

Reduction of Space Heating Energy through Minimisation of Life Cycle Cost Using Combined Simulation and Optimisation

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SUMMARY

In the current study, minimisation of Life Cycle Cost (LCC) for a single family detached house is achieved by combined simulation and optimisation. The house has a typical Finnish construction with initial U-values in accordance with the Finnish National Building Code C3 of 2003. The house is heated by a direct electric heating system. The implemented approach is coupling the IDA ICE 3.0 building performance simulation program with the GenOpt 2.0 generic optimisation program to find optimised values of five selected design variables in the building construction and HVAC system. These variables are three continuous variables (insulation thickness of the external wall, roof and floor) and two discrete variables (U-value of the windows and type of heat recovery of ventilation air) which are defined within set limits.

The assumptions for the LCC data are: number of years under study (20 and 50 years), escalation of electric energy price (1 and 5%) and real interest rate (2.94 and 4.90%). The general solution for the LCC minimisation goes towards reducing the energy cost for space heating by investing in the insulation of the house and using better windows. It suggests lowering the U- values for the external wall, roof, floor and the window from their initial values to be equal to, and sometimes lower than, those for the so-called "Low Energy House". The optimisation results indicate that 28 to 49% reduction in space heating is achieved compared with the reference case (Standard House 2003).

Keywords: life cycle cost, heating energy, simulation, optimisation

SIMULATION AND OPTIMISATION

Simulation tools are increasingly used in analysing building performance. If the designer decides to improve the building envelope and/or HVAC system parameters, he usually makes a guess for the values of the design parameters to be modified and runs the simulation many times trying to find the effect of the changes on the simulation output and to conclude a relation between the studied parameters. This is an inefficient procedure in time and labour. Besides, the relation between the parameters may not be simply understood, especially when there are many parameters to be studied, due to nonlinear interaction between the parameters.

To overcome such difficulties, it is possible to do automatic simulation-optimisation using search techniques that require little effort and time. GenOpt, a generic optimisation program can be used for such a purpose. GenOpt 2.0 [1] is an optimisation program for the minimisation of a cost function that is evaluated by an external simulation program. It is

developed for optimisation problems where the cost function is computationally expensive and its derivatives are not available or may not even exist. GenOpt can be coupled to any simulation program that reads its input from text files and writes its output to text files. The independent variables can be continuous variables (with lower and upper bounds), discrete variables, or both. It is to note that minimisation of the cost function could represent minimisation (or maximisation) of any specified objective function (e. g. annual energy consumption, indoor air quality, equipment efficiency etc). However, optimisation is not easy: The efficiency and success of any optimisation is strongly affected by the properties and the formulation of the objective function and by the selection of an appropriate optimisation algorithm. Refs. [2 and 3] indicate that GenOpt has been implemented in the optimisation of building design and HVAC system parameters.

GenOpt has an open interface on both the simulation program side and the optimisation algorithm side. In this study GenOpt is combined with the IDA Indoor Climate and Energy 3.0 program (IDA ICE 3.0). IDA ICE 3.0 is a whole-building dynamic simulation program which makes simultaneous performance assessments of all issues fundamental to a building design: shape, envelop, glazing, HVAC systems, controls, light, indoor air quality, comfort, energy consumption etc. The accuracy of the IDA ICE 3.0 was assessed through the IEA solar heating and cooling programme, Task 22, sub Task C [4]. IDA ICE 3.0 has been chosen by a group of specialist as one of the major twenty building energy simulation programs which are subjected to analysis and comparison [5].

The task in the current study is to minimise the Life Cycle Cost (LCC) of a single family detached house having Finnish construction by combined simulation and optimisation (IDA ICE 3.0 and GenOpt 2.0).

DESCRIPTION OF THE HOUSE AND HVAC SYSTEM

The dimensions and construction of the detached house are generally based on those for the RET project [6]. The dimensions are indicated in Fig. 1.

The U-values for the external wall, roof and floor are 0.25, 0.16, 0.15 W/m²K, respectively. Among other layers in the construction, following are the thickness and thermal conductivity λ (W/mK) of the insulation: 122 mm mineral wool ($\lambda = 0.035$) in External wall, 299 mm Blow-in wool ($\lambda = 0.050$) in Roof, and 165 mm Polyurethane ($\lambda = 0.026$) in Floor. The windows are 3 layers glass having $U = 1.4$ W/m²K. The U-value for external doors is 0.35 W/m²K. The loss factor of the building's thermal bridges is 8.3 W/K. Those U-values are in accordance with the Finnish National Building Code C3 for 2003 [7]. Therefore, this construction will be called here "Standard House 2003".

The heating system is a direct electric heating system where heating energy is supplied by two means: electric radiators inside the rooms and an electric heater in the air handling unit (AHU). The AHU heater keeps the supply air temperature at 18 °C when the incoming outdoor air temperature is lower than this limit. There is a thermostat on the electric radiators to keep the temperature of air inside the zone at a lower set-temperature of 21 °C. The ventilation system (always ON) supplies fresh air to the house by a supply fan (62 dm³/s) and an exhaust fan (67 dm³/s). The exhaust air flow = 0.65 air change per hour. There is a heat exchanger for heat recovery from exhaust air (efficiency = 70%). Good air tightness of the house is considered: the air leakage value $n_{50} = 1.0$ l/h. The internal heat gain is 5.1 W/m² of

the floor area. The location of the house is in Jyväskylä in middle of Finland. The hourly weather file for 1979 is considered.

The building with the above mentioned specifications for the construction and HVAC system is considered as a **reference case** in this study.

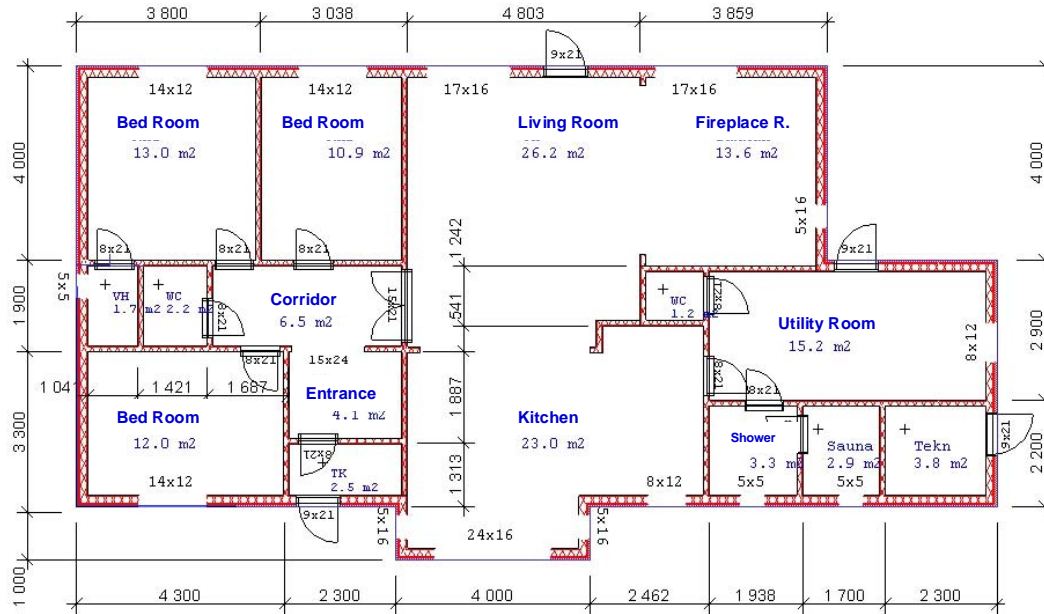


Fig. 1. Dimensions of the single family detached house (internal height is 2.5 and net floor area is 142 m²) [6].

CALCULATION OF LIFE CYCLE COST

The life cycle cost (LCC) is the sum of the investment and running costs for the building and the system over a specified life span. In the current investigation, the absolute value of the LCC is not calculated but the difference in the LCC for any case (dLCC) from that for the reference case. This way, it is not necessary to include data for all components of the building and system but only the differences produced by variation of specified parameters between the reference case and any other case. Besides, variations in the maintenance cost are not considered. Thus the LCC difference dLCC (€) calculated at present date is

$$dLCC = dIC + dOC + dRC$$

where dIC is the difference in the investment cost for specified items, dOC is the difference in the operating cost and dRC is the difference in the replacement cost.

The difference in the operating cost is due to the difference in electric energy consumption of the heating system $dOC = a e_p dE$ where e_p is the electric energy price at present date (€/kWh), dE is the difference in annual electric energy consumption E of the heating system (kWh), a is the discount factor which takes into account the effects of inflation and escalation of electric energy price $a = (1 - (1 + r_e)^{-n}) / r_e$, n is the number of years under study, r_e is the real interest rate including effect of escalation of electric energy price $r_e = (r - e) / (1 + e)$, e is

the escalation in electric energy price (%/a), r is the real interest rate $r = (i - f)/(1 + f)$, f is the inflation rate (%/a) and i is the nominal interest rate (%/a).

The difference in the replacement cost is due to replaced items in specified years $dRC = dR_0 / (1+r)^k$, where dR_0 is the difference in the replacement cost at present date, k is the year number at which the replacement takes place.

The following data are assumed for the LCC calculations:

Nominal interest rate $i = 7\%$ and inflation rate $f = 2\%$. Accordingly, the real interest rate $r = 4.90\%$. Two values are assumed for the escalation in electric energy price $e = 1\%$ and a high value of 5% . Two values are assumed for the life span $n = 50$ and 20 years. Two discrete variables are considered (window type and heat recovery type), which have lower life than 50 years. Therefore, two replacements are assumed to take place in year number $k = 17$ and 34 when $n = 50$ years. When $n = 20$ years, no replacement costs are considered. The electrical energy price e_p for direct electric heating is 0.0767 €/kWh at 1.4.2005 [8]. Insulation price are according to data from Isover Company : Prices for mineral wool in the external wall, blow-in wool in the roof and Polyurethane in the floor are, respectively, 5.63 , 3.25 and 26.8 €/m^2 per 10 cm thickness. The change from windows having U-value of 1.4 to $1.0 \text{ W/m}^2\text{K}$ is considered to cost 397 € for all of the windows of the house. The change of the heat-recovery exchanger from a plate type (efficiency = 70%) to a rotary type (efficiency = 80%) is considered to cost 730 €

DESIGN VARIABLES AND OBJECTIVE FUNCTION

Five design variables are considered in this study: Three continuous variables and two discrete variables. The continuous variables are additional insulation thickness dX of the existing insulation material in the external wall, roof and floor. The discrete variables are: U-value of the window (with two options, 1.4 and $1.0 \text{ W/m}^2\text{K}$) and type of heat recovery (with two options, plate type with 70% efficiency and rotary type with 80% efficiency). Table 1 shows these variables. Constraints on the continuous variables are indicated as minimum and maximum bounds. The initial and the minimum values correspond to the reference case which means that the optimisation starts from the Standard House 2003.

Table 1. Variable parameters and bounds.

	dXextwall (m)	dXroof (m)	dXfloor (m)	Uwindow (W/m ² K)	Heat Recovery
Min (m)	0	0	0	1.0	Plate type (Eff= 0.7)
Max (m)	1.0	1.0	1.0	or	or
Step (m)	0.05	0.05	0.05	1.4	Rotary (Eff=0.8)
Initial value (m)	0	0	0	1.4	Plate type (Eff= 0.7)

The task is to find optimised values of the specified five variables which result in a minimum value for the objective function (dLCC). The combined simulation tool (IDA ICE 3.0) and optimisation tool (GenOpt 2.0) are used to find the optimum values in each case. IDA ICE is iteratively called by GenOpt. The objective function result is checked and values of the design variables are changed in each iteration till a solution is reached. The required annual energy for space heating is calculated by IDA ICE 3.0 based on the hourly input weather file for one year. The used optimisation algorithm is the GPSPSOCCHJ [1]. This is a hybrid global optimisation algorithm that initially does a Particle Swarm Optimisation for all variables and then switches to the Hooke-Jeeves Generalized Pattern Search algorithm to refine the continuous variables.

OPTIMISATION RESULTS

Five cases are studied, and as indicated by table 2, with the following assumptions: Two life spans $n = 20$ and 50 years, two values for the escalation of electric energy price $e = 1\%$ and 5%. These four cases are with a real interest rate $r = 4.90\%$. Case 5 is same as case 3 but with $r = 2.94\%$ (nominal interest rate $i = 5\%$ and inflation rate $f = 2\%$). It is to note that 50 years is closer to the building life, while 20 years is closer to the system life. The optimisation results are indicated in table 2. It shows that minimum value of dLCC is reached (negative value) as a result of the reduction made in the electric energy cost for heating (negative value) due to the investment made (positive value) in the insulations, windows and heat recovery and associated replacement costs and as shown in Fig. 2. Highest reduction in LCC is obtained in case 4 when $e = 5\%$ and $n = 50$ years.

Table 2. Studied cases and optimisation results.

Case	1	2	3	4	5
No. of years	20	20	50	50	50
Escl. in electric price	1 %	5 %	1 %	5 %	1 %
real interest rate	4.90 %	4.90 %	4.90 %	4.90 %	2.94 %
dLCC, €	-2102	-4388	-4680	-18437	-8722
dOC, €	-4229	-8042	-8201	-27747	-14371
dIC+dRC, €	2127	3655	3521	9309	5649
Components of dIC+dRC					
dCost Walls, €	983	1393	1556	2683	1966
dCost Roof, €	747	1136	1315	2809	1838
dCost Floor, €	0	0	0	1973	0
dCost Windows*, €	397	397	650	650	650
dCost HtRecovery*, €	0	730	0	1195	1195
Space heating					
kWh/m ² a	71	63	65	50	58
ratio to reference case, %	72	64	66	51	59
Additional insulation thick.					
dXextwall, m	0.150	0.213	0.238	0.409	0.300
dXroof, m	0.156	0.238	0.275	0.588	0.384
dXfloor, m	0.000	0.000	0.000	0.050	0.000
Uextwall, W/m ² K	0.121	0.099	0.093	0.064	0.080
Uroof, W/m ² K	0.107	0.091	0.085	0.056	0.072
Ufloor, W/m ² K	0.150	0.150	0.150	0.116	0.150
Uwindow, W/m ² K	1.0	1.0	1.0	1.0	1.0
Eff. Ht. Recovery	0.7	0.8	0.7	0.8	0.8

* including those for replacement.

Relevant values for the reference case (Standard House 2003) and values from the INDUCON building concept report [9] for the Low Energy House and Minimum Energy House are indicated on the y-axis of Figs 3 and 4 for comparison with results obtained by this study.

The IDA ICE 3.0 calculations show that the required space heating is 99 kWh/m²a for the reference case compared with 100 kWh/m²a for the Standard House 2003 as defined by [9]. The optimisation results indicate that 28 to 49% reduction in space heating is achieved compared with the reference case. The highest is for case 4. Fig. 3 shows the required space

heating for the studied cases. It shows that for the studied cases, the space heating for the optimum house is lower than that for the Low Energy House.

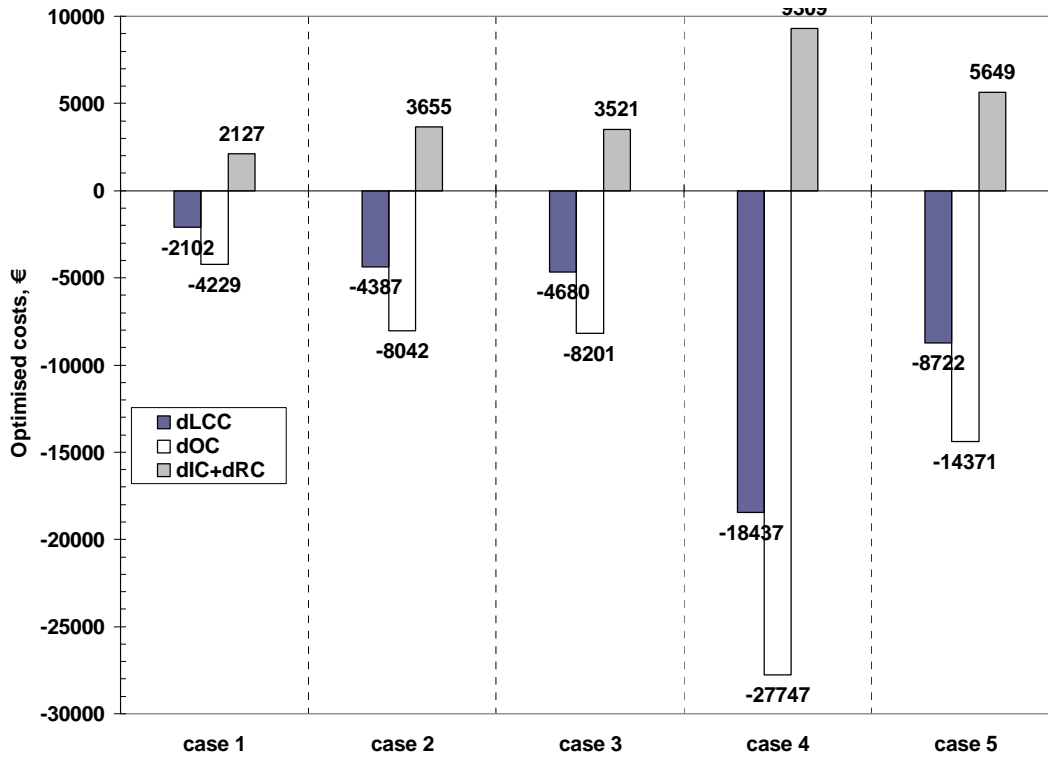


Fig. 2. Difference in LCC (dLCC), energy cost (dOC) and investment and replacement costs (dIC+dRC) for the studied cases.

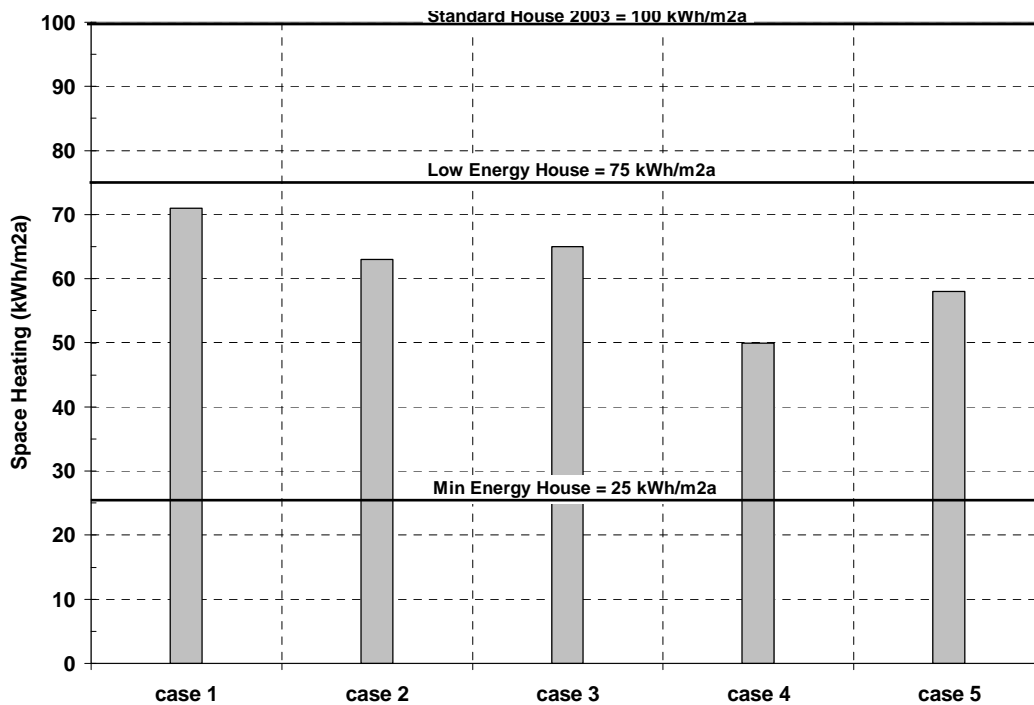


Fig. 3. Space heating of the optimised house for the studied cases.

The results for the U-values are shown in Fig. 4. The optimised U-values for the external wall U_{extwall} are much lower than that for the Standard House 2003. The optimisation suggests increasing the thickness of the mineral wool insulation in the external wall so that U_{extwall} is

lower than that for the Low Energy House and even lower than that for the Minimum Energy House for most cases. The U-value of the roof U_{roof} comes close to that for the Low Energy House (which is also the Minimum Energy House) and is even lower for two cases. Due to the high price of Polyurethane as insulation in the floor, the optimisation keeps U_{floor} at its initial value according to the Standard House 2003 (which is equal to that for the Low Energy House) for four cases, while it drops to a lower value for case 4, when $e = 5\%$ and $n = 50$. Polyurethane high price is due to its good characteristics (low thermal conductivity, good compressive strength and resistance to moisture ingress).

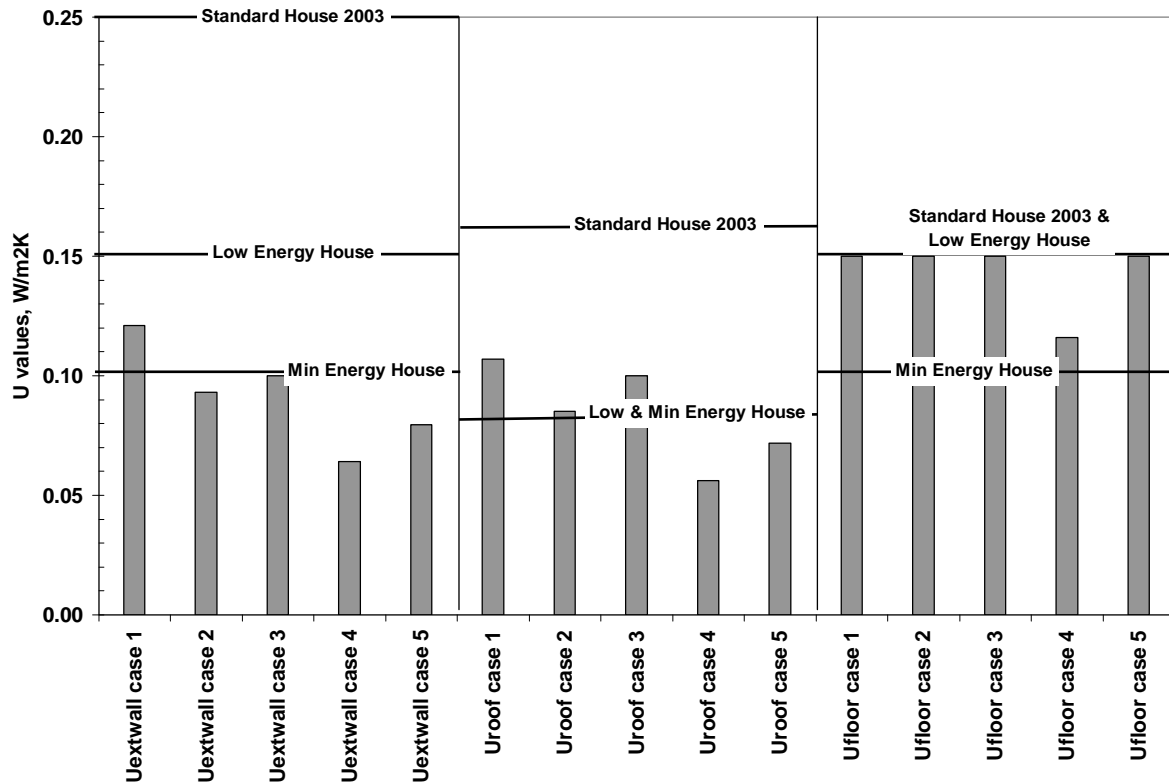


Fig. 4. Optimised U-values for the external wall, roof and floor for the studied cases.

For the two studied discrete variables, table 2 indicates that the optimised U-value for the windows U_{window} is $1.0 \text{ W/m}^2\text{K}$ for the five cases, which is equal to that for the Low Energy House. While for the heat recovery, the rotary type with efficiency of 80% is selected for three cases when $e = 5\%$ or $r = 2.94\%$. For case 5, it is concluded from table 2 that assuming the real interest rate $r = 2.94\%$ allows making higher investment which produces higher saving in electric energy and higher reduction in dLCC compared with case 3 ($r = 4.90\%$).

CONCLUSIONS

This investigation shows the advantages gained from the implemented approach of combining the IDA ICE 3.0 simulation program with the GenOpt 2.0 generic optimisation program in the minimisation of the life cycle cost of a typical Finnish detached house. The house is electrically heated. This approach enabled finding optimised values of selected design variables in the building construction (insulation thickness of the external wall, roof, floor and U-value of the windows) and HVAC system (type of heat recovery unit) which achieved minimum LCC value for the studied cases.

With different assumptions for the following LCC data; number of years under study (20 and 50 years), escalation of electric energy price (1 and 5%) and real interest rate (2.94 and 4.90%), the general trend of the solution goes towards investing in the insulation of the house and using better windows. It suggests lowering the U-value for the external wall, roof, floor and window to be close to, and sometimes lower than, those for the Low Energy House. The change of the heat recovery system to a more efficient type seems to be feasible for the studied cases when the escalation in the electric energy price is 5% or the real interest rate is 2.94%. The space heating energy for the optimised house is between 50 and 71 kWh/m²a which makes a reduction between 28 and 49% compared with the reference case (Standard House 2003).

ACKNOWLEDGEMENTS

This study was funded by the Finnish National Technology Agency (TEKES) and the companies: Are, Helsingin Energia, Isover, Optiplan and Uponor.

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