RESIDENTIAL HOUSE COST AND ENERGY OPTIMIZATION USING MULTI OBJECTIVES PARETO FRONT METHOD

Summary

This article presents the multi-objective optimization of a residential house. The goal is to find the optimal Pareto front which minimizes both the heating energy needs and the construction cost. A real residential house to be constructed has been used as a use case. 2 simulations software have been used to compute the energy demands of the house: the PHPP and the TRNSYS software. In this paper, the results obtained with the PHPP software are presented. The cost evaluation function was developed in this project and the optimization was performed using XTREME, a commercial optimization software.

SYMBOLS

PHPP	Passive House Planning Package (http://passive.de)
TRNSYS	Transient System Simulation Tool (http://www.trnsys.com)
XTREME	Numerical Optimization Software (http://www.optimalcomputing.be)
U	Thermal conductance (W/m^2K)
g or SHGC	Solar Heat Gain Coefficient (%)

INTRODUCTION

Reducing the C02 production around the world and in all sectors is now recognized as a mandatory objectives in the near future. Among the biggest consumer sector is the householders sector, which in Europe represents around 24.8% of the energy use [1].

Therefore, since several years the construction of low energy or even passive building attracts a lot of interest from many stakeholders: private person to construct their personal house, public authorities, European commission …

Energy consumption targets have been set for the passive house but the extra cost required to reach this passive standard is often a barrier for individual persons. It is difficult to evaluate precisely the return on investment period for such a passive building.

This paper has 3 objectives:

1. Demonstrate how numerical optimization techniques in general and Pareto Front optimization in particular can be used to find the set of best solutions for typical houses depending on their energetic performance.
2. Deduce from this Pareto front, the **return on investment time** of a standard residual house in terms of energy demands and construction cost.
3. Deduce important **best practice**s depending on the target heat consumption (standard house, low energy house, passive house, …)

The outcome of this study will be to demonstrate that the return on investment time for several energy targets can be evaluate using Pareto front optimization techniques.

This paper first presents the house used has a base line in this study. Then, the next 2 sections present the software used to simulate the energy performance and the cost function developed to calculate the construction cost. The fourth section present the optimization software used as well as how it was coupled to the simulation software. Finally, the optimization results are presented and analysed.

1. THE HOUSE

The house is a standard family house with 4 bedrooms. The internal surface is 171 m^2 with a living room (36 m^2), a kitchen (11.5 m^2), an office room (12.5 m^2), one utility room (7 m^2) on the ground floor and 4 bedrooms at the first floor (16 m^2, 15 m^2, 12 m^2 and 10 m^2) and 2 bathrooms (6 m^2 and 5 m^2). A 3D view of the house is shown Figure 1.

The house is oriented with the living room as well as the main roof slope facing the south.

In the next section the house specification are further described with the focus being placed on the passive techniques used to have a highly efficient thermal insulation of the house.

The walls of the external envelope are constructed based on a 3 layer structure (Figure 2): an internal clay block, a thermal insulation layer including back ventilation and a façade made of bricks. The use of 1mm special mortar ensures optimal thermal insulation.

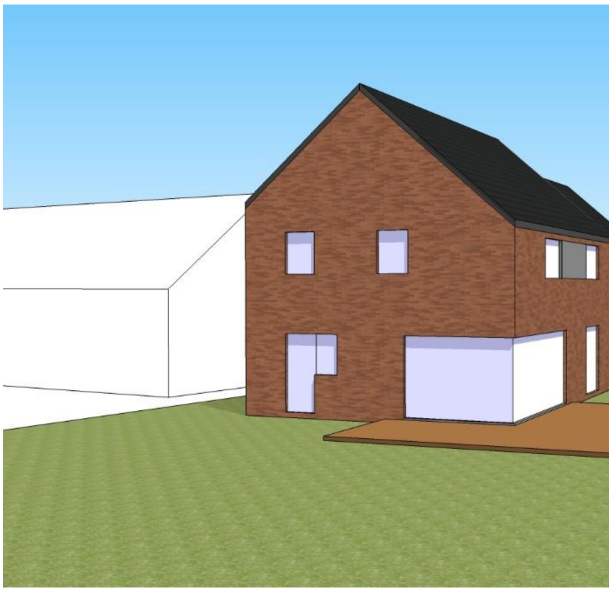

Figure 1: 3D view of the residential house used in this study

The ground floor is insulated with protected polyurethane. The standard thickness for a passive house is 15 cm (Figure 3).

The roof has 2 sides, one oriented to the south and one to the north, both with a slope of 40 deg. The roof structure and insulation thickness is the same for the 2 roof sides. The south facing roof is fully equipped with solar panels while the north facing roof is equipped with classical tiles without solar cells.

Figure 2: External envelope wall

The detailed layer components of these 3 structures (wall, roof and ground) are provided in Table 1, Table 2 and Table 3.

The roof is insulated using cellulose (Figure 4).

Figure 3: Ground floor insulation

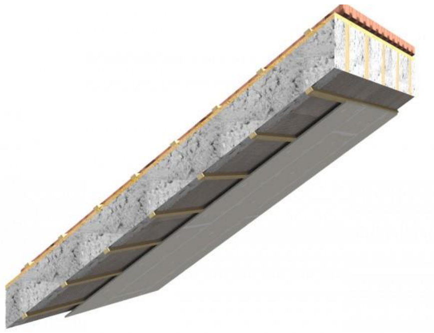

Figure 4: Roof insulated with Cellulose

WALL		
Layer	**λ [W/(mK)]**	**Thickness [mm]**
External brick	0.77	90
Air	-	30
Insulation PUR	0.023	220
Bloc	0.300	140
Ceiling	0.520	10

Table 1: Wall layers, thermal properties and reference thicknesses(Total U=0.098 W/m²K)

FLOOR		
Layer	**λ [W/(mK)]**	**Thickness [mm]**
XPS insulation	0.036	100
Concrete	1.7	200
Projected PUR	0.028	150
Concrete topping	0.300	60
Floor tiles	1.200	10

Table 2: Floor layers, thermal properties and reference thicknesses (Total U=0.11 W/m²K)

ROOF		
Layer	**λ [W/(mK)]**	**Thickness [mm]**
OSB	0.130	18
Cellulose insulation	0.039	400
OSB	0.130	10
Air layer	0.355	58
Gyproc	0.130	10

Table 3: Roof layers, thermal properties and reference thickness (Total U = 0.12 W / m²K)

2. HOUSE ENERGY CONSUMPTION SIMULATION

A software must be used to compute the heat demand based on the insulation characteristics. Three different software have been considered:

- **PHPP** (Passive House Planning Package) is a software capable to compute the energy efficiency of passive houses. The software is integrated inside a **Microsoft Excel** project and is capable to provide the Heating / Cooling energy demands, the maximum heating and cooling loads or the frequency of overheating [2].
- **TRNSYS** (Transient System Simulation Tool) if an extremely flexible software capable to simulate the behaviour of transient systems. This software has its own graphical user interface and is primarily used to assess the performance of thermal or electrical systems while it can be used to model many other dynamic systems [3].
- **Energy Plus** is a building energy simulation used to model energy consumption in buildings [4]. This is an open source software.

In this study, both the PHPP and TRNSYS have been used. In this paper, the focus is on the presentation of the results obtained using the PHPP software mainly because this software was used by the architects in charge of the house design (Figure 5).

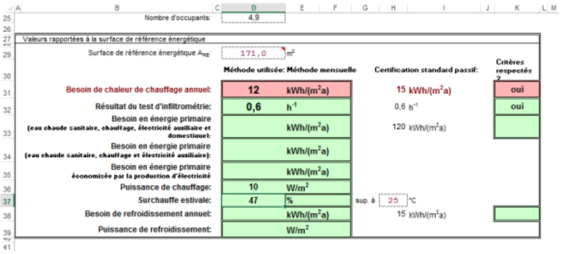

Figure 5: PHPP software

3. CONSTRUCTION COST CALCULATION

This cost optimization is focussed on the energy efficiency aspects of the house. Six house components have been included in this study:

- The walls
- The roof
- The floor
- The windows
- The ventilation and air tightness
- The required (or not) heating system

The cost of 3 of the components (wall, roof and floor) is first evaluated by the 'first' order cost being the cost of the main insulation layer.

The accuracy of this study was much increased by taking into account 2 other effects:

- What we call the 'second' order effect. When an insulation thickness is increased/decreased then more/less material of another layer is required. This is the case for the floor insulation. Increasing the floor insulation from 0mm to 150 mm requires to increase the height of the external insulated wall in order to keep the same internal height of the internal volumes.
- The second effect taken into account is the price jump that can occurs when increasing some insulation thickness. For example when increasing the wall insulation and moving from one layer insulation to 2 layers insulation.

More details regarding this cost calculation is provided hereafter. The cost used in this study contains the cost of the materials **and** the cost of the work force required to construct the component.

The walls

The wall insulation price is computed using the 'first' order term composed of the price of the insulation layer. The second terms taken into account for the external walls are:

- The extra external wall surface required when increasing the insulation thickness
- The extra foundation surface required when increasing the insulation thickness

Those 2 'second' order terms are computed based on the assumption that the internal area of the house is kept constant and the internal bloc remains at the same place when the insulation thickness is increase. As a consequence, the external wall layer of bricks is moving outwards as the insulation thickness is increased.

The roof

The roof insulation price is computed using the cost of the insulation itself as a first order term. Then 2 second order terms are taken into account:

- When the size of the insulation thickness is changed, the height of the roof beam must be increased as well. This is one of the second order term taken into account
- In order to keep the same height of the interior volumes, the height of the brick walls must be increase in the same way as the roof insulation thickness.

The floor

A similar procedure is used for the floor insulation price. The first order term is the price of the floor insulation thickness while a second order term is calculated based on the extra wall height that must be constructed to compensate the extra thickness of floor insulation. This is a consequence of the constraint that the same internal room high must be kept independently of the floor insulation thickness.

The windows

For the window glass, 3 types of glazing are considered:

- Double glazing with a U value of 1.1 W/m²K and a g value of 0.609
- Triple glazing with a U value of 0.59 W/m²K and a g value of 0.402
- Triple glazing with improved g value. U value is 0.59 W/m²K and g value is 0.584.

The ventilation and air tightness

Four types of ventilation are considered:

- Simple flux ventilation and basic air tightness
- Simple flux ventilation and better air tightness
- Mechanical controlled ventilation with an efficiency of 87 % and a passive house air tightness
- Mechanical controlled ventilation with an efficiency of 92 % and a passive house air tightness

In the case of the double ventilation an extra cost is imposed because of the required air tightness of the house in order to use effectively the ventilation with heat recovery.

The heating system

The design of the heating system is not a design variable in this study. The choice and therefore the cost of the heating system is a consequence of the heat requirement of the house. This heat requirement is computed using the PHPP once the design variables of the five preceding house component are chosen (wall, roof, floor, window and ventilation).

In this study, 5 heating systems have been defined based on 5 required heat demands: > 50 kwh/m2/year, between 30 and 50 kwh/m2/year, between 20 and 30 kwh/m2/year, between 15 and 20 kwh/m2/year and below 15 kwh/m2/year

Reference price

The construction cost is evaluated relatively to a reference house. The reference house is characterized by:

- Roof insulation thickness of 20 cm
- Wall insulation thickness of 10 cm
- Floor insulation thickness of 5 cm
- Double glazing with a U value of 1.1 W/m²K
- No specific air tightness and no specific ventilation system

4. OPTIMIZATION

THE OPTIMIZER

The optimizer **Xtreme** is used [5]. This optimizer is based on artificial intelligence techniques such as artificial neural networks and genetic algorithms. The software proposes 4 different very efficient optimization algorithms:

- **Genetic algorithm**. Compare to the state of the art genetic algorithm (GA), Xtreme GA includes various innovations that increase the performance of the design process and the convergence robustness.
- **Fast genetic algorithm**. In this algorithm, the genetic algorithm is coupled to an artificial neural network that drastically improves the performance of the design process. The number of function evaluations is usually reduced by a factor of 100 compared to standard genetic algorithm. This algorithm is the best solution when dealing with time consuming function evaluations.
- **Pareto-front genetic algorithm**. This type of algorithm targets multi-objectives optimization. In this case, the Pareto front technique is used to find the front of optimal solutions to a given target. The Pareto front algorithm inside Xtreme contains several innovating techniques that makes the algorithm much more performant that well know algorithms.
- **Fast Pareto-front genetic algorithm**. In this algorithm, the Pareto front genetic algorithm is accelerated by an artificial neural network in the same way as performed for the fast genetic algorithm. In a similar way, the design process is improved by a factor of 100 in most industrial applications

In this study, the Pareto-front genetic algorithm is used. The Pareto front algorithm is used when 2 or more objectives must be minimized (or maximized) together and the full set of optimal solution must be found. The Pareto front concept is illustrated in Figure 6 by comparing the orange, blue and red points to the yellow point considering that both objective must be minimized:

- The orange point is worse than the yellow point because the both objective are worst compared to the yellow point,
- The red point is better than the yellow point because both objective are better
- The blue points are neutral compared to the yellow point because one objective is better while another objective is worst.

Then a non-dominated point is a point that is not dominated by any other point. The goal is to find the optimal Pareto front containing the series of points that are non-dominated (see at the bottom of Figure 6).

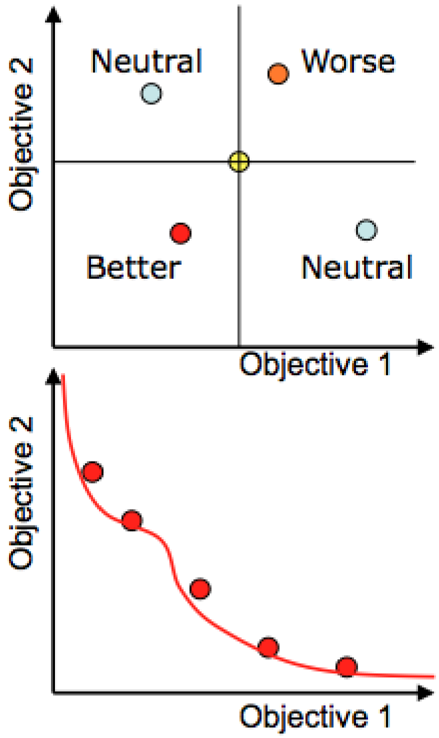

Figure 6: Pareto front

A big advantage of all **Xtreme** optimization algorithms is that they can use continuous design variables but also discrete design variables:

- Continuous design variables are for example the insulation thickness that can vary between 100 mm and 200 mm
- Discrete variables are for example the type of window (3 types in the present study)

5. THE APPLICATION

During the optimization process, the **design variables** are:

- Wall insulation thickness
- Roof insulation thickness
- Floor insulation thickness
- Glazing type
- Ventilation type and efficiency of heat recovery.

The variation limits for these design variables are summarized in Table 4.

Design variable	**Lower bound**	**Upper bound**
Wall insulation thickness (cm)	4	30
Roof insulation thickness (cm)	12	50
Floor insulation thickness (cm)	0	20
Glazing type	3 types of windows	
Ventilation type	4 types of ventilation	

Table 4: Design variables names and variation limits

In this application, 2 objectives are being minimized together at the same time:

- The energy demands computed by the PHPP software
- The construction cost calculated using simple formula based on the principles exposed in section 4.

As a consequence, the Pareto Front genetic algorithm optimization technique is used. The optimization software **Xtreme** is used and in particular the Microsoft Office Add-In version is used. The cost function is calculated in an extra sheet inside the PHPP project.

OPTIMIZATION SETTINGS

The multi objective Pareto front genetic algorithm is used for this optimization. A population of 100 individuals is chosen and a number of reproduction cycles of 100 cycles. This makes a total of 10 000 function evaluations (evaluation of the house energy performance and construction cost).

GLOBAL OPTIMIZATION RESULTS

The results are presented in details from Figure 7 to Figure 15.

Figure 7 shows that the house configuration found ranges from an energy demand of 10.03 kWh / m² / year to 89.61 kWh / m² / year. Regarding the price in relative value, it ranges from -6288 € up to +27 609 €. -6288 € means that this house cost less than the reference house.

The highest energy efficient house has the following characteristics reaching the maximum limits for each design variable:

- Wall insulation thickness 30 cm
- Roof Insulation thickness 50 cm
- Floor insulation thickness 20 cm
- Triple glazing (U = 0.59 and g=0.584)
- Highly efficient ventilation (92%)

The lowest efficient house (but cheapest) has the following characteristics reaching the minimum limits for each design variable:

- Wall insulation thickness 4 cm
- Roof Insulation thickness 12 cm
- No floor insulation thickness
- Double glazing (U = 1.1 and g=0.609)
- No ventilation and no specific air tightness

The price difference between these 2 extreme configurations is 33 898 €. As the house surface is 217 m^2 (including the Attic), the maximum budget difference per square meter is 33 898 € / 217 m^2 = **156 € / m^2**. This extra budget looks reasonable from an investment perspective based on the energy budget that will be saved during many years when the house enter into service and based on the extra building value.

Another very interesting conclusion that can be learned from this study is the extra construction cost required to increase the house energy efficiency:

- In the range [60, 90] kwh/m^2/year reducing the energy demand by 1 kwh/m^2/year requires 0.78 € / m^2
- In the range [40, 60] it requires 1.025 €/m^2
- In the range [30, 40] it requires 1.48 €/m^2
- In the range [20, 30] it requires 2.49 €/m^2
- In the range [15, 20] it requires 4.54 €/m^2
- In the range [12.5, 15] it requires 7.45 €/m^2
- In the range [10, 12.5] it requires 12.92 €/m^2

As a practical example for the house used in this study, decreasing the energy consumption **from 20 to 15 kWh/m^2/year:**

- Will required 4.54 * 5 * 217 = **<u>4925 € of extra construction cost</u>**.
- The energy saving will be of 5 kWh/m^2/year * 217 m^2 = 1085 kWh / year.
- The cost of energy saving will be (based on a price of energy of 0.1 €/kWh) of 108.5 € / year.
- This means that only based on the energy saving the return on investment will be around 50 years (ignoring the current and future value of money and inflation).
- However, the building also has an extra value based on its better energy performance. This is hard to evaluate in the context of this study.

This example shows that the tool developed in this project will help any company or private persons to decide based on their own budget or their own specific design the best cost optimal solution.

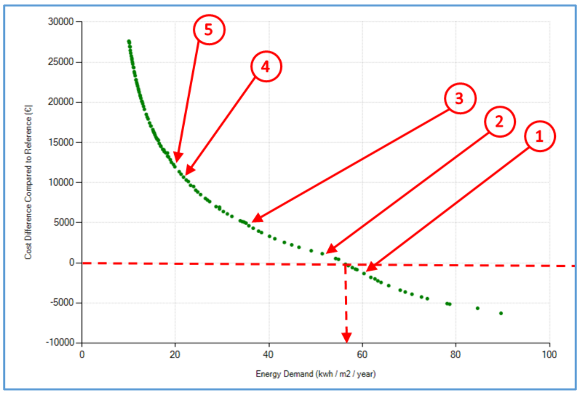

Figure 7: Pareto Front in the space Energy Demand – Cost Difference

DETAILED OPTIMIZATION RESULTS

Another very interesting group of lessons can be learned from this study by moving along the Pareto front from the low cost/high energy house solutions to the high cost / low energy house solutions. The Figure 7 shows 5 interesting points that will be further detailed hereafter:

1. From the low cost house until point 1, only the roof and wall insulation thickness is used and increased (Figure 11 and Figure 12). Double glazing is used (Figure 8), no specific air tightness (Figure 9) and no floor insulation (Figure 10) is required or is cost-optimal.
2. Starting at point 1, the cost-effective solution is to move directly to triple glazing with enhanced solar factor (Figure 8) and reduce a little the roof and wall insulation
3. Then at point 2, the cost effective solution is to go back to double glazing and add a ventilation system (Figure 9).
4. At point 3, the triple glazing with enhanced solar factor comes back (together with the ventilation system) as the cost optimal solution.
5. Then at points 4 and 5 (around 20 kWh/ m^2/year) the cost-optimal solution requires to switch to the best ventilation efficient system and to start insulating the floor.

This studies also allowed to conclude that the triple glazing windows without enhanced solar factor does not appear at all in the front of cost-optimal solution. However, this conclusion must be taken with care as the cooling demand for this house was not taken into account on one side and that on the other side, usually for very low energy house the windows are usually equipped with solar protection system to avoid overheating and that was not considered in this study.

This study also shows that the floor insulation is only cost-optimal when designing house below 20 – 25 kwh/m^2/year.

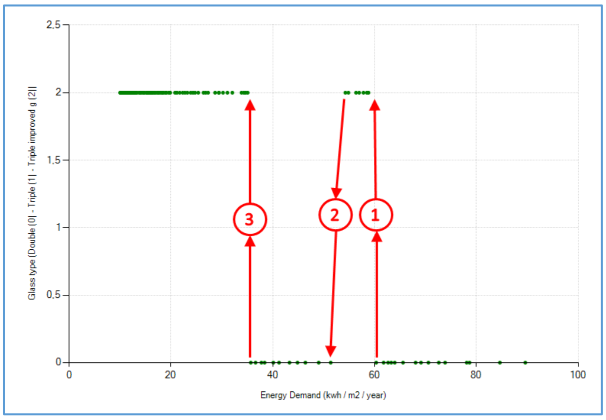

Figure 8: Required glass type as a function of the target energy demand

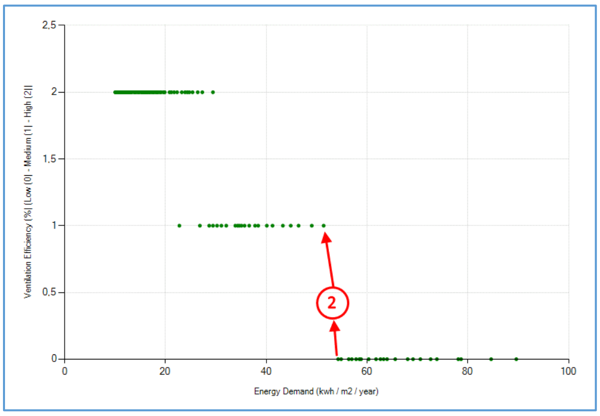

Figure 9: Required ventilation efficiency as a function of the target energy demand

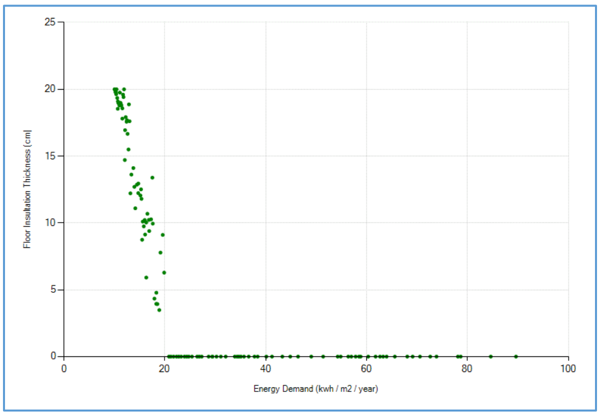

Figure 10: Required floor insulation thickness as a function of the target energy demand

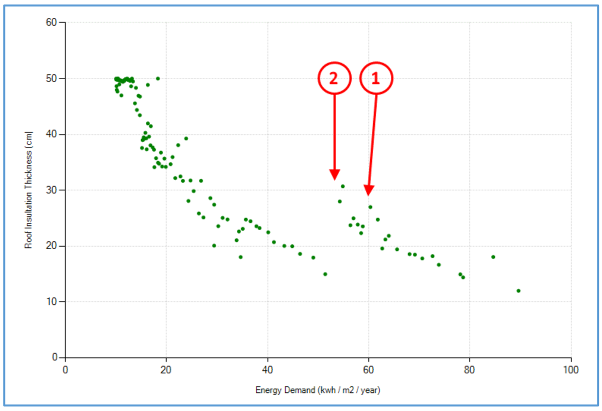

Figure 11: Required roof insulation as a function of the energy demand

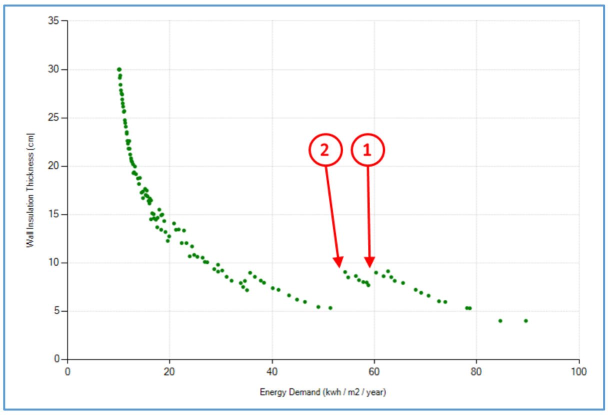

Figure 12: Required wall insulation as a function of the target energy demand

Some other conclusions are also very interesting:

- Based on the Figure 13, floor insulation is also cost-optimal only when the roof insulation (using cellulose) is thicker than 30 cm.
- Based on the Figure 14, floor insulation is also cost-optimal only when the wall insulation thickness is larger than 12 cm
- Finally, Figure 15 shows that the roof insulation thickness (made of cellulose) must be twice the wall insulation thickness (made of PUR).

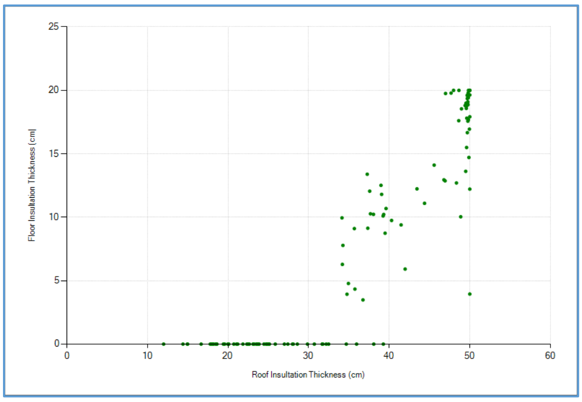

Figure 13: Relation between the optimal Floor Insulation Thickness and the Roof Insulation Thickness

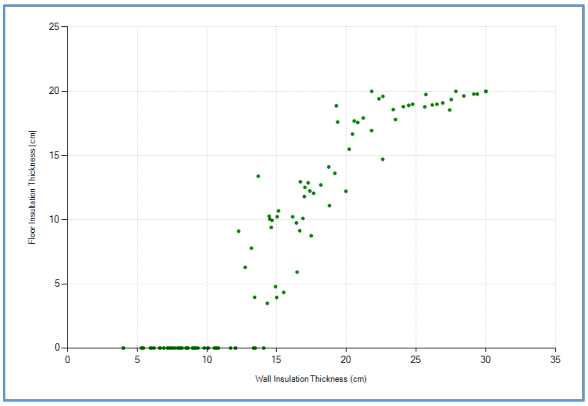

Figure 14: Relation between the optimal Floor Insulation Thickness and the Wall Insulation Thickness

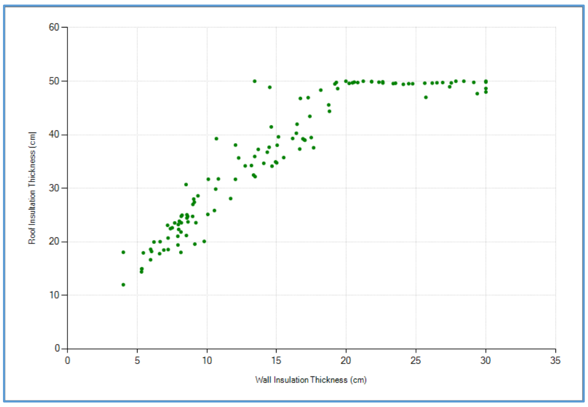

Figure 15: Relation between the optimal Roof Insulation Thickness and the Wall Insulation Thickness

6. CONCLUSIONS

In this study we have demonstrated how a numerical optimization software such as **Xtreme** can be used in order to find the Pareto front of cost-optimal solutions for residential houses.

It was also possible to draw general conclusions on construction choices based on particular technology jumps identified along the Pareto front. Of course those cost-optimal technology jumps might be slightly different for other construction principles but the tool developed in this project would allow any design office to transpose the calculation to their own design principle.

This project was part of a real design and construction process. The final house is shown on Figure 16. The final design parameters are:

- 40 cm roof insulation
- 22 cm wall insulation
- 15 cm floor insulation
- Triple glazing with enhanced solar factor
- High efficiency double flux ventilation

This solution was identified as the cost-optimal solution for an energy consumption in the range 14 – 15 kwh/m^2/year.

Figure 16: Final residential house

7. REFERENCES

[1] http://ec.europa.eu/eurostat/statistics-explained/index.php/Consumption_of_energy

[2] http://www.passiv.de/en/04_phpp/04_phpp.htm

[3] http://www.trnsys.com/

[4] https://energyplus.net/downloads

[5] http://www.optimalcomputing.be/ xtreme-description.php