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Energy systems in cost-optimized design of nearly zero-energy buildings

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Abstract

Cost optimization is one of the key elements of the EU regulatory framework concerning the energy performance of buildings. From this economic point of view, the optimum occurs when the global cost over the lifecycle of a building is minimized, and the cost-optimal energy performance level is that related to the minimum global cost. To determine this cost-optimal level by evaluating a great number of design alternatives, it is necessary to exploit automated optimization search procedures. The work presented here concerns the application of cost-optimal methodology, as defined by European regulation, to a low-consumption single-family house in France. The calculation is performed through an iterative input-output process in a computing environment that combines TRNSYS®, transient system simulation tool, with GenOpt®, generic optimization program. The methodology that was adopted allowed around ten thousand building configurations to be simulated in a reasonable computational time. The paper focuses on how the energy system affects the technical and economic optimal design solutions of the building in two different French climate conditions.

Keywords: EPBD recast; cost-optimal analysis; dynamic building simulation; automated optimization; optimization algorithm; particle swarm optimization; France; cost function; single family house; design parameters

1 Introduction

In the context of the European Unionôs efforts to reduce growing energy consumption, it is widely recognized that the building sector plays an important role, accounting for 40% of the total energy consumption in the European Union [1]. The recast of the Energy Performance of Buildings Directive (EPBD) [2] imposes the adoption of measures to improve energy efficiency in order that all new buildings will be nearly zero-energy buildings (nZEBs) by 2020 [3]. As the results in terms of energy efficiency are evaluated at a global (or at least European) scale, it is a remarkable fact that a good nZEB design is strictly related to the local scale, depending on parameters such as climatic conditions, available technologies and materials and population lifestyle.

The architectural design process (new construction, renovation or retrofit) includes important choices that may greatly affect the energy performance of the building, mostly related to the envelope design and the energy system.

Traditionally, the nZEB design [4] consists in two steps: firstly, minimizing the energy demand of the building, which, for given boundary conditions (weather, orientation, building typology), depends on the building envelope geometry and construction; secondly, minimizing the primary energy demand of the building through the use of high efficiency energy systems and renewable energy sources. In order to reach these objectives, it is necessary not only to investigate the impact of the different design variables on the energy performance of the building, but also to study how they influence each other when looking for the optimized building configuration in a specific boundary context. In [5] the authors developed a methodology for performing this kind of research concerning the design variables related to the building envelope and geometry, but variables related to the energy system have not previously been studied.

Moreover, as the measures for reaching a high energy performance in a building are not always profitable in terms of costs [6], it is necessary to perform some economic studies in order to evaluate the global cost of different design options from a lifetime perspective, that is designing the building from the so called cost-optimal point of view [7].

One of the main challenges of cost-optimal calculation methodology is to ensure that while all the possible measures impacting the primary energy demand of a building are evaluated, the calculation exercise remains manageable and proportionate, as the great number of variables involved in the building design can easily result in thousands of design alternatives.

Many studies [8][9] concerning this cost-optimal methodology have been conducted by manually selecting a limited number of packages of energy efficiency measures. However, this manual procedure may not lead to a high level of accuracy when looking for the minimum global cost of the building and an automated process could improve the accuracy of the search [10].

In [11] ZEB design was studied from the aforementioned cost perspective by combining the energy efficiency measures related to the envelope design with others related to the energy system and evaluating their global cost. It was found, when looking for the cost-optimal building configurations, that the optimal envelope design varies depending on the energy system considered. Therefore, as a further step in the context of the cost-optimal analysis, this paper aims to apply an automated optimization method in order to study:

- how the selection of a specific energy system affects the cost-optimal level of the energy performance of a building and the related cost-optimal design of the envelope;
- the influence of the choice of the energy system on the global cost of the building, evaluating both the investment and the operational costs;
- the comparison between the influence of systems in the cost-optimized design of nZEBs in different climatic conditions.

The automated search was conducted by combining dynamic simulation and optimization algorithms in order to evaluate a great number of design options and perform deep and accurate optimization research.

2 The case-study building

The case-study building is a two-floor residential building situated in Ambérieu-en-Bugey, in the French region of Rhône-Alpes. Because of its typical and recent construction (it was built in 2011), the house can be considered as representative of a high-performing new construction of a single-family house in this French region and it was taken as the Reference Building configuration (RB) for the purposes of the present study.

2.1 The building envelope

The conditioned volume of the case study has a compact shape that minimizes the exchange surface between the outside and inside, leading to a Surface-to-Volume ratio equal to 0.68m^{-1}. The conditioned floor area is equal to 155 m^2 (Figure 1).

The envelope is well insulated (Figure 2): the external walls (overall thermal resistance R = 7.53 m^{2}K/W) are composed of 20 cm of concrete blocks (thermal resistance

R = 1 m^2K/W) and 20 cm of internal insulation (R = 6.3 m^2K/W), the wooden roof (overall thermal resistance R = 12.81 m^2K/W) includes 40 cm of insulation (R = 12.5 m^2K/W) and the floating slab (overall thermal resistance R = 10.92 m^2K/W) incorporates 30 cm of insulation material (R = 9.3 m^2K/W). Based on this data, the thermal transmittance of the vertical walls is U_o=0.13 W/m^2K, the thermal transmittance of the roof is U_r=0.08 W/m^2K and the thermal transmittance of the slab is U_s=0.09 W/m^2K.

The use of thermal bridge breakers limits the thermal bridge at the intermediate floor. All windows have triple glazing for a thickness of 44 mm (4/16/4/16/4), the solar factor is equal to 0.5 and the thermal transmittance U_w of the entire opening (glasses and frame) is equal to 0.7 W/m^2K.

These values are fully compliant with the Passivhaus standard, which requires that all parts of the opaque envelope have a U-value lower than 0.15 W/m^2K and the windows have a U-value lower than 0.8 W/m^2K.

Coherently with the principles of passive or low consumption houses, in order to reduce heat loss due to windows and benefit from solar gains, the majority of large openings are south-oriented (49% of the total glass surface on the south external wall, 19% on the south roof slope), while the percentage of openings in the east and west orientations is less relevant (10% and 15% of the total glass surface, respectively) and there are only very small north oriented openings (7% of the total glass surface). The window area is approximately 1/5 of the floor area; so the minimum imposed by national regulations [12], which is equal to 1/6 of the floor area, is largely exceeded. A roof overhang protects the south-oriented windows.

A double-height internal wall made of stone and concrete increases the internal thermal mass.

A blower door test has been performed, attesting that the air tightness of the house is equal to 0.6 m^3/hm^2.

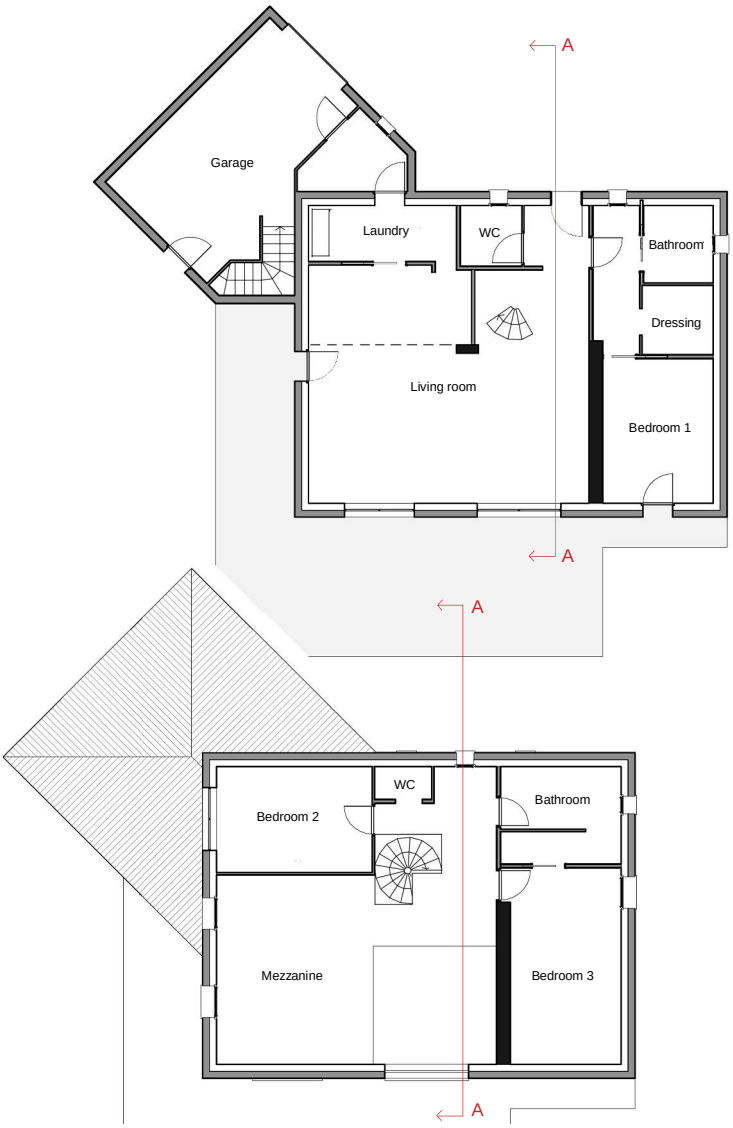

Figure 1. Plans of the case study building. Ground floor (up), second floor (down)

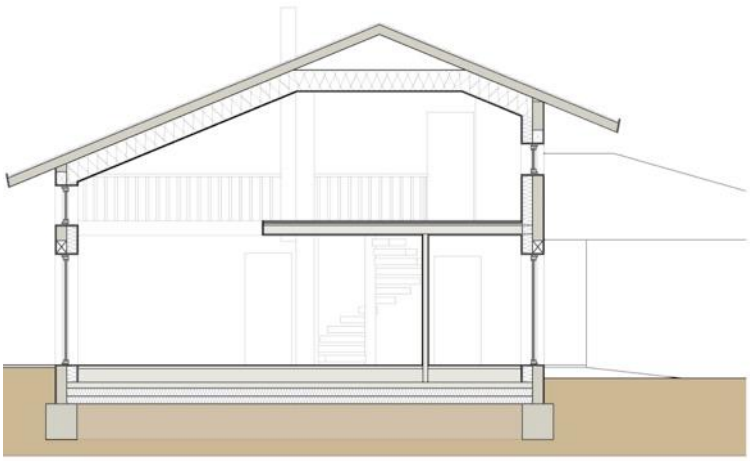

Figure 2. Case study building, transversal section AA

2.2 The energy system

The case-study building is equipped with an all-in-one energy system, which is composed of a dual-flow mechanical ventilation system combined with a cross-flow heat exchanger and an air-to-air reversible heat pump. Before entering the cross-flow heat exchanger, the air is pre-treated by a geothermal heat exchanger. Once the desired internal set point temperature is met, the system is able to modify its operation mode and manage the comfort through the perfect control of flows induced by ventilation while providing air to guarantee internal comfort regardless of the season.

In winter, the temperature control system is generally set to the heating mode, and the heat pump is on. The cross flow heat exchanger is able to recover about 60% of heat from the extracted air. The heating/cooling capacity of the heat pump varies depending on the outdoor temperature, the desired indoor temperature and the flow rate. The different capacity levels are regulated by the variation of the compressor speed of the heat pump. The global coefficient of performance (COP - Table 1), which takes into account both the heat pump efficiency and the heat recovery from heat exchangers and air recycling, also varies in relation to the combination of all these parameters, going up to 7.6 in particular conditions. It is interesting to note that, contrarily to the case of a simple heat pump, the global COP of this packaged system is higher when the outdoor air temperature is lower (for the same conditions of others parameters), because of the heat recovery performed by heat exchangers.

Table 1. Global COP of the all-in-one energy system of the case-study building as a function of air temperatures, air flow rate and compressor speed ï heating and cooling mode.

	Outdoor air temperature	**Indoor air temperature**	**Air flow rate [m^3/h]**	**Heating capacity [W]**	**Global COP**
Heating Mode	-7°C	20°C	160	1663	7.6
				2861	4.2
				3220	3.4
	7°C	20°C	160	1130	5.1
				2881	3.4
				3468	2.8
Cooling Mode	**Outdoor air temperature**	**Indoor air temperature**	**Air flow rate m^3/h**	**Cooling capacity [W]**	**Global COP**
	35°C	27°C	160	925	2.9
				1626	2.0
				1854	1.4

In summer, the described system works in cooling mode so that the heat pump reverses its cycle and cools the air entering the house. Its cooling power and EER also varies depending on the outdoor and indoor temperatures, the flow rate and the compressor speed and the medium seasonal EER is equal to 3.2. In addition, a system of over-ventilation is

implemented when the outside air is cooler than the indoor air (particularly at night). Finally, the heat exchanger can also be switched on if the internal temperature is colder than the outside temperature, in order to help cooling the fresh air.

The ventilation-only mode allows mediating between the heating mode and the cooling mode, when heating or cooling requirements are very low, typically in spring and autumn. In this case, the heat pump never turns on and the only energy consumptions are due to the fans allowing the requested airflow rate to pass through the heat exchanger.

The detailed operation and the performances of this system are described in [13].

2.3 The calibrated model for dynamic simulation

The case-study building was modeled using the TRNSYS dynamic building simulation program. Each room was modeled as a thermal zone, in order to better evaluate the evolution of temperatures and the thermal exchanges from one zone to the other, as the HVAC system is considered active only in the main rooms of the house. In fact, the set-point temperatures for heating (19°C) and cooling (26°C) were set only in the living-room, in the bedrooms and in the mezzanine, while other zones like restrooms, dressing and passages are not directly conditioned but they are supposed to benefit from the heat exchanges with the adjacent conditioned zones. The garage and laundry were considered as non-conditioned zones.

Lighting and appliance loads (8 W/m^2, dressing and passages excluded) and occupancy (100 W/person) were modeled using schedules for a standard 5 people family working life, week-ends were taken in account but holidays were not considered. The internal gains that were set in the model correspond to those set in the real house through some human simulation devices and a home automation system. The simulation weather file was created with data registered by the on-site weather station (external temperature, solar radiation and wind speed).

The model was calibrated via trial and error through data collected from the monitoring system installed in the house. The calibration of the model was based on the energy consumption of the HVAC system during one year, from May 2011 to April 2012. Other model adjustments were made based on indoor air temperatures in two typical weeks of the year, in winter and summer conditions.

This calibration procedure was carried out in order to provide a reliable model for the cost-optimal calculation reported in this paper. It has to be noted that, when performing

simulations for the cost-optimal analysis, the reference weather files for the selected locations were used, as indicated in the European guidelines.

Considering the TRNSYS calculation of sensible heating and cooling energy demands for all zones (SQHEAT-NTYPE 32 and SQCOOL-NTYPE 33, outputs of Type 56-Multi-Zone building) for a test reference year, with a fixed infiltration and ventilation rate with external air of 0.7 ach, the heating energy need [14] of the RB is equal to 48 kWh/m^2/year, while the cooling energy need is equal to 12 kWh/m^2/year. Taking into account the model of the packaged all-in-one heat pump for heating, cooling and ventilation, the site energy use is 12,44 kWh/m^2/year and the primary energy (as defined in EN 15603: ñEnergy that has not been subjected to any conversion or transformation processò [15]), considering a conversion factor of 2.58 for electricity, is estimated to be equal to 32.1 kWh$_{ep}$/m^2/year.

3 Methodology

3.1 The cost-optimal methodology

Since the aim of this study is the evaluation from the cost-optimal perspective of building configurations with different energy systems, the economic assessment was performed according to the cost-optimal methodology. This methodology, which is defined in the Guidelines [16] accompanying the Regulation [17] supplementing the EPBD recast of 2010, consists of different steps. Firstly, a Reference Building must be identified as a representative model of the national building stock. Secondly, a set of energy efficiency measures (EEMs) must be defined, in order to improve the energy performance of the building. EEMs can be combined in packages of measures. Then, the energy consumptions related to the various packages of EEMs are calculated through energy simulations, and the costs of the different packages are estimated, in order to establish which of them has the lowest global cost and, consequently, represents the cost-optimal level. Finally, the gap between the cost-optimal performance (the energy performance - in terms of primary energy - leading to the minimum Global Cost over the calculation period) and the ZEB target can be assessed and evaluated, orienting policies for reducing this gap.

The Global Cost method described in the European Standard EN 15459 [18] indicates how to calculate the cost over the calculation period of all the systems that are able to affect the energy performance of the building. The global cost is determined by summing up the initial investment costs, the periodic and replacement costs, the annual costs and the energy costs and subtracting the final value, referring all this cost to the starting year of calculation. Therefore, the equation of Global Cost can be written as

$$C_G(\tau_0) = CI + \sum_j \sum_{i=1}^{\tau} C_{a,i}(j) * R_d(i) - V_{f,\tau}(j) \qquad (1)$$

where:

- $C_G(\tau_0)$ = global cost referred to starting year τ_0
- CI = initial investment cost
- $C_{a,i}(j)$ = annual cost for component j at the year i
- $R_d(i)$ = discount rate for year i
- $V_{f,\tau}(j)$ = final value of component j at the end of the calculation period.

The discount rate coefficient R_d is used to refer the replacement costs and the final value to the starting year. It is expressed as

$$f_{r} = \frac{1}{(1+R_r)^{i}} \qquad (2)$$

where R_r is the real interest rate and *i* is the year of calculation (e.g. i = 15 for calculating the replacement cost of a component having a lifespan of 15 years).

When annual costs occur for many years, such as in case of running costs, the present value factor f_{pv} must be used, which is expressed as a function of the number of years *n* and the interest rate R_r as

$$f_{pv}(n) = \frac{(1+R_r)^{n}-1}{R_r\cdot(1+R_r)^{n}} \qquad (3)$$

This study refers to the current French market conditions. According to the European Guidelines, the real interest rate (R_r) was set to 4%. The rate of evolution of prices is included in the inflation rate, which the Guidelines suggest to set to 2%. No energy price evolution rate other than the inflation rate was considered. The calculation period (n) was set equal to 30 years and the related present value factor (f_{pv}) is equal to 17.29. More details about this calculation methodology and the choice of financial data can be found in [11].

3.2 The automated optimization process

The search of cost-optimal level can be seen as a complex optimization problem, whose objective function is the Global Cost Function C_g (1). Its complexity is given by the fact that some terms composing the objective function, such as the energy costs and the related energy performance, depend on a great number of variables in a complex system of equations. Because of the high number of design variables and the complexity of the calculation, it would be practically impossible to minimize the objective function and obtain an exact optimal solution using analytical methods.

The calculation engine of dynamic simulation software, which is denoted by Φ in this paper, is able to perform such a complex calculation, which involves solving the system of partial and ordinary differential equations coupled to algebraic equations that define the thermodynamic model of the building (air heat balance and all the other equations). Within the boundaries and constraints of our problem, in order to perform an accurate optimization, it is necessary to evaluate a great number of building configurations, each corresponding to a different combination of design variables. However, it is clear that evaluating all the possible combinations of design variables would be very complex and time-consuming. As a reference, considering that a simulation of the case study building model takes about 1 minute to be performed and considering that 5 values for 9 design variables lead to 5^9 possible design

alternatives to be evaluated, the computational time for an exhaustive search would be very huge (around 6 months if parallel computation were performed). Therefore, the coupling of the engine with algorithms for optimization allows avoiding the evaluation of all the possible combinations of design variables and going faster towards an optimal solution. This is generally known as simulation-based optimization [19].

In this way, the optimization problem is solved using iterative methods driven by optimization algorithms [20][21] that construct sequences of progressively better approximations to the solution point satisfying an optimality condition within the search-space. This approach is very popular to solve problems concerning the optimization of building systems during operation [22][23]. In this work, the coupling of the TRNSYS® [24] building dynamic simulation program with the Generic Optimization program GenOpt® [25] was performed in order to address a building design optimization problem.

GenOpt is an optimization program for the minimization of a cost function, which can be evaluated by an external simulation program. It can be used with any simulation program that reads inputs from and writes outputs to text files. Differently from other simulation tools, TRNSYS has a dedicated interface for GenOpt, which is named TRNOPT. However, it only allows the variables of the simulation model that are defined in the DCK file (the main TRNSYS input file, created with the Simulation Studio interface) to be set as optimization parameters for running GenOpt. Therefore, within TRNOPT, it is not possible to deal with variables located in the BUI file (the input file created by TRNBuild, the TRNSYS interface for editing the Type 56 for multi-zone buildings) and to define the equations implementing relationships between different optimization variables. As all the variables concerning building constructions are specified in the BUI file, it is therefore impossible to use TRNOPT within the building cost-optimal search.

To do so, it is necessary to create simulation templates by directly editing the BUI and the DCK simulation input files with variables readable by GenOpt. Moreover, it is required to create the configuration file, which refers to the call of the TRNSYS software; the command file, in which the variables are defined as optimization parameters; and the initialization file, which contains specifications concerning the locations of input, configuration and command files and the position of the objective function value. The whole simulation-optimization framework is shown in Figure 3. The TRNSYS 16.01.003 version was used, together with GenOpt 3.0.0. To run the programs, one of the Java 2 versions (i.e. Java 2 Runtime Environment Version 1.4.2) is also required.

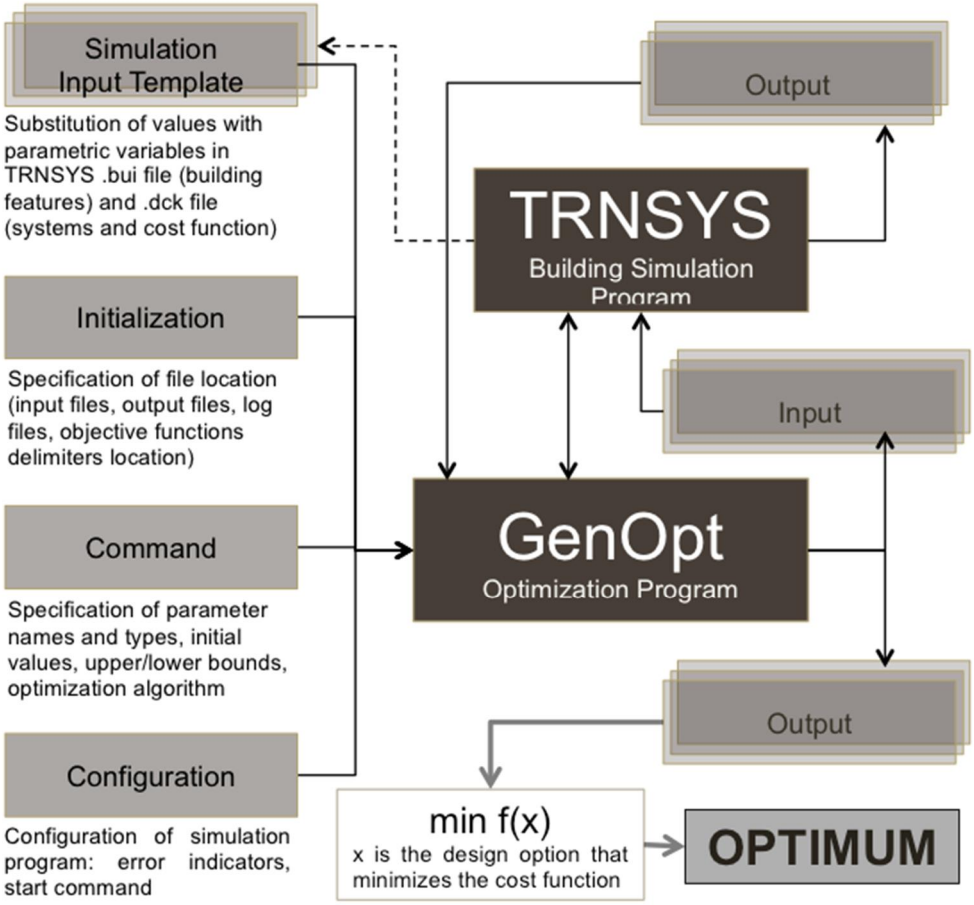

Figure 3. TRNSYS-GenOpt framework

Given this context, in order to state the optimization problem, let E_d be the energy performance, calculated by the thermodynamic model engine $\mathcal{E}$; let $S_{d,i}$ be one among the *m* user-defined technical systems, let $\mathcal{P}$ be the set of *n* user-defined envelope design parameters p_i, where $p_{i,d}$ denotes a value assumed by the parameter p_i in a potential design solution *d*. Since all the design parameters *p* are discrete variables, let $p_{i,min}$ and $p_{i,max}$ be the lower and the upper values of the parameter interval of variation, respectively, and let $n_{i,steps}$ be the number of discrete steps in which the interval is divided and where all steps are numbered with consecutive integers from 0 to $n_{i,steps}$. Based on this, $p_{i,d}$ denotes the value assumed by the parameter p_i corresponding to the step number $n_{i,d}$.

The building design optimization problem related to the present work can be stated as follows

Find $p_{i,d}$ $\forall i \in \{1,2,3,\dots,n\}$ such that (4.1)

minimize $f_{\mathcal{E}}(E_d, S_{d,1}, \dots, S_{d,m}, p_{1,d}, \dots, p_{n,d})$ $i \in \{1,2,\dots,n\}$ (4.2)

where $$\mathbf{x} = [x_1, x_2, x_3, \dots, x_n] \subset \mathbb{Q}^n \quad (4.3)$$

subject to $$\mathbf{y} = f(\mathbf{x}, \mathbf{p}) \quad (4.4)$$

$$x_{i\,min} \le x_i \le x_{i\,max} \qquad \forall i \in \{1,2,3,\dots,n\} \quad (4.5)$$

$$x_i = x_{i\,min} + \frac{x_{i\,max} - x_{i\,min}}{x_{i\,max} - x_{i\,min}} \cdot (x_{i\,max} - x_{i\,min}) \qquad x_i \in \{0,1,\dots,x_{i\,max}\} \quad (4.6)$$

In order to solve this problem, among the optimization algorithms available in GenOpt, the particle swarm optimization (PSO) was chosen, which is a population-based probabilistic optimization algorithms firstly proposed by Kennedy and Eberhart [26] to solve problems with possibly discontinuous objective functions, as is often the case in the problems. PSO algorithms exploit a set of potential solutions to the optimization problem. Each potential solution, which is related to specific values for each independent variable, is called a *particle*, and the set of potential solutions in each iteration step is called a *population*. The first population is initialized using a random number generator to spread the particles uniformly in a user-defined hypercube, which is the *n*-dimensional space (*n* being the number of independent variables) in which all the potential solutions are located. A particle update equation, which is modeled based on the social behavior of members of bird flocks or fish schools, determines the location of each particle in the next generation, until the maximum number of generation j_{max} is reached. More mathematical details about the algorithm can be found in [27]. In particular, a PSO algorithm binary version for discrete independent variables was used in this study [28], as the box-constraints on independent design variables is expressed as a user-specified set with a finite, non-zero number of integers for each variable. The algorithm parameters used in the optimization runs were set as recommended in [25] and used in [29]: the von Neumann neighborhood topology was selected, the neighborhood size was set to 5, the number of particles was set to 20, the number of generations was set to 40, the cognitive acceleration to 2.8 and the social acceleration to 1.3.

The whole optimization process that was set up for this work, from pre-processing to post-processing, is shown in Figure 4. The user-defined inputs are reported in red squares, the automated engines are reported in black elliptic shapes, the outputs of the automated process are represented in blue squares. The user external elaboration of the output data are represented in dotted squares.

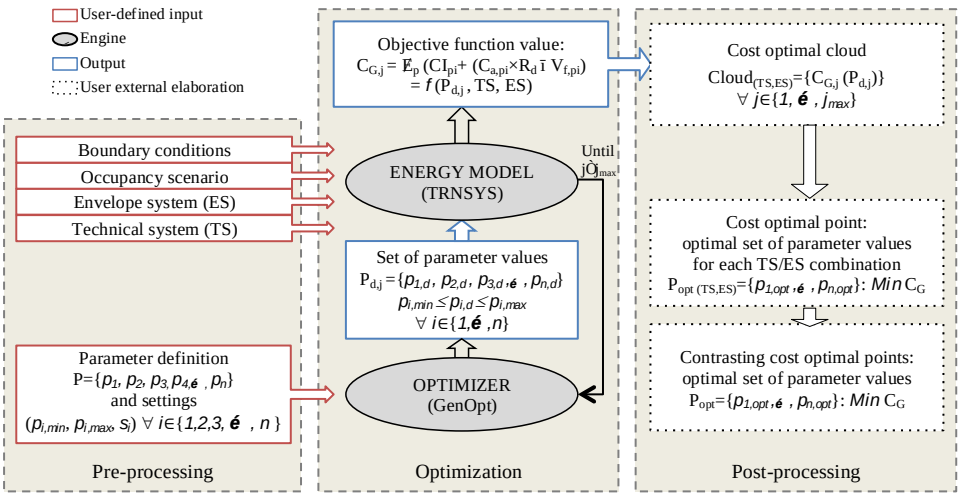

Figure 4. Pre-processing, optimization and post-processing phases of the proposed methodology.

3.3 Case-study specifications

Based on the previous sections, the optimization problem related to the case study proposed in this work deals with 9 envelope design parameters p_i (n=9 in Eq. 4.1) and 4 technical systems TS_k (m=4 in Eq. 4.4). Table 2 reports a list of all the optimization variables that are used in this work with their name, description and reference to the others tables in the text, where settings of each variable are reported with more details. In fact, settings such as the lower and upper bounds ($p_{i,min}$, $p_{i,max}$) and the consequent number of steps (s_i) of variation of the 9 envelope parameters p_i were set differently for each of the three envelope systems (ESs) that were studied in this work.

The four energy systems (TSs) were associated to the three envelope systems (ESs) into 12 combinations. For each of these ES/TS combinations, the optimization problem described by equations (4) was solved and the sets of parameter values composing the 12 cost-optimal building configurations were found, allowing to investigate the variation in the cost-optimized design of each envelope system depending on the selected energy system.

This analysis was conducted for the case study building located in two French locations corresponding to different climate conditions. The first is the actual location of the building, that is Ambérieu-en-Bugey, Rhône Alpes, France. This is a low altitude area with temperate climate, which is classified by the French thermal regulation RT2012 [12] as a H1c zone, where the maximum amount of annual primary energy needs for heating, cooling, DHW, ventilation and lighting (Cep_{max}) for residential buildings is equal to 60 kWh_{pe}/year [30]. The

other location is Marseille, in the region of Provence-Cote dôAzur, where the Mediterranean influence leads to warmer climate than in the Rhône Alpes region. This region is classified as a H3 zone (Cep_{max} = 40 kWh_{pe}/year).

Table 2. List of the optimization variables used in this work and reference to their details

Parameter	Name	Description	Ref.
p_1	*ResO*	Thermal resistance of the wall insulation layer	*Table 7*
p_2	*ResR*	Thermal resistance of the roof insulation layer	*Table 7*
p_3	*ResS*	Thermal resistance of the slab insulation layer	*Table 7*
p_4	*Bm*	Width of the window at the first floor on the south façade (fixed height of 0.80 m)	*Table 7*
p_5	*Blr*	Width of the window at the ground floor on the south façade (fixed height of 2.15 m)	*Table 7*
p_6	*Hr*	Roof window height (w= 2.28 m)	*Table 7*
p_7	*WT*	Window Type of North - East -West walls	*Table 8*
p_8	*WTS*	Window Type of South wall	*Table 8*
p_9	*WTR*	Window type of roof	*Table 8*
TS_1	*TS 1*	Technical system composed by a reversible heat pump and mechanical ventilation	*Table 3*
TS_2	*TS 2*	Traditional all-electrical technical system (electric radiators and multi-split)	*Table 4*
TS_3	*TS 3*	Technical system composed by a condensing boiler and a multi-split system	*Table 5*
TS_4	*TS 4*	Technical system composed by a wood-pellet boiler and a multi-split system	*Table 6*

4 The energy and financial modeling of the energy systems

As presented, this work is focused on how the design variables related to the energy system affect other design variables related to the building envelope and geometry. In order to perform this study, four energy systems (named technical systems - TSs) were selected among those currently used in France and were modeled in TRNSYS.

It has to be noted that if the sizing of some technical system is strictly dependent on the specific building configuration, for others the sizing is not influenced by the specific heating/cooling load of the building. This can happen, for example, in case of the gas condensing boiler (heating system for TS 3), where the boiler is always oversized and capable of supplying the design thermal load in each building configuration, or in case of the all-in-one electrical system (TS 1) or the wood-pellet boiler (heating system for TS 4). The system efficiencies were modelled as dependent on the instant load.

The capacity of other systems, such as the traditional all-electric system (TS 2) and the cooling system of TS 3 and TS 4, was determined based on the maximum heating/cooling load assessed during the yearly simulation.

All details about modeling and calculations related to each of the systems are reported in the following sections.

4.1 Technical system #1: reversible heat pump and mechanical ventilation

The first energy system, called TS 1, is the one currently installed in the RB and described in section 2. This packaged all-in-one system uses electricity as the energy source for heating, cooling and ventilation. Therefore, in order to obtain the consumption in terms of primary energy, the energy use has to be multiplied by the French primary energy conversion coefficient, which is equal to 2.58. The value is then divided by the net floor area of the house (155 m^2), as shown in the equation (5).

$$\square_{\square\square\square\square\square\square\square\square\square\square\square\square} = \frac{\square\square\square\square_{\square\square} \times \square.\square\square}{\square\square\square} \; [\mathrm{kWh/m^2year}] \qquad (5)$$

The choice of the energy system influences the global cost calculation not only for the investment cost, but also for the energy cost, which is affected by the system efficiency and the type of energy source that is required. Table 3 contains all the costs related to the energy system. The investment cost of the system was provided by the manufacturer. A lifespan of 20 years was assumed for this kind of system. Therefore, it is expected to be replaced one time and to have a positive final value at the end of the 30 years of calculation period. The cost for the installation of the system in the building was taken from real estimates provided by a local firm. The energy prices were set according to the current French tariffs. Among the electricity fees, the double-time band was chosen, as it is the most used in residential buildings. The annual maintenance costs were assumed equal to the average value reported in the annex A of the Standard EN 15459.

*Table 3. Costs related to TS 1. **ñVarò** indicates the Variable costs depending on building configuration*

Description		**Unit cost CU [ú]**	**Unit number**	**CI [ú]**	**Lifespan [years]**	**Disc. Rate R_d**	**Replacement Cost CR [ú]**	**Final Value V_f [ú]**
All-in-one system TS1	*Supply*	14000	1	14000	20	0.46	6440	2170
	Installation	450	2 (workdays)	900	20	0.46	414	140

Description		**Unit cost**	**Total cost in 30 years [ú]**
Maintenance		2.5% CI [ú]	6441
Energy cost: Electricity	*Night (10pm ï 7am)*	0.0567 [ú/kWh]	Var = $Q_{electricity\_night}$*0.0567*17.29
	Day (7am ï 10pm)	0.0916 [ú/kWh]	Var = $Q_{electricity\_day}$*0.0916*17.29
	Contract and taxes	0.0228 [ú/kWh]	Var = $Q_{electricity\_tot}$*0.0228*17.29

4.2 Technical system #2: traditional all-electrical system

The energy system #2 (called TS 2) is another all-electrical energy system. It represents the typical traditional French heating system and is composed of electric radiators for heating and multi-split system for cooling. No mechanical ventilation system was considered, therefore the ventilation and infiltration rate (fixed to 0.7 ach) was supposed to be supplied directly through window opening throughout the all year. The heating efficiency (ɖ) of this electrical energy system is expected to be equal to 1, it means that the heating energy need is equal to the annual heating energy use (6).

$$Q_{heating\_use} = \frac{Q_{heating\_need}}{\eta} = \frac{Q_{heating\_need}}{1} = Q_{heating\_need} \text{ [kWh/year]} \quad (6)$$

Otherwise, the efficiency of the cooling system (EER) is assumed to be equal to 3 in the calculation of the energy use (7).

$$Q_{cooling\_use} = \frac{Q_{cooling\_need}}{EER} = \frac{Q_{cooling\_need}}{3} \text{ [kWh/year]} \quad (7)$$

As in the previous case, the primary energy consumption is computed with a conversion factor of 2.58 for electricity (8).

$$Q_{primary\ energy\ consumption} = \frac{(Q_{heating\_use} + Q_{cooling\_use}) \times 2.58}{Area} \text{ [kWh/m}^2\text{year]} \quad (8)$$

All these equations were inserted in the TRNSYS model through some equation types. The values of annual energy use was taken as an input for a "Costs" equation type, where the part of the Global cost related to the energy consumptions was calculated and added to other costs. All the costs related to the energy system are shown in Table 4.

*Table 4. Costs related to TS 2. **ñVarò** indicates the Variable costs depending on building configuration*

Description		**Unit cost CU [ú]**	**Unit number**	**CI [ú]**	**Lifespan [years]**	**Disc. Rate R_d**	**Replacement Cost CR [ú]**	**Final Value V_f [ú]**
Radiator (P=0.5 kW) TS2	*Supply*	300	Var = int($Pmax_{heat}$/0.5)+1	Var = n*300	20	0.46	Var = IC*0.46	Var = IC*0.16
	Installation	450	2 (workdays)	900	20	0.46	414	140
Fans (P=2.5 kW) TS2	*Supply*	1500	Var = int($Pmax_{cool}$/2.5)+1	Var = n*1500	15	0.56	Var = IC*0.56	0
	Installation	450	0.5 (workdays)	225	15	0.56	126	0

Description		**Unit cost**	**Total cost in 30 years [ú]**
Maintenance		2.5% CI [ú]	6441
Energy cost: Electricity	*Night (10pm ï 7am)*	0.0567 [ú/kWh]	Var = $Q_{electricity\_night}$*0.0567*17.29
	Day (7am ï 10pm)	0.0916 [ú/kWh]	Var = $Q_{electricity\_day}$*0.0916*17.29
	Contract and taxes	0.0228 [ú/kWh]	Var = $Q_{electricity\_tot}$*0.0228*17.29

The investment costs related to radiators and multi-splits are taken from estimates provided by a French firm, while other costs related to maintenance and energy prices are considered equal to those set for TS 1. However, the total investment cost (and thus the replacement cost and the final value) of radiators and chillers is not fixed, but it depends on the maximum heating/cooling capacity required throughout the yearly simulation. The maximum heating capacity P_{max} is obtained through an iterative process in TRNSYS that allows to compare the required capacity in each timestep (P_{ts}) to the previous stored value ($P_{max,old}$) and to replace the old value only if the current value is higher. At the end of simulation, the maximum value results as stored under the P_{max} variable.

$$P_{max} = \max(P_{ts}, P_{max,old}) \cdot P_{max} + \max(P_{ts}, P_{max,old}) \cdot P_{max,old} \quad [kW] \qquad (9)$$

The Eq. (9) is entered in the model through an equation type, where P_{ts} and $P_{max,old}$ are respectively taken as inputs from the outputs of type 56 (Multi-zone building) and type 93 (Input value recall). The so obtained maximum capacity is then divided by the capacity of a

standard electrical radiator (0,5 kW), in order to determine the required number of radiators n_{rad} for supplying the heating demand (10).

$$n_{rad} = \left\lfloor \frac{P_d}{0{,}5} \right\rfloor + 1 \tag{10}$$

A similar procedure is used to determine the number of splits for supplying the cooling demand. The total investment cost is then determined by multiplying the number of elements (radiators or splits) for the related unit cost. The installation cost does not change, as suggested from market estimates, because the variation in the number of elements to install is not expected to be high enough to cause significant variations in the total installation costs.

4.3 Technical system #3: condensing boiler and multi-split system

The third selected energy system is composed by a gas condensing boiler for heating and a multi-split system, the same used for TS 2, for cooling.
The gas condensing boiler was modeled by calculating its instant efficiency (η_t) as a function of the design heating capacity (P_d), the instant required heating capacity (P_t) and the design efficiency (η_d) of the boiler. Given that the design efficiency was set to 0.95, the resulting part load efficiency was calculated for each timestep as follows (11)

$$\eta_t = \eta_d \cdot PLF \tag{11}$$

where the part load factor (PLF) is a function of the part load ratio (PLR), according to the equation (12), reported in [6]

$$PLF = 1.103 + 4.096 \cdot PLR - 1.896 \cdot PLR^2 + 2.162 \cdot PLR^3 - 7.791 \cdot PLR^4 \tag{12}$$

The PLR depends on the design power and the instant power of the boiler (13).

$$PLR = \frac{P_t}{P_d} \tag{13}$$

In the present study, the design heating capacity for the gas boiler is considered equal to 10 kW. A fixed design heating capacity was chosen, as it is expected that in the case of a

single family building, in the current French market context, the variation of the required heating capacity related to the variation of parameters is not high enough to require changes in the boiler size. Moreover, most of the market boilers for this building type have an adjustable capacity from 4kW to 15kW without significant cost variations.

Given that the efficiency is a time step variable, the annual heating energy use is calculated as follows (14).

$$Q_{heating\_year} = \sum_{heating} \frac{Q_{heating\_hourly}}{\eta_{h}} \qquad \text{[kWh/year]} \qquad (14)$$

Therefore, the primary energy for heating is calculated using the French primary energy conversion coefficient for gas fuel, which is equal to 1 (15).

$$Q_{heating\ primary\ energy} = \frac{Q_{heating\_year} \times 1}{Area} \qquad \text{[kWh/m}^2\text{year]} \qquad (15)$$

The cooling primary energy was calculated as in previous case. Table 5 reports the all costs related to the described system.

Table 5. Costs related to TS 3. ñVarò indicates the Variable costs depending on building configuration

Description		**Unit cost CU [ú]**	**Unit number**	**CI [ú]**	**Life-span [years]**	**Disc. Rate R_d**	**Replacement cost CR [ú]**	**Final Value V_f [ú]**
Condensing boiler (P = 4 -15 kW) + radiant floor TS3	*Supply (boiler)*	7178	1	7178	20	0.46	3301	1112
	Supply (floor)	978	1	978	20	0.46	450	152
	Installation	450	5 (workdays)	2250	20	0.46	1035	349
Fans (P=2.5 kW) TS3	*Supply*	1500	Var = $int(Pmax_{cool}/2.5)+1$	Var = n*1500	15	0.56	Var = IC*0.56	0
	Installation	450	0.5 (workdays)	225	15	0.56	126	0

Description		**Unit cost**	**Total cost in 30 years [ú]**
Maintenance		2.0% CI [ú]	Var = $CI_{boiler+floor+fan}$*0.02*17.29
Energy cost: Electricity	*Night (10pm ï 7am)*	0.0567 [ú/kWh]	Var = $Q_{electricity\_night}$*0.0567*17.29
	Day (7am ï 10pm)	0.0916 [ú/kWh]	Var = $Q_{electricity\_day}$*0.0916*17.29
	Contract and taxes	0.0228 [ú/kWh]	Var = $Q_{electricity\_tot}$*0.0228*17.29
Energy cost: Gas	*Night and day*	0.0567 [ú/kWh]	Var = Q_{gas_tot}*0.0570*17.29
	Contract and taxes	0.0228 [ú/kWh]	Var = Q_{gas_tot}*0.0228*17.29

4.4 Technical system #4: wood-pellet boiler and multi-split system

A wood-pellet boiler for heating is included in the last selected energy system. The same multi-split system used in TS 2 and TS 3 provides cooling energy. In order to calculate the energy use, a fixed value of efficiency was set equal to 85 %, which is equal to the annual average efficiency of a standard wood-pellet boiler. Therefore, the energy use is calculated as follows (16).

$$Q_{pellet\_tot} = \frac{Q_{pellet\_tot}}{\eta} = \frac{Q_{pellet\_tot}}{0{,}85} \text{ [kWh/year]} \qquad (16)$$

The primary energy for heating is calculated using the French primary energy conversion coefficient for biomass, which the RT 2012 set equal to 1.

The cooling primary energy was calculated as in previous case, using the coefficient 2.58.

Table 6 shows all the costs related to the technical system #4 (TS 4).

The calculation of the energy cost related to wood-pellets started from a market analysis leading to determine that the average cost of a 15 kg sack of pellets is around 5 ú. Therefore, the cost of 1 kg of pellets is around 0,33 ú. Given that, according to the efficiency of the selected boiler, the combustion of 1 kg of pellets produces 5 kWh of thermal energy, the cost of one kWh is around 0,07 ú/kWh. Other costs are calculated as in previous cases.

*Table 6. Costs related to TS 4. **ñVarò** indicates the Variable costs depending on building configuration*

Description		**Unit cost CU [ú]**	**Unit number**	**CI [ú]**	**Lifespan [years]**	**Disc. Rate R_d**	**Replacement Cost CR [ú]**	**Final Value V_f [ú]**
Pellet boiler (P= 2-10 kW) and pipes TS4	*Supply*	7788	1	7788	20	0.46	3582	1207
	Installation	450	2 (workdays)	900	20	0.46	414	140
Fans (P=2.5 kW) TS2	*Supply*	1500	Var = int($Pmax_{cool}$/2.5)+1	Var = n*1500	15	0.56	Var = IC*0.56	0
	Installation	450	0.5 (workdays)	225	15	0.56	126	0

Description		**Unit cost**	**Total cost in 30 years [ú]**
Maintenance		2.5% CI [ú]	6441
Energy cost: Electricity	*Night (10pm ï 7am)*	0.0567 [ú/kWh]	Var = $Q_{electricity\_night}$*0.0567*17.29
	Day (7am ï 10pm)	0.0916 [ú/kWh]	Var = $Q_{electricity\_day}$*0.0916*17.29
	Contract and taxes	0.0228 [ú/kWh]	Var = $Q_{electricity\_tot}$*0.0228*17.29
Pellet	*Material*	0.0700 [ú/kWh]	Var = Q_{pellet_tot}*0.0700*17.29

5 The envelope systems and their cost functions

The described energy systems were combined with three envelope systems (ESs).

The first (ES 1) corresponds to the envelope of the actual Reference Building, described in section 2. The second (ES 2) was created by changing the order of the wall layers of ES 1, placing the insulation on the external side. This may produce a variation in energy consumptions due to a higher amount of internal inertial mass. Roof and slab are the same as in ES 1. The ES 3 uses the Oriented Strand Board system for external walls and roof: the insulated wooden panel layer, having the same thickness of the blocks layer of envelope systems 1 and 2 (20 cm), is completed with an additional exterior insulation package. The aim is to evaluate the difference between a massive envelope (like ES 1 or ES 2) and a light envelope. The slab of ES 3 is equal to the previous ones.

Within the cost-optimal methodology, the selection of Energy Efficiency Measures concerning the building envelope may consist in changing the whole envelope technology, but also in varying construction elements and properties. Therefore, in this study, the energy efficiency measures within the same envelope system are expressed through parameters identifying the geometry features or the construction features that are able to influence the final energy need of the building. These parameters are referred to the insulation thickness of the external walls, the roof and the slab (parameters ResO, ResR, ResS), the window type in different orientations (parameters WT, WTS and WTR) and the window dimensions (parameters Bm, Blr and Hr), as represented in Figures 5 and 6. The range and the step of their variation were set according to regulation requirements (e.g. the minimum window area was set to the limit imposed by the French national regulation), technical feasibility (e.g. the maximum insulation thickness was set to the current technical practice) and market criteria (e.g. the window types were selected among those available on the French market).

The variation of the building parameters produces not only the variation of costs related to energy (intended as the sum of costs concerning the energy system and the energy consumptions) but also the variation of the initial investment costs related to the building construction. Replacement costs are not considered for building construction elements, as their lifetime is supposed to be equal to the calculation period.

In order to calculate and evaluate the Global Cost function at each TRNSYS simulation, the GenOpt-TRNSYS system has to be able to calculate the investment cost related to the selected values of parameters. Therefore, in order to be able to assess the contribution of each

parameter to the global cost calculation, a cost function was associated to each parameter of each envelope system and the investment cost term *CI* of equation (1) can be re-written as

$$CI = \sum_{i=1}^{n} f_i(p_i) \tag{16}$$

where p_i is the parameter and f is the cost function related to the same parameter p_i. Details about the complete process for determining the cost functions can be found in [11]. The specifications of the parameters related to the opaque envelope are reported in Table 7, while those related to the transparent envelope are reported in Table 8.

Table 7. Settings and cost functions for the opaque envelope parameters for each ES

	Parameter name and description	**Unit**	**Min**	**Max**	**Step**	**RB**	**Related cost function [ú]**
ES1	*ResO - Thermal resistance of wall internal insulation*	[m^{2}Kh/kJ]	0.25	5.00	0.25	1.75	$C_{resO\,wall} = (37.639 \cdot R_{resO}^{0.000} + 92.25) \cdot A_{resO\,wall}$
	ResR - Thermal resistance of roof insulation layer	[m^{2}Kh/kJ]	0.50	5.00	0.25	3.50	$C_{resR} = (43.478 \cdot R_{resR}^{0.000} + 105.30) \cdot A_{resR}$
	ResS - Thermal resistance of slab insulation layer	[m^{2}Kh/kJ]	0.25	3.00	0.25	2.50	$C_{resS} = 38.115 \cdot R_{resS}^{0.000} \cdot A_{resS}$
ES2	*ResO - Thermal resistance of wall external insulation*	[m^{2}Kh/kJ]	0.25	2.25	0.25	1.75	$C_{resO\,wall} = (82.481 \cdot R_{resO}^{0.000} + 66.57) \cdot A_{resO\,wall}$
	ResR - Thermal resistance of roof external insulation	[m^{2}Kh/kJ]	0.50	5.00	0.25	3.50	$C_{resR} = (43.478 \cdot R_{resR}^{0.000} + 105.30) \cdot A_{resR}$
	ResS - Thermal resistance of slab insulation layer	[m^{2}Kh/kJ]	0.25	3.00	0.25	2.50	$C_{resS} = 38.115 \cdot R_{resS}^{0.000} \cdot A_{resS}$
ES3	*ResO - Thermal resistance of wall additional insulation*	[m^{2}Kh/kJ]	0.25	2.25	3.00	1.75	$C_{resO\,wall} = (109.75 \cdot R_{resO}^{0.000} + 83.66) \cdot A_{resO\,wall}$
	ResR - Thermal resistance of roof additional insulation	[m^{2}Kh/kJ]	0.50	3.00	0.25	2.25	$C_{resR} = (53.729 \cdot R_{resR}^{0.000} + 42.31) \cdot A_{resR}$
	ResS - Thermal resistance of slab insulation layer	[m^{2}Kh/kJ]	0.25	3.00	0.25	2.50	$C_{resS} = 38.115 \cdot R_{resS}^{0.000} \cdot A_{resS}$
ES1 ES2 ES3	*Blr - Ground floor south window width (h= 2.15 m)*	[m]	2.20	7.80	0.20	4.20	*All the opaque envelope cost functions depends on these parameters, since* $A_{resO\,wall}$, A_{resR} *and* A_{resS} *results from the difference between the entire envelope area and the wall area.* *Also the window cost functions (see Table 8) depend on the window area, which is related to these parameters.*
	Bm - First floor south window width (h= 0.80 m)	[m]	0.20	7.80	0.20	2.20	
	Hr - Roof window height (w= 2.28 m)	[m]	0.00	4.72	0.59	4.72	

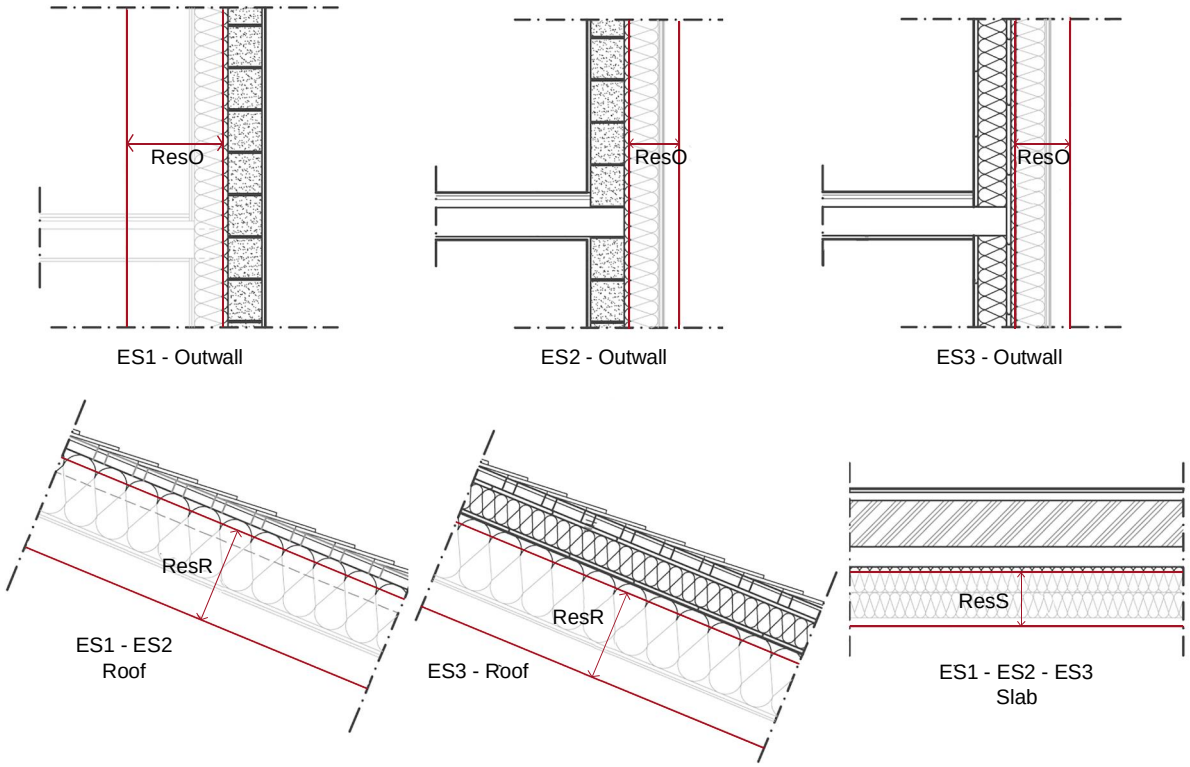

Figure 5. Representation of the opaque envelope parameters for each Envelope System

Table 8. Settings and cost functions for the transparent envelope parameters for each ES

	Name	**Description**	**U-value [W/(m²K)]**	**g-value**	**Related cost function [ú]**		
	1	*4/16/4 - Double glazing*	2.00	0.70	$\text{ú}_{\text{g g}} = 349 \cdot \text{ú}_{\text{g g}} + 28$		
	2	*4/16/4 - Double glazing, low-e with Argon*	1.43	0.58	$\text{ú}_{\text{g g}} = 390 \cdot \text{ú}_{\text{g g}} + 29$		
	3	*4/16/4/16/4 - Triple glazing*	0.70	0.50	$\text{ú}_{\text{g g}} = 454 \cdot \text{ú}_{\text{g g}} + 36$		
	4	*4/16/4/16/4 - Triple glazing, with Argon*	0.40	0.40	$\text{ú}_{\text{g g}} = 470 \cdot \text{ú}_{\text{g g}} + 36$		
	Window parameter name and description		**Unit**	**Min**	**Max**	**Step**	**RB**
ES1, ES2, ES3	*WT*	*- Window Type of North - East -West walls*	-	1	4	1	3
	WTS	*- Window Type of South wall*	-	1	4	1	3
	WTR	*- Window Type of Roof*	-	1	4	1	3

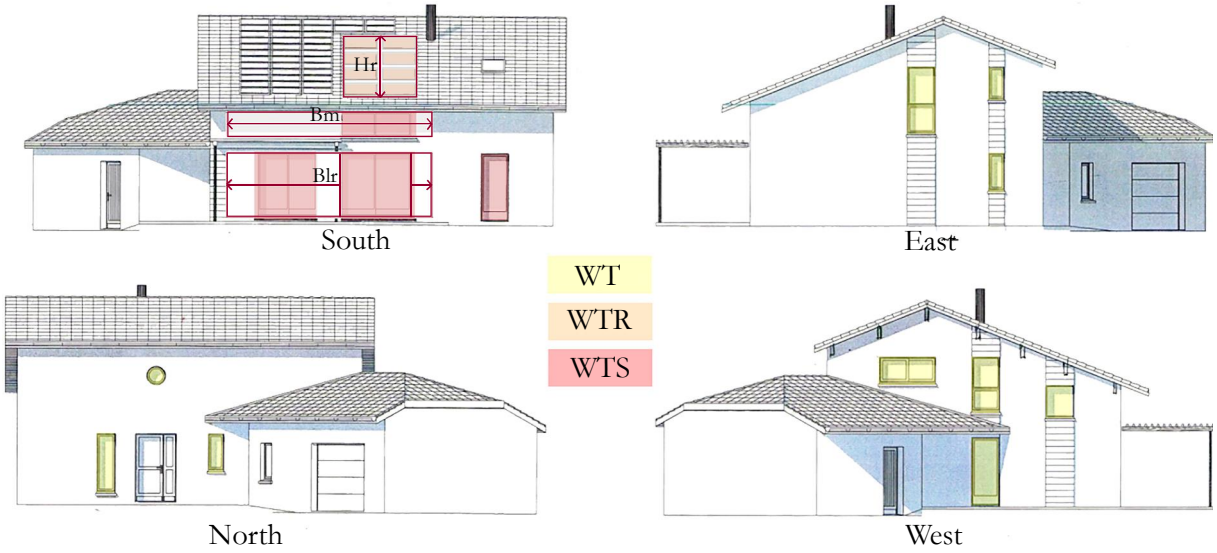

Figure 6. Fronts of the case study building with representation of the transparent envelope parameters

6 Results

Results are presented into two types of diagrams. The first type (e.g. Figure 7) reports on the horizontal axis the energy performance, expressed in kWh of annual primary energy need per square meter of conditioned floor area, and on the vertical axis the global cost, expressed in euros per square meter of conditioned floor area. In these graphs, each point represents one building configuration that refers to one ES/TS combination having a different set of parameter values. The points representing the different sets of parameter values related to the same combination of ES and TS are clustered in clouds, where points have the same color and shape (e.g. Figure 8). The color of points indicates the envelope system, while the shape of points indicates the technical system. The point corresponding to the lowest cost in each cloud represents the cost-optimal point (OPT), which corresponds to the package of measures where the design can be considered cost-optimized. The name of these points includes two digits, the first indicating the ES number and the second reporting the TS number, and a letter, indicating the reference location (e.g. the point OPT-2.1-A indicates the cost-optimal point of the combination of ES 2 and TS 1 in Ambérieu-en-Bugey, while the point OPT 3.4-M indicates the cost-optimal point related to ES 3 and TS 4 in Marseille).

The second type of diagrams reports the set of parameter values of these relevant points (e.g. Figure 9). On horizontal axis, the different parameters are reported, while the vertical axis reports the percentage value indicating the variations in energy needs (heating and cooling, without considering the energy system) produced by the variation of one parameter at a time, when all others are fixed to their reference value. The black horizontal line, corresponding to a percentage variation of 0, indicates the set of reference values of parameters that are reported in the ñRBò column of Table 6. Positive values of percentage correspond to the increase of energy performance with respect to the reference case (a better energy energy performance is intended as a lower total primary energy demand for heating and cooling, as calculated with equations (4) and (14), depending on the primary energy conversion factors), while negative values correspond to a lower energy performance related to higher primary energy consumptions. On these axes, the colored profiles report the set of parameter values composing the cost-optimal points, giving a synthetic representation about the role of the cost-driven variation of each parameter in the increase or decrease of the total energy performance with respect to the RB configuration.

The analysis was conducted in progressive steps, presented in the following sections. Results related to the building located in Ambérieu-en-Bugey are firstly discussed and then compared with the results obtained for the same building located in Marseille.

6.1 The influence of the energy system on the reference building configuration

Starting from the reference configuration of the case study building, as presented in section 2, the differences in Global Cost and Energy performance due to the sole variation of the energy system with respect to the reference building configuration (ES 1, set of parameter values reported in the ñRBò column of Table 6) were identified.

The reported variations in percentages are referred to the RB configuration with TS 1. Since TS 1 is the most efficient energy system among those selected, it is clear that, for the fixed reference envelope design, the primary energy need increases when using less efficient systems. These results show a linear correlation between the energy performance decrease and the global cost decrease. However in some cases, such as those concerning TS 3, the variation of the system does not produce significant variations in terms of global cost, while it highly increases the energy needs.

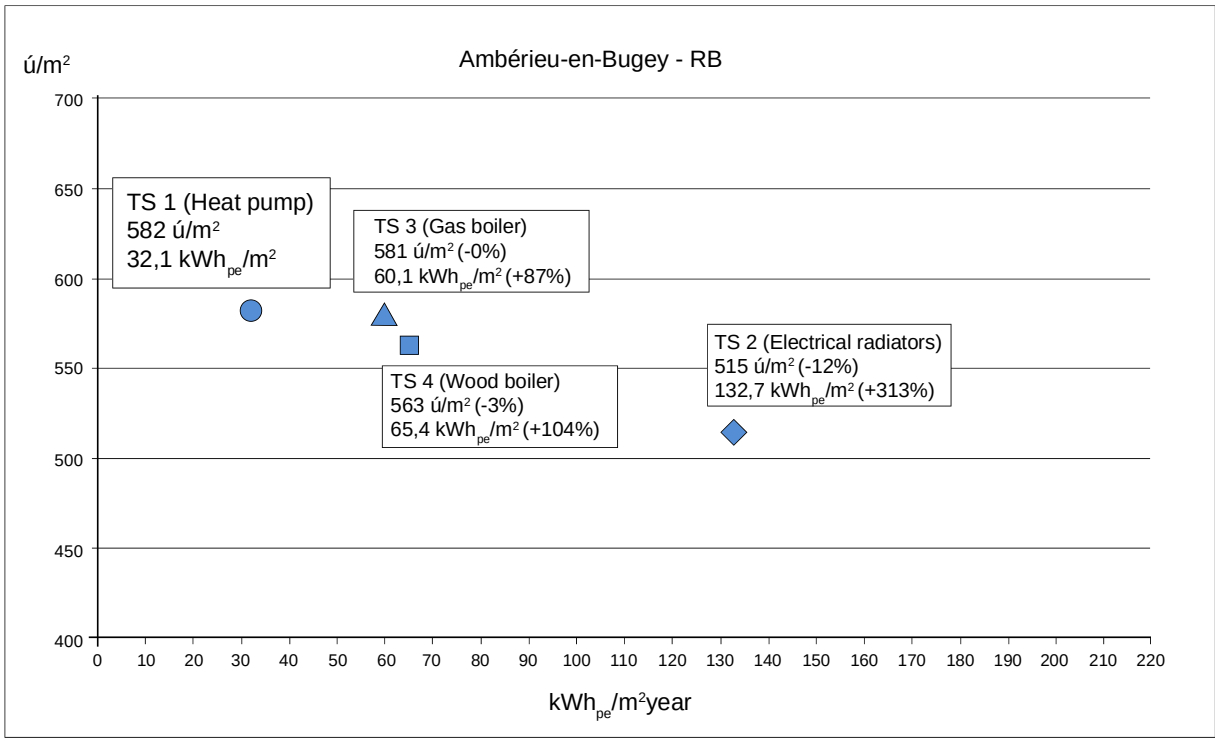

Figure 7. Differences in global cost and energy performances of the reference building envelope configuration (RB - ES 1 ï Ambérieu-en-Bugey)

6.2 The influence of the energy system on the design of massive outside insulated envelope

The results related to the cost optimization of ES 1 for the four TSs are compared and, based on Figure 8, some considerations concerning the shape of the clouds can be done. As shown,

the width of the clouds is different when passing from a high performing system, such as TS 1 (the 1.1 cloud has a width of 40 kWh_{pe}/m^2), to the 4-times less performing TS 2 (the width of the 1.2 cloud is almost 100 kWh_{pe}/m^2). It means that the same variations in building design may double their impact on the building energy performance when combined to a low efficient energy system with respect to a high-efficient energy system.

When exploring the points within the cloud, it can be seen that the cost-optimal points have different locations inside the clouds: if the point OPT_1.1 is located in the right part of the pertinent cloud, towards higher energy performances, the point OPT_1.2 is in the left part of the related cloud. This indicates the higher weight of the building operational costs, which is directly related to the building energy performance, when the energy system is less efficient.

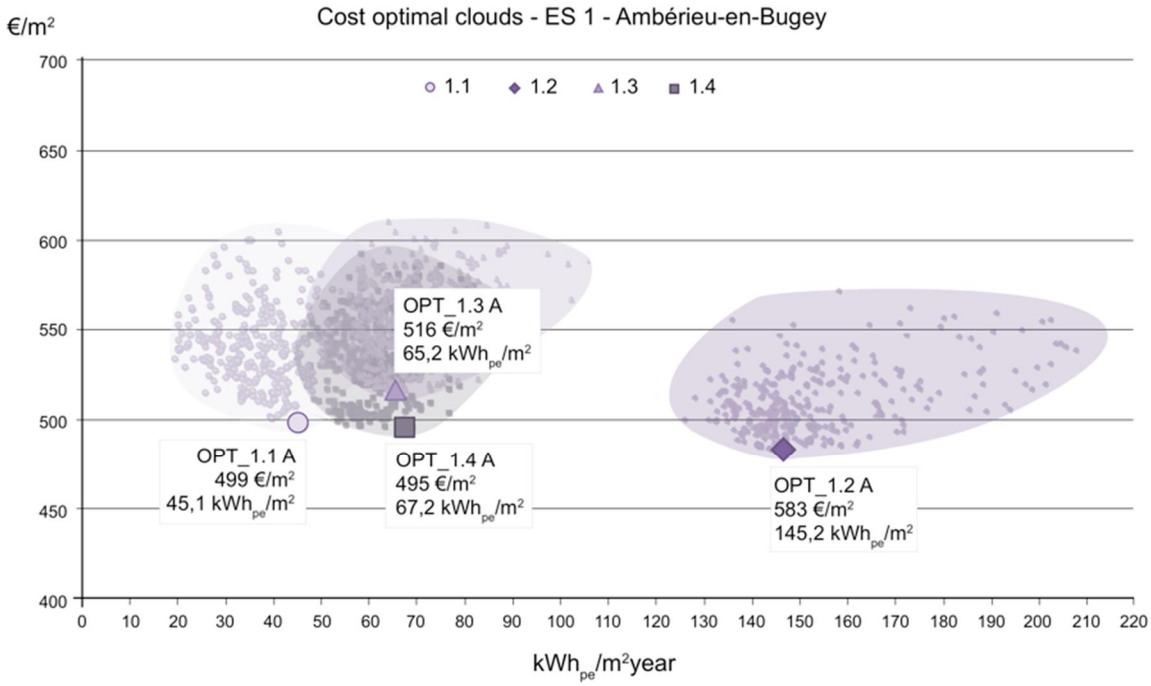

Figure 8. Cost-optimal clouds related to ES 1 combined to the four TSs, with indications of the cost-optimal points (Ambérieu-en-Bugey)

This becomes clear when entering inside the set of parameters values composing the cost-optimal points (Figure 9). In fact, the profile OPT_1.2 indicates a building design with high level of insulation in both opaque and transparent envelope, while the profile OPT 1.1 is attested at low insulation levels, demonstrating that in this last case the influence of the investment costs on the global cost is bigger than that of the operational costs. The other profiles lay in the middle. The window dimension parameters are all set to their minimum values in all cases.

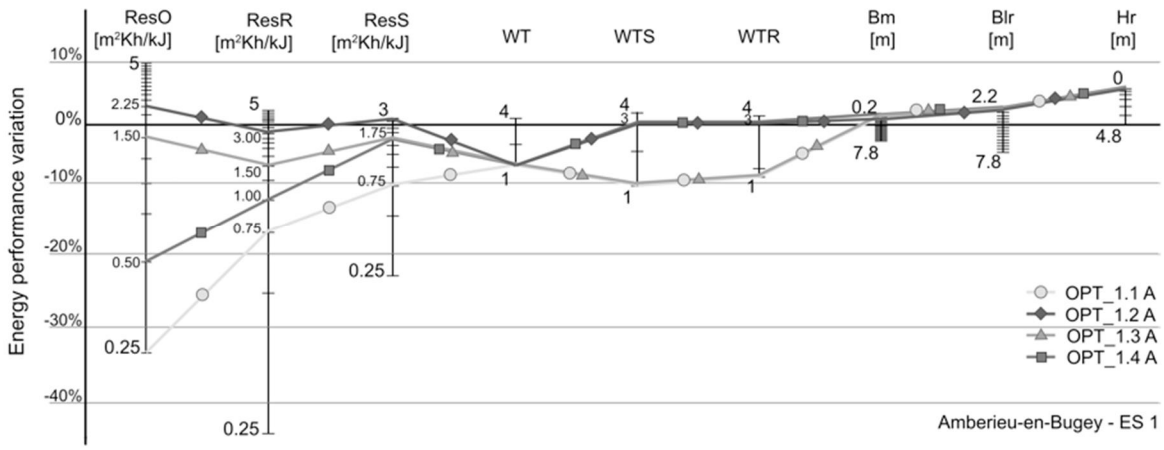

Figure 9. Profiles reporting the set of parameters values for each cost-optimal point related to ES 1

When comparing the four cost-optimal points, the lowest global cost is related to OPT_1.2, which is associated to a very high annual primary energy demand. However, it is possible to strongly reduce this demand with a little increase in global cost, when choosing other energy systems and the related cost-optimized design of the building, such as for points OPT_1.4 (the global cost increase is equal to 12 ú/m^2 but the energy demand reduction is equal to 78 kWh$_{pe}$/m^2) or better the points OPT_1.1 (16 ú/m^2 of global cost increase for 100.1 kWh$_{pe}$/m^2 of energy demand reduction), which is the closest to the target nZEB.

6.3 The influence of energy system on the design of massive inside insulated envelope

The insulation layer on the external side of this envelope system causes higher variable investment costs and lower fixed investment costs (see cost functions in Table 7) and adds an higher inertial effect that, despite an annual energy performance similar to the one of ES 1, modifies the daily profiles of energy demand and causes variations in energy costs due to the double band tariff (Tables 2,3,4,5). This leads to different balances between investment and operational costs when calculating the cost-optimal points.

As shown in Figure 10, the shape and width of the clouds are quite similar to the corresponding clouds resulted from optimization of ES 1 (Figure 8). However, the position of the cost-optimal points within the clouds and their related set of parameter values changes.

In fact, as shown in Figure 11, the point OPT_2.1 is associated to very low values for both the groups of parameters related to the opaque and the transparent envelope (the only exception is represented by the value ñ4ò for the parameter WT, indicating high performing windows for north, east and west orientations). The profiles of points OPT_2.2, OPT_2.3 and OPT_2.4 are

quite similar. The lowest global cost between the four cost-optimal points is represented by the point OPT_2.1, whose high performing energy system is associated to a very low-insulated envelope.

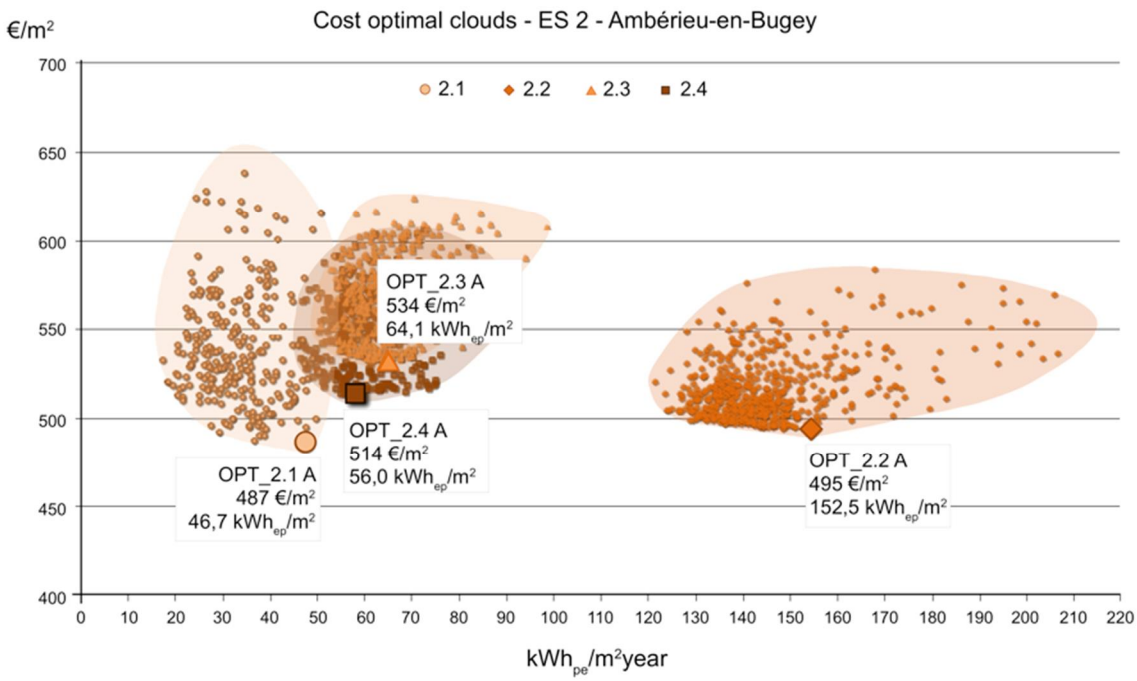

Figure 10. Cost-optimal clouds related to ES 2 combined to the four TSs, with indications of the cost-optimal points (Ambérieu-en-Bugey)

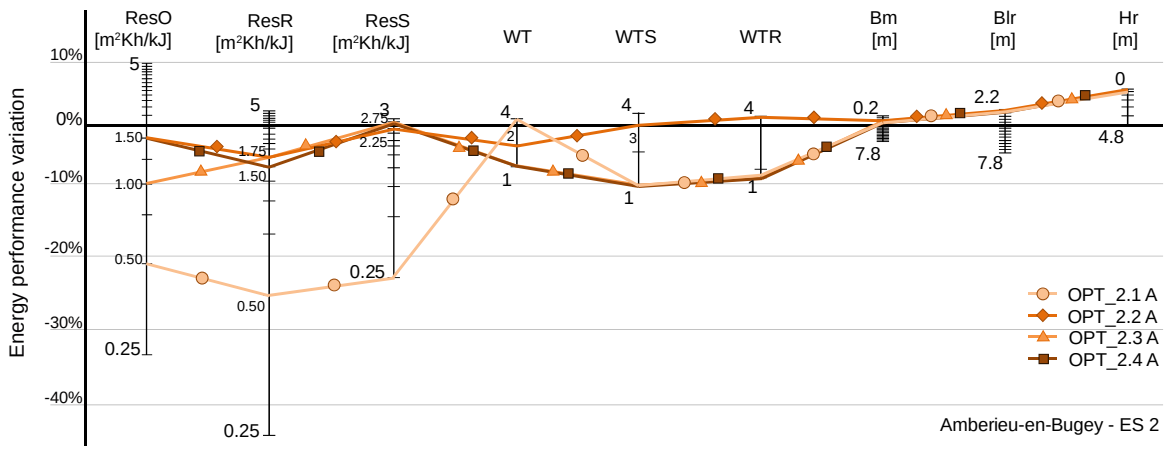

Figure 11. Profiles reporting the set of parameters values for each cost-optimal point related to ES 2

6.4 The influence of energy system on the design of light mass envelope

This envelope system (high insulation with light mass) is less subject to the effect of the inertial mass, with consequences on operational energy costs. Moreover, the cost functions

related to the external wall and the roof are steeper than for the others envelope system, leading to high investment costs. This is the reason why the clouds in Figure 12 have a greater height than the clouds related to the other ESs.

The parameters ResO and ResR present their minimum values (see Table 7) in all profiles in Figure 13, indicating that for the cost-optimized design of this envelope system the additional external insulation is no more required (see the wall and roof construction in Figure 3). However, the values of parameters related to the windows design are different in all profiles, leading to different combinations of glazing type and opening dimensions (see details in Figure 13). The TS 1 leads to a building cost-optimal configuration (OPT_3.1) that has medium performance windows in all orientations, with the smallest possible values for parameters Hr and Blr but the highest possible value for parameter Bm. Small and high performing windows are associated to the low-efficient TS 2 (OPT_3.2), while the optimal design with TS 3 (OPT_3.3) requires small and low performance windows in all orientations except for the south windows, where the window type 4 should be used. The TS 4 leads to a building cost-optimal configuration (OPT_3.4) with high performing windows with big dimensions (the parameter Bm is set to its maximum value).

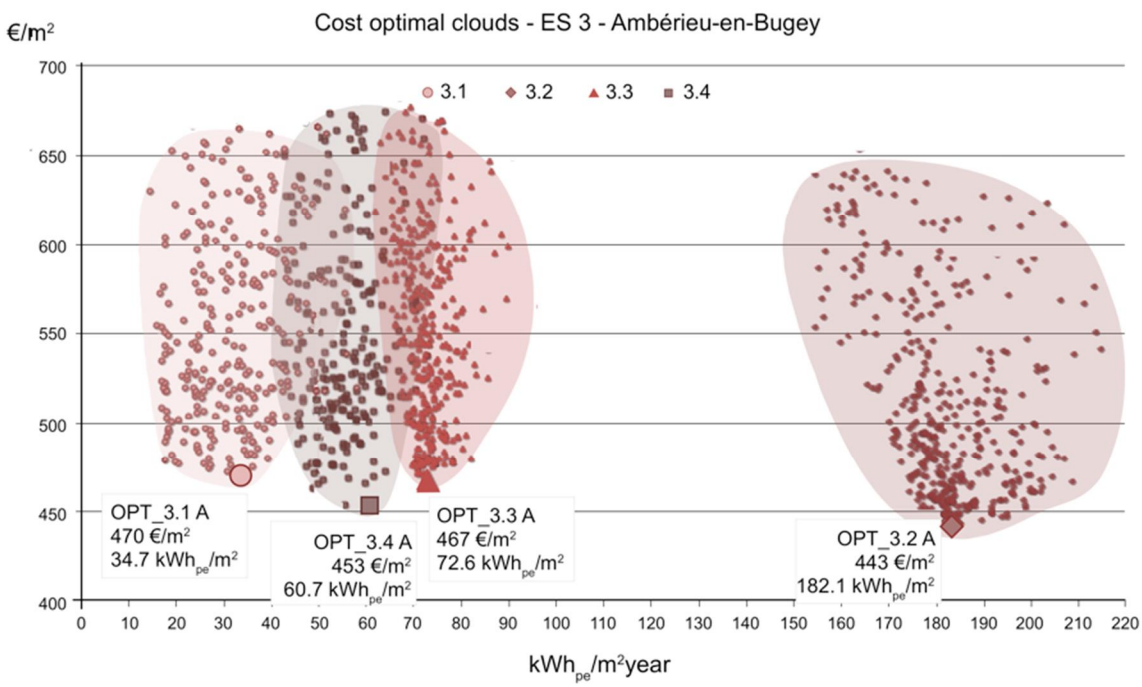

Figure 12. Cost-optimal clouds related to ES 3 combined to the four TSs, with indications of the cost-optimal points (Ambérieu-en-Bugey)

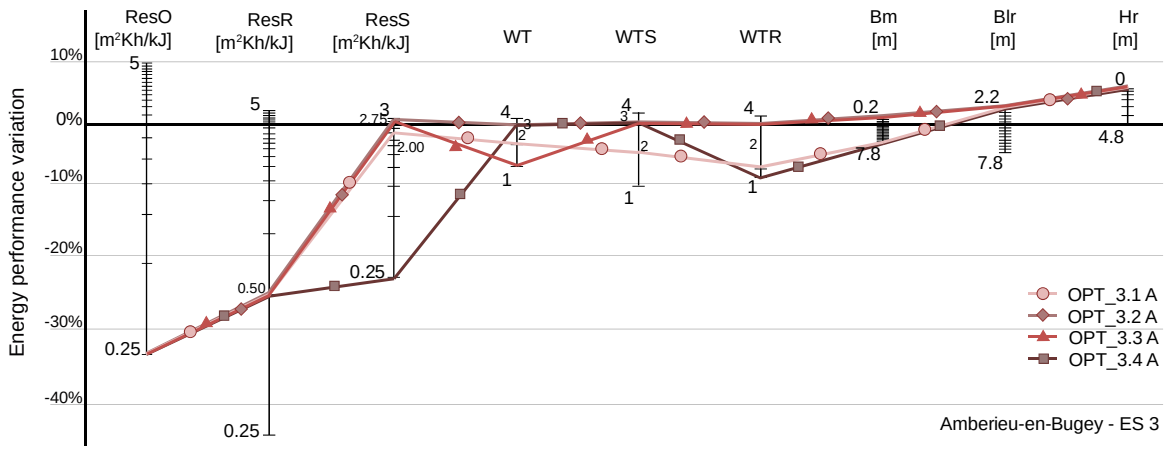

Figure 13. Profiles reporting the set of parameters values for each cost-optimal point related to ES 3

6.5 *The influence of energy system on the design in a different climate condition*

As mentioned above, the same optimization procedure shown in the previous sections was performed for the same building located in Marseille, in order to appreciate and quantify the differences in the results related to warmer weather conditions.

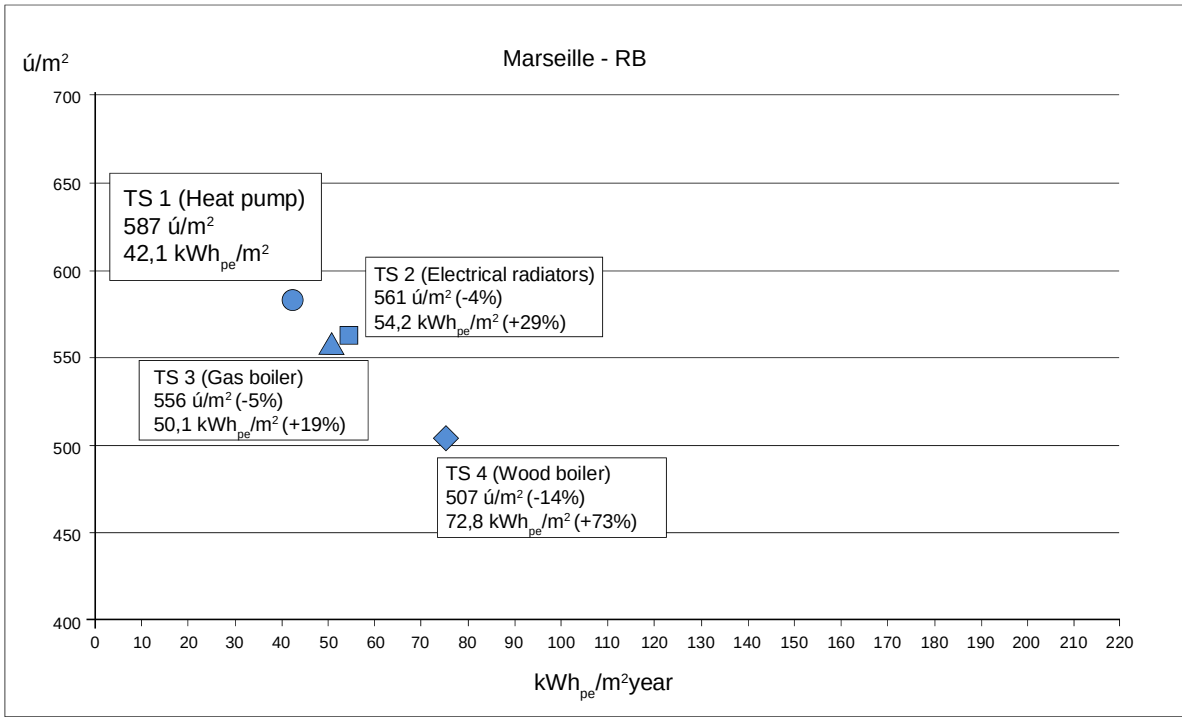

Figure 14. Differences in global cost and energy performances of the reference building envelope configuration (RB ï ES 1 - Marseille)

The Figure 14 reports the global costs in relation to the energy performances of the reference building configuration (RB - ES 1 M) with the four TSs. If the global cost decreases following a trend similar to that in Figure 7, the distance between the highest and the lowest

annual primary energy demand is reduced from more than 100 kWh_{pe}/m^2 (Ambérieu, Figure 7) to around 40 kWh_{pe}/m^2 (Marseille, Figure 14).

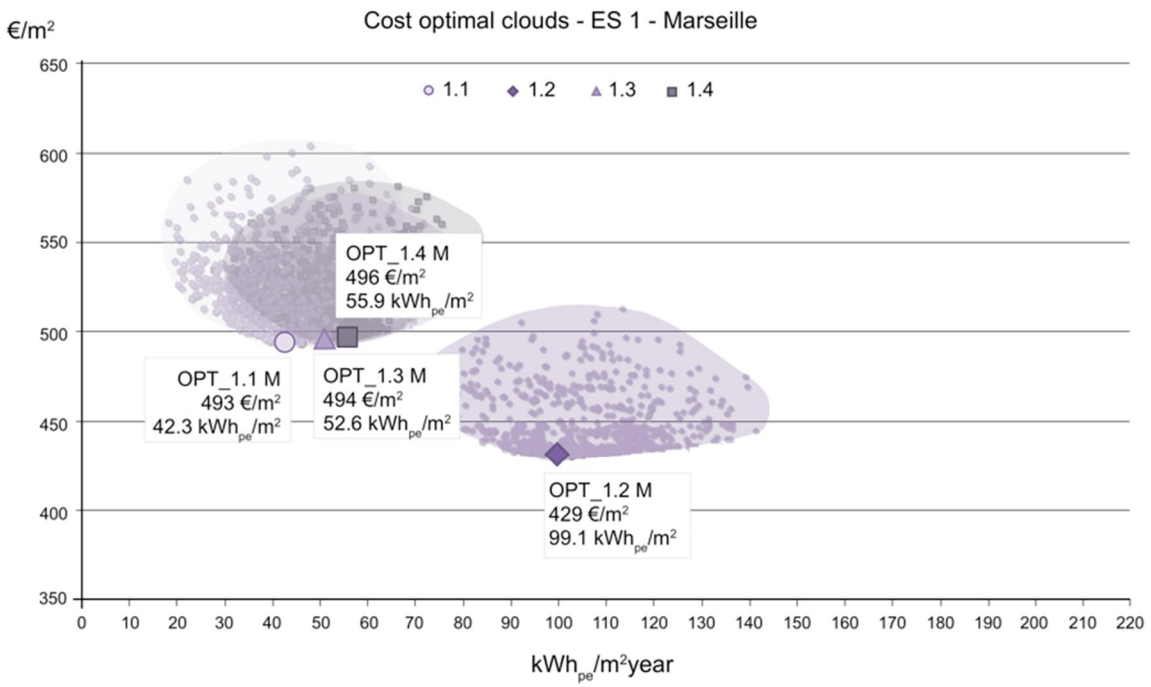

Figure 15. Cost-optimal clouds related to ES 1 combined to the four TSs, with indications of the cost-optimal points (Marseille)

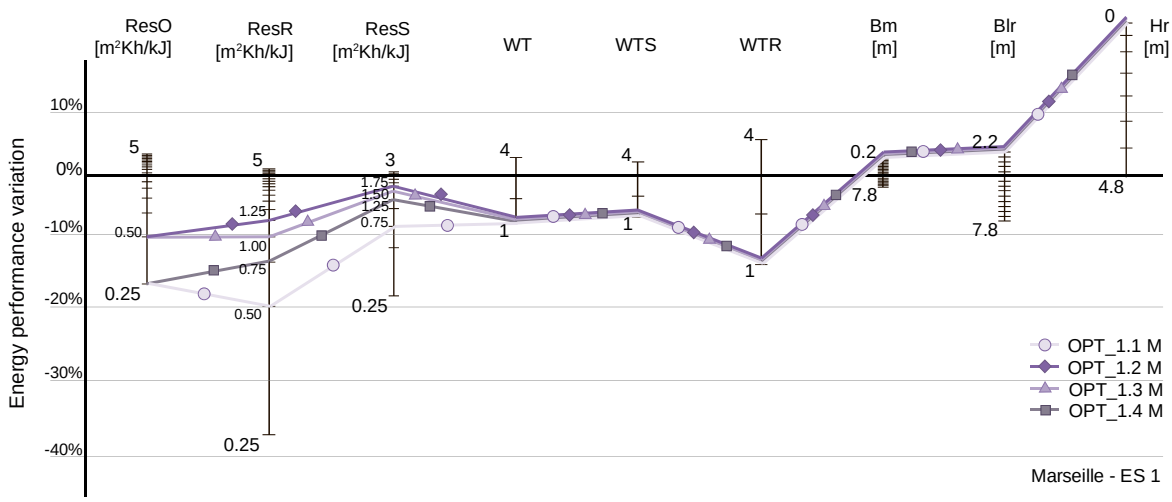

Figure 16. Profiles reporting the set of parameters values for each cost-optimal point related to ES 1

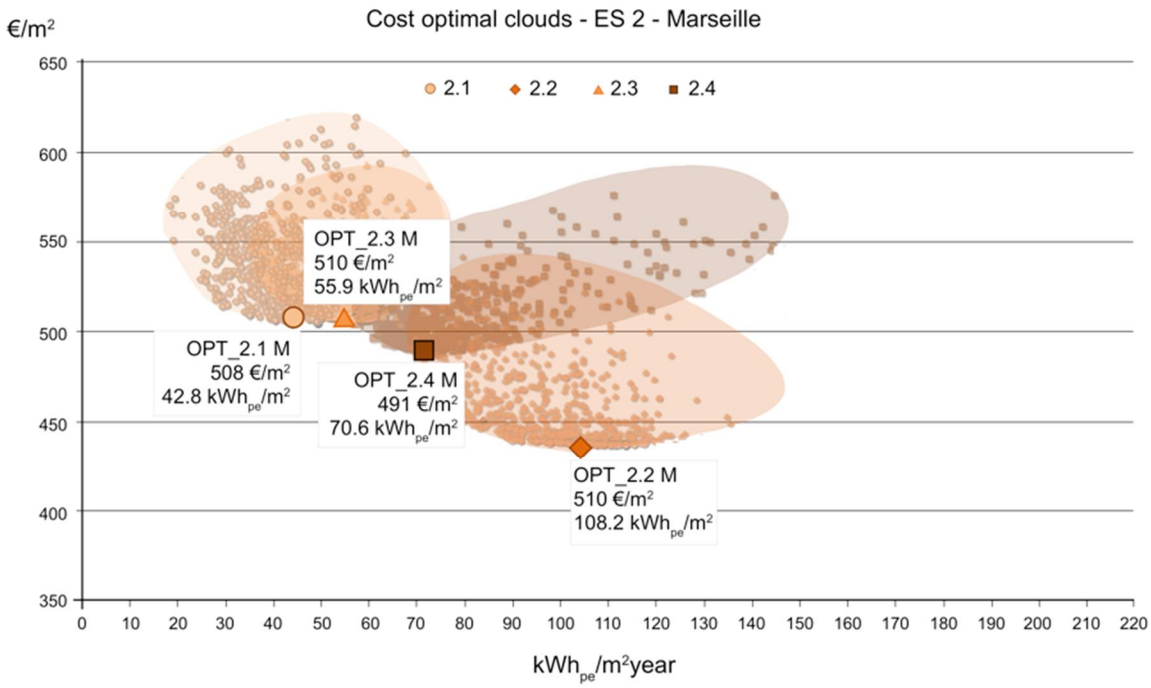

Figure 17. Cost-optimal clouds related to ES 2 combined to the four TSs, with indications of the cost-optimal points (Marseille)

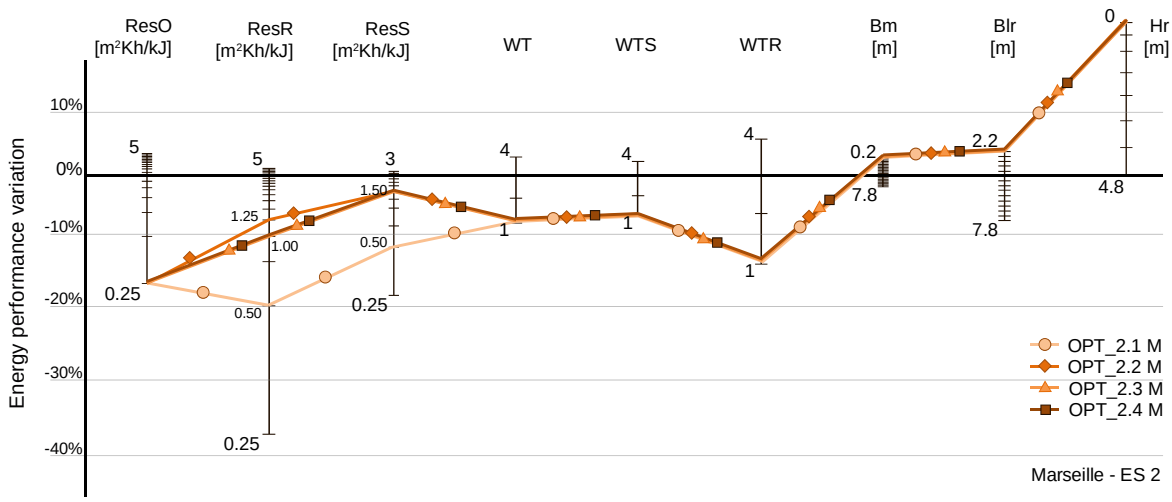

Figure 18. Profiles reporting the set of parameters values for each cost-optimal point related to ES 2

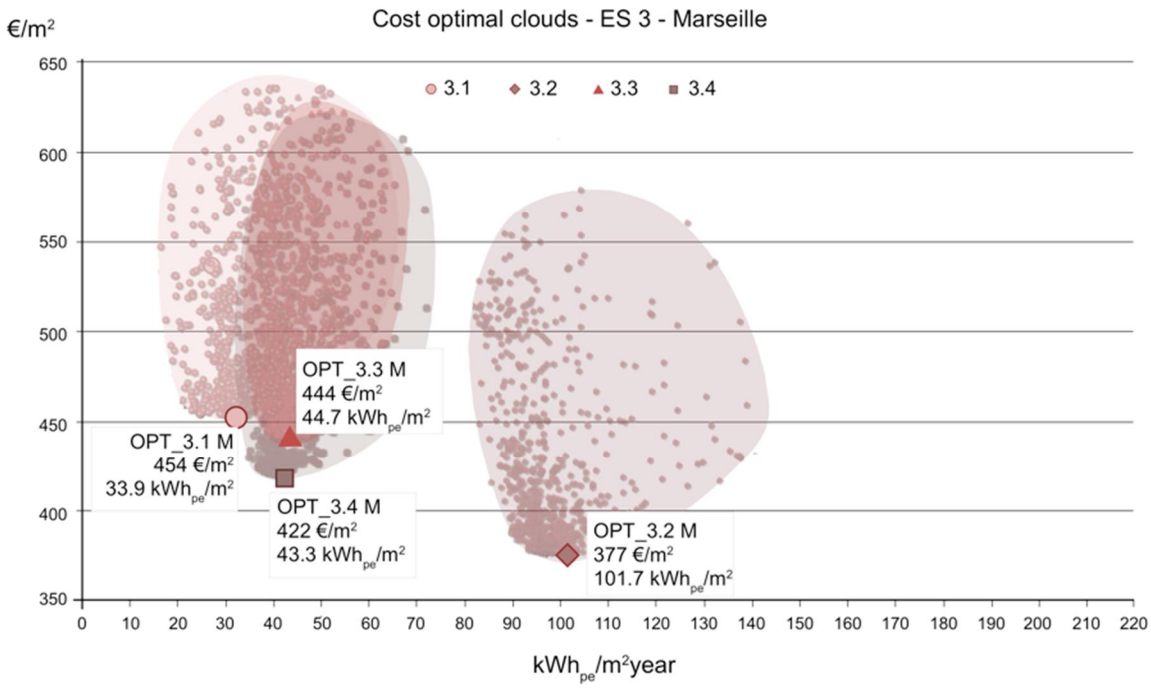

Figure 19. Cost-optimal clouds related to ES 3 combined to the four TSs, with indications of the cost-optimal points (Marseille)

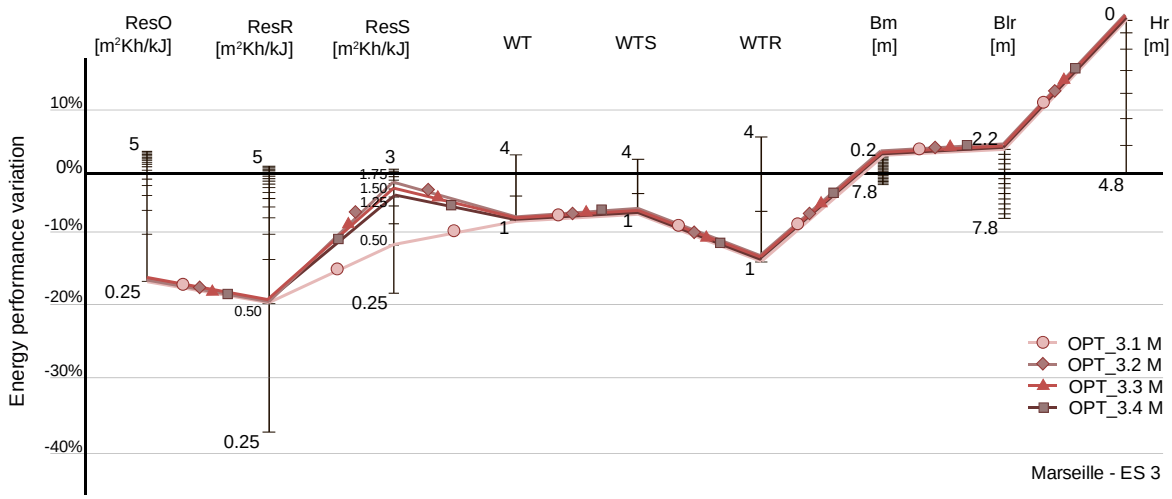

Figure 20. Profiles reporting the set of parameters values for each cost-optimal point related to ES 3

As shown in Figures 15, 17 and 19 (Marseille) all the global cost values of cost-optimal points are lower than the corresponding values in Figures 8, 10 and 12 (Ambérieu), and for all ESs in Marseille the energy system leading to the lowest global cost is TS 2, that is related to the highest annual primary energy demand, far from the ZEB target. When moving towards higher energy performances (lower energy needs), the global cost strongly increases.

Moreover, in Marseille the influence of the variation of each parameter on the global energy performance changes, as shown in Figures 16,18 and 20 by the vertical axes corresponding to each parameter. In particular, the influence of parameters related to the opaque envelope decreases while the impact of parameters related to the transparent envelope increases.
In the mentioned figures, when comparing the profiles of the cost-optimal points resulting from the optimization of the 12 ES/TS combinations in Marseille, the parameters related to the transparent envelope assume the same values in all profiles, that is low-performance windows (parameters WT, WTS, WTR) having the smallest possible dimensions (parameters Bm, Blr, Hr). The only differences concern the parameters related to the opaque envelope, as it is shown that the more efficient the energy system is, the lower values the parameters assume, similarly to the results referred to Ambérieu. In all cases, however, the cost-optimal building configurations in Marseille are less insulated that the corresponding configurations in Ambérieu.

7 Conclusions

This study demonstrated the nZEB design is strictly related to the building energy system. In fact, only using an appropriate system [31] it is possible to efficiently design and operate a ZEB.

First of all, it was found that in cost-optimal diagrams the selected energy system determines the position of the ñcloudò of possible design options on the energy performance axis. Then, only in case the energy system allows reaching high performances in terms of primary energy, a good design of the envelope can further move the design solution close to the ZEB target, while locating the design options in the low part of the cost-optimal cloud, where the global cost is minimized.

Moreover, this study highlighted the fact that the envelope design cannot be done disregarding the energy system selection since the early design stage, especially when looking for cost-optimal solutions, which result from a balance between the investment costs and the operational costs that are affected by both the envelope and the energy system.

In summary, this study demonstrated that the less performing the energy system, the more performing envelope design is associated to the cost-optimal points. This is more evident when the compared energy systems use the same energy source, as TS 1 (all-in-one packaged system) and TS 2 (all-electrical traditional energy system) in this study, because of the same unit cost of energy. In presence of a low performance of the energy system that leads to higher operational costs, it becomes profitable over the calculation period to invest in a very-high performing envelope.

In other cases, the differences in global costs related to different energy systems are due not only to the different performance of the system, but also to the different energy sources, such as in case of TS 3 (gas boiler) and TS 4 (pellet boiler).

Besides, it can be noted that significant reductions in primary energy use can be found with a small increase of the global cost, while there is still a large gap between the cost-optimal level and the global cost related to the zero-energy point.

The comparison of the results related to the two different climate conditions proved again the strict correlation existing between the nZEB design and the local scale. In fact, the same energy system can have a different impact on the envelope design of the same building in different locations, affecting not only the amount of heating and cooling energy for satisfying the annual needs of the building, but also the daily distribution of loads and the consequent differences in costs due to the currently used time-based energy tariff.

In conclusion, this study demonstrated that a good nZEB design can only result from the simultaneous optimization of the many involved design variables, among which the energy system plays a fundamental role, and proposes a modelling and simulation tool and a methodology for addressing the optimization problem and quantify that role.

As a further development, a sensitivity analysis will be performed, in order to evaluate the robustness of the results under uncertainty related to future environmental, social and financial scenarios. Moreover, some investigations will be done concerning the optimization algorithm used in the methodology proposed in this work, in order to define which are the parameters values for the PSO algorithm leading to better and faster convergence to the solution of the problem of the cost-optimal search. Also, other algorithms will be implemented and adapted to support the nZEB optimization problem, in order to optimize the proposed automated methodology.

Nomenclature

Acronyms

EPBD	Energy Performance of Buildings Directive
ES	Envelope System
HVAC	Heating, Ventilation and Air Conditioning system
nZEB	nearly zero-energy building
PSO	Particle Swarm Optimization algorithm
RB	Reference Building
TS	Technical System

Latin letters

A	Area (m^2)
Blr	Width of the window at the ground floor on the south façade (m)
Bm	Width of the window at the first floor on the south façade (m)
C_a	Annual cost (ú)
C_G	Global Cost (ú)
CI	Investment cost (ú)
COP	Coefficient of Perfomance (-)
CR	Replacement cost (ú)
EER	Energy Efficiency Ratio (-)
EP	Energy Performance (kWh/m^2)
f_{pv}	Present Value factor (-)
Hr	Roof window height (m)
p	Parameter
s	Parameter variation step
Q	Energy consumption (kWh)
R	Thermal resistance (m^2K/W)
R_d	Discount rate (-)
ResO	Thermal resistance of the wall insulation layer (m^2Kh/kJ)
ResR	Thermal resistance of the roof insulation layer (m^2Kh/kJ)
ResS	Thermal resistance of the slab insulation layer (m^2Kh/kJ)
Var	Variable value
V_f	Final value (ú)
WT	Window Type of North - East -West walls (-)

WTR	Window type of roof (-)
WTS	Window Type of South wall (-)
U	Thermal transmittance (W/m²K)

Subscripts

o	Outwall
r	Roof
s	Slab
w	Window

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