to renewable sources Perc_PV and Perc_TH) they could decrease for higher parameter values but their benefit in terms of reduced energy cost does not compensate their investment and maintenance costs, therefore increasing the global cost objective function.

The sensitivity of results to the variation of financial parameters was also performed and is reported in Figure 20. According to the European Guidelines [5], a 4% real interest rate R_r was used as discount rate to perform the calculations presented above (refer to section 2.2.2.1 and to [4] for details on the use of Rr in the computation of the global cost objective function). The resulting cloud (global cost on the y-axis, total primary energy on the x-axis) is reported in grey in Figure 20 together with the clouds related to integrated optimization performed with Rr equal to 2% (orange) and to 6% (yellow). The optimum (points named OPT) and the related neighborhood is highlighted in each cloud. As shown, the absolute global cost increases for lower real interest rates, leading to different location of the clouds within the cost-optimal diagram. Moreover, as expected, the primary energy consumption related to the cost-optimal point decreases when Rr decreases, because of the higher weight of energy costs in the computation of global cost and therefore the higher cost-effectiveness of energy efficiency measures. This also emerges from Table 5, where the resulting optimal parameter values for the different optimization runs are reported. As shown, greater PV area (Perc_PV) and higher performance of vertical walls (ResO-N and ResO-EWS) and windows (WTEW) are included in the optimal design option related to Rr 2%, while lower solar thermal area (Perc_TH) refer to the optimal design option related to Rr 6%. The optimal values of other parameters are the same as resulting from the integrated optimization with Rr 4%.

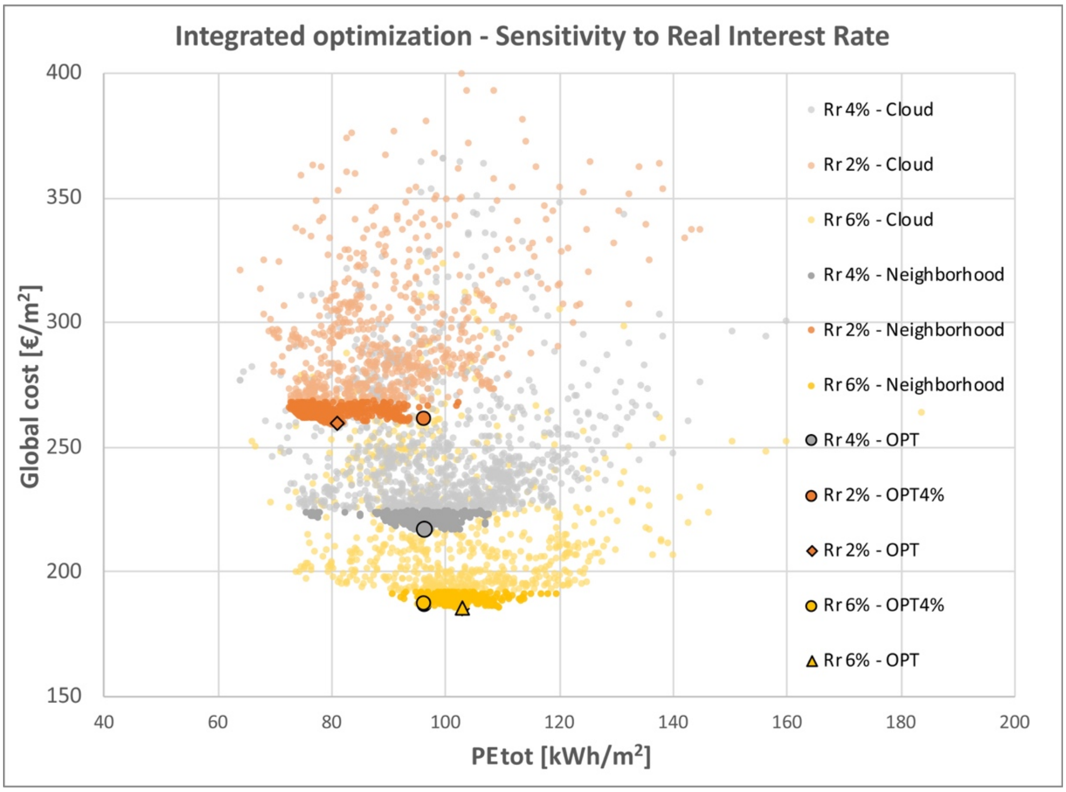


Figure 20: Sensitivity analysis: cost-optimal clouds with indication of optimal solutions and optimum neighborhoods for different values of real interest rate.

Table 5: Optimal parameter values related to points highlighted in Figure 20.

Parameter	Unit	Rr 2% OPT	Rr 6% OPT	Rr 4% OPT	Rr 2% OPT4%	Rr 6% OPT4%
T_Gen	-	1	1	1	1	1
T_Ter	-	2	2	2	2	2
T_PV	-	1	1	1	1	1
Dim_WS	l/m^2	100	100	100	100	100
T_Aux	-	1	1	1	1	1
Perc_PV	%	**76**	31	31	31	31
Perc_TH	%	11	**6**	11	11	11
ResO-N	m^{2}K/W	**0.475**	0.317	0.475	0.475	0.475
ResO-EWS	m^{2}K/W	**0.475**	0.317	0.475	0.475	0.475
Res2	m^{2}K/W	0.317	0.317	0.317	0.317	0.317
ResR	m^{2}K/W	0.337	0.337	0.337	0.337	0.337
WTS	-	2	2	2	2	2
WTN	-	2	2	2	2	2
WTEW	-	**5**	2	2	2	2
WFactor	%	80	80	80	80	80
GCost	€/m^2	259.1	185.5	216.6	260.4	186.4
PEtot	kWh/m^2	80.9	103.1	96.3	96.3	96.3
PEnren	kWh/m^2	67.1	81.5	75.0	75.0	75.0

Furthermore, the points named OPT4% in Figure 20 refer to the location of the design option related to the optimum of the grey cloud (integrated optimization with Rr=4%, Figure 10) if its global cost is calculated with the real interest rate of 2% (point Rr 2%-OPT4%) and 6% (point Rr 6%-OPT4%). It is interesting to note that this solution falls within the optimum neighborhood of both the orange and the yellow cloud, therefore demonstrating a certain robustness of results presented in section 4.3.

5. Conclusions

The innovative Energy Demand and Supply Simultaneous Optimization methodological framework, combining simulation and automated optimization, to be applied to the cost-effective nearly Zero Energy Building design was proposed and applied to a complex multi-family case study building.

The study of the global cost function minimization demonstrated that a building is a complex entity composed by three main sub-systems: building envelope, technical plant and renewable sources. So, if we want to design a nearly Zero Energy Building we cannot neglect interactions between these components. This is particularly true for multi-family buildings, that is a complex system in which there are many different thermal zones with independent set-point temperatures and heating system regulations.

The optimal design of a multi-family building in the Italian context is different with respect the current design configuration. Concerning the building envelope, the insulation of outside walls is not external as in the design phase, but it is internal. Then, transparent components with a lower value of thermal transmittance are installed. This leads to increase the heating energy demand by 8% but, at the same time, to reduce the cooling energy demand by 38%, which means reducing the primary energy need by 6%, if efficiencies of the reference technical system [52] are considered. However, in the optimized configuration, the higher efficiency of the technical system further reduces primary energy needs by 25%. In fact, instead of relying on the district heating network of the city, a heat pump is used to satisfy heating and cooling energy demand, while solar thermal collectors with an auxiliary heater is used for domestic hot water production. Besides, the installation of both thermal and electric solar renewable sources are exploited to reduce the total primary energy consumption of the building and to respect the Italian D.Lgs. 28/2011 about the use and promotion of renewable sources in the building sector. Results of simulations confirm that the heat pump is the best heating and cooling generator for a multi-family building. It is an efficient and versatile machine and it avoids the installation of a double generator that would increase investment and maintenance costs.

In addition to an efficient heat generator, the building envelope has a fundamental role in minimizing the total primary energy needed by the building. Anyway, it is disadvantageous to have a super-insulated envelope because, in this climate conditions, it would increase too much the net cooling energy demand and the investment cost of insulations and transparent components.

Concerning renewable sources, a reasoning similar to the one carried out for the building envelope can be done. The optimal solution is found with a partial coverage of the total available area. This is because the actual Italian market conditions are not advantageous for large installations, but at the same time a small PV production increases too much the amount of electric energy bought from the grid. The reported sensitivity analysis demonstrates the robustness of results.

In general, the use of the EDeSSOpt method proves that a simultaneous integrated optimization of the three main sub-systems of a nZEB building (envelope, technical system and renewable sources) allows exploring many more solutions with respect to a two- or three-step sequential optimization in which at every step a single sub-system is optimized under some assumptions. In the application to this case-study, it was proved that these further solutions can perform better in comparison to the optimum resulting from the sequential approach. Moreover, this study shows that exploration is as much important as optimization. In fact, beyond the resulting optimal design option, a wider exploration of the design space and of the neighborhood of the optimum is essential for higher robustness of optimal design and for design choices motivation in real contexts.

Concerning the applicability of EDeSSOpt in real design process, it has to be noted that the main drawback that prevents the application of simulation-based optimization techniques to real cases is the lack of time and the computational effort, that will not be significantly different between the two approaches (integrated one and sequential one). It was demonstrated that the integrated one may reduce the computational effort since the setting of the optimization variables and parameters will be done once instead of twice as in the sequential one.

Several successful applications to real context have been derived from the present work and will be presented in future works.

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