Multi-objective optimization applied to minimize the cost and the environmental impact of a building: An Irish case study

Joan Carreras[1], Dieter Boer[1,*], Shane Colclough[2], Gonzalo Guillén-Gosálbez[3,4], Laureano Jiménez[3], Marc Medrano[5], Luisa F. Cabeza[5]

[1]Departament d'Enginyeria Mecanica, University Rovira i Virgili, Av. Paisos Catalans 26, 43007 Tarragona, Spain, Phone: 34-977 55 96 31, e-mail: dieter.boer@urv.net

[2]Centre for Sustainable Technologies, University of Ulster

[3]Departament d'Enginyeria Química, University Rovira i Virgili, Av. Països Catalans 26, 43007 Tarragona, Spain

[4] School of Chemical Engineering and Analytical Science, University of Manchester, Mill, Sackville Street, Manchester M13 9PL, United Kingdom

[5]GREA Innovació Concurrent, Edifici CREA, Universitat de Lleida, Pere de Cabrera s/n, 25001-Lleida, Spain

1. Abstract

Today when developing building projects specialists require general and operational knowledge. Many energy efficiency strategies can improve the energetic performance of a building improving also the environmental impact and without compromising comfort. Among them building insulation appears as a promising option. This study presents a systematic methodology for determining the optimal insulation thickness for external surfaces. A multi-objective optimization model will be used to minimize simultaneously the cost and environmental impact associated with both the construction materials and the energy consumption over the operational phase of the building. The thermal loads were calculated using EnergyPlus, a building energy simulation program. The environmental impact was quantified following the life cycle assessment methodology. We applied our approach to a case study of a house-like cubicle located in Dublin. Our model identifies the optimal insulation thickness which reduces both the environmental impact and the cost by approximately 40%, with respect to a base case (cubicle without insulation). Our method is intended to assist decision-makers in the design of buildings.

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

2. Introduction

Worldwide buildings are responsible for approximately 40% of the total annual consumption of energy. Most of this energy is provided for lighting, heating, cooling, and air conditioning [1].

Many countries in OECD Europe have enacted measures to improve energy efficiency in the building sector. The European Union (EU) has approved a set of binding legislation to ensure it meets its ambitious climate and energy targets for 2020. In March 2007, the European Commission published the 20-20-20 plan, which includes a 20-percent improvement target for energy efficiency in the European Union.

To meet this goal multiple energy efficiency strategies can be applied. Among them different forms of thermal energy storage (TES) are considered as promising options. Building insulation is another example. Appropriate insulation decreases the demand of both heating and cooling.

The application of thicker insulation has the effect of reducing energy consumption. But another important aspect to consider is how this affects the overall environmental impact. Consideration should be given not only to the reduced environmental impact during the operation phase, but also the environmental impacts of the construction and disposal of the insulation. This environmental impact can be quantified following the life cycle assessment (LCA) approach. A considerable research gap is evident in the field, as the environmental impact of buildings, even for new constructions, has barely been evaluated in a systematic way [2–4].

The purpose of this work is to analyse how the thickness of an insulation material affects the energy consumption, the total cost and the environmental impact of a building. The analysis is developed using a multi-objective optimization (MOO). From these results we determine the optimum values in order to obtain the minimum cost, the minimum environmental impact (which typically does not correspond to the same insulation thickness), and illustrate the trade-off between both objectives.

3. Methodology

3.1. Computational implementation

To evaluate the energy consumption of the building, the building energy simulation program EnergyPlus will be used. The energy consumed over the building lifetime helps us to assess the related economic cost and the environmental impact. The climatic data of Dublin has been used.

When dealing with multiple design parameter options, such as the case of this work, the possible final results can be wide-ranging, and hence an exhaustive and time-consuming search would be necessary. However some existing software tools (e.g. JEPlus, Genopt) allows the user to perform complex parametric analysis simultaneously and to collect results afterwards. In the present work JEPlus [5], an EnergyPlus simulation manager for parametric studies, is used.

3.2. Objective functions

3.2.1. Economic indicators

The cost of the building, the insulation material plus the value of energy consumption over the lifetime of the building will be considered. The objective will be to achieve the minimum total cost [6–9].

An inventory list of the materials used for the cubicle construction, the used quantity and the correspondent cost is presented in

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

Where $Cost_{cub}$ is the cubicle total cost, $Price_k$ 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 consumed electricity is multiplied by the electricity cost in the domestic sector in Ireland (0.1928 €/kWh) considering an Annual Rate of Electricity Inflation Inf = 5% The equation is presented herein:

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

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

3.2.2. Environmental indicators

The environmental impact caused by the consumed energy and the construction materials will be quantified following the life cycle assessment (LCA) based on the Eco-indicator 99 (EI99) [11], extracted from the database EcoInvent [12]**.** This method divides the impact into three different damage categories (human health, ecosystem quality and resources) which in turn are composed of 10 specific impact categories. The sum of the three damage categories results into a single score. The evaluation of each impact is given by:

$$Imp_{cub} = \sum_{k} Imp_k \cdot Quant_k \tag{3}$$

Where Imp_{cub} is the cubicle total EI99 impact, Imp_k , is the coefficient of damage per kilogram of component k (an information that is available in the EcoInvent database[12]), and $Quant_k$ is the corresponding quantity in kilograms of component k.

Three different phases have been taken into consideration: the manufacturing, the dismantling and the operational. In the manufacturing and dismantling phase an inventory list of all the materials and the corresponding quantity used for the construction of the cubicles is created. A single impact point is assigned to each component. Data of the Irish electricity production system are used for the operational phase [12]

. Regarding the prices of the construction materials the ITeC database is used [10]. The total price of each cubicle is given by:

$$Cost_{cub} = \sum_{k} Price_k \cdot Quant_k \tag{1}$$

Where $Cost_{cub}$ is the cubicle total cost, $Price_k$ 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 consumed electricity is multiplied by the electricity cost in the domestic sector in Ireland (0.1928 €/kWh) considering an Annual Rate of Electricity Inflation Inf = 5% The equation is presented herein:

$$Cost_{elec\_n} = \sum_{n} Cons_{elec} \cdot PCost_{elec} \cdot (1 + Inf)^n \tag{2}$$

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

3.2.2. Environmental indicators

The environmental impact caused by the consumed energy and the construction materials will be quantified following the life cycle assessment (LCA) based on the Eco-indicator 99 (EI99) [11], extracted from the database EcoInvent [12]**.** This method divides the impact into three different damage categories (human health, ecosystem quality and resources) which in turn are composed of 10 specific impact categories. The sum of the three damage categories results into a single score. The evaluation of each impact is given by:

$$Imp_{cub} = \sum_{k} Imp_k \cdot Quant_k \tag{3}$$

Where Imp_{cub} is the cubicle total EI99 impact, Imp_k , is the coefficient of damage per kilogram of component k (an information that is available in the EcoInvent database[12]), and $Quant_k$ is the corresponding quantity in kilograms of component k.

Three different phases have been taken into consideration: the manufacturing, the dismantling and the operational. In the manufacturing and dismantling phase an inventory list of all the materials and the corresponding quantity used for the construction of the cubicles is created. A single impact point is assigned to each component. Data of the Irish electricity production system are used for the operational phase [12]

3.3. Solution procedure

The solution of the multi-objective model is given by a set of Pareto points [13,14] representing the optimal compromise between the objectives considered. In our study the models presented must attain two different targets: minimum total energy and material cost and minimum environmental impact.

4. Case study

4.1. Cubicle description

The experimental cubicles have identical dimensions (five plane walls with 2.4 x 2.4 x 0.15 m), but different materials (diverse types of bricks and insulation materials) in order to evaluate their performance. The structure of the cubicle was made of four mortar pillars with reinforcing bars, one in each edge of the cubicle. The base consists of a concrete base of 3 x 3 m with reinforcing bars. The walls consist of 6 material layers, herein we enumerate them from the external to the internal one; a cement mortar finish, a hollow bricks structure, an air chamber of 5 cm, a layer of insulation, 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 is placed over the concrete, protected with a cement mortar roof with a slope of 3 % and a double asphalt membrane. Also a reference cubicle with no insulation is considered.

4.2. Model constrains

For the cubicle simulation, an internal set point temperature of 24°C is considered for all the year [15,16]. The heating and the cooling is supplied by a heat pump with a COP of 3. Neither windows nor doors are considered. We assume a fixed infiltration rate of 0.12 ACH (air changes per hour) [17] and no mechanical or natural ventilation is used. There is no internal mass and no human occupancy.

We consider a building lifetime of 20 years. Referring to the economic cost of the cubicle materials we suppose the total inversion is assumed the first year. As for the electricity cost a price of 0.19 €/kWh is considered with a yearly 5% increase cost.

4.3. Case study

The case study addresses the design of a cubicle with the specified construction system. In this case the insulation thickness will be varied uniformly in the four vertical surfaces and the roof from 1 to 30cm and a reference case with no insulation will also be analysed. Initially partial solutions will be evaluated, on one hand the economic optimal solution and on the other the environmental impact. Finally a set of Pareto solutions representing the optimal trade-off between both conflicting objectives will be analysed.

5. Results and discussion

5.1. Case I: homogenous insulation thickness

5.1.1. Economic cost analysis

When the insulation thickness of the cubicle surfaces increases, the material cost increases linearly, hence, more insulation material implies a higher cost for the cubicle. However, energy cost decreases as the insulation thickness increases. Hence, there are two conflicting effects, and the minimum cost solution corresponds to the point representing the optimal balance between the two economic variables. In this case, the minimum cost solution involves a thickness of 12 cm for the PU (polyurethane), 16 cm for the EPS (polystyrene) and 17 cm for the MW (mineral wool) (Fig. 1.a).

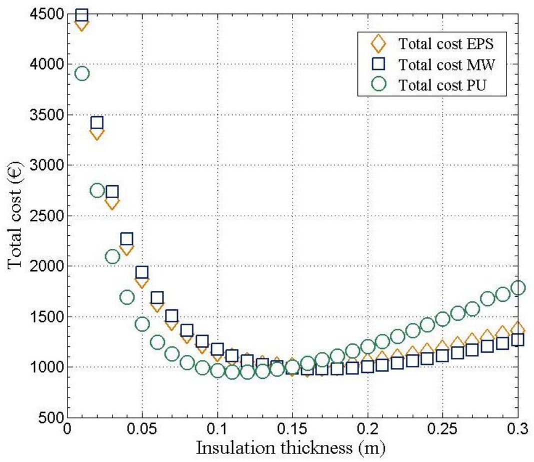
Note that, as expected, the solution with minimum energy cost is not the one with the best economic performance. Hence, neglecting the cost of the materials, leads to a suboptimal solution. The same can be said for the analysis of the minimum environmental impact solution.

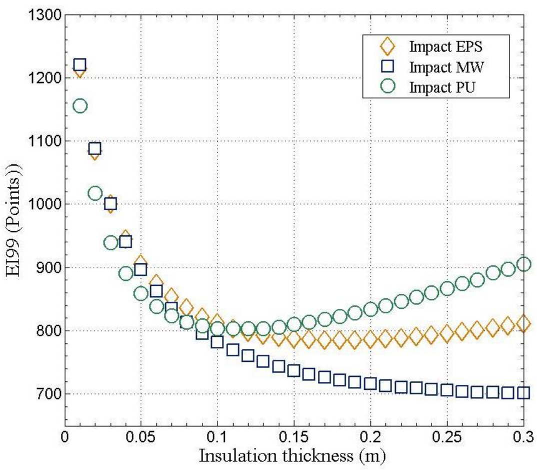
5.1.2. Environmental impact analysis

The energy impact decreases with the insulation thickness, while the material impact increases linearly with the insulation thickness. The minimum impact solution involves a thickness of 12 cm for the PU, 17 cm for the EPS, and 29 cm for the MW (Fig.1.b). The thickness with minimum impact for the MW is more than 10 cm higher than that corresponding to the other. 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.

Figure 1.a:Simulations obtained from the variation of the cubicle cost with the insulation thickness for PU, MW and EPS

Figure 1.b:Simulations obtained from the variation of the cubicle impact with the insulation thickness for PU, MW and EPS

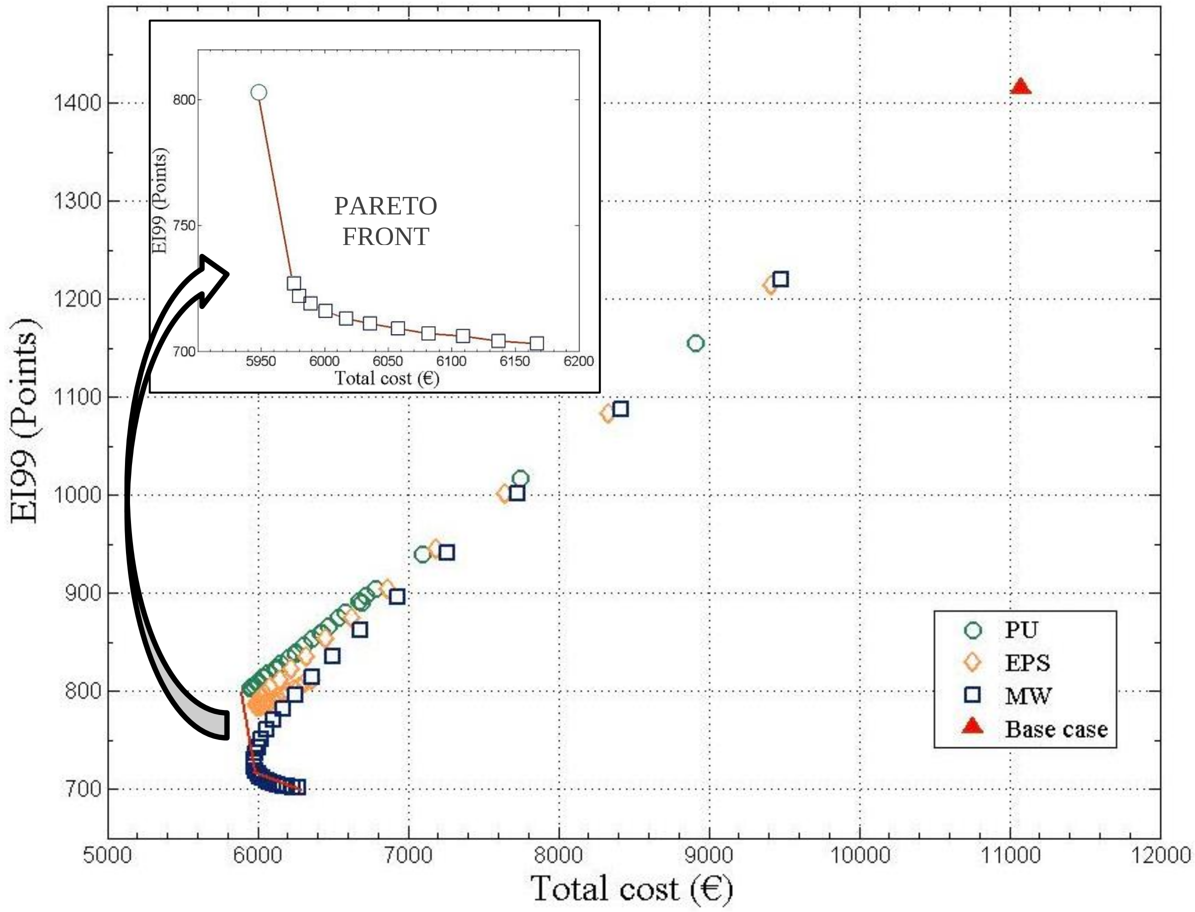




5.1.3. Multi-objective analysis

In this section we analyse the total cost and environmental impact, of both energy and materials, simultaneously. Each point in **Error! Reference source not found.**(Eco-indicator 99 *vs* cost) represents a different combination of insulation thicknesses. For each insulation material, we obtain the extreme solutions of each objective (i.e., minimum cost and minimum environmental impact). Between these two points, we obtain a set of trade-off alternatives, 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 minimize/maximize all the objective functions of the multi-objective problem at once. Regarding the EPS case, the best economic insulation thickness is 16 cm, while the best environmental solution involves a thickness of 17 cm. Finally, the best insulation thicknesses for the MW case are 17 cm (economic) and 29 cm (environmental).

Figure 2: 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



5.3. General observations

How much do the insulated optimal solutions improve compared to the reference case? As we can see in Table 1 the different optimal solutions are around 45% better than the reference case results for both, the economic and environmental values.

Table 1: Presentation of the referent case results and the best economic and environmental results for both case studies.

		Cubicle model	Economic cost (€)	EI99 (Points)	Improvement (%)	
					Economic	EI99
		Reference case	11081	1416	0	0
Case study	Best economic solution	All surfaces 12cm PU	5948	803	46	43
	Best EI99 solution	All surfaces 29cm MW	6232	702	44	50

6. Conclusions

In the present paper a cubicle like building has been modelled and analysed. Different insulation thicknesses for its external surfaces have been tested in order to find the sets of alternatives that optimize simultaneously its economic and environmental performance. Starting from an initial reference case with no insulation, we have developed two case studies and different analyses, working progressively with more optimized solutions.

The systematic procedure presented here readily facilitates simultaneous consideration of the environmental impact of the construction material and their capital cost and the environmental impact and operational cost of the consumed energy. We can conclude that taking into consideration the environmental impact of the materials is of paramount importance since it can modify the final optimal solutions as can be observed in this work.

Concerning the specific results of this paper we can determine that, for our case studies, to find the optimal insulation thickness is of crucial importance to consider not only the economic cost but also the environmental impact.

Acknowledgment

The authors would like to acknowledge financial support from the Spanish Government ENE2011-28269-C03-03, ENE2011-22722, DPI2012-37154-C02-02, CTQ2012-37039-C02) and to thank the Catalan Government for the quality accreditation given to their research groups SUSCAPE and GREA (2009 SGR 545, 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).

References

[1] A.M. Omer, Energy, environment and sustainable development, Renewable and Sustainable Energy Reviews. 12 (2008) 2265–2300. doi:10.1016/j.rser.2007.05.001.

[2] K. Menoufi, A. Castell, M.M. Farid, D. Boer, L.F. Cabeza, Life Cycle Assessment of experimental cubicles including {PCM} manufactured from natural resources (esters): A theoretical study, Renewable Energy. 51 (2013) 398–403. doi:10.1016/j.renene.2012.10.010.

[3] A. Singh, G. Berghorn, S. Joshi, M. Syal, Review of life-cycle assessment applications in building construction, Journal of Architectural Engineering. 17 (2011) 15–23. doi:10.1061/(ASCE)AE.1943-5568.0000026.

[4] O. Ortiz, F. Castells, G. Sonnemann, Sustainability in the construction industry: A review of recent developments based on LCA, Construction and Building Materials. 23 (2009) 28–39. doi:10.1016/j.conbuildmat.2007.11.012.

[5] JEPlus, an EnergyPlus simulation manager for parametric studies - www.jeplus.org/ [Accessed: May 2014], (2014). www.jeplus.org/.

[6] M. Ozel, Thermal, economical and environmental analysis of insulated building walls in a cold climate, Energy Conversion and Management. 76 (2013) 674–684. doi:10.1016/j.enconman.2013.08.013.

[7] O. Kaynakli, A review of the economical and optimum thermal insulation thickness for building applications, Renewable and Sustainable Energy Reviews. 16 (2012) 415–425. doi:10.1016/j.rser.2011.08.006.

[8] M. Ozel, Determination of optimum insulation thickness based on cooling transmission load for building walls in a hot climate, Energy Conversion and Management. 66 (2013) 106–114. doi:10.1016/j.enconman.2012.10.002.

[9] J. Yu, C. Yang, L. Tian, D. Liao, A study on optimum insulation thicknesses of external walls in hot summer and cold winter zone of China, Applied Energy. 86 (2009) 2520–2529. doi:10.1016/j.apenergy.2009.03.010.

[10] BEDEC Database - www.itec.es/nouBedec.e/bedec.aspx [Accessed: May 2014]

[11] PRé Consultants. The Eco-indicator 99A damage oriented method for life cycleimpact assessment. Methodology report and manual for designers., Technical Report, PRé Consultants, Amersfoort, The Netherlands. (2000).

[12] The Ecoinvent Center. A competence centre of ETH; PSI; Empa & ART, (n.d.). www.ecoinvent.ch/. .

[13] R. Brunet, D. Cortés, G. Guillén-Gosálbez, L. Jiménez, D. Boer, Minimization of the LCA impact of thermodynamic cycles using a combined simulation-optimization approach, Applied Thermal Engineering. 48 (2012) 367–377. doi:10.1016/j.applthermaleng.2012.04.032.

[14] E. Antipova, D. Boer, L.F. Cabeza, G. Guillén-Gosálbez, L. Jiménez, Uncovering relationships between environmental metrics in the multi-objective optimization of energy systems: A case study of a thermal solar Rankine reverse osmosis desalination plant, Energy. 51 (2013) 50–60. doi:10.1016/j.energy.2013.01.001.

[15] L.F. Cabeza, A. Castell, M. Medrano, I. Martorell, G. Pérez, I. Fernández, Experimental study on the performance of insulation materials in Mediterranean construction, Energy and Buildings. 42 (2010) 630–636. doi:10.1016/j.enbuild.2009.10.033.

[16] A. Castell, K. Menoufi, A. de Gracia, L. Rincón, D. Boer, L.F. Cabeza, Life Cycle Assessment of alveolar brick construction system incorporating phase change materials ({PCMs)}, Applied Energy. 101 (2013) 600–608. doi:10.1016/j.apenergy.2012.06.066.

[17] Residential Prototype Building Models. U.S. Department of Energy, (2013). www.energycodes.gov/development/commercial/90.1_models.