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Appraising the effect of the primary systems on the cost optimal design of nZEB: A case study in two different climates

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Abstract

The work concerns the application of the cost-optimal methodology to a low-consumption French single-family house in order to study how the primary energy system influences the envelope design of a cost optimal nZEB. This is done applying a simulation based optimization method that combines TRNSYS with GenOpt in an iterative process. Four primary energy systems were considered (a gas condensing boiler, a wood boiler, an all-electrical radiator system and a combined reversible air to air heat pump) and the optimization was performed in two different French locations (Amberieu-en Bugey and Marseille).

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Keywords: simulation-based optimization method; primary systems; cost optimal analysis; nZEB.

1. Introduction

It is well known that the design of an nZEB [1] consists in two steps: first, minimizing the energy demand of the building, which depends, for given boundary conditions (weather, orientation, building typology), on the building envelope geometry and construction; second, minimizing the building primary energy demand by 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.

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In [2] a simulation based optimization method was set out and applied to a French case study in order to study the nZEB design from the cost perspective, by combining the energy efficiency measures related to the envelope design and others related to the energy systems. There are other papers dealing with the cost optimal analyses of specific systems [3,4], however they are not focused on the effect that the primary system has on the cost optimal solution. As a further step of research in the context of the cost optimal analysis, this paper aims at studying:

- how the selection of a specific energy system affects the cost optimal level of 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 building global cost, evaluating both the investment cost and the operational cost, in different climate conditions.

2. Methodology

The study was conducted within the framework of the Cost Optimal methodology set out by the EPBD recast and the pertinent Guidelines [5]. In particular, full details of the various steps of the methodology and of the calculation of the global cost over a 30-year period as applied by the Authors can be found in [2].

The optimization problem can be stated as finding the values to assign to design parameters such that the global cost is minimized. The parameters are subject to the constraints given by their minimum and maximum values and the building energy simulation tool. The optimization problem is solved using iterative methods driven by optimization algorithms that construct sequences of progressively better approximations to the solution point satisfying an optimality condition within the search-space. In this work, the coupling of the TRNSYS® building dynamic simulation program with the Generic Optimization program GenOpt® was performed. In order to solve this problem, among the optimization algorithms available in GenOpt, the particle swarm optimization (PSO) was chosen. It is a population-based probabilistic optimization algorithms first proposed by Kennedy and Eberhart [6] to solve problems with possibly discontinuous objective function, as the Global Cost function is.

3. The case study building and the design options

The case study building is a two-floor residential building situated in Ambérieu-en-Bugey, in the French region of Rhône-Alpes. The house can be considered as representative of new construction of high-performing single-family house in this French region and it was taken as the case study. The conditioned volume has a Surface-to-Volume ratio equal to $0.68m^{-1}$. The conditioned floor area is equal to 155 m^2. The case study building was described in its real configuration in [2], however different envelope technologies can be applied to this real case study. In the present paper the envelope system #2 (ES2) was selected, which corresponds to an externally insulated massive envelope technology. In the initial building configuration (called RB in Table 1), the external walls are composed by 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 includes 40 cm of insulation (R = 12.5 m^2K/W) and the floating slab incorporates 30 cm of insulation material (R = 9.3 m^2K/W). 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. The majority of large openings are south-oriented. The window area is approximately 1/5 of the floor area. A roof overhang protects the south-oriented windows in summer periods.

The case study building is equipped with an all-in-one energy system, which is composed by a mechanical dual flow ventilation system combined to a cross flow heat exchanger and an air-air reversible heat pump. Before entering this system, the air is pre-treated by a geothermal heat exchanger. The detailed operation and the performances of this system are described in [7].

3.1. The envelope design parameters and costs

The energy efficiency measures indicating design options related to this envelope system are expressed in this study through parameters identifying geometry features or construction features that are able to influence the final energy need of the building. These are referred to the insulation thickness of the outwall, 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). The range and the step of their variation (Table 1) were set according to regulation requirements (e.g. the minimum window area is set to the limit imposed by the French national regulation), technical feasibility (e.g. the maximum insulation thickness is set to the current technical practice) and market criteria (e.g. the window types are selected among those available on the French market). The investment cost functions related to the parameters, derived from French market prices, are also reported in Table 1.

Table 1. Parameter definition and related cost functions

Parameter name and description		Min	Max	Step	RB	Related cost function [€]
ResO -Thermal res. of wall insulation	[m^{2}Kh/kJ]	0.25	2.25	0.25	1.75	$CI_{outwall2} = (82.481 \cdot ResO^{0.164} + 66.57) \cdot A_{outwall}$
ResR - Thermal res. of roof insulation	[m^{2}Kh/kJ]	0.50	5.00	0.25	3.50	$CI_{roof2} = (43.478 \cdot ResR^{0.309} + 105.30) \cdot A_{roof}$
ResS - Thermal res. of slab insulation	[m^{2}Kh/kJ]	0.25	3.00	0.25	2.50	$CI_{slab2} = 38.115 \cdot ResS^{0.186} \cdot A_{slab}$
Blr - South window 1 width (h=2.15m)	[m]	2.20	7.80	0.20	4.20	
Bm - South window 2 width (h= 0.80 m)	[m]	0.20	7.80	0.20	2.20	The opaque envelope cost functions depend on these window dimension parameters, since $A_{outwall}$, A_{roof} and A_{slab} results from the difference between the entire envelope area and the wall area.
Hr - Roof window height (w= 2.28 m)	[m]	0.00	4.72	0.59	4.72	
WT- Window Type North-East-West	-	1	4	1	3	
WTS - Window Type South	-	1	4	1	3	The window cost functions depend on the window type and window dimension parameters.
WTR - Window Type of Roof	-	1	4	1	3	

Window description	U-value [W/(m^{2}K)]	g-value	Related cost function [€]
1 - 4/16/4 -Double glazing	2.00	0.70	$CI_{W1} = 349 \cdot A_{w2} + 29$
2 - 4/16/4 -Double glazing, low-e,Argon	1.43	0.58	$CI_{W2} = 390 \cdot A_{w2} + 29$
3 - 4/16/4/16/4 - Triple glazing	0.70	0.50	$CI_{W3} = 454 \cdot A_{w3} + 36$
4 - 4/16/4/16/4 - Triple glazing, Argon	0.50	0.40	$CI_{W4} = 470 \cdot A_{w4} + 36$

3.2. The primary systems

As already presented, this work is focused on how the energy system design variable affects the other variables related to the building envelope and geometry. In order to perform this study, four primary systems (also called technical systems -TSs) were selected among those currently used in France and modeled in TRNSYS. These are:

- Primary system #1 – reversible heat pump and mechanical ventilation [7];
- Primary system #2 – traditional all-electrical system;
- Primary system #3 – condensing boiler and multi-split system;
- Primary system #4 – wood-pellet boiler and multi-split system.

The first selected energy system, called TS1, is the one currently installed in the RB and described in section 2. This packaged all-in-one system uses electricity for all its function, including heating, cooling and ventilation. Therefore, in order to obtain the final consumption in terms of primary energy, the final energy consumption has to be multiplied by the French primary energy conversion coefficient, which is equal to 2.58. The initial investment cost of TS1 is 14000 €, its lifespan is 20 years and the annual maintenance cost is 2.5% of investment cost. The electricity price was set equal to the current double band French tariff (0.0567 €/kWh$_{day}$ and 0.0916 €/kWh$_{night}$).

Primary system #2 (TS2) is another all-electrical energy system, but its performances are much lower than in previous case. It represents the typical traditional French heating system and is composed by electric radiators for heating and a 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 with external air. The heating efficiency (η) of this electrical energy system is expected to be close to 1. The initial investment cost of TS2 is 500 € for each kW of required power, its lifespan is 20 years and the annual maintenance cost is 2.5% of investment cost.

Primary system #3 (TS3) is composed by a gas condensing boiler for heating and the same multi split system already used in the previous case for cooling. The gas condensing boiler was modeled by calculating its instant efficiency as a function of the design heating capacity, the instant required heating capacity and the design efficiency of the boiler (set to 0.95) by means of performance curves. The initial investment cost of TS3 is 9500 €, its lifespan is 20 years and the annual maintenance cost is 2.0% of investment cost. The gas price is 0.0567 €/kWh.

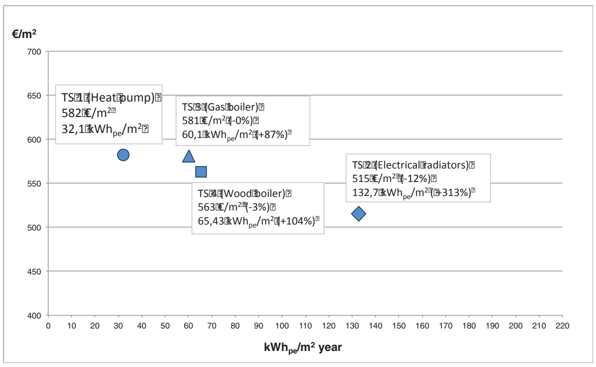
A wood-pellet boiler for heating composes the last selected energy system (TS4). Cooling is provided by the same multi-split system used in previous cases. In order to calculate the energy consumption, a fixed value of efficiency is set, which is equal to the annual average efficiency of a standard wood-pellet boiler: 85%. The assumed initial investment cost of TS4 is 9500 €, its lifespan is 20 years and the annual maintenance cost is 2.5% of investment cost. The price of the TS4 fuel (pellet) was assumed to be 0.07 €/kWh.

4. Results

The four energy systems (TSs) were associated to the envelope systems (ES2) into 4 combinations. For each of these combinations, the optimization process was performed and the sets of parameter values composing the 4 cost optimal building configurations were found. The analysis was conducted for the case study building located in two different French regions corresponding to different climate conditions: Amberieu-en-Bugey and Marseille. The first is a low altitude area with temperate climate, classified by the French thermal regulation RT2012 as a H1c zone (2672 dd), the second has a maritime climate and is classified as H3 zone (1627 dd, Cep_{max} = 40 kWh_{pe}/m^2year).

Results are presented into two types of diagrams. The first type (Fig. 1, Fig. 2) 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. Points related to the same combination of ES and TS and only varying the set of parameter are clustered in clouds (Fig. 2), where points have the same color and shape. Circles are referred to points related to TS1, diamonds to TS2, triangles to TS3 and squares to TS4. The point with the lowest cost of each cloud represents the cost optimal point (OPT), whose name includes two digits, the first indicating the ES and the second representing the TS, and a letter, indicating the reference location (e.g. the point OPT-2.1A indicates the cost optimal point of the combination with ES2 and TS1 in Amberieu, while the point OPT 2.4M indicates optimal result related to TS4 in Marseille).

The second type of graphs (Fig. 3, Fig. 4) reports the set of parameter values of these relevant points. They have on the horizontal axis the different parameters and on the vertical axis the percentage value indicating the variation in the total 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 the percentage variation of 0 % indicates the set of the RB reference values of parameters. Positive values of percentage correspond to the increase of energy performance (savings in energy needs with respect to the reference value), while negative values represent the decrease of energy performance. On these axes, the colored profiles report the set of parameter values composing the cost optimal points, giving a synthetic picture 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.



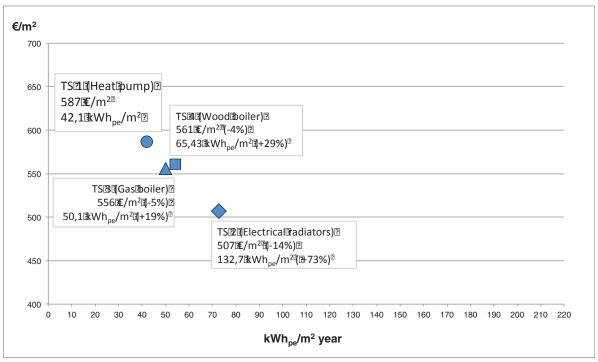


Fig. 1. Differences in global cost and energy performances of the RB case in Ambérieu (left) and Marseille (right).

Starting from the reference configuration of the case study building, the differences in Global Cost and Energy performance due to the sole variation of energy system, were reported in Fig. 1. Since TS1 is the most efficient energy system among those selected, it is clear that, for the fixed reference envelope design, the total primary energy needs increase when using less efficient systems. The results seem to show a linear correlation between the decrease of energy performance and the decrease of global cost. In Marseille the annual energy needs for heating are lower than in Ambérieu, while cooling needs are higher. If the global cost decreases following a trend similar to that of Ambérieu, the distance between the highest and the lowest annual primary energy demand is reduced from more than 100 kWh_{pe}/m^2 to around 40 kWh_{pe}/m^2.

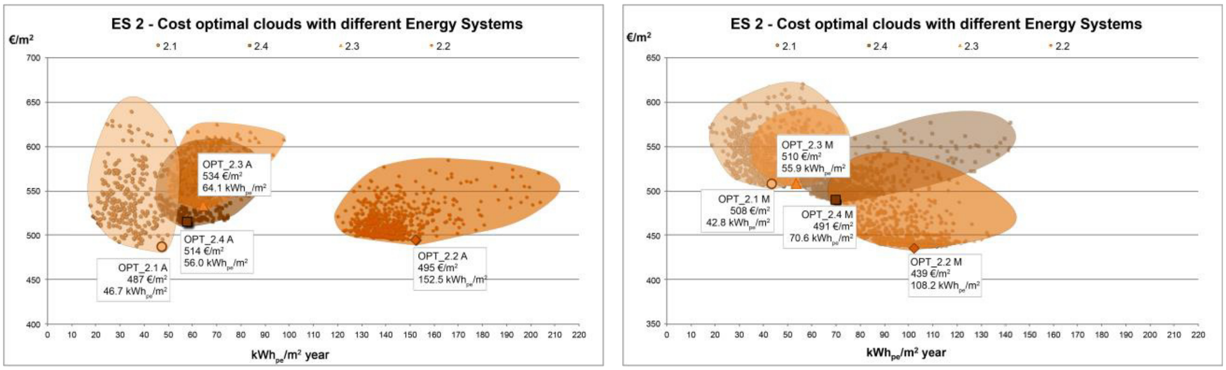


Fig. 2. Cost optimal clouds for each TS with indications of the cost optimal points in Ambérieu (left) and Marseille (right).

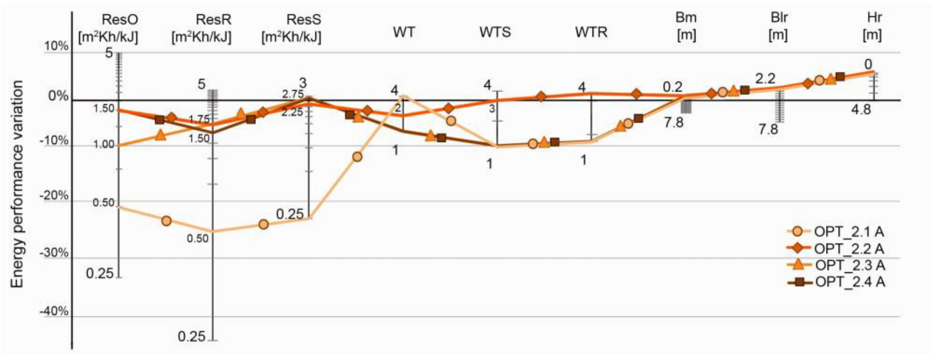


Fig. 3. Profiles reporting the set of parameters values for each cost optimal point in Ambérieu.

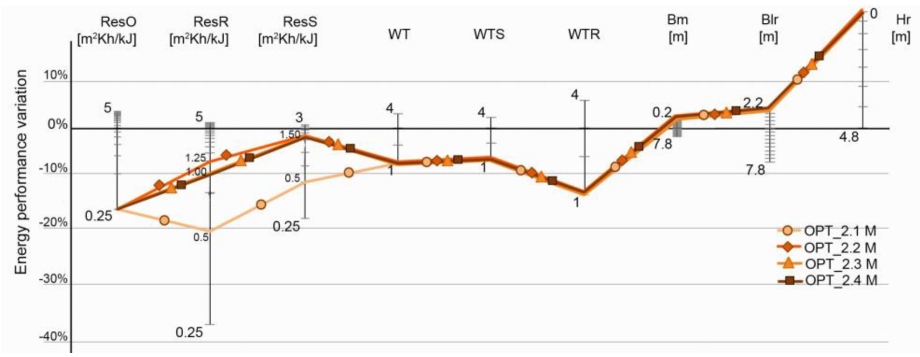


Fig. 4. Profiles reporting the set of parameters values for each cost optimal point in Marseille.

The insulation layer on the external side of the envelope system causes higher variable investment costs and lower fixed investment costs and adds a higher inertial effect that modifies the daily profiles of energy demand and causes variations in energy costs due to the double band tariff. This leads to different balances between investment and operation costs when calculating the cost optimal points. As shown in Fig. 3, the point OPT_2.1A is associated with very low values for both the groups of parameters related to the opaque and the transparent envelopes. The only exception is represented by the value "4" for the parameter WT, indicating high performing windows for north, east and west orientations. The profiles of points OPT_2.2A, OPT_2.3A and OPT_2.4A are quite similar. The only differences are represented by a less insulated outwall for OPT_2.3A and a higher performing windows for OPT_2.2A. The window dimension parameters are all set to their minimum value in all profiles.

When comparing the four cost optimal clouds and their cost optimal points (Fig.2), the lowest global cost is represented by OPT_2.1A, whose high performing energy system is associated to a very low-insulated envelope.

In the case of Marseille (Fig. 4), the influence of parameters related to the opaque envelope decreases while the impact of parameters related to the transparent envelope increases. The parameters related to the transparent envelope assume the same values in all profiles (Fig.4): low-performance windows (value "1" for parameters WT, WTS, WTR) having the smallest possible dimensions (low values for parameters Bm, Blr, Hr). The only differences concern the parameters related to the opaque envelope: the higher efficient the energy systems, the lower parameters values, similarly to the results referred to Amberieu. In all cases, however, the cost optimal building configurations in Marseille are less insulated that the corresponding configurations in Amberieu.

4. Conclusions

This study demonstrated the nZEB design is strictly related to the building primary system. In fact, a key role in the design and operation of ZEBs is played by the system [8]. First of all, it was found that in cost optimal diagrams the selected energy system determines the position of the "cloud" of possible design options on the energy performance axis. Then, only in case the energy system allows to reach high performances in terms of primary energy, a good design of envelope can further move the point representing the building design solution towards a lower energy demand close to the ZEB target, while locating the design options in the low part of the cost optimal cloud, minimizing the global cost. 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 operation costs.

The comparison of the results related to the two different climate conditions proves 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 design of the envelope 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.

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