

Multi-objective optimization of thermal modelled cubicles considering the total cost and life cycle environmental impact

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Abstract

Energy efficiency strategies, such as building insulation, improve the building performance without compromising comfort. This study presents a methodology for determining the optimal insulation thickness for external building surfaces. Our approach is based on a multi-objective optimization model that minimizes simultaneously the cost and environmental impact associated with both the energy consumption over the operational phase and the generation of the construction materials (including the waste produced during the disposal phase). The thermal loads of the modelled cubicles were calculated using EnergyPlus, a widely used simulation program for buildings. The environmental impact was quantified following the life cycle assessment (LCA) methodology. This methodology was applied to a case study of a house-like cubicle located in Lleida (northeast Spain). Taking as a basis a standard cubicle without insulation, our approach identifies solutions that reduce around 40% both, the

cost and environmental impact. Optimal solutions show also important economic and environmental improvements compared to cubicles constructed with the Spanish legislation requirements. Our method is intended to assist decision-makers in the design of buildings.

Keywords: Multi-objective optimization, Life cycle assessment (LCA), Modelling, Buildings, Insulation

Nomenclature

Abbreviations

| | |
|---------|--|
| IEO | International Energy Outlook |
| MOO | Multi-objective optimization |
| LCA | Life cycle assessment |
| PU | Polyurethane |
| MW | Mineral wool |
| EPS | Polystyrene |
| NSGA-II | Non-dominated sorting genetic algorithm-II |
| EA | Evolutionary algorithms |
| EI99 | Eco-indicator 99 |
| IO | Input-Output |
| GLO | Average global impact |
| ACH | Air changes per hour |

List of symbols

| | |
|--------------|----------------------------|
| $Cost_{cub}$ | Cubicle cost |
| $Price_k$ | Price of the component |
| $Quant_k$ | Quantity of the component |
| COP | Coefficient of performance |

| | | |
|----|------------------|---|
| 54 | $Cost_{elec_n}$ | Electricity cost over n years |
| 55 | $Cons_{elec}$ | Electricity consumption |
| 56 | $PCost_{elec}$ | Present cost of the electricity |
| 57 | n | Years |
| 58 | Inf | Year electricity inflation rate (%) |
| 59 | $Cost_{total}$ | Total cost |
| 60 | Imp_{cub} | Cubicle impact |
| 61 | Imp_k | Coefficient of damage per kilogram of raw material |
| 62 | Imp_{elec} | Electricity impact |
| 63 | Imp_{kWh} | Coefficient of damage per kWh of electricity in Spain |
| 64 | $Quant_{kWh}$ | Consumed electricity over the lifetime of the cubicle |
| 65 | Imp_{total} | Total impact |
| 66 | \bar{z} | Objective function |
| 67 | X | Space of feasible solutions |
| 68 | z_1 to z_j | Components of the objective function |
| 69 | x_1 to x_i | Decision variables |

70

71 **1. Introduction**

72 Nowadays buildings are responsible for approximately 40% of the total annual worldwide
73 consumption of energy [1]. Most of this energy is used for lighting, heating, cooling and air
74 conditioning [2]. The IEO2013 (International Energy Outlook 2013) forecast model indicates that the
75 energy demand for buildings will increase by 1.6 % every year in the next decades. Households in
76 OECD Europe accounted for 22% of the world's total residential delivered energy consumption in
77 2010. However, their share is expected to fall to 17% by 2040, mainly because of the increasing
78 efficiency and low population growth [3].

79

Many countries in OECD Europe have enacted measures to improve energy efficiency in the building sector. For example, the European Union (EU) approved a binding legislation, which aims to meet its ambitious climate and energy targets for 2020. The plan was launched in March 2007, and after months of tough negotiations it was adopted by the European Parliament [4].

Multiple energy efficiency strategies can be applied to achieve the reduction goals commented above. Among them, building insulation is particularly appealing, since it decreases the demand of both heating and cooling, thereby leading to significant environmental savings. For both, new and existing buildings, there is a huge potential for improvements in this direction. According to the National Statistics Institute of Spain, 26% of the total houses in Spain were constructed before 1980 [5]. The first Spanish law requiring insulation in buildings dates back from 1979 [6]. Because of this, a high percentage of the buildings in Spain are not insulated, unless they were recently rehabilitated. From that moment on, it was required to include insulation in the constructions, but it was not until 2006 that a more restrictive law imposed higher levels of insulation in the buildings [7].

Insulation materials can be implemented in all types of constructions. In the European market, inorganic fibrous materials, glass wool and stone wool account for 60% of the insulation materials, while organic foamy materials, expanded and extruded polystyrene and to a lesser extent polyurethane accounts for about 27%. The three most common insulation materials used in Spanish buildings are polyurethane (PU), mineral wool (MW) and polystyrene (EPS) [8].

The current trend is to promote thicker insulation because it reduces energy consumption within the building. However, the extent to which this strategy reduces the environmental impact is still poorly understood. Thicker insulation does not necessarily involve less impact. This is because the impact generated during the construction and disposal phases might be significant. Neglecting this impact embodied in the insulation materials may lead to solutions where energy savings might be attained at the expense of increasing the environmental burdens elsewhere. Blengini et al. [9] conducted a detailed study on the impact caused in all the stages of the life of a low energy family house and

concluded that the shell-embedded materials represented the highest relative environmental impact. Along the same lines, Stephan et al. [10] showed that the energy embodied in passive houses can represent up to 77% of the total (embodied and operational) energy over 100 years.

Many tools and indicators are available for assessing and benchmarking environmental impacts of different systems, including Life Cycle Assessment, Strategic Environmental Assessment, Environmental Impact Assessment, Environmental Risk Assessment, Cost-Benefit Analysis, Material Flow Analysis, and Ecological Footprint [11]. Among them, life cycle assessment (LCA) [12], has recently emerged as the prevalent approach. This methodology accounts for the impact caused in all the stages in the life cycle of the product being assessed. LCA quantifies the life cycle impact through a set of indicators that can be either midpoint or endpoint. The former refers to emissions, while the latter refers to impact in the human health, ecosystem quality and natural resources. Discussion amongst LCA experts showed that because of the mutually exclusive aspects of uncertainty and relevance, the midpoint/endpoint debate is controversial and difficult to reconcile. Lenzen [13] argued that if endpoint information is too uncertain to allow a decision to be made with reasonable confidence, then the assessment can be carried out in midpoint terms or even can be based on the stakeholders' subjective judgments about the more certain midpoint levels. In the present study we will work with endpoint levels. In general, a considerable research gap emerges in the field of environmental impact of buildings, as even the impact of new constructions has barely been evaluated in a systematic way [9,14–17].

Previous approaches for optimizing the insulation thickness considered only cooling loads [18–20], heating loads [21–25] or both cooling and heating loads [26–30], but neglected the impact of the construction materials. In addition, to find the energy loads, most of these studies applied the degree-days methodology [18,23,31–33], a heuristic approach that due to its narrow scope might lead to suboptimal alternatives. Recent developments in numerical methods and software applications have led to more precise tools, but their application in this field has been quite scarce. The degree-days method consider static conditions, while other studies take into account dynamic transient conditions

[34–38]. Ozel [39] analysed the effect of insulation location in the wall, finding that this has a significant effect on the yearly averaged time lag and decrement factor, but little impact on the yearly transmission loads and optimum insulation thickness. Al-Sanea et al. [35] analysed the optimum insulation thickness depending on the electricity tariff as well as the cost of insulation material, lifetime of the building, inflation and discount rates, and coefficient of performance of the air-conditioning equipment. They found that the optimal thicknesses vary from 4.8 to 16 cm depending on the case study.

The aim of this study is to analyse how the selection of an insulation material and its thickness affects the energy consumption, the total cost and the environmental impact of the building. The final goal is to determine the thickness of the insulation that minimizes simultaneously the cost and environmental impact. Note that the minimum cost solution will differ, in general, from the minimum impact one. Hence, there will be a natural trade-off between both of them, and the solution of the problem will be given by a set of Pareto optimal points, each achieving a unique combination of cost and impact, rather than a single optimal solution. Polyurethane (PU), Polystyrene (EPS) and Mineral Wool (MW) are considered as insulation materials. Our multi-objective optimization (MOO) approach offers decision makers a suitable framework to identify solutions to improve simultaneously different economic and environmental targets [40]. Our systematic methodology can work with different types of decision variables and objective functions.

The article is structured as follows. Section 2 provides the problem statement. Section 3 describes our methodology and the multi-objective optimization tool. The case study is explained in detail in Section 4. In Section 5 the results are presented and discussed, while the conclusions of the study are finally drawn in Section 6.

2. Problem statement

To derive our approach, it is considered, without loss of generality, a general cubicle type building in which the space heating and cooling requirements are covered by a reversible heat pump. A

construction profile is depicted in Fig. 1. Details about the cubicle configuration are provided in Sections 4.1. Cubicle description and 4.2. Model specifications.

The goal of the analysis is to find the type of insulation material and the thicknesses of the insulation wall that simultaneously minimize the total cost and the environmental impact of the building. The latter considers the impact associated with the generation of the energy consumed by the building as well as the manufacture of the construction materials.

3. Methodology

3.1. Mathematical model

Our approach relies on the integration of a simulation model of the building with an external optimization algorithm. More precisely, the energy loads are calculated using EnergyPlus v.8 [41–43] a software for energy simulations in buildings. In mathematical terms, the problem contains a system of partial differential equations (PDEs) that describe a set of energy balances. These are required to determine the energy consumption for a given set of materials and associated thickness values. EnergyPlus has three basic components: a simulation manager, a heat and mass balance simulation module, and a building system simulation module. Simulation capabilities include integrated simulation, combined heat and mass transfer balance and multizone airflow and HVAC loops (flexible system and plant simulation). EnergyPlus allows to define sub-hourly time steps for the interaction between the thermal zones and the environment as well as between the thermal zones and the HVAC systems [42]. EnergyPlus has five models that calculate the beam solar radiation and reflectance from exterior surfaces that strike the building and, ultimately, enter the zone (MinimalShadowing, FullExterior and FullInteriorAndExterior, FullExteriorWithReflections, FullInteriorAndExteriorWithReflections). This study uses the FullExterior option, which computes all shadow patterns on exterior surfaces caused by detached shading, wings, overhangs, windows and door reveals, and exterior surfaces of all the zones. The beam solar radiation entering the zone is assumed to fall on the floor, where it is absorbed according to the floor's solar absorptance. Any

radiation reflected by the floor is added to the transmitted diffuse radiation, which is assumed to be uniformly distributed on all interior surfaces [44].

As already mentioned, our goal is to find the insulation thickness values that optimize the cost and environmental impact. Hence, a range of thicknesses of different insulation materials are considered as decision variables. Our final aim is to develop a general methodology for dealing with complex problems. Exhaustive and time-consuming searching strategies can be implemented in existing software tools (e.g. JEPlus [45], Genopt [46]). This complex parametric analysis might lead to large calculations that will not even ensure convergence to an optimal solution. Hence, when the search space is large, it is more convenient to resort to rigorous optimization algorithms. In this work a multi-objective optimization tool based on a customized non-dominated sorting genetic algorithm-II (NSGA-II): JEPlus+EA [47], is combined with EnergyPlus. The overall numerical procedure is summarized in Fig. 2. Note that the simulation model of the building could be coupled with other optimization algorithms, in a similar manner as was done before by the authors in other works [40].

Genetic algorithms belong to the larger class of evolutionary algorithms (EA), which generate solutions to optimization problems using techniques inspired by natural evolution, such as inheritance, mutation, selection, and crossover. Genetic algorithms start with an initial chromosomes population composed of a random set of solutions. From this initial set, they generate new generations by applying some numerical operators based on natural evolution. In each generation, the fitness of every individual in the population is evaluated. This fitness corresponds to the value of the objective function associated with the member of the population (solution) being assessed. Each new generation is constructed by selecting some of the parents and offsprings, based on the fitter chromosomes, and rejecting the others, thereby keeping the population size constant. After a number of generations, the algorithm converges to a final solution [48].

Genetic algorithms have already been applied in the context of buildings optimization. Murray et al. [49] presented a degree-days simulation technique coupled with a genetic algorithm that was applied

to the retrofit of buildings. The objective functions were the payback, the carbon emissions and the energy cost. Asady et al. [50] presented a similar study, but in their case the objective functions were the energy consumption, the retrofit cost, and the thermal discomfort hours. Yuan et al. [51] proposed a multi-objective global optimization method that combined a refrigerator dynamic model that was coupled with a NSGA-II genetic algorithm in order to increase the overall performance. In this study the objective was to minimize the total cost along with the energy consumption. Gossard et al. [52] presented a methodology that combines an artificial neural network (that reduces computational requirements compared to dynamic yearly thermal simulations) and the genetic algorithm NSGA-II. The objective was to improve the thermal efficiency of a building envelope. The optimization variables in this study were the thermophysical properties of the external walls (thermal conductivity and volumetric specific heat), while the optimization targets were the annual energy consumption and the summer comfort degree.

3.2. Objective functions

The next sections describe how the economic and environmental performance of each design alternative is assessed.

3.2.1. Economic indicators

The economic performance is quantified through the cost, which accounts for the cost of the insulation material and the cost of the electricity consumed for heating and cooling over the lifetime of the building. The objective is to achieve the minimum total cost [33,39,53,54].

An inventory list of the required materials for the cubicle construction, and the corresponding quantities and cost is given in Table 1. Details on the cubicle description can be found in section 4.1. Cubicle description. As an illustrative example, we show how to calculate the cost of a cubicle with 1 cm of insulation thickness in all of their surfaces. The thermo-physical properties and the specific cost

of the insulation materials are presented in Table 2. Data were retrieved from LIDER [55] and ITeC [56] databases. The total price of the materials for the construction of the cubicle is given by:

$$Cost_{cub} = \sum_k Price_k \cdot Quant_k \quad (1)$$

Where $Cost_{cub}$ is the total cost of the materials for the construction of the cubicle, $Price_k$ is the price per kilogram of raw material k and $Quant_k$ is the correspondent quantity in kilograms of raw material k used in the construction (i.e. kg of concrete).

The required electricity for heating and cooling is obtained by converting the useful thermal energy output (heating and cooling) to energy input (or energy consumed). In the case of this study we are considering a heat pump with a COP of 3. The COP is defined as the ratio between useful thermal energy to electrical energy consumed. Thus, the electricity consumption is calculated by dividing the heating and cooling demand by the COP. This consumed electricity is multiplied by the electricity cost in the domestic sector in Spain (0.16 €/kWh) [57] considering a cost increase of 5 % per year as proposed in [53], as shown in the following equation:

$$Cost_{elec_n} = \sum_n Cons_{elec} \cdot PCost_{elec} \cdot (1 + Inf)^n \quad (2)$$

where $Cost_{elec_n}$ is the electricity cost over n years, $Cons_{elec}$ is the consumed electricity in kWh for heating and cooling, $PCost_{elec}$ is the present cost of the electricity kWh in Spain, and Inf is the yearly increase of the electric cost.

As mentioned previously, the model seeks to minimize the total cost. The total cost ($Cost_{total}$) accounts for the cost of the materials for the construction of the cubicle ($Cost_{cub}$) and the cost of the electricity consumed over the operational phase of the cubicle ($Cost_{elec_n}$), as follows:

$$Cost_{total} = Cost_{cub} + Cost_{elec_n} \quad (3)$$

3.2.2. Environmental indicators

The environmental impact associated with the generation of the electricity consumed and the manufacture of the construction materials is assessed through the Eco-indicator 99 (EI99) methodology [12,58] which is based on LCA principles and which has already been used by other authors in similar case studies [14,59–61]. LCA is a method for evaluating the environmental impacts of products by adopting an holistic approach that accounts for the direct and indirect impacts. Process-based LCA and input-output LCA (IO) are two methods that attempt to quantify these impacts. Process-based LCA applies mass and energy balances to determine the inputs of energy and materials resources, along with the outputs (amount of waste generated and emissions to air, soil and water). In the first step of the process-based LCA, it is required to define the system boundaries. This might lead to a so called truncation error that can arise when some parts of the supply chain are neglected [62–64]. The IO approach quantifies the interdependences between sectors through monetary flows, each of which has an associated use of resources. In this LCA method, outputs of an industrial sector are inputs to others, for example, the outputs of sand extraction will be used in the concrete industry. This type of approach makes use of aggregated economic and environmental data. Input-output analysis has some limitations regarding the high level of aggregation in industry or commodity classifications [62]. Another limitation in input-output analysis concerns the uncertainties stemming from inaccurate or updated measurements [65]. Hybrid methods that combine to some extent both approaches have been proposed to overcome the limitations mentioned above [62,66–68]. One such approach consists of analysing and quantifying the different stages using process-based to then resort to IO equations when a lack of data is identified. Another one is based on a more general characterization that combines IO and process-based data. These hybrid methods should provide more accurate results [11,63] compared to either process-based or EIO. However, as pointed by Majeau-Bettez et al. [69],

these hybrid assessments have yet to enter mainstream practice and become an explicit priority of the field's guidelines [70] and standards [12,71].

This study follows the Eco-indicator 99 methodology, a process-based method which is based on LCA principles. More on this selection will be commented in Section 5. Results and discussions. This method quantifies 10 impacts that are aggregated into 3 different damage categories (human health, ecosystem quality and resources). These categories are then translated into Ecoindicator 99 points using normalization and weighting factors. In the calculations, two main sources of impact are considered: the manufacture of the materials used in the construction of the cubicle (including the impact in the dismantling phase) and the amount of electricity consumed during the time horizon. The first term is determined as follows:

$$Imp_{cub} = \sum_k Imp_k \cdot Quant_k \quad (4)$$

Where Imp_{cub} is the total EI99 impact of the construction materials of the cubicle, Imp_k , is the coefficient of damage per kilogram of raw material k (an information that is available in the EcoInvent database[72]), and $Quant_k$ is the corresponding quantity in kilograms of raw material k .

Table 3 summarizes the main sources of impact associated with the materials in the manufacturing and dismantling phases. As an illustrative example, Table 3 displays as well the environmental impact of a cubicle with 1 cm of insulation thickness in all of their surfaces.

EcoInvent data of the Spanish electricity production system are used to translate the electricity consumed over the operational phase into EI99 impact points as follows:

$$Imp_{elec} = Imp_{kWh} \cdot Quant_{kWh} \quad (5)$$

Where Imp_{elec} is the total EI99 impact of the consumed electricity over the operational phase of the cubicle, Imp_{kWh} is the coefficient of damage per kWh of electricity in Spain (0.032078 EI99 points per kWh [72]) and $Quant_{kWh}$ is the consumed electricity over the lifetime of the cubicle.

As in the case of the economic cost, for the environmental impact the objective is again to achieve a minimum impact. The total impact (Imp_{total}) includes the impact of the materials for the construction of the cubicle (Imp_{cub}) and the impact of the consumed electricity over the operational phase of the cubicle (Imp_{elec}):

$$Imp_{total} = Imp_{cub} + Imp_{elec} \quad (6)$$

3.3. Solution procedure

The goal of the analysis is to find the values of the insulation thickness that minimize simultaneously the cost and the environmental impact. For optimization purposes, the simulation model implemented in EnergyPlus is expressed in mathematical terms as an explicit function of the form:

$$\vec{z} = \{Cost_{total}, Imp_{total}\} = f^{MOD}(\vec{x}) \quad (7)$$

That is, the vector \vec{z} (objective function), which is composed of the cost and environmental impact, is obtained from the simulation model after specifying the values of the decision variables. The decision variables are in turn encoded in the vector \vec{x} , which contains the values of the thickness of each wall.

The resulting multi-objective optimization model can be expressed in compact form as follows:

$$\min_{\vec{x} \in X} (z_1, \dots, z_j) = \min_{\vec{x} \in X} f^{MOD}(x_1, \dots, x_i) \quad (8)$$

where X represents the space of feasible solutions, z_1 to z_j are the j components of the objective function (the cost and the j -1 environmental impacts) and x_1 to x_i are the decision variables. The optimization problem contains only one block of constraints that are explicit, which impose lower and upper bounds on the values of the decision variables (thickness values should fall within lower and upper limits). Other implicit constraints, like mass and energy balances, are enforced by the simulator model.

There are many methods available to solve multi-objective optimization problems [73–76]. The solution of a MOO problem is given by a set of points (called Pareto solutions) that represent the optimal trade-off between the objectives considered in the analysis [40,77]. These Pareto optimal solutions have the property that it is impossible to improve them simultaneously in all of the objectives without necessarily worsening at least one of them.

Mathematically, $x \in X$ is an efficient solution or Pareto optimal solution if there does not exist any $x' \in X$ such that $f_i(x') \leq f_i(x)$ for all i , and $f_j(x') < f_j(x)$ for some j . If x' is Pareto optimal, then $z' = f(x')$ is called non-dominated point or efficient point. The set of all non-dominated points is referred to as non-dominated frontier or Pareto frontier.

In this paper, without loss of generality, the multi-objective model is solved using multi-objective genetic algorithms.

4. Case study

4.1. Cubicle description

The research group GREa, possesses an experimental installation of house-like cubicles in Puigverd, (Lleida, Spain) [8]. The cubicles have identical dimensions (five plane walls with $2.4 \times 2.4 \times 0.15$ m),

but implement different materials (diverse types of bricks and insulation materials). According to the Worldwide bioclimatic classification system of Rivas-Martinez et al. [78], Lleida presents a Mediterranean Xeric Oceanic bioclimatic type of weather, which is characterized by moderate cold winters and dry hot summers.

The cubicle represents a conventional Mediterranean construction system. The structure of the cubicle is made of four mortar pillars with reinforcing bars, one in each edge of the cubicle. The base consists of a concrete base of 3×3 m with reinforcing bars. The walls consist of 6 material layers (enumerated from outside to inside): a cement mortar finish, a hollow bricks structure, an air chamber of 5 cm, a layer of an insulation material (PU, EPS or MW depending on the model), perforated bricks and a plaster plastering layer. The roof was constructed using concrete precast beams and 5 cm of concrete slab. The internal finish is plaster plastering. The insulating material (PU, EPS or MW) is placed over the concrete, and it is protected with a cement mortar roof with a slope of 3 % and a double asphalt membrane. Moreover, a reference cubicle with no insulation is also considered [8,60] for comparison purposes.

4.2. Model specifications

The cubicle simulation reproduces the conditions of the experimental cubicles. These conditions imply many simplifications when comparing to a real operative building, which are used to simplify an analysis that would be otherwise very hard to perform. In future studies, more complex building models will be considered in order to apply this methodology to more realistic conditions, taking into account as well the main uncertainty sources affecting the calculations. The specifications of the model are listed herein:

- An internal set point temperature of 24°C is fixed for the whole year. This is indeed a quite high value for winter season that was chosen so as to facilitate the comparison with previous studies [8,59].
- Neither windows nor doors are considered (i.e., cubicles without openings). The aim here is that the simulated configuration will be as close as possible to the real one.
- The heating and cooling are supplied by a heat pump with a COP of 3.
- A fixed infiltration rate of 0.12 ACH (air changes per hour) [79] is assumed and no mechanical or natural ventilation is used. These conditions again might be uncommon in a real operative building. However, this simplification enables us to easily analyze the specific performance of the different insulation materials.
- There is no internal mass and no human occupancy.
- A building lifetime of 20 years is considered [34,80].
- The total inversion for the construction materials takes places the first year of the time horizon.
- As for the electricity, a price of 0.16 €/kWh is considered [57] with a yearly increase in cost of 5% as proposed in [53]. There is no universal method widely accepted for calculating the evolution of the electricity cost. Hence, this study considers a fix increasing tax.

4.3. Case I: homogenous insulation thickness

The base case for both case studies is based on a cubicle with the aforementioned specifications but without insulation.

In the first case study, the insulation thickness is varied uniformly in the four vertical surfaces and in the roof from 1 to 25 cm. That is, the same thickness is set in the vertical surfaces and in the roof. The range considered (1-25 cm) was based on practical aspect, since in a first approach it was observed that optimal solutions did not surpass 25 cm of insulation thickness. In our case studies, we do not combine different materials in the same model. We start by analysing each single objective separately, and then look for the set of Pareto solutions representing the optimal trade-off between both conflicting objectives.

4.4. Case II: heterogeneous insulation thickness

In the second case study, instead of changing the thickness of all of the surfaces uniformly, we analyse the effect of different insulation thickness for each surface [39]. The range considered for the insulation thicknesses is the same as in case I, but this time we combine different thickness values for the walls and roof.

To determine the set of optimal thickness values, we implemented the model in EnergyPlus and the optimization algorithm described above in JEPlus+EA. The optimization method is based on a modified version of the NSGAII algorithm [81]. The default settings of the JEPlus+EA toolbox were used in the simulations.

The algorithm takes around 1900 to 2000 CPU seconds to generate the Pareto solutions for each material (PU, EPS, MW) on a computer HP Compaq Pro 6300 SFF with an Intel Core Processor 3.30 GHz and 3.88 GB of RAM. The maximum number of generations was fixed to 200, with an initial population size of 10. Each calculation was repeated 10 times in an attempt to avoid local optima.

5. Results and discussions

Before proceeding to the next section we remark that the results are conditioned by the specifications of our model (4.2. Model specifications). The cubicles present many simplifications compared to a real operating building. These simplifications, however, are consistent with the experimental settings. Moreover, these simplified models enable us to easily evaluate the performance of the different insulation materials separately, since other possible effects (human occupancy, openings) are neglected.

A process-based approach was used in the LCA analysis. Process-based LCA might fail to quantify a fraction of the activities required to fulfil any given final demand [82,83]. If this happens, the environmental impacts will be underestimated. As stated by Majeau-Bettez et al. [69] the consequences of this truncation bias are expected to depend on the goal of the LCA study. If a LCA analysis strictly pretends to compare products or processes whose value chains involve activities within a similar industry mix, as is the case of this study, it may be expected that all the inventories will suffer from similar levels of incompleteness, in which case the ranking would be relatively insensitive to truncation error [63,69].

5.1. Case I: homogenous insulation thickness

5.1.1. Economic cost analysis

Fig. 3 shows that when the insulation thickness of the cubicle surfaces increases, the material cost increases linearly, while the energy cost decreases. Hence, there are two conflicting effects, and the minimum cost solution corresponds to the point representing the optimal balance between the two economic terms. In this case, the minimum cost solution involves a thickness of 8 cm for the PU, 10 cm for the EPS and 11 cm for the MW (Fig. 3). PU is more expensive than the other insulation materials. However, its thermal conductivity is lower, so its energy savings compensate for the extra

cost, making PU the most competitive material from the economic perspective. Note that, as expected, the solution with minimum energy cost is not the one with the best economic performance. Hence, the minimization of the energy consumption without considering the cost of the materials might lead to a suboptimal solution. The same can be said for the analysis of the minimum environmental impact solution.

5.1.2. Environmental impact analysis

The energy impact decreases with the insulation thickness, while the material impact increases linearly with the insulation thickness. The minimum impact (Eco-indicator99) solution involves a thickness of 8 cm for the PU, 12 cm for the EPS, and 23 cm for the MW (Fig. 4). The thickness with minimum impact for the MW is more than 10 cm higher than that corresponding to the others. This occurs because the environmental impact of the MW is much lower than the others. Specifically, this is due to the small fossil fuels depletion impact, which is ten times lower than the impact of PU and EPS. Because of this, the energy savings of the building are higher than the impact of the insulation.

5.1.3. Multi-objective analysis

In this section we analyse the total cost and environmental impact of both, energy and materials, simultaneously. Each point in Fig. 5 (Eco-indicator 99 vs cost) represents a different combination of insulation thicknesses. For each insulation material, we first obtain the extreme solutions of each objective (i.e., minimum cost and minimum environmental impact). Between these two points, a set of trade-off alternatives are identified, some of which might be Pareto optimal (recall that we are not using any rigorous optimization algorithm at this stage). For PU, since the best solution is the same for both objectives, we attain the utopia point, which by definition minimizes/maximizes all the objective functions of the multi-objective problem simultaneously. Regarding the EPS case, the best economic insulation thickness is 10 cm, while the best environmental solution involves a thickness of 12 cm.

Finally, the best insulation thicknesses for the MW case are 11 cm (economic) and 23 cm (environmental).

The best solutions identified appear in Fig.6, where we have plotted the envelope of the points depicted in Fig. 5, that is, only the best points in terms of economic and environmental performance are shown here. The extreme solutions are as follows: the optimal thickness from the environmental point is 23 cm with MW, and from the economic perspective is 8 cm with PU. The points configuring the curve between these two extremes are the best solutions in terms of the two criteria. In this case, we have 16 optimal solutions, one of them using PU and the others using MW. Analysing in more detail Fig. 6, from the extreme economic best solution to the extreme environmental best solution, it can be observed that, initially, a slight increase in cost leads to an important environmental impact reduction. However, as we get closer to the extreme environmental solution, higher economical efforts are required in order to reduce the environmental impact. With these results, we would recommend the intermediate solution of 11 cm with MW, as it increases 0.5 % the total cost while reducing the environmental impact by 9 %.

5.2. Case II: heterogeneous insulation thickness

This case assumes that the insulation thickness can be changed independently in each surface, which allows getting adapted to the orientation (N-S-W-E). The range considered (1-25 cm) was based on practical aspects.

Fig. 7 shows all of the intermediate points generated by the genetic algorithm during the calculations. The envelope of these points is the final approximation to the Pareto set. Note that the algorithm tends to produce points close to the Pareto set sought, but not necessarily optimal.

Fig. 8 shows the optimal results considering the three materials. The curve, which corresponds to the envelope of the points shown in Fig. 7, is the final approximation of the “true” Pareto set of the problem. For the PU case, a utopia point that is optimal in both objectives is identified. For the EPS, there are 8 optimal solutions but they do not appear in the Pareto front of Fig. 8, since they are

suboptimal when considering the results of the other materials. 41 best solutions implement MW. This happens, as mentioned, because this material has lower environmental impact. The highest environmental performance is achieved using MW with a thickness of 23 cm in all of the external surfaces, while the cheapest alternative implements PU with an insulation thickness of 8 cm in the North exterior facade, 6 cm in the South, 7 cm in the West and East, and 9 cm in the roof.

5.3. Discussion

Some important questions emerge from the analysis of the results: How much do the insulated best solutions improve compared to the reference case? Are the differences between the best solutions of homogeneous and heterogeneous insulation significant to justify the practical issues associated during construction? Are the results of this analysis in agreement with other studies? Are the optimal solutions in accordance with the recommendations of actual energy performance of buildings directives?

Table 4 shows the different extreme optimal solutions of cases I and II and their improvements (around 35 - 40 % better) with respect to the base case (without insulation). These results confirm the importance of selecting a proper insulation thickness to achieve reductions from the economic and environmental standpoints.

Comparing both case studies, we find that the best economic solution of case study II is only 0.25% better than its corresponding counterpart for case study I. In both cases, the best environmental solutions are the same. We therefore conclude that for the cubicle, and considering the climate conditions of Lleida, implementing the same insulation thicknesses in the external surfaces is a good strategy, and it provides near optimal solutions. Similar results were found by Al-Sanea et al. [84] using climatic data of Riyadh and by Daouas [27] using climatic data of Tunis. Yu et al. [33] analysed the effect of heterogeneous thicknesses of different orientated external surfaces for different climates

in China. They concluded that in Shanghai and Changasa, heterogeneous thicknesses in different orientations should be considered, while in Shaoguan and Chengdu, the effect was negligible.

Comparing the best economic solution of PU and MW, we find that increasing the cost by 0.5 %, decreases the environmental impact by 9%.

Table 5 presents the optimal insulation thickness for different case studies of other authors considering only the economic objective function. Athens, West Bank and Elâzığ show very similar weather conditions than those in Lleida. In the cases of West bank and Elâzığ, the results are similar to those obtained in our study with an insulation thicknesses ranging between 5 and 8 cm.

In the cases with different insulation thicknesses for the different orientated surfaces, the south wall is the one with the minimum thickness. The north wall is the one presenting the largest insulation thickness in [30] and in our analysis (for the optimal economic solution), while in other studies this is not the case. In [27,84] the north wall is the one presenting the thinnest thickness, probably because in these locations (Tunis and Riyadh) the temperatures during the summer months are extremely hot. Although North orientation provides the highest loads in winter it also provides the lowest in summer. The south orientation provides the lowest loads in winter and allows for natural heating in this season. Therefore, a slightly thinner insulation thickness is required for the south and north walls compared to the east and west walls in those locations.

Optimal insulations thicknesses obtained in the present study are not close to the application values required by the the regulatory framework that establishes the requirements to be met by buildings in relation to the basic requirements of safety and habitability established by [7]. The law required thermal transmittance is $0.66 \text{ W/m}^2\cdot\text{K}$ for the external facade walls in the location of Lleida, but our results suggest lower values between 0.35 and $0.26 \text{ W/m}^2\cdot\text{K}$ for the best economic solution and $0.135 \text{ W/m}^2\cdot\text{K}$ to achieve the best environmental performance. For the roof, the same situation is observed, since the law requires a thermal transmittance of $0.38 \text{ W/m}^2\cdot\text{K}$, and our analysis suggests values of $0.285 \text{ W/m}^2\cdot\text{K}$ for the best economical solution and of $0.135 \text{ W/m}^2\cdot\text{K}$ for the solution with minimum

environmental impact. Considering the requirements of the law, the simulated cubicles would have a total cost and environmental impact (considering the consumed electricity and the material cost) 10% higher than the best economic solution found by our approach. The solution with minimum impact identified in our study is also 3% cheaper and shows an impact 23 % lower compared to the cubicle constructed according to the Spanish law requirements.

6. Conclusions and future work

The thermal behaviour of a cubicle has been modelled and analysed. Different insulation materials have been considered for the external surfaces and their thickness has been changed in order to find the alternatives that simultaneously optimize the economic and environmental performance of the facility. Starting from the base case with no insulation, we have developed two cases (homogeneous and heterogeneous insulation thickness). The optimal environmental solution is achieved by using MW with a thickness of 23 cm in all of the external surfaces, while the economic optimum is obtained by using PU with an insulation thickness of 8 cm in the North exterior facade, 6 cm in the South, 7 cm in the West and East and 9 cm in the roof.

The systematic procedure developed herein quantifies the environmental impact of the construction materials together with its economic cost, along with the environmental impact and cost of the consumed energy. We conclude that for a proper assessment of the environmental impact of a building, it is necessary to take into consideration the environmental impact of the construction materials along with the impact of the energy consumed. This is important because suboptimal solutions can be generated if we only look at the impact avoided with the energy savings.

The current results and conclusions depend on the specifications of the model and especially on the parameters values used in the thermal and economic analysis. They indicate that, for our case studies, calculating the optimal insulation thickness is of paramount importance to reduce the economic cost

and the environmental impact. Results indicate that improvements of around 40% can be achieved with respect to the base case. In addition, implementing the same insulation thickness for the different orientated surfaces seems a good strategy, since the improvement attained by asymmetric designs with orientation dependent thicknesses is marginal. The optimal solutions identified by our method show also significant economic and environmental improvements compared to cubicles constructed with the Spanish legislation requirements.

This work will be extended in order to consider more scenarios (e.g., climate conditions, building models...) and to incorporate as well the main uncertainty sources (e.g, insulation cost, energy cost, inflation rate, emissions data, etc.).

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Tables

Table 1.

Inventory list of the materials used for the cubicle construction and their corresponding economic cost.

| Component | Used Mass (kg) | Cost (€) |
|-----------------|-------------------|-------------|
| Brick | 5,456 | 287 |
| Base plaster | 518 | 43 |
| Cement mortar | 608 | 30 |
| Steel bars | 262 | 157 |
| Concrete | 1,240 | 44 |
| In-floor bricks | 1,770 | 62 |
| Asphalt | 153 | 317 |
| PU (1 cm) | 20.25 | 79 |
| EPS (1 cm) | 13.50 | 59 |
| MW (1 cm) | 18 | 55 |

Table 2.

Properties of the insulation materials.

| Insulation material | Density (kg/m ³) | Thermal conductivity (W/(m·K)) | Specific heat (J/(kg·K)) | Cost (€/m ³) |
|---------------------|---------------------------------|-----------------------------------|-----------------------------|-----------------------------|
| Polyurethane | 45 | 0.027 | 1,000 | 175 |
| Polystyrene | 30 | 0.038 | 1,000 | 131 |
| Mineral Wool | 40 | 0.04 | 1,000 | 122 |

Table 3.

Inventory list of the materials used for the cubicle construction and their corresponding EI99 punctuation.

| Component | Name in the data base Eco Invent corresponding to the component | Used mass (kg) | EI 99 (Points/kg) | Total EI99 (Points) |
|--------------------------------|---|----------------|-------------------|---------------------|
| Brick | market for brick, GLO [kg] | 5,456 | 0.0196 | 106.714 |
| Base plaster | market for base plaster, GLO [kg] | 518 | 0.0126 | 6.552 |
| Cement mortar | market for cement mortar, GLO [kg] | 608 | 0.0147 | 8.939 |
| Steel bars | market for section bar rolling, steel, GLO [kg] | 262 | 0.0135 | 3.531 |
| Concrete (m3) | market for concrete, normal, GLO [m3] | 0.577 | 18.8780 | 10.888 |
| In-floor bricks | market for concrete roof tile, GLO [kg] | 1,770 | 0.0160 | 28.237 |
| Asphalt | market for mastic asphalt, GLO [kg] | 153 | 0.0284 | 4.342 |
| Disposal bricks | market for waste brick, GLO [kg] | 5,456 | 0.0028 | 15.078 |
| Disposal plaster | market for waste mineral plaster, GLO [kg] | 518 | 0.0057 | 2.976 |
| Disposal mortar | market for waste cement in concrete and mortar, GLO [kg] | 608 | 0.0062 | 3.798 |
| Disposal concrete + steel bars | market for waste reinforced concrete, GLO [kg] | 1,492 | 0.0042 | 6.203 |
| Disposal in-floor bricks | market for waste concrete, not reinforced, GLO [kg] | 1,770 | 0.0028 | 5.029 |
| Disposal asphalt | market for waste asphalt, GLO [kg] | 153 | 0.0020 | 0.307 |
| PU | market for polyurethane, rigid foam, GLO [kg] | 20 | 0.3973 | 8.046 |
| EPS | market for polystyrene foam slab for perimeter insulation, GLO [kg] | 14 | 0.3975 | 5.366 |
| MW | market for rock wool, GLO [kg] | 18 | 0.1024 | 1.842 |
| Disposal PU | market for waste polyurethane foam, GLO [kg] | 20 | 0.0743 | 1.504 |
| Disposal EPS | market for waste polystyrene, GLO [kg] | 14 | 0.0281 | 0.380 |
| Disposal MW | market for waste mineral wool, GLO [kg] | 18 | 0.0073 | 0.132 |

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850 Table 4.

851 Comparison of the base case results and the best economic and environmental results for both case studies.

| | | | Cubicle model | Economic cost (€) | EI99 (Points) | Improvement (%) | |
|------------------|------------------------|------------------------|---------------|----------------------|------------------|-----------------|------|
| | | | | | | Economic | EI99 |
| Base case | | | No insulation | 6,460 | 873 | 0.0 | 0.0 |
| Case study I | Best economic solution | PU - All surfaces 8cm | | 3,940 | 566 | 39.0 | 35.1 |
| | Best EI99 solution | MW - All surfaces 23cm | | 4,252 | 496 | 34.2 | 43.1 |
| Case study II | Best economic solution | PU - E7_N8_S6_W7_R9 | | 3,930 | 565 | 39.2 | 35.2 |
| | Best EI99 solution | MW- All surfaces 23cm | | 4,252 | 496 | 34.2 | 43.1 |

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Table 5.

Economic optimum insulation thickness for all wall types and orientations of different studies.

| Study | Location | Insulation materials | Optimum insulation thickness (m) | | | |
|------------------------|-----------------------|----------------------------------|----------------------------------|-------|-------|-------|
| | | | North | South | East | West |
| Present study | Lleida (Spain) | Polyurethane | 0.08 | 0.06 | 0.07 | 0.07 |
| | Erzurum (Turkey) | | 0.105 | 0.105 | 0.105 | 0.105 |
| Çomaklı et al. [22] | Kars (Turkey) | Stropor (Expandable polystyrene) | 0.107 | 0.107 | 0.107 | 0.107 |
| | Erzincan (Turkey) | | 0.085 | 0.085 | 0.085 | 0.085 |
| Axaopoulos et al. [30] | Athens (Greece) | Extruded polystyrene | 0.101 | 0.071 | 0.1 | 0.1 |
| Hasan [25] | West Bank (Palestine) | Rock wool | 0.068 | 0.068 | 0.068 | 0.068 |
| | Gaza (Palestines) | Polystyrene | 0.052 | 0.052 | 0.052 | 0.052 |
| | | Rock wool | 0.035 | 0.035 | 0.035 | 0.035 |
| Daouas [27] | Tunis (Turkey) | Expanded polystyrene | 0.026 | 0.026 | 0.026 | 0.026 |
| | | | 0.101 | 0.101 | 0.117 | 0.116 |
| Al-Sanea et al. [84] | Riyadh (Saudi Arabia) | Molded polystyrene | 0.088 | 0.087 | 0.092 | 0.092 |
| Ozel [85] | Elâzığ (Turkey) | Extruded polystyrene | 0.06 | 0.055 | 0.06 | 0.06 |

List of figure captions

Fig.1.

Construction profile of the experimental cubicles in Puigverd de Lleida (Spain).

Fig.2.

JEPlus+EA optimization process coupled with *EnergyPlus*.

Fig. 3.

Simulations obtained from the variation of the cubicle cost with the insulation thickness for PU, MW and EPS for case study I.

Fig. 4.

Simulations obtained from the variation of the cubicle EI99 scores with the insulation thickness for PU, MW and EPS for case study I.

Fig. 5.

Solutions obtained from the simultaneous variation of all of the thickness values in the 2-D space environmental impact (Eco-indicator 99) vs total cost for case study I.

Fig. 6.

Projection of the Pareto frontier with the optimal points obtained from the simultaneous variation of all of the thickness values in the 2-D space environmental impact (Eco-indicator 99) vs total cost for case study I.

Fig. 7.

Solutions obtained from the simultaneous variation of all of the thickness values in the 2-D space environmental impact (Eco-indicator 99) vs total cost for case study II.

Fig. 8.

Projection of the Pareto frontier with the optimal points obtained from the simultaneous variation of all of the thickness values in the 2-D space environmental impact (Eco-indicator 99) vs total cost for case study II.

Figures

Fig.1.

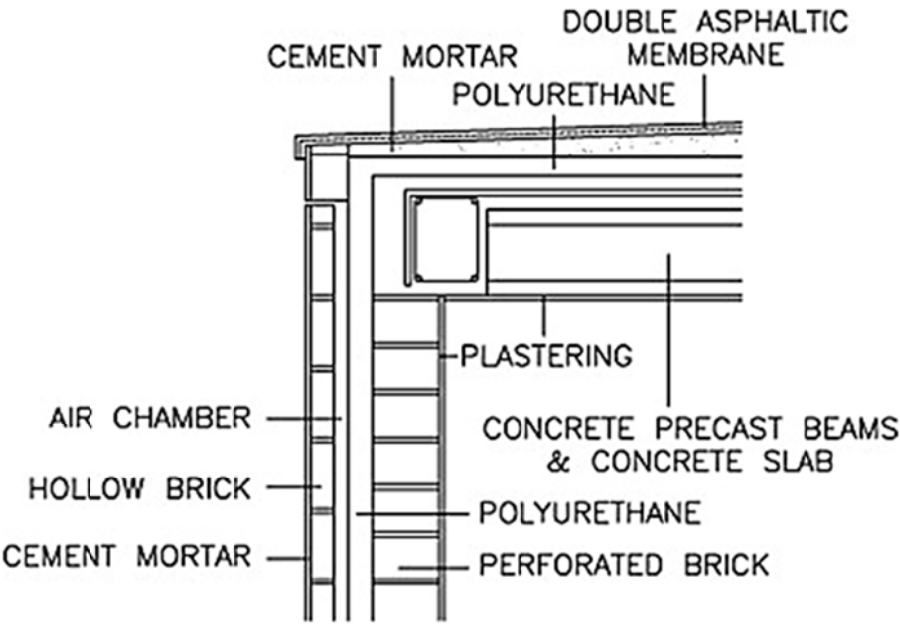
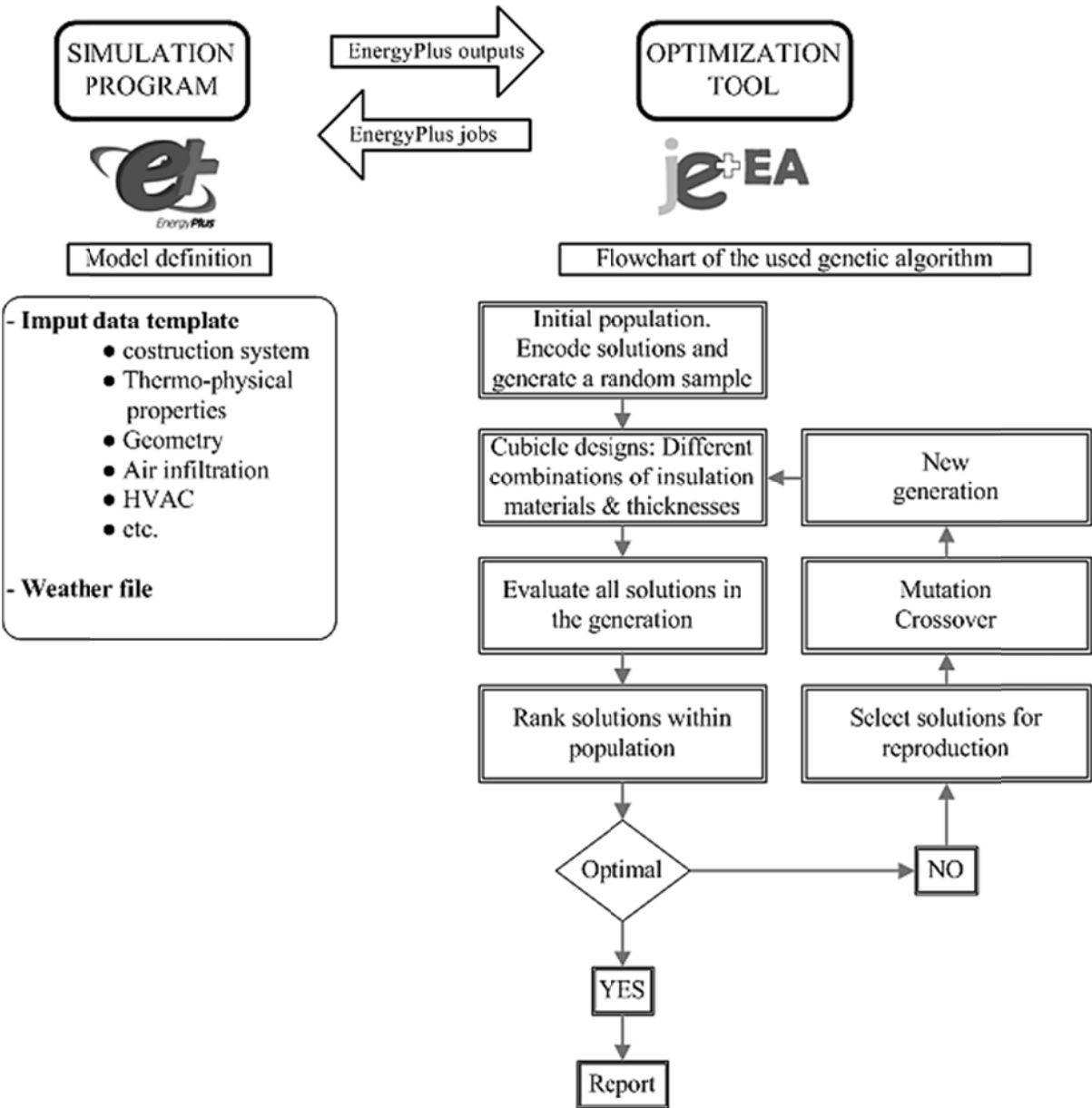
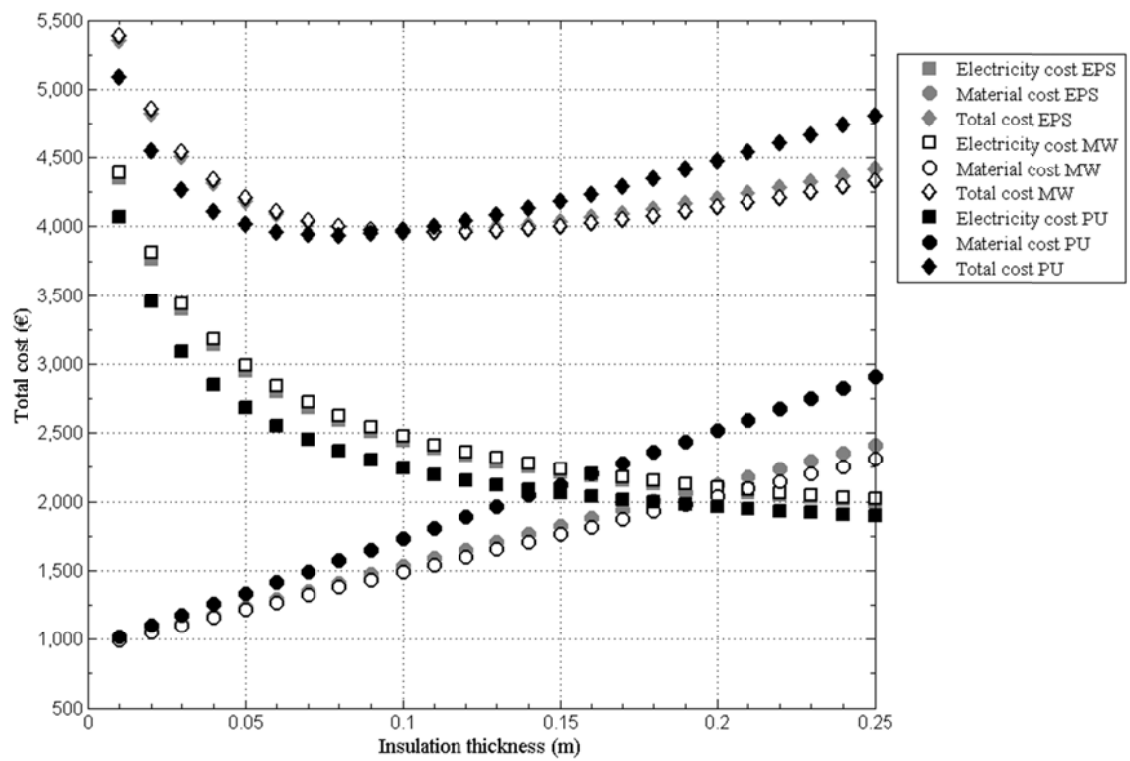


Fig.2.



893 Fig.3

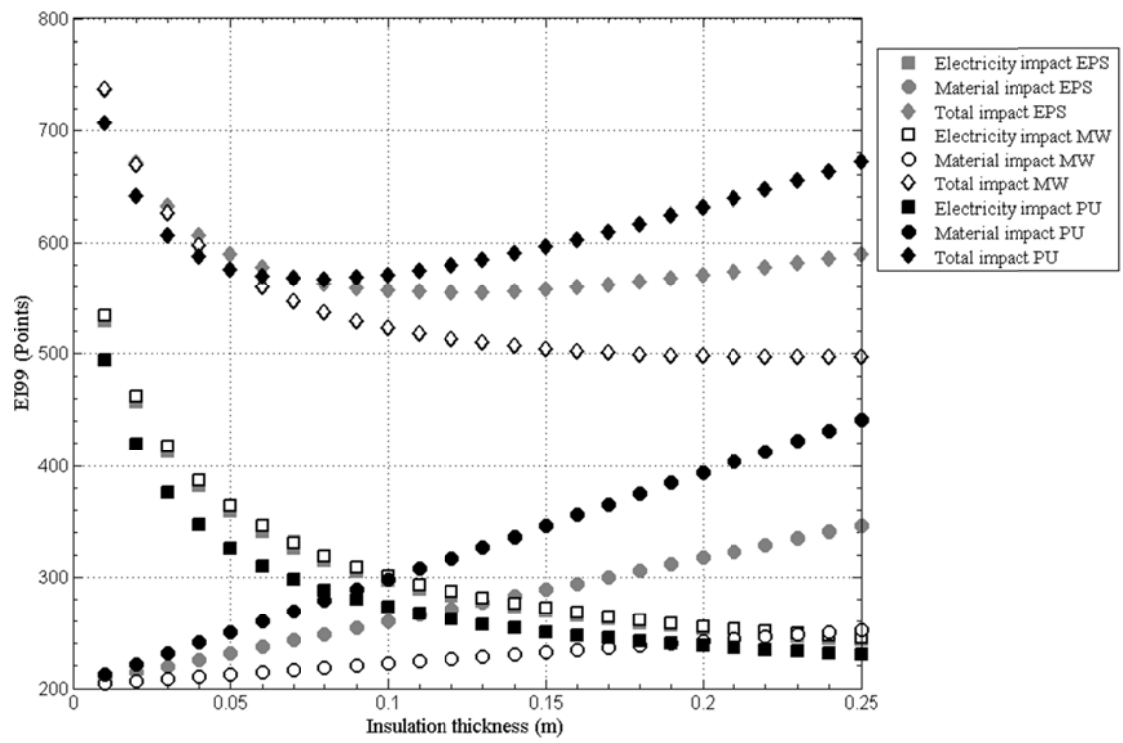
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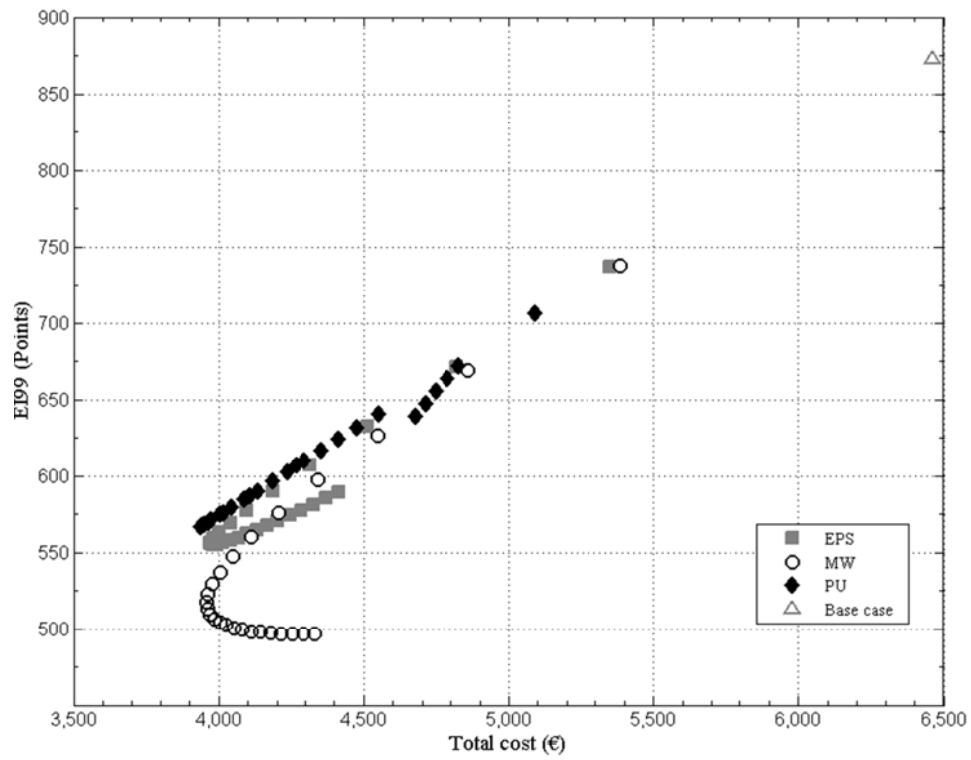
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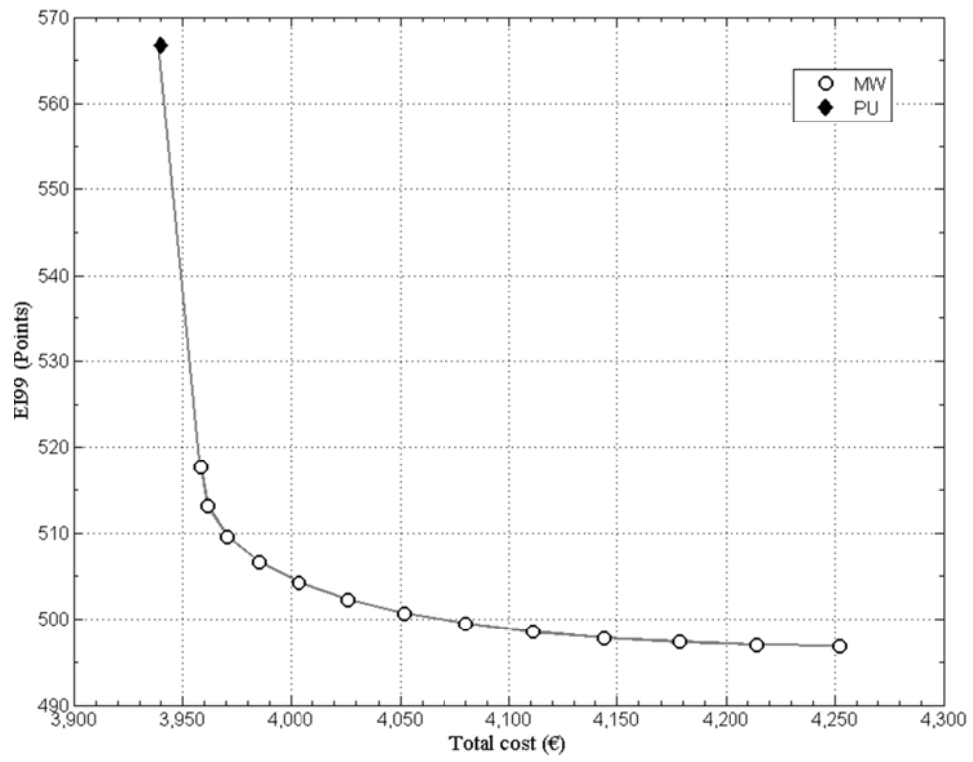
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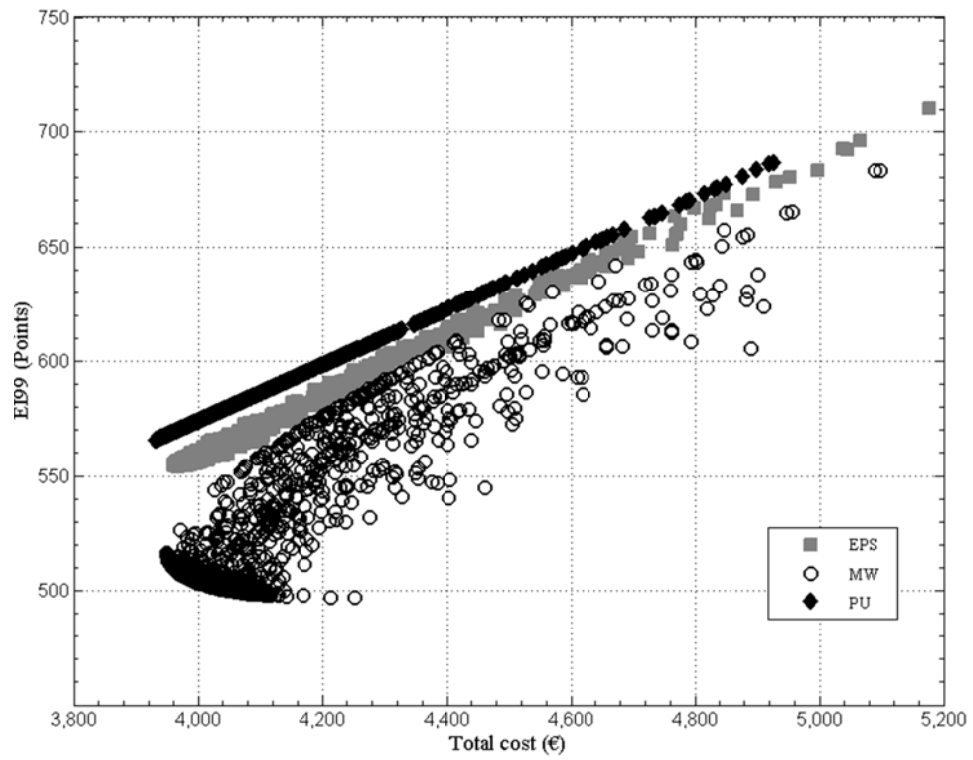
903 Fig.6



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906 Fig.7

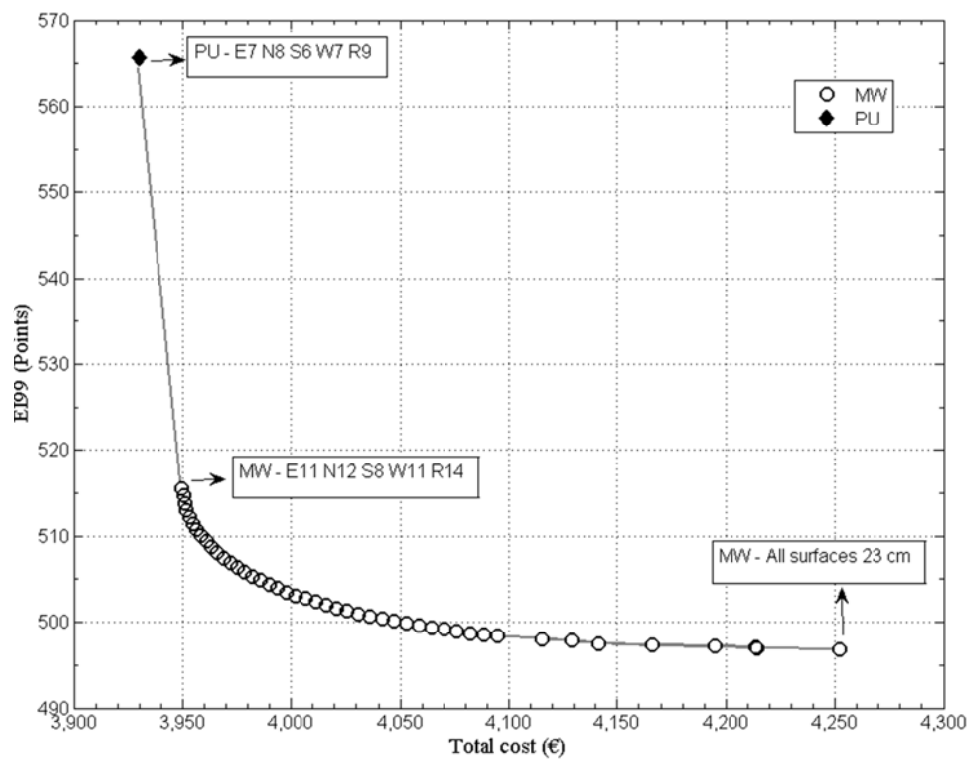


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909 Fig.8

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