Modeling zero energy building: technical and economical optimization

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SUMMARY

This study was born in the context of new challenges imposed by the recast of Energy Performance of Buildings. The aim of this work is to provide a useful method to deal with a huge number of simulations corresponding to a large number of single-family house configurations in order to optimize a constructive solution from both technical and economical point of view. The method combines the use of TRNSYS, building energy simulation program, with GenOpt, Generic Optimization program.
The reference building is a low-consumption house case-study situated in Amberieu-en-Bugey, Rhône-Alpes, France. After a short description of the case-study and of TRNSYS model, the link and the configuration files which have been created between the simulation program and the optimization software are illustrated. A first parametric study is performed in order to evaluate the impact of variation of various parameters of envelope and shading elements on the total annual energy consumption for heating and cooling. As a second study, the global cost method is applied to the case-study, and GenOpt is used to determine the cost optimal level of the reference building. Beyond the result, we think this study shows useful method and tools that could support technical and cost optimal level research, providing an easy and fast way to explore various building configuration with a huge number of simulations, as requested by European Standard.

INTRODUCTION

In the context of the European Union efforts to reduce the growing energy expenditure, it is widely recognized that the building sector has an important role, accounting 40% of the total energy consumption in the European Union [1]. The recast of the Directive on the Energy Performance of Building (EPBD)[2] imposes the adoption of measures to improve energy efficiency in buildings in order to reach the objective of all new buildings to be nearly Zero Energy Building (nZEB) by 2020. This practice could lead to greenhouse gas emission reduction in the building sector of 80-90% by 2050. As the results in term of energy efficiency are evaluated at a global (or at least European) scale, it is remarkable that a good nZEB design is strictly related to the local scale, depending on climatic data, available technologies and materials, population lifestyle. Moreover, as usual, measures related to ecological sustainability could not be pursued without taking into account an economical sustainability. It is obvious that the design of a zero-energy building is not yet profitable in terms of costs, and that this will lead to different results depending on the country, the age of the building and its use (commercial buildings, residential, etc.). Consequently, EPBD recast has set out that Member States (MSs) ensure that minimum energy performance requirements are set with a view to achieve the cost optimal level, that is defined as the energy performance

level which leads to the lowest cost during the estimated economic lifecycle. Based on Global Cost method, the aim is to define for each MSs the most effective strategies to improve building performance with the lowest global cost.
In order to develop general strategies, a huge number of case study should be examined and a common method to compare a large number of simulations has to be established.
We have collaborated between France and Italy in order to improve our methodologies and to apply them on the single-family houses, with references buildings, constructive solutions, typical sources of energy accessibility, costs, etc...In the present article we present one carried out with TRNSYS computing environment with a view to establish a procedure for techno-economic optimization using the tool GenOpt.

The reference building.

The Reference Building (RB) is a new single-family house situated in Amberieu-en-Bugey, Rhône-Alpes, France. It is representative of new construction of single family house in the region.
The gross floor area (GFA) of the two floors is equal to 155 m^2 (see plans in figure 2).
It's possible to recognize many design features generally used in passive/low consumption houses: the insulated living space is a cubic compact shape (S/V ratio is equal to about 0,68 m^{-1}, S being the heat losses area and V the heated volume) that minimize the exchange surface between the outside and inside. In order to reduce heat loss due to windows and benefit of solar gains, the maximum of large openings are south-oriented (49% of total glass surface (TGS) on the south external wall, 19% on the south roof slope) while the percentage of openings in east and west orientation is less relevant (respectively 10% and 15% of TGS) and there are only very small north oriented openings (7% of TGS). Window area is approximately 1/5 of the GFA: the minimum imposed by the national regulation [3], which is equal to 1/6 of GFA, is largely exceeded. A roof overhang protects south-oriented windows.

Figure 1. Facades of reference building. a) South, b) North, c) West, d) East.

Thermal insulation is made on the internal side, thereby creating a thermal bridge on the intermediate floor, which has been limited by use of thermal bridge breakers. However, this solution eliminates thermal bridges at the slab and roof levels. At the moment, 20 cm of insulating material are used on external walls, 30 cm on the slab and 40 cm on the roof.

RB was modeled using TRNSYS [4], dynamic building simulation program [5]. Each room was modeled as a thermal zone, in order to better evaluate the evolution of temperature and the thermal exchange from one zone to the other, as the HVAC system is considered active only in the main rooms of the house. Set-point temperature for heating (19°C) and cooling (26°C) was set only in the living-room (PP), in the bedrooms (C1, C2, C3) and in the mezzanine (M), while other zones as restrooms (R1, R2), dressing (D) and passages (DGT1, DGT2) are supposed to take heat (or cool) from transmission through internal walls and doors. Garage (G) and laundry(B) are considered non-conditioned zones.

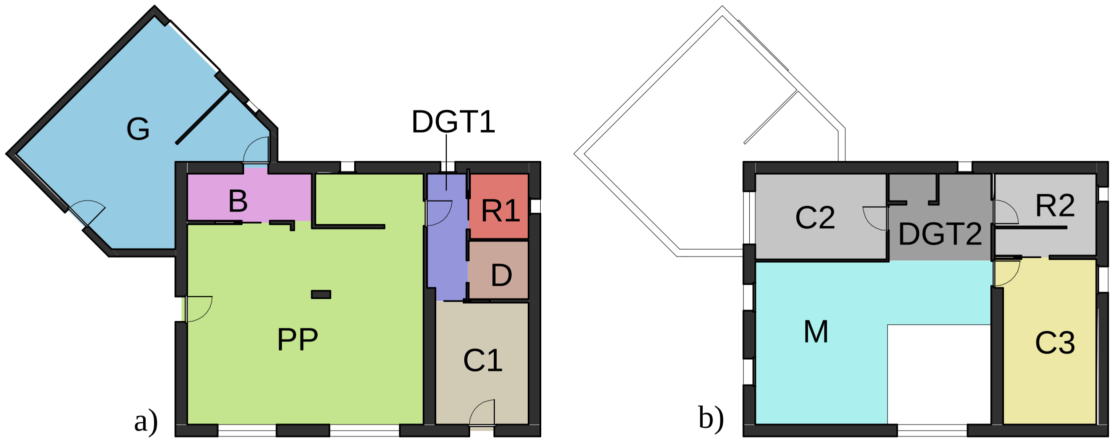

Figure 2. Plans of reference building, 1:200. a) First floor, b) Second Floor.

The standard meteonorm weather file of Amberieu-74820 were used in the simulation. Lighting and occupancy were modeled using schedules related to a standard 4 people family working life, week-ends are taken in account but holidays are not considered. The sum of infiltration and ventilation rate is fixed equal to 0.7 ach as a medium value for all the zones. Based on these settings, heating needs are estimated to be 48 kWh/m^2/year, while cooling needs are equal to 12 kWh/m^2/year.

METHODS – PARAMETRIC STUDY

In order to allow multiple simulation and optimal level research, building simulation software was coupled with the general optimization software GenOpt and configuration files were created [6].

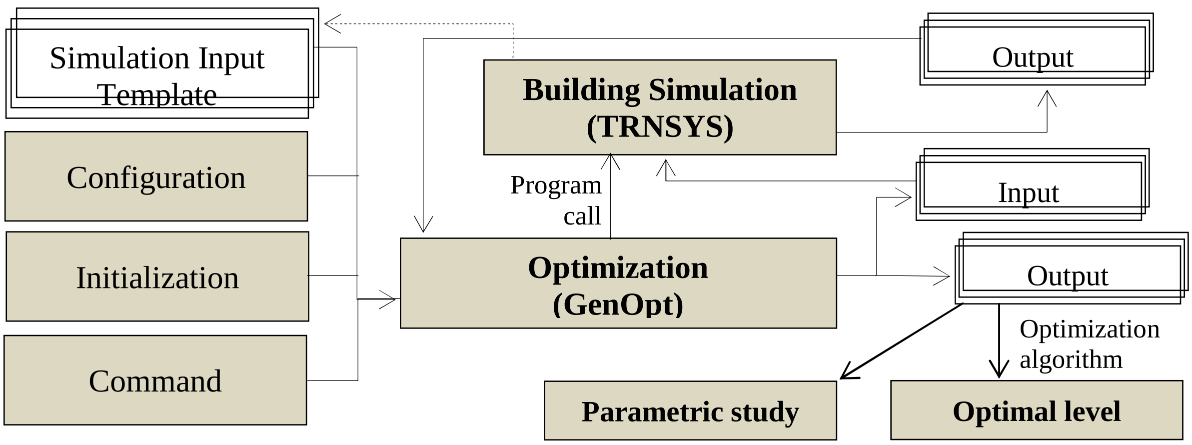

Figure 3. Simulation-optimization framework.

Configuration file contains building simulation software configuration, error indicators and start command, the command file contains parameter list and settings and related functions which were inserted in simulation input files to obtain simulation input template. GenOpt run is based on the initialization file, where location of input files and position of the objective function are specified.

The more a house is energy efficient, the bigger is the influence of envelope design on the final energy demand. In order to estimate the impact of the variation of each element of building envelope and geometry (wall, roof and slab insulation, window type, window and solar protection dimension) on the final total annual energy consumption, a parametric study on the reference building was done. All set parameters and values referred to the house section are shown in the figure below. Note that minimal window dimension corresponds to the limit imposed by French regulation.

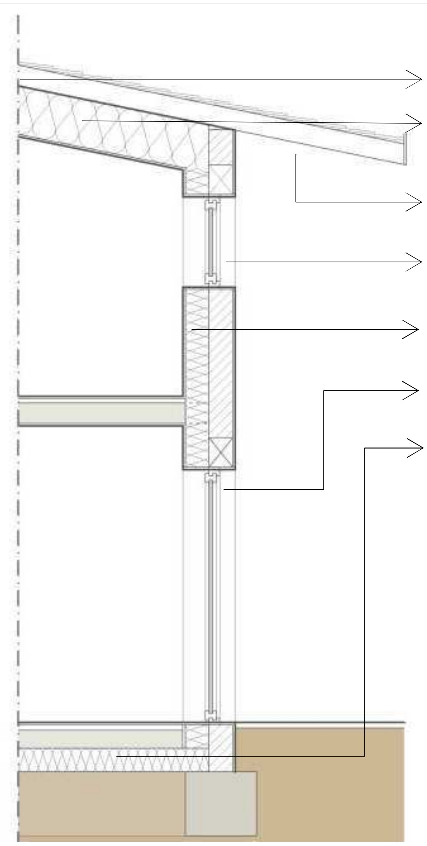

Figure 4. Parameter list.

1. Parameter	Min	Max	Step	Rel. Function
hr – Roof window height [m]	0	4.72	0.3	Roof window area
ResR – Roof insul. [m^2Kh/KJ]	0.25	5	0.25	-
S - Overhang projection [m]	0.2	3.6	0.2	Overhang height
bm - mezzanine south window width [m]	2.2	7.8	0.2	Mezzanine south window area
ResO-Outwall ins.[m^2Kh/KJ]	0.25	5	0.25	-
Bpp – living room south window width [m]	2.2	7.8	0.2	Living room window area
Res S – Slab insul. [m^2Kh/KJ]	0.25	3.5	0.25	-
Min – Inertie wall thickness	0.02	0.4	0.08	-
WT- Window Type N-E-W, WTS - Window Type S, WTR -Window Type Roof	1	5	1	-

Table 1. Parameter settings

2. Window Type	U [W/m^2K]	g-value [%/100]
1 – Double	2	0.7
2 – Double, Low-e	1.76	0.59
3 – Double, Low-e Argon	1.43	0.58
4 – Triple	0.7	0.5
5 – Triple, Xenon	0.4	0.4

Table 2. Window Types

The initial value (Ini) is the fixed value assumed by parameters during the parametric run. Four Ini scenarios were set: one is referred to the low-cossumption RB, the others are respectively representative of a very less-insulated building, a standard insulated building, and the last is an utopic very strong insulation. Geometric parameters are always equal to RB.

	ResO	ResR	ResS	s	Bm	bpp	hr	MIn	WT	WTR	WTS
Low	0.5	0.75	0.5	0.8	2.4	4.2	4.72	0.4	1	1	1
Medium	1	2	1.5	0.8	2.4	4.2	4.72	0.4	2	2	2
RB	1.75	3.5	2.5	0.8	2.4	4.2	4.72	0.4	4	4	4
Strong	3.5	4.5	3	0.8	2.4	4.2	4.72	0.4	5	5	5

Table 3. Initial value scenarios

RESULTS – PARAMETRIC STUDY

Here below results related to RB scenario are shown. Winter and summer performances are separately evaluated and compared, while percentages are referred to the total annual energy needs. Positive values of percentages indicate energy savings corresponding to decreases in energy demand.

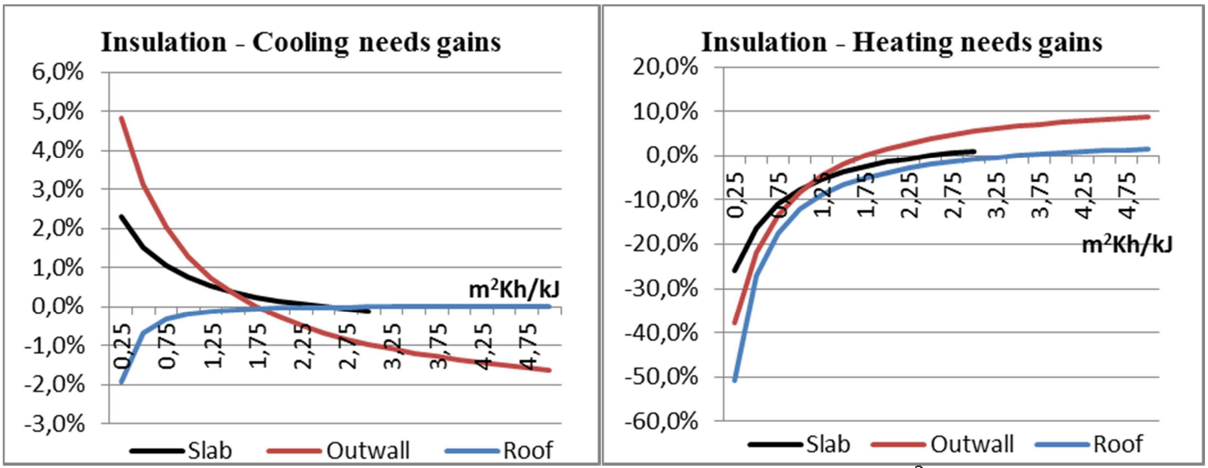

Figure 5. Impact of opaque envelope insulation in term of resistance (m^2Kh/kJ) on energy demand gains – RB scenario.

It is clear that insulation of opaque envelope takes an important role among energy savings measures. In details, roof insulation accounts the most relevant impact in both summer and winter case. In case of outwall and ground slab an increase of insulation corresponds to an increase of heating energy savings and a decrease of cooling energy savings, while in roof case insulation increase causes energy savings during all the year. This is due to the fact that most of roof surface is south oriented and a major solar absorption is caused by dark color of tiles.

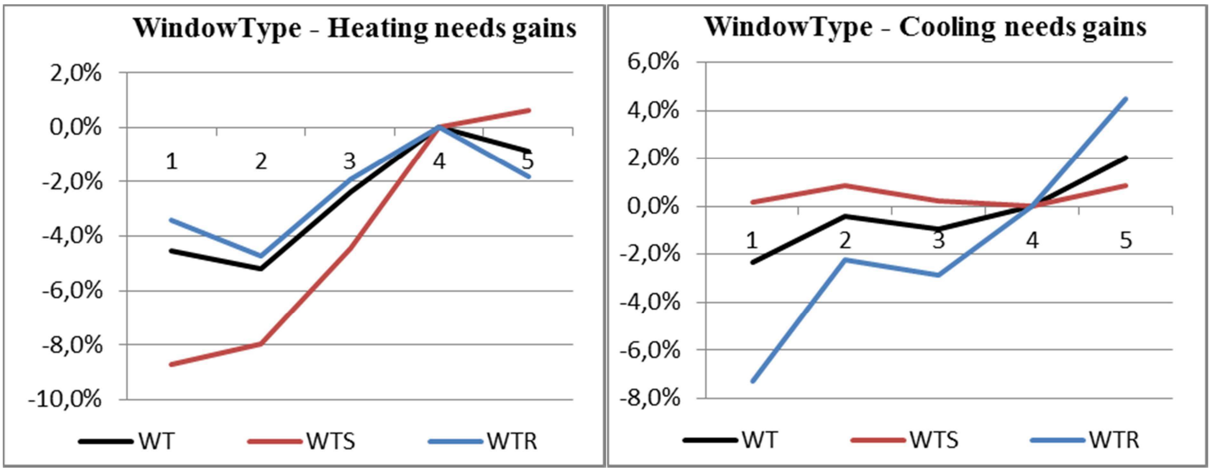

Figure 6. Impact of window type (see table 2) on energy demand gains – RB scenario.

Results related to window type clearly show the impact of g-value and window orientation on transparent envelope performances. A differentiation of window type based on optimization of these parameters could be desirable taking into account also shading devices geometry and window dimensions (see figure 7).

Results based on other scenarios revealed mostly the same curves, but it is clear that the higher performances are set in initial scenarios, the higher is impact of parameter variation in terms of percentage of energy demand.

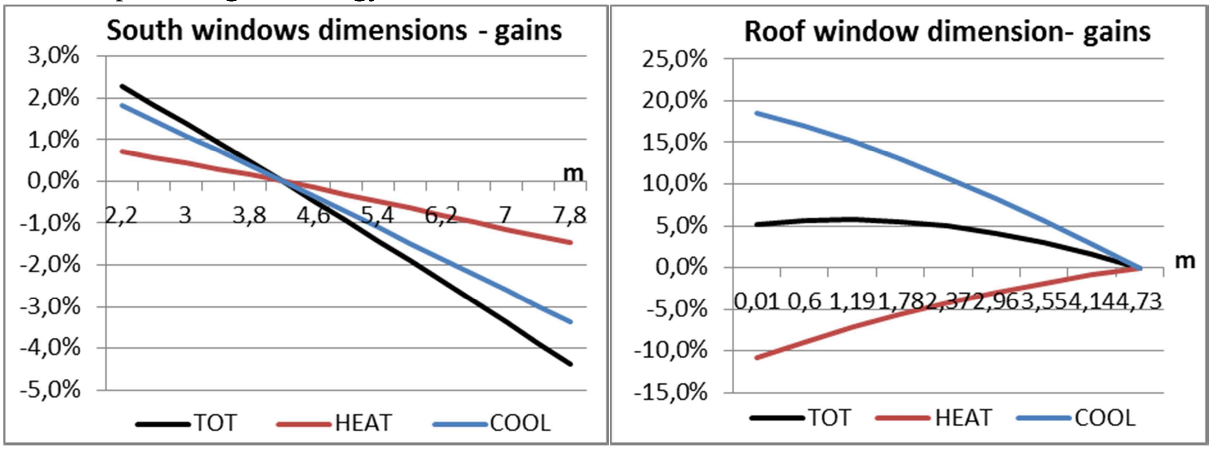

Figure 7. Impacts of roof window dimension and shading overhang length on total energy demand – RB scenario.

METHODS – ECONOMICAL OPTIMIZATION

In accordance with the EPBD, global cost calculations result in a net present value of costs incurred during a defined calculation period, taking into account the residual values of components with longer lifetimes. Following the procedure described in the European Standard EN 15459 [7], global cost is directly linked to the duration of the calculation τ and it can be written as:

$$C_G(\tau) = C_I + \sum_j \left(\sum_{i=1}^{n} C_{a,i}(j) \cdot R_d(i) - V_{f,\tau}(j) \right) \quad (1)$$

where C_G represents the global cost referred to starting year τ_0, C_I is the initial investment cost, $C_{a,i}(j)$ is the annual cost for component *j* at the year *i* (including running costs and periodic or replacements costs), $R_d(i)$ is the discount rate for year *i*, $V_{f,\tau}$ is the final value of component *j* at the end of the calculation period (referred to the starting year τ_0).
In the context of cost optimal research in this method costs are written as function of parameters p. So the terms of the previous equation become:

$$C_I = \sum_j f_j(p) \quad (2) \qquad\qquad C_{a,i}(j) = f_{a,j}(p) \quad (3)$$

Where $f_j(p)$ is the cost function of the component *j* related to parameter *p*.

Investment Cost	Parameter	Unit	Unit cost function (€/unit)
Outwall internal insulation	ResO	m^2	37.639*exp(0.351*ln(ResO))
Slab insulation	ResS	m^2	38.115*exp(0.186*ln(ResS))
Roof insulation	ResR	m^2	43.478*exp(0.309*ln(ResR))
Window Type 1	Area	m^2	349.35x+28.17
Window Type 3	Area	m^2	390.85x+29.37
Window Type 4	Area	m^2	454.16x+36.62
Window Type 5	Area	m^2	460.45x+34.45

Table 4. Cost function of parameters.

Cost functions were determined combining French price lists [8] and quotations of local construction companies, all costs are comprehensive of human work and installation costs. Cost analysis revealed that insulation cost functions are exponential functions, while window cost were simplified in linear function.
A typical all-electrical energy system was considered, whose investment cost is 300 €/kW of maximal power installed, with a replacement time of 15 years. Energy price was assumed equal to current prices of major electricity companies based on difference in tariffs for night and day. In details, costs were fixed equal to 0.07952 €/kWh during the night and 0.11442 €/kWh during the day. Market interest rate was assumed to be 4%, calculation period is 30 years.

RESULTS – ECONOMICAL OPTIMIZATION

All combination of parameters value performed by the optimization program can be considered as a package of Energy Efficiency Measures, according to the European Guidelines [9]. Note that in (1) only variable cost related to variation of parameters were considered. So the objective function of optimization represents the global cost for each EEM. Particle Swarm Optimization algorithm for discrete variables was used.
The first optimization run was performed only with parameters related to opaque and transparent envelope resistance as variables. Geometric parameters (window dimensions and shading overhang length) were fixed equal to RB values.
Here below cost values are shown referred to primary energy consumption (primary energy conversion factor for electricity in France is equal to 2.58). Values are normalized to GFA.

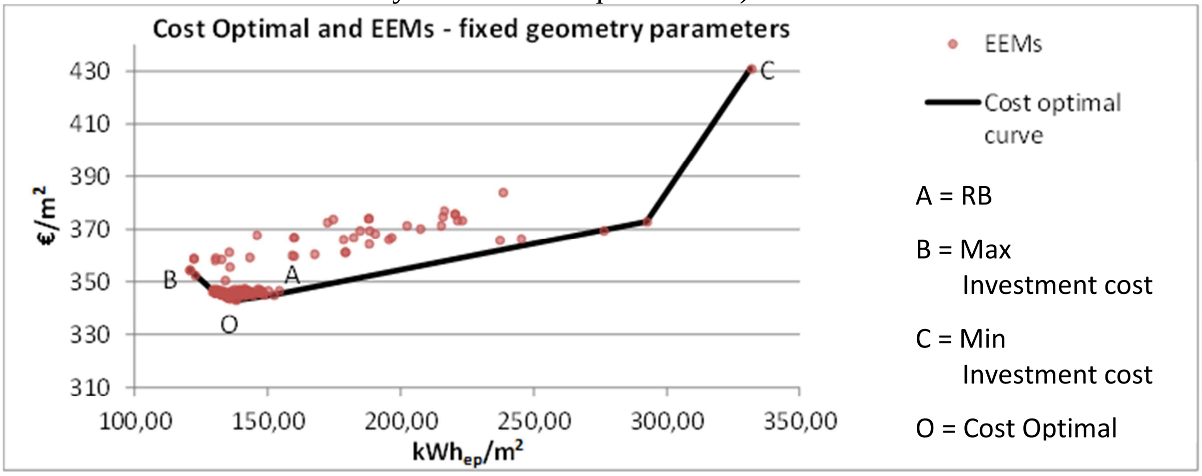

Figure 8. Cost optimal curve for RB geometry

Cost Optimal level corresponds to 343 €/m^2 for a primary energy consumption of 120 kWh$_{ep}$/m^2/year. In details, ResO is 1.75 m^{2}Kh/kJ, ResR is 2.5 m^{2}Kh/kJ, ResS is 2 m^{2}Kh/kJ and window type is 5. The maximal investment cost corresponds to the minimal energy consumption and leads to a global cost of 353 €/m^2, while the minimal investment cost corresponds to the maximal energy consumption which leads to a global cost of 431 €/m^2.
A second optimization run was performed in order to estimate the variation of global cost with variation of window dimension. In this case cost optimal corresponds to 297 €/m^2 for a primary energy consumption of 120 kWh$_{ep}$/m^2 year. In details, ResO is 1.75 m^{2}Kh/kJ, ResR is 3 m^{2}Kh/kJ, ResS is 3 m^{2}Kh/kJ. South oriented window area is half of RB windows area and WTS is 3. Roof window area is equal to 0 and window type of other windows is 5. Talking about window dimension, internal comfort and natural light should be considered before taking decision to reduce window area.

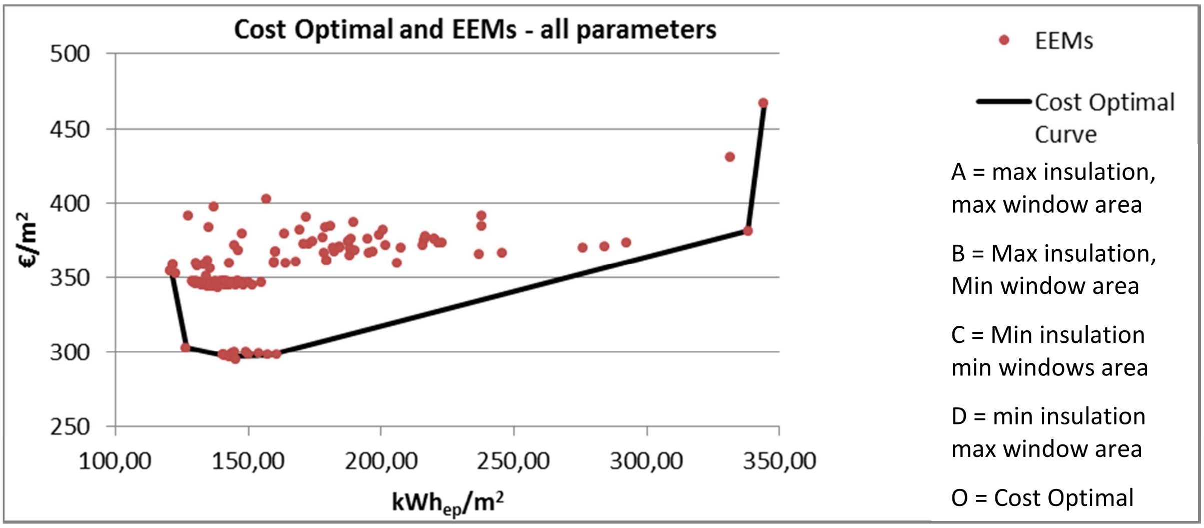

Figure 9. Cost optimal curve based on variation of all parameters.

DISCUSSION

As cost of electricity is quite high, it is clear that considering global cost for 30 years an initial high investment cost in high-performances of envelope is recommended also from economical point of view. This is only an example, as this work attempted to establish a fast and precise procedure for optimization which could be applied to different case-studies. It is known that the use of more efficient energy system could lead to different solution. Moreover, further studies have to be performed in terms of sensitivity analysis based on variation of financial data and product costs.

ACKNOWLEDGEMENT

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