Eco-costs implementation for the optimal design of buildings with better environmental performance

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Abstract

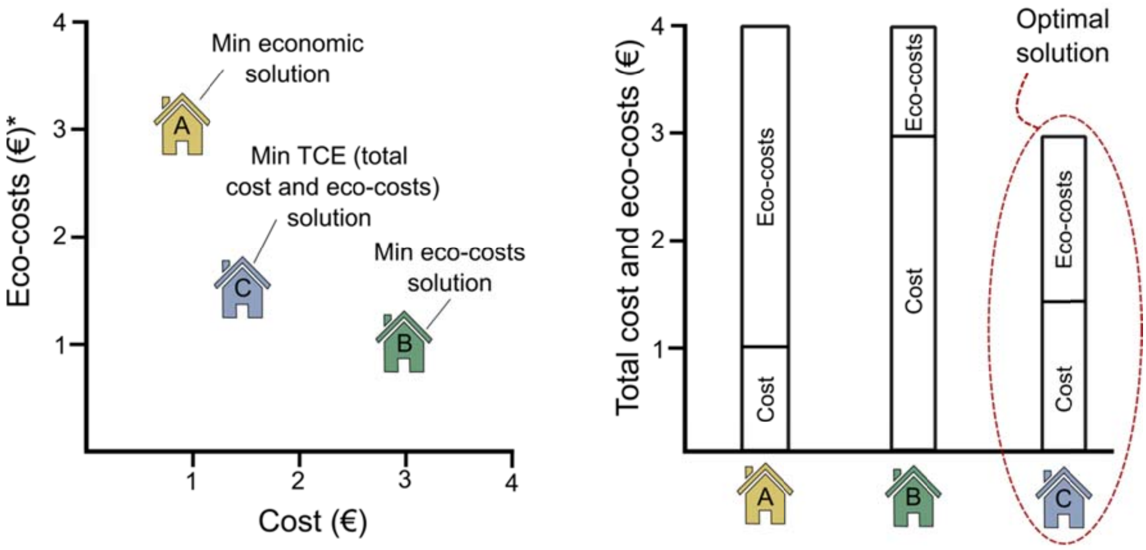
At present, most products and processes are optimized according only to their economic performance and disregarding environmental aspects. To promote a more sustainable economy, however, the environmental performance should be accounted for in the analysis. Here we present a methodology based on the use of eco-costs to translate the environmental impact of a building into monetary units that are incorporated explicitly into its economic performance assessment. The capabilities of the methodology presented are illustrated through a case study where the objective is to optimize the thermal insulation of a building envelope in different climate zones. Our approach identifies building solutions that significantly improve the environmental performance at a marginal increase in cost.

Keywords: Eco-costs, Optimization, Life cycle assessment (LCA), Modelling, Buildings, Insulation

Highlights

- A methodology to determine the optimal building insulation thickness is proposed.
- Optimal designs simultaneously reduce the cost and associated environmental impact.
- Eco-costs is used to translate the environmental impact into monetary units.
- A unique optimum is reached avoiding having to decide among different solutions.

Graphical abstract



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*Eco-costs is implemented to translate the environmental impact into monetary units

Nomenclature

Abbreviations

LCA	Life Cycle Assessment
MOO	Multi-Objective Optimization
SOO	Single-Objective Optimization
LCIA	Life Cycle Impact Assessment
EVR	Eco-costs / Value Ratio

NSGA-II	Non-dominated sorting genetic algorithm-II
LCI	Life Cycle Inventory
ECN	Energy research Centre of the Netherlands
ILCD	Life Cycle Data System
JRC	European Commission Joint Research Centre
TCE	Total conventional cost and eco-costs
PU	Polyurethane
MW	Mineral wool
ITeC	Instituto de Tecnología de la Construcción (Institute of Construction Technology)
GLO	Average global impact
EI99	Eco-indicator 99
ACH	Air changes per hour
COP	Coefficient of performance

Variables

COST	Cost [€]
UCOST	Unitary Cost [€/kg]
M	Quantity [kg]
CONS	Consumption [kWh]
ECO_COSTS	Total Eco_costs [€]
UECO_COSTS	Unitary Eco_costs [€/kg]

Indices

TOT	Total
MAT	Materials

EN	Energy

Sets

k	Construction materials
n	Years

Symbols

ir	Electricity inflation rate (%)
z	Objective functions
x	Decision variables
X	Space of feasible solutions

1. Introduction

Environmental issues are gaining wider interest in engineering, which strives to develop more sustainable products and processes. Specifically, the building and construction sector offers many opportunities for environmental improvements. This sector represents 40% of the total annual energy consumption worldwide [1]. Improving the energy efficiency in new and existing buildings is therefore becoming a priority objective in the EU and US [2,3]. One of the most promising energy efficiency strategies in this context is the application of a proper thermal insulation in the building envelope [4,5].

At present, the trend in the construction sector is to promote high insulation thicknesses in order to reduce energy consumption for heating and cooling. This strategy may lead to sub-optimal solutions when one seeks to optimize the economic and environmental performance simultaneously. This is because the environmental impact embodied in the insulation material can be significant, to the point that it may not eventually compensate for the associated energy savings. In the European and North American market, the most widely used insulation materials are inorganic fibrous materials, glass wool and stone wool, followed by organic foamy materials, and expanded and extruded polystyrene [6,7]. Some studies showed that the impact embodied in these construction materials can indeed contribute very significantly to the total environmental impact of a building [8,9].

To properly assess the impact of buildings it is needed to adopt a life cycle approach. Life cycle assessment (LCA) is an objective methodology to quantify the environmental burdens of a product considering all the stages in its life cycle [10,11]. Environmental indicators based on LCA enable us to quantify a wide variety of environmental problems related to human health, ecosystem quality and resources depletion.

Economic and environmental objectives tend to be conflicting targets. Hence, to optimize both criteria simultaneously, we need to resort to multi-objective optimization (MOO) techniques [12–16]. Usually the final result of a MOO consists of a set of Pareto optimal solutions, each achieving a unique combination of objective function values. When different players take part in the decision-making process and particularly when the problem covers many conflicting criteria, it might be difficult to generate the Pareto points and identify a final alternative to be implemented in practice. As an example, some decision-makers might prefer the solution showing the maximum economic performance, whereas others may chose an intermediate trade-off solution (or even the least impact one).

This work explores the use of monetization techniques to incorporate environmental aspects in the design of buildings. The advantage of this approach is that it avoids the use of multi-objective optimization models, which might be difficult to handle when several environmental impacts need to be incorporated into the model. In essence, we aim to develop a model for building design where everything is expressed in monetary terms, and in which the trade-offs between economic and environmental objectives are explicitly considered via economic penalties that lead to a single-objective optimization (SOO) with a unique optimal solution.

Different approaches exist to convert environmental impacts into cost. They can be classified into two main methods [17–19]. The first is the damage-based approach, in which the monetary cost is assigned at the end of the life cycle impact assessment (LCIA). This value expresses monetarily the amount of wellness losses due to the impacts of a product or activity. The quantification is based on the people's willingness to pay to avoid an impact, which reflects individual preferences [20,21]. The second is the prevention based approach (also known as Marginal Abatement Cost); in this case the damage cost depends on the policy targets fixed by each government regarding each specific environmental problem. In this context society fixes indirectly the environmental policies through their vote to one or another political proposal. These costs are based on the cost of additional impacts reduction measures. These political targets, theoretically, reflect the collective preferences of society [22,23].

Eco-costs is a prevention based approach. However, this approach differs from other prevention methods in that the goal is not based on policy targets, but rather established by "the earth's estimated carrying capacity". This capacity is established according to the definition of eco-efficiency made by the World Business Council for Sustainable Development [24]. Eco-costs translates the environmental impact into economic cost by measuring the cost of preventing a given amount of environmental burden [23] . The eco-costs indicator has found applications in the assessment of different products. Vogtländer et al. [25] used eco-costs to compare the environmental impact of bamboo materials, shipped to Western Europe, with commonly used materials such as timber. Morales-Mora et al. [26] evaluated the marginal prevention cost for an increment in the production capacity of an acrylonitrile plant in Mexico. Baeza-Brotons et al. [27] used eco-costs to compare the environmental impact of concrete with and without addition of waste. Kravanja and Čuček [28] presented a novel indicator called eco-profit which is based on the concept of eco-costs. Eco-profit considers not only the environmental burden of a product or activity but also its environmental credits (i.e. unburden on the environment). These credits consider that some products or activities can have benefits on the environment (e.g., when waste is used). Vogtländer et al. [23] introduced also a new indicator based on the eco-costs concept called eco-costs / value ratio (EVR). As stated by the authors, the design with the lowest eco-costs might not be always the best choice because product quality plays as well a key role. The EVR overcomes this problem by adding the "value" to the eco-costs indicator.

This is the perception of the consumer towards the product and it is related with its overall quality, service quality and image.

Here we explore the capabilities of eco-costs in the context of finding the optimal thermal insulation for building envelopes in 5 European locations. This approach leads to solutions attaining significant environmental improvements at a marginal increase in cost.

The article is organized as follows. Section 2 formally states the problem of interest. Section 3 defines the methodology and the eco-costs approach. In Section 4, the case study is introduced. In Section 5, the results are presented and discussed. The conclusions of the study are finally provided in Section 6.

2. Problem statement

We consider a cubicle type building (specifications about the cubicle can be found in Sections 4.1 and 4.2), where a set of different insulation materials and different thicknesses can be established to improve the building performance. The goal of the analysis is to find the building design that minimizes the total cost, considering the design, operation and associated environmental impact.

3. Methodology

3.1. Mathematical model

The building is modelled with EnergyPlus v.8 [29–31] a building energy simulation program that quantifies the energy loads of the system. In mathematical terms, the building can be modelled as a system of partial differential equations describing the energy balances involved. The variables optimized are the insulation materials and their thicknesses, and the objectives to minimize are the economic cost and the environmental impact. Note, however, that this general methodology can work with different decision variables and objective functions.

Without loss of generality, in this work the model of the building is optimized with a genetic algorithm-II (NSGA-II): JEPlus+EA [32], which is combined with EnergyPlus following an approach similar to the one used in a previous work [33]. Other optimization algorithms could be used at this point, but we found from numerical examples that genetic algorithms work well in this case, mainly because of the nonconvex nature of the system of equations that need to be optimized.

3.2. Objective functions

3.2.1. Economic indicators

One of the pursued objectives is to minimize the economic cost [34–36]. The total cost ($COST^{TOT}$) includes the cost of the construction materials ($COST^{MAT}$) and the cost of the energy required for heating and cooling over the life-time of the cubicle ($COST^{EN}$).

$$COST^{TOT} = COST^{MAT} + COST^{EN} \tag{1}$$

The total price of the materials for the construction of the cubicle is quantified as shown in equation 2.

$$COST^{MAT} = \sum_{k \in K} UCOST_k^{MAT} \cdot M_k \tag{2}$$

Where $UCOST_k^{MAT}$ is the unitary cost per kilogram of raw material *k* and M_k is the correspondent quantity in kilograms of raw material *k* (*i.e.*, kg of concrete).

The energy used for covering the cooling and heating requirements over the operational life of the building was obtained via the following equation:

$$COST^{EN} = \sum_{n \in N} CONS_n \cdot UCOST^{EN} \cdot (1+ir)^n \tag{3}$$

where $CONS_n$ is the energy consumed (expressed in kWh) for heating and cooling in year *n*, $UCOST^{EN}$ is the current cost of the kWh of electricity, and *ir* is the yearly interest rate of the electricity cost.

3.2.2. Environmental indicators (eco-costs)

As already mentioned, the environmental impact is expressed in economic terms using the eco-costs indicator [37]. Specifically, this indicator quantifies the cost of preventing a certain amount of environmental burden related to a product or activity. Eco-costs considers the cradle to grave environmental impact of a material, including all the phases in the life cycle of the product. These are regarded as virtual costs, since they are not yet integrated into the real costs of the product under study.

The eco-costs account for the following 5 elements (see [38] for further details):

- The virtual pollution prevention costs '99.
- The eco-costs of energy.
- The material depletion costs.
- The eco-costs of depreciation.
- The eco-costs of labour.

These elements are calculated following LCA principles, as established in the ISO 14041.

The virtual pollution prevention costs ‘99 are calculated from the life cycle inventory (LCI) of emissions associated with a specific activity, in the case of this study the building design and operation. The LCI emissions (expressed in equivalent kilograms) are quantified first and then multiplied with the corresponding “prevention cost” which is the marginal costs (per kilogram of emission) related to bringing back the pollution to a level which is considered “in line with earth's carrying capacity” [38,39].

The eco-costs of energy correspond to the cost of replacing conventional systems (i.e. fossil fuels or nuclear) by sustainable energy sources. Data from the database MARKAL developed by ECN (Energy research Centre of the Netherlands) are used to this end [40]. These eco-costs might change, declining over time as renewable energy sources replace gradually nonrenewable ones.

The eco-costs of material depletion is assumed to be the same as the market cost of the virgin material (when the materials are not recycled). When a fraction “fr” of the used material is recycled, then a correction factor is applied (eco-costs of material depletion = ' virgin material market cost ' x (l - fr)) [38].

The eco-costs of labour are those indirect costs associated to the environmental impacts of i.e. the energy consumed for heating or lighting a building. In our case study we consider those costs related to the heating and cooling requirements.

The eco-costs of depreciation of product facilities are those indirect costs that consider the reduction in the value of a product arising from its use or the passage of time. In this study no depreciation is considered because the cost of the building is agreed to pay the first year.

The data used in our analysis was taken from the database developed by the Delft University of Technology, which is based on LCIs retrieved from ecoinvent. The eco-costs (expressed in €/kg or €/MJ) of a wide variety of materials are available, including the ones widely used in the construction of buildings [37].

The total cost of the environmental impact (ECO_COSTS^{TOT}) accounts for the cost of the impact of the construction materials (ECO_COSTS^{MAT}), and the cost of the impact of the energy consumed for heating and cooling over the operational phase of the building (ECO_COSTS^{EN}):

$$ECO\_COSTS^{TOT} = ECO\_COSTS^{MAT} + ECO\_COSTS^{EN} \tag{4}$$

The total eco-costs of the materials for the construction of the cubicle (ECO_COSTS^{MAT}) is calculated as follows:

$$ECO\_COSTS^{MAT} = \sum_{k \in K} UECO\_COSTS_k^{MAT} \cdot M_k \tag{5}$$

Where $UECO\_COSTS_k^{MAT}$ is the marginal prevention cost per kilogram of raw material *k* (an information that is available in the eco-costs database [37], and M_k is the corresponding quantity (expressed in kilograms) of raw material *k*.

To translate the energy consumed to eco-costs, the data of the energy production system of each country is used. The impact of energy production depends on the country where the energy is consumed, while the impact of the materials is assumed to be the same for all the countries. The total eco-costs of the consumed energy (ECO_COSTS^{EN}) is calculated as follows:

$$ECO\_COSTS^{EN} = \sum_{n \in N} CONS_n \cdot UECO\_COSTS^{EN} \qquad (6)$$

Where $UECO\_COSTS^{EN}$ is the eco-costs per kWh of energy in each country and $CONS_n$ is the yearly consumed energy in period *n*.

3.2.3. Enviro-economic indicator

Converting the environmental impact to monetary terms enables us to reformulate the multi-objective problem into a single-objective one with a unique objective function. The total cost is therefore calculated as follows:

$$TCE = COST^{TOT} + ECO\_COSTS^{TOT} \qquad (7)$$

Where TCE is the total cost, which includes both, the conventional cost ($COST^{TOT}$) and the eco-costs (ECO_COSTS^{TOT}). Thus, we seek to minimize the value of *TCE*.

3.3. Solution procedure

The EnergyPlus simulation model can be expressed in mathematical terms as an explicit function as follows:

$$z = \left\{ z_1, \ldots, z_p \right\} = f^{MOD}\left(x \right) \qquad (8)$$

Where vector z is the objective function that combines the real cost with the virtual eco-costs. The value of the objective function is determined from the outcome of the simulation model after specifying the insulation material and the thickness values. These decision variables are represented by vector x. The single-objective problem can be expressed in a compact form as follows:

$$\min_{x \in X} (z) = \min_{x \in X} f^{MOD}(x) \tag{9}$$

where X denotes the feasible space of possible solutions, z is the objective function and x is the vector of decision variables. The constraints of the model, which are solved implicitly in the simulation package, are given by equations based on first principles (*e.g.*, mass and energy balances). The only explicit constraint handled externally (by the optimization algorithms instead of the simulation package) imposes lower and upper bounds on the insulation thickness.

4. Case study

4.1. Cubicle description

Real cubicles located in an experimental installation in Puigverd de Lleida (Lleida, North-East Spain) are modelled in our work. All cubicles consist of five plane walls of 2.4 × 2.4 m. They show the same structure and differ only in the insulation materials implemented. The cubicles present four mortar pillars frames with reinforcing bars. The base consists of a concrete foundation of 3 × 3 m. The roof frame is made of concrete precast beams and 5 cm of concrete slab. The external layer is a double asphaltic membrane which covers a cement mortar coating with a slope of 3%. The insulation material is located under the cement mortar and is connected with the insulation of the walls avoiding possible thermal bridges. The internal finish is a plastering layer. The walls consist of 6 material layers. The external one is a cement mortar coating covering a layer of hollow bricks. There is an air chamber of 5 cm between the hollow bricks and the insulation material (PU or MW depending on the model). The internal face of the wall is made of a perforated bricks structure and a plaster plastering layer [41,42].

The real cubicles are located in Lleida, but in the present study we consider as well other potential locations (specifications in 4.3).

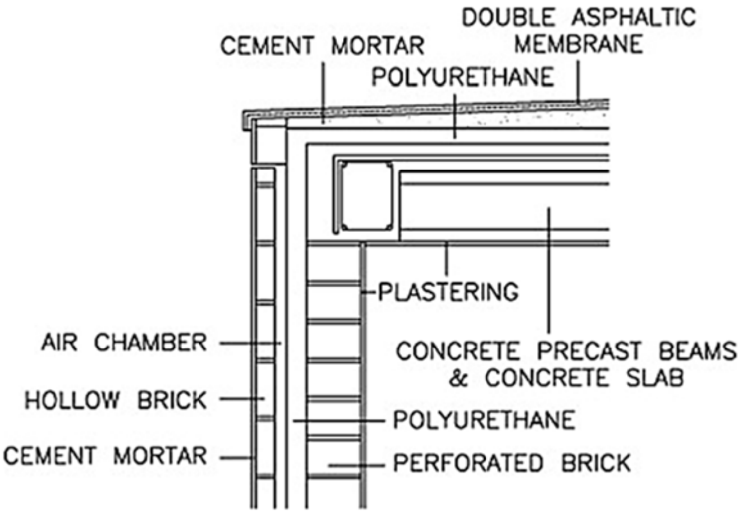

Fig.1. Construction profile of the experimental cubicles in Puigverd de Lleida (Spain).

To quantify the cost of the materials we use the date provided in [33]. Table 1 presents the specific cost and the thermo-physical properties of the insulation materials considered. These data were obtained from the LIDER [43] and ITeC [44] databases.

Table 1.

Properties of the insulation materials.

Insulation material	Density (kg/m^3)	Thermal conductivity ($W/(m{\cdot}K)$)	Specific heat ($J/(kg{\cdot}K)$)	Cost (€/m^3)
Polyurethane	45	0.027	1,000	175
Mineral Wool	40	0.04	1,000	122

The electricity used for covering the cooling and heating requirements over the operational life of the building was obtained by dividing the useful thermal energy by the COP (coefficient of performance) of the heat pump (which is assumed to be equal to 3). The electricity consumed is then multiplied by the electricity cost in the domestic sector of each country, considering a yearly increasing cost of 5% per year [34].

The eco-costs parameters are presented in Table 2. As in the economic case, Table 2 also presents an indicative example of the eco-costs of a cubicle with 1 cm of insulation thickness in all of their surfaces.

Table 2. Inventory list of the materials used for the cubicle construction and their corresponding eco-costs.

Component	Name in the data base Ecoinvent corresponding to the component	Used mass (kg)	Eco-costs (Euro/kg)	Total eco-costs (Euro)
Brick	market for brick, GLO [kg]	5,456	$6\cdot10^{-2}$	345.39
Base plaster	market for base plaster, GLO [kg]	518	$6\cdot10^{-2}$	31.57
Cement mortar	market for cement mortar, GLO [kg]	608	$6\cdot10^{-2}$	39.10
Steel bars	market for section bar rolling, steel, GLO [kg]	262	$1\cdot10^{-1}$	25.50
Concrete	market for concrete, normal, GLO [m3]	1,240	$4\cdot10^{-2}$	49.23
In-floor bricks	market for concrete roof tile, GLO [kg]	1,770	$1\cdot10^{-1}$	183.68
Asphalt	market for mastic asphalt, GLO [kg]	153	$7\cdot10^{-2}$	10.51
Disposal bricks	market for waste brick, GLO [kg]	5,456	$-4\cdot10^{-3}$	-26.93
Disposal plaster	market for waste mineral plaster, GLO [kg]	518	$-5\cdot10^{-3}$	-2.96
Disposal mortar	market for waste cement in concrete and mortar, GLO [kg]	608	$-7\cdot10^{-3}$	-4.28
Disposal concrete + steel bars	market for waste reinforced concrete, GLO [kg]	1,492	$-5\cdot10^{-3}$	-8.65
Disposal in-floor bricks	market for waste concrete, not reinforced, GLO [kg]	1,770	$-5\cdot10^{-3}$	-9.07
Disposal asphalt	market for waste asphalt, GLO [kg]	153	$-4\cdot10^{-3}$	-0.71
PU	market for polyurethane, rigid foam, GLO [kg]	20	1.03	20.57
MW	market for rock wool, GLO [kg]	18	$4\cdot10^{-1}$	7.29
Disposal PU	market for waste polyurethane foam, GLO [kg]	20	$2\cdot10^{-1}$	3.06
Disposal MW	market for waste mineral wool, GLO [kg]	18	$3\cdot10^{-3}$	0.07

4.2. Model specifications

Some simplifications were considered in the simulations of the cubicles in order to fit more closely the predictions with the experimental observations. According to former studies, an internal temperature of 24°C is taken as set point for the whole year [41,45]. A heat pump with a COP of 3 is considered to supply the heating and cooling demands. No openings are taken into account. No natural or mechanical ventilations are considered, but a fixed infiltration rate of 0.12 ACH (air changes per hour) [46] is assumed. No internal mass and no human occupancy are included in the model. We assume a building lifespan of 20 years [36,47]. The cost of the implemented materials for the construction of the building is assumed the first year. As for the electricity, the specific price per kWh in each country is considered [48,49].

The insulation thickness range is varied from 1 to 30 cm of insulation, this choice was based on practical aspects, since no thicker insulation is usually applied in real projects [7]. The materials considered are PU and MW. In our case studies, we do not combine different insulation materials in the same design.

4.3. Considered locations

Five different locations have been considered, as shown in Table 4. The Köppen–Geiger Climate Classification [50] was used to select representative locations of different climates in Europe. This classification defines the climatic conditions with a single metric composed of three characters. The first one defines the main climate: A: equatorial, B: arid, C: warm temperate, D: snow and E: polar. The second character defines the level of precipitation: W: desert, S: steppe, f: fully humid, s: summer dry, w: winter dry, m: monsoonal. And finally, the third character provides details about the temperature: h: hot arid, k: cold arid, a: hot summer, b: warm summer, c: cool summer, d: extremely continental, F: polar frost, T: polar tundra. The electricity cost of the different locations was obtained from [51], the electricity impact from [52], and the electricity eco-costs from [37].

Table 3. Climate condition and electricity cost, impact and eco-costs for the considered locations.

Locations	Climate type	Electricity cost (€/kWh)	Electricity impact (EI99 points/kWh)	Electricity eco-costs (€/kWh)
Lleida (Spain)	BSk	0.223	0.034	0.008
Dublin (Ireland)	Cfb	0.203	0.043	0.011
Athens (Greece)	Csa	0.156	0.089	0.018
Stockholm (Sweden)	Dfb	0.21	0.010	0.002
Berlin (Germany)	Dfb	0.292	0.030	0.009

5. Results and discussions

In a prelaminar analysis (Section 5.1.), we present the results of considering cubicles with homogeneous insulation thickness in all their external surfaces (from 1 to 30 cm) in the location of Lleida. This analysis provides insight into the influence of the insulation thickness on the cost and environmental impact. We first present the results of the costs, then the eco-costs and finally the TCE results.

In a second analysis (Section 5.2.), we consider cubicles with heterogeneous insulation thickness; that is, different insulation thicknesses for the roof and the walls (the four walls have the same insulation thickness). In this case study we present results for 5 different European locations (Section 4.3.). As in the first analysis, we start by analysing each single objective separately (cost and eco-costs), and then look for the final optimal solution considering both economic concepts (TCE).

Finally (Section 5.3), we will compare the optimal solution of each case with those obtained by performing a MOO considering the economic cost (€) and the environmental impact as different objective functions and assessing the environmental impact with the Eco-Indicator 99 (EI99) [11,53], a metric calculated following LCA principles.

5.1. Prelaminar analysis: Cubicles with homogeneous insulation thickness

5.1.1. Economic cost analysis for the case of cubicles with homogeneous insulation thickness

Figure 2 presents the results of the analysis that evaluates the variation of the cost and environmental impact with an increasing insulation thickness of a cubicle located in Lleida, Spain. As seen, the material cost increases linearly when the insulation thickness increases, whereas the energy cost decreases. Note that the total cost includes two terms: materials and energy cost. In the case of Lleida, and considering the same insulation thickness in all the surfaces, the cubicle solution presenting a better economic performance is the one with 9 cm of PU.

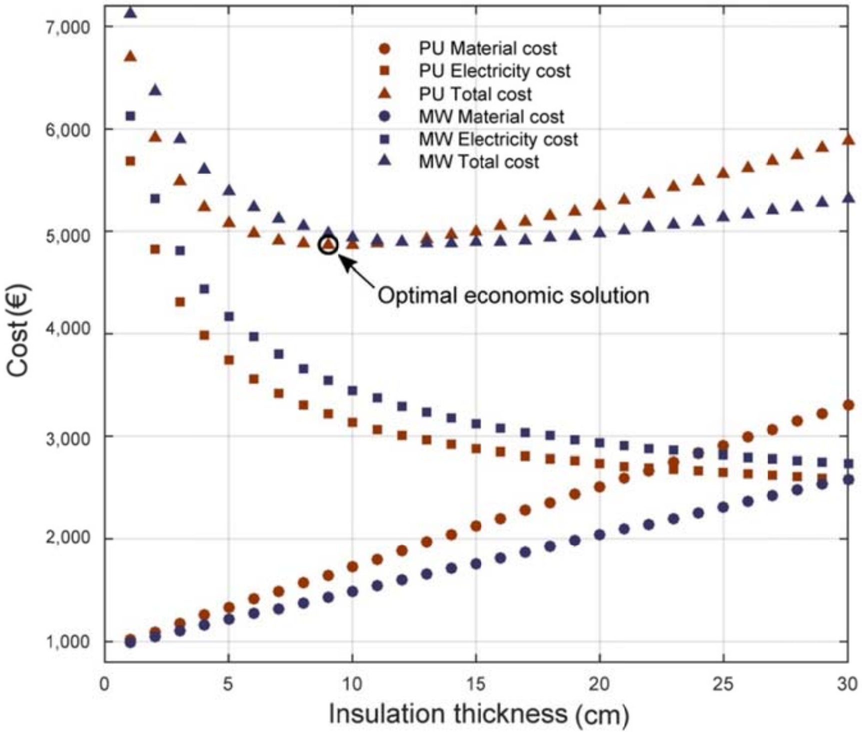

Fig. 2. Variation of the cubicle cost with the insulation thickness for PU and MW considering a cubicle with homogeneous insulation thickness in roof and walls. Results for Lleida, Spain

5.1.2. Environmental analysis (eco-costs) for the case of cubicles with homogeneous insulation thickness

Figure 3 shows that as the insulation thickness increases, the eco-costs of the materials increases linearly while the eco-costs of the electricity decreases. In the case of Lleida, and considering the same insulation thickness in all the surfaces, the best cubicle has 21 cm of MW.

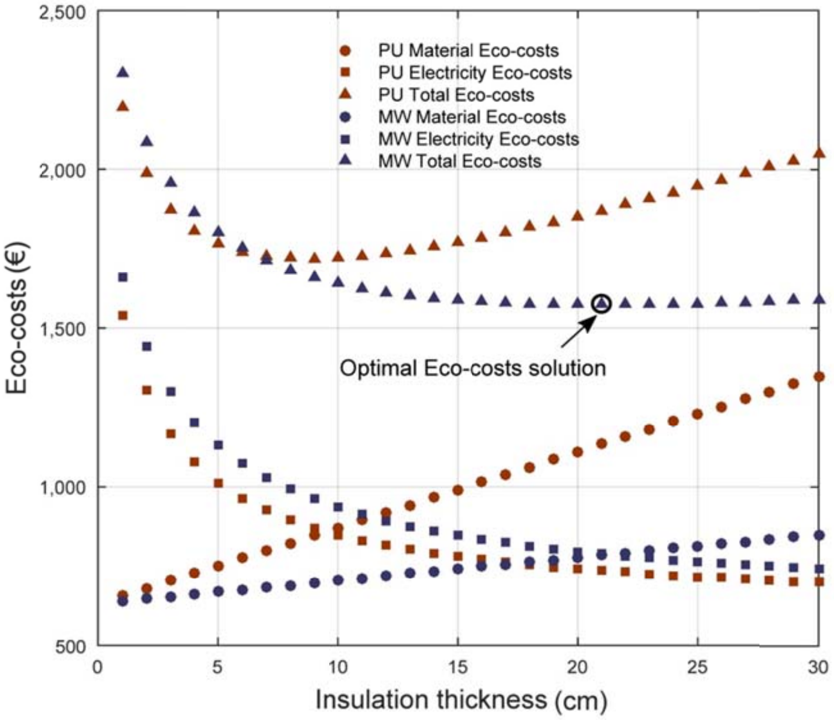

Fig. 3. Variation of the cubicle eco-costs with the insulation thickness for PU and MW considering a cubicle with homogeneous insulation thickness in roof and walls. Results for Lleida, Spain.

5.1.3. Total cost and eco-costs (TCE) analysis for the case of cubicles with homogeneous insulation thickness

In this section the total cost, considering the current cost and the eco-costs of materials and electricity, is analysed. The TCE of the material increases as the insulation thickness increases, whereas the TCE of the electricity decreases. In this case, the goal is to find the cubicle solution that minimizes the TCE (conventional cost and eco-costs). For the particular case of Lleida, the solution presenting a minimum TCE is attained with an insulation thickness of 15 cm of MW (Figure 4).

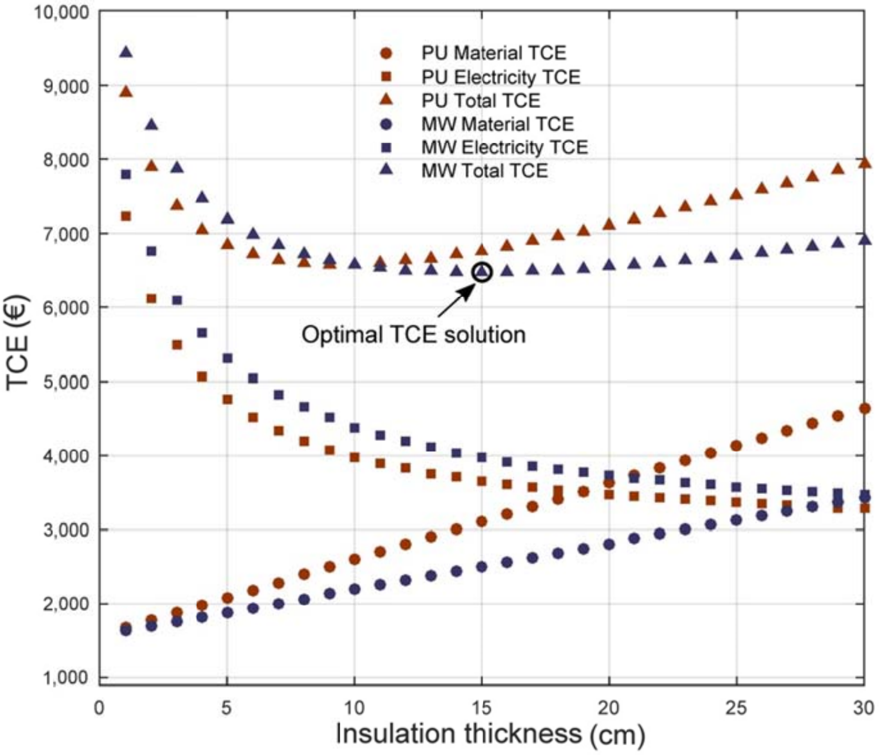

Fig. 4. Variation of the cubicle TCE with the insulation thickness for PU and MW considering a cubicle with homogeneous insulation thickness in roof and walls. Results for Lleida, Spain.

5.2. Optimization results using the proposed approach

5.2.1. Minimization of the cost using the optimization algorithm

In this section we present the optimal economic solutions considering different insulation thicknesses for the roof and the walls for the five locations (Table 4).

Table 4. Optimal economic results for cubicles presenting different insulation thicknesses in roof and walls. In this case all the solutions use PU.

	Walls insulation thickness (cm)	Roof insulation thickness (cm)	Economic cost (€)
Athens (Greece)	6	9	3,493
Lleida (Spain)	9	11	4,852
Dublin (Ireland)	11	13	6,190
Stockholm (Sweden)	13	15	7,060
Berlin (Germany)	14	16	8,028

PU turns out to be the most competitive material from the economic standpoint in all of the locations. PU is more expensive than MW, but its thermal conductivity is lower, so its energy savings compensate for the extra cost. In all locations, the insulation thickness of the walls is slightly thinner than the one in the roof (2 or 3 cm of difference). The difference between the economic costs of the solutions depends on the climate conditions and on the electricity cost of the location. Athens is the location with the lowest cost and Berlin the one with the highest cost.

5.2.2. Minimization of the eco-costs using the optimization algorithm

The optimal environmental solutions considering different thicknesses in the walls and roof are presented in Table 5.

Table 5. Optimal eco-costs results for cubicles presenting different insulation thicknesses in roof and walls. In this case all the solutions use MW.

	Walls insulation thickness (cm)	Roof insulation thickness (cm)	Eco-costs (€)
Stockholm (Sweden)	12	14	1,055
Lleida (Spain)	21	24	1,572
Berlin (Germany)	29	30	2,156
Dublin (Ireland)	29	30	2,453
Athens (Greece)	30	30	2,292

For all locations, the solution with minimum environmental impact uses MW as insulation material. This occurs because the environmental impact of MW is much lower than the impact of PU. Specifically, the fossil fuels depletion impact of MW is ten times lower than the impact of PU. In this case, the insulation thickness of the walls is also thinner than that implemented in the roof, except in Athens, where the thickness is the same. Athens, despite showing mild weather conditions, is the location leading to the largest insulation thickness due the high impact of its electricity mix. On the other hand, in Stockholm a thicker insulation could be expected because of the harsh climate conditions. However, Stockholm shows the smallest thickness because of the low impact of its electricity mix (9 times lower than in Athens).

5.2.3. Minimization of the total cost, including the eco-costs (TCE), using the optimization algorithm

Table 6 shows the optimal TCE solutions for the five locations.

Table 6. Optimal TCE results for cubicles presenting different insulation thicknesses in roof and walls. In this case all the solutions use MW.

	Walls insulation thickness (cm)	Roof insulation thickness (cm)	TCE €
Athens (Greece)	13	17	5,988
Lleida (Spain)	14	17	6,468
Stockholm (Sweden)	18	22	8,167
Dublin (Ireland)	19	21	8,739
Berlin (Germany)	22	25	10,238

In all locations, the insulation material implemented is MW. In all scenarios, the optimal solutions show thicker insulation layers than in the optimal economic case, but lower than in the environmental one (except in Stockholm, where the optimal environmental solution presents a lower thickness than the TCE one, due to the lower impact of electricity production). Therefore, to move from the conventional economic optimal solution to a solution that also integrates the environmental impact in the final cost, it is necessary to resort to a more environmentally friendly material (i.e. to replace PU by MW) and to increase the insulation thickness (between 5 and 11 cm, depending on the case).

5.2.4. Summary results

Figure 5 shows the economic, environmental and TCE optimal solutions for each location. PU is the material achieving better economic results, while MW leads to better environmental performance in all locations. When resorting to the optimal TCE solutions, in all locations the building designs with better performance use MW. In all optimal scenarios, the roof shows thicker insulation than the walls, except for the optimal environmental solution of Athens (where all surfaces present the same thickness). This is due to the high environmental impact associated to the generation of electricity in this country. All optimal TCE solutions show larger thicknesses than the optimal economic solution, and lower than the best environmental ones, except for the case of Stockholm (due to the lower impact of electricity production).

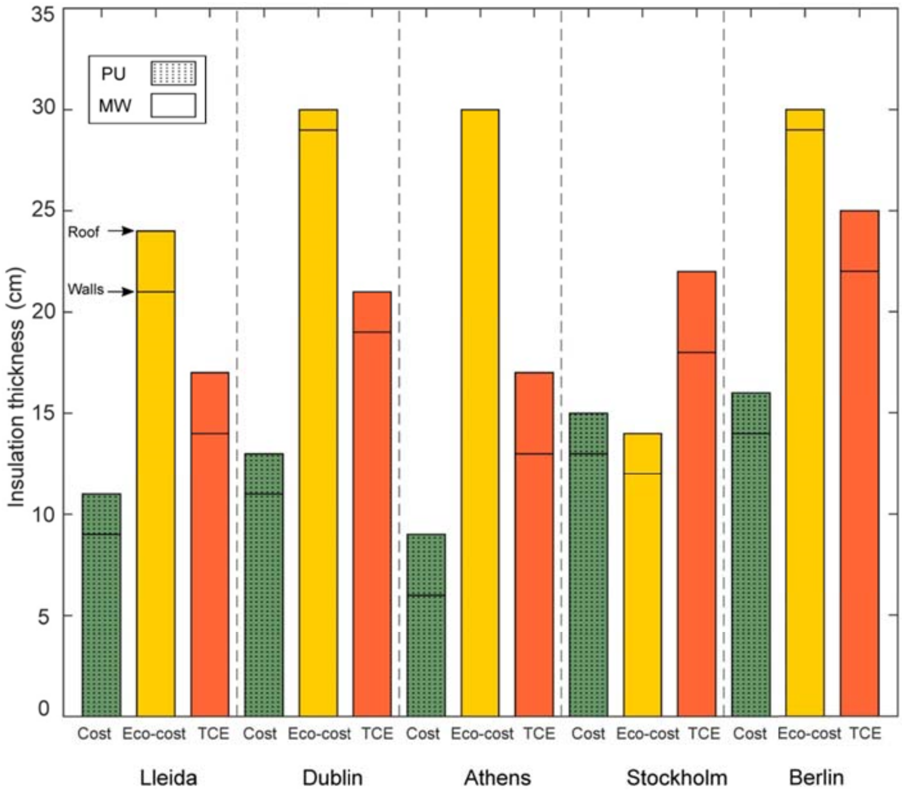

Fig. 5. Optimal economic, environmental and TCE cubicle solutions for the five locations considering different insulation thicknesses in walls and roof.

5.3. Comparative analysis: MOO vs SOO

In this section we study the implications of designing buildings following a multi-objective approach that optimizes the cost against an aggregated environmental metric, such as the Eco-indicator 99 (EI99 from now on) [53]. The EI99 is a LCA based method that considers 11 impacts aggregated into 3 damage categories: human health, ecosystems quality and depletion of resources, which are further translated into a single aggregated metric using normalization and weighting factors. This metric has been extensively used in the optimization of sustainable processes [54,55].

The results of the problem when the environmental impact is not expressed in monetary terms but in impact points are expressed in terms of a set of Pareto optimal points. There are two extreme optimal solutions, the optimal economic and minimum environmental impact alternatives, and a set of intermediate optimal solutions lying between them (Figures 6).

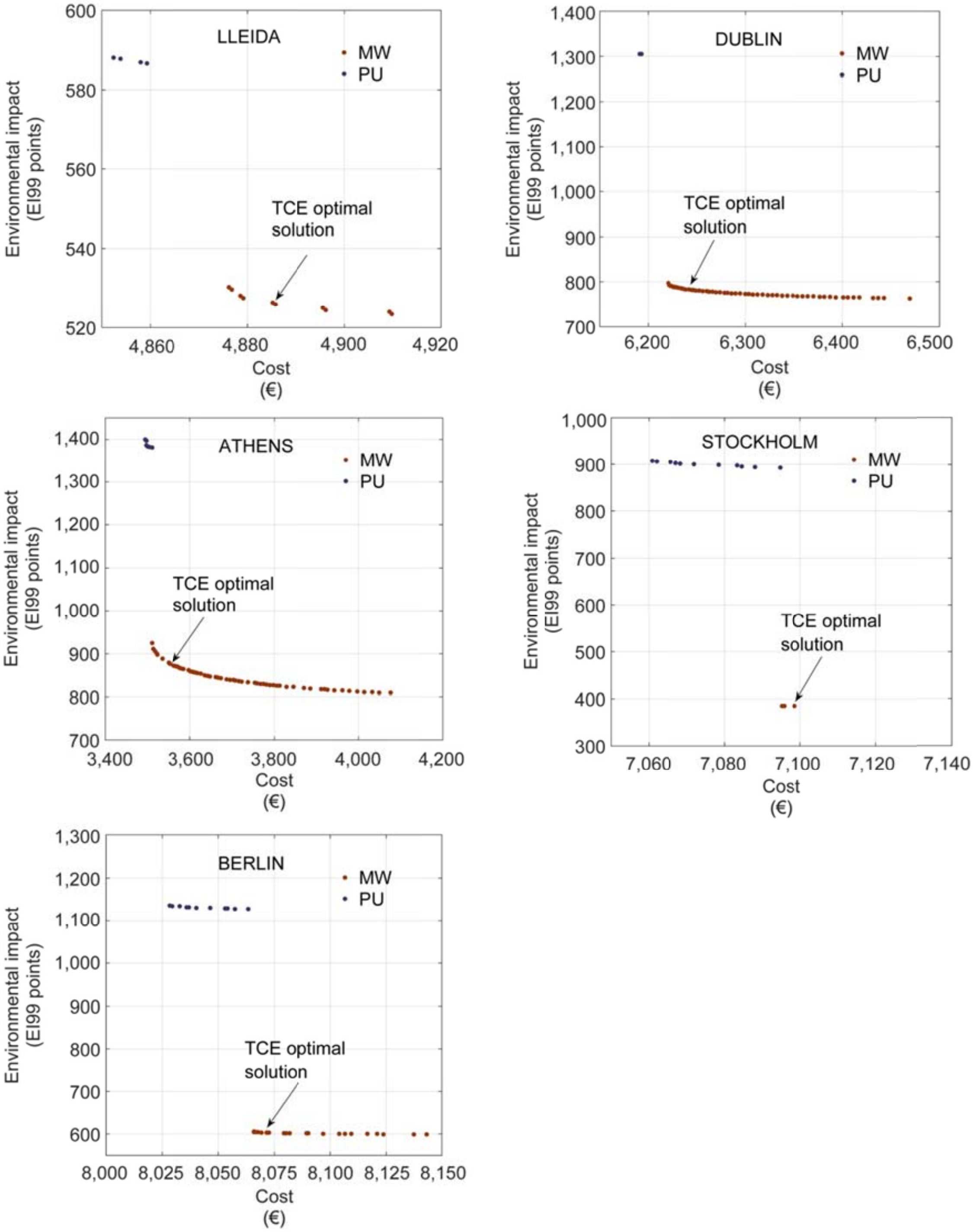

Fig. 6. MOO optimal cubicle solutions and TCE optimal solution for the five considered locations considering different insulation thicknesses in walls and roof.

Figure 6 shows that the TCE optimal solutions are intermediate solutions of the MOO problem for all locations. In all the cases, the solutions implement MW and are close to the extreme economic optimal solution (but with a clear improvement in environmental performance). Hence, the use of eco-costs leads to solutions that belong to the Pareto front cost vs Eco-indicator 99, but avoids the need to conduct any post-optimal analysis of the Pareto solutions (as the weights to be assigned to every objective are explicitly established beforehand).

6. Conclusions

Nowadays the prevalent method to quantify the cost of a product is through its economic cost. However, the society is becoming more environmental conscious. As a result, many companies and consumers seek for products that are cost efficient but also environmentally friendly.

This work presents a methodology to design buildings considering their economic and environmental performance simultaneously using eco-costs. Eco-costs is an indicator that quantifies the cost related to the environmental burden of an activity or a product on basis of the prevention of that burden. The use of eco-costs in the design of buildings avoids the formulation and solution of complex multi-objective problems accounting for the simultaneous optimization of a wide range of environmental objectives.

The capabilities of the proposed method are illustrated through a case study, where the main goal is to optimize the insulation thickness of the envelope of a building minimizing its cost and environmental impact simultaneously. For the economic and environmental analysis, we consider the cost and impact of the materials used in the construction of the building and the cost and impact of the energy consumed for cooling and heating during its operational life. Different European locations were considered in the analysis to compare the effect of different weather conditions and the importance of the cost and the impact of the energy consumed.

Results show that to move from the conventional economic optimal solution to a solution that also considers the environmental impact, it is necessary to: i) resort to a more environmentally friendly material (replace PU by MW), and ii) increase the insulation thickness (since MW presents a higher thermal conductivity than the PU).

The monetization of the environmental impact through the eco-costs overcomes the problem of deciding among different optimal solutions, attaining one unique alternative and facilitating the decision-making process.

In all the scenarios analysed, the minimum TCE solution is a Pareto point of the MOO problem cost vs Eco-indicator 99. Specifically, the single-objective approach produces solutions that implement MW and are close to the Pareto points lying near the extreme economic optimal solution (yet they show a clear improvement in environmental impact with respect to the minimum cost alternative of the Pareto set).

7. Acknowledgements

The authors would like to acknowledge financial support from the Spanish Government (DPI2012-37154-C02-02, CTQ2012-37039-C02) and to thank the Catalan Government for the quality accreditation given to their research groups GREA (2014 SGR 123). The research leading to these results has received funding from the European Commission Seventh Framework Programme (FP/2007-2013) under grant agreement no. PIRSES-GA-2013-610692 (INNOSTORAGE).

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