UNIVERSITAT ROVIRA I VIRGILI

MATHEMATICAL PROGRAMMING FOR ENERGETIC, ECONOMIC AND ENVIRONMENTAL OPTIMIZATION OF BUILDING DESIGN

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Mathematical programming for energetic, economic and environmental optimization of building design

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Mathematical programming for energetic, economic and environmental optimization of building design

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That the present study entitled "Mathematical programming for energetic, economic and environmental optimization of buildings design", presented by Joan Carreras Ubach for the award of the degree of Doctor, has been carried out under our supervision at the Mechanical Engineering Department of the University Rovira i Virgili.

Tarragona 2nd September 2016,

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Summary

Nowadays society is becoming more aware of the importance of being environmentally conscious. As a result, the authorities and many companies and consumers seek products that are cost efficient but also environmentally friendly and sustainable. Within this context broad studies should be performed to evaluate the economic and environmental potential improvements of any activity or product design.

The building sector presents a significant improvement margin since it represents 40% of the total annual energy consumption worldwide [1] and it is responsible for one third of global greenhouse gas emissions, in both developed and developing countries [2]. Given its importance, many countries in the OECDE have dictated measures to reduce energy consumption in buildings. In March 2007, the European Parliament approved a binding legislation with several goals: to achieve a 20% reduction in EU greenhouse gas emissions from 1990 levels; to increase the share of EU energy consumption produced from renewable resources to 20%; and to improve the EU's energy efficiency by 20% [3]. To achieve these key targets, several strategies can be adopted. Building insulation appears as a promising one, since it decreases the cooling and heating demand without compromising comfort and it is applicable in both, new and refurbished buildings.

In this thesis we present several systematic mathematical decision-support tools for the design of optimal buildings with minimum cost and minimum environmental impact. To illustrate the capabilities of our approaches, we consider a case study consisting in a house-like cubicle. Our variables are the materials and thicknesses used for the external thermal insulation and our goals to achieve the minimum economic cost and minimum environmental impact. Note, however, that our methodologies are general enough to work with different building models, decision variables and objective functions.

The first paper [4] of the thesis describes the application of a multi-objective optimization (MOO) developed to minimize simultaneously the cost and environmental impact associated with both the construction materials and the energy consumed over the operational phase of the building. The results are shown in the form of Pareto frontier (*i.e.*, an objective cannot be further improved without worsening the other).

The proposed methodology relies on a simulation-based optimization framework that combines a model that predicts the building's energy performance (EnergyPlus) with an optimization algorithm that seeks the optimal building designs (JEPlus+EA). EnergyPlus is a building energy simulation program widely used by architects and engineers. Without loss of generality, we solve the multi-objective model using multi-objective genetic algorithms. Hence, the simulation

software is coupled with an optimization algorithm implemented in JEPlus+EA [5] that minimizes the multi-dimensional objective function by changing the values of the decision variables. This optimization software makes use of the multi-objective genetic algorithm NSGA-II [6]. Our framework, however, is general enough to work with other optimization algorithms, similarly to the work that can be found in the literature in other engineering problems [7].

The environmental impact, quantified following the life cycle assessment (LCA) methodology, is explicitly incorporated into the multi-objective model as an additional objective to be optimized along with the cost. LCA is a method for evaluating the environmental impacts of products by adopting a holistic approach that accounts for the direct and indirect impacts. Particularly, to assess the environmental impact, the Eco-indicator 99 (EI99) methodology [8,9] was implemented. EI99 covers 10 specific impact indicators which are then aggregated into three different damage groups (human health, ecosystem quality and resources) and these three groups are further clustered to attain a single indicator. The aggregated form of the EI99 is the indicator used in this first approach.

Numerical results show how significant economic and environmental improvements (win-win scenarios) can be obtained with respect to a base case (cubicle with no insulation). The economic improvements range from 34 to 39%, while the environmental impact is reduced between 35 and 43%. Polyurethane shows better economic performance while mineral wool has less impact. The minimum impact design tends to implement thicker thicknesses. Among the Pareto solutions, intermediate optimal solutions of mineral wool are particularly appealing, as they attain significant environmental impact reductions with a marginal increase in cost.

The second paper [10] focuses on the eco-costs evaluation for the optimal design of buildings with lower environmental impact. Eco-costs is a monetization technique to convert environmental impact into economic cost. It quantifies the cost of preventing a certain amount of environmental burden related to a product or activity. These are regarded as virtual costs, since they are not yet integrated into the real costs of the product under study, and are calculated considering the cradle to grave environmental impact of a material (including all the phases in its life cycle).

As in the first paper the goal is to attain those insulation designs with minimum cost and minimum environmental impact. Economic and environmental objectives tend to be conflicting targets. Hence, to optimize both criteria simultaneously, we usually need to resort to multi-objective optimization (MOO) techniques. The final result of a MOO typically consists of a set of Pareto optimal solutions, each achieving a unique combination of objective function values. When several players take part in the decision-making process and/or many conflicting criteria need to be analysed, it might be difficult to generate the Pareto points and identify from them a final alternative to be implemented in practice. Through the use of eco-costs the environmental impact of a product or activity can be incorporated explicitly into the economic performance assessment. Hence, a unique optimal solution is attained, thereby avoiding the task of deciding among different optimal alternatives.

In this second study several scenarios were analysed. Different European locations were considered in the analysis to compare the effect of different weather conditions and the importance of the specific cost and impact of the energy consumed. In all scenarios optimal results where attained with those building designs using mineral wool as insulation material. Solutions present important environmental improvements at a marginal increase in cost.

In the third paper [11] we focused on implementing mathematical techniques to expedite the resolution of problems. The case study was the same as in the first article but in this case the environmental impact was quantified considering the 10 specific impact indicators comprising EI99 and we also measured its aggregated form.

On the one hand we resort to dimensionality reduction methods [12], which remove redundant objectives from the multi-objective model while still preserving its structure. And on the other hand, we resort to surrogate models [13]. Despite reducing the number of objective functions, estimating the energy performance of a building (using dynamic simulation) remains computationally challenging. That is, even if the optimization is performed in a reduced domain of objectives, it might yet be difficult to evaluate the objective functions as this requires solving a system of partial differential equations (PDE). A surrogate model is a method used when an outcome of interest cannot be easily directly measured, so a model of the outcome is used instead. To create a surrogate model first a sample of the total possible results is created. Based on this set of solutions the surrogate model is conformed and validated. This is a black box model fitted with rigorous simulation points that provides approximated results but it is faster to solve than the original model.

Results clearly demonstated important reductions in the time required to solve the problem. Results shows that 3 objectives (two environmental indicators and the economic one) suffice to optimize the system while keeping its original dominance structure. The surrogate model notably reduces the computational burden of the optimization task, thereby expediting the overall solution time (*i.e.*, 8 times). The results of the case study demonstrate significant improvements with respect to the base case (cubicle without insulation). In particular, using the appropriate insulation strategy, the cost can be reduced by 26%, one of the environmental impacts indicators (carcinogenics impact) can be mitigated by 17%, and the other (ionising radiation impact) can be decreased by 51 %.

In summary this thesis provides a set of systematic tools to guide decision-makers towards the adoption of more sustainable designs as well as policy-makers during the development of more effective regulations for improving the economic and environmental performance in the building sector.

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1. Introduction

Nowadays building sector is responsible for approximately 40% of the total annual worldwide consumption of energy [14]. Most of this energy is used for lighting, heating and cooling [15]. This energy production has associated several environmental impacts, for example, it is responsible for one third of global greenhouse gas emissions. In this context a priority objective is to strive to develop more sustainable and energy efficient buildings. Many OECD countries have dictated measures for minimizing energy consumption in the building sector. The European Union (EU) approved 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 [3]. As a result of these efforts, energy strategies must be adopted to achieve the corresponding economic and environmental targets.

Multiple energy efficiency strategies can be applied to achieve the aforementioned energy reduction goals. These include, for example, the implementation of better insulation strategies, different types of windows as well as the more appropriate window to wall ratio or the installation of renewable energy systems and thermal energy storage. Regardless of the applied strategy a broad study should be performed to evaluate the economic and environmental potential improvements. This includes, apart from a laborious environmental and economic assessment, a rigorous evaluation of the energy performance of the building as well as optimization techniques to obtain the best building designs.

The economic assessment is a recurrent and well-known evaluation. However the environmental assessment is a more complex methodology that incorporates more subjectivity. Many tools and indicators are available for assessing and benchmarking environmental impacts of different systems. Among them, life cycle assessment (LCA) [16] 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 (see in Article 1 section “3.2.2. Environmental indicators” and in Article 3 section “3.1.4. Environmental indicators” for more details).

In building science, designers often use dynamic simulation software to analyse the energy performance of a building and to attain specific objectives (*i.e.*, improving the economic or environmental performance). Although many software applications are available to evaluate the energy performance of buildings the commonly-used simulators are EnergyPlus and TRNSYS [17] (see in Article 1 section “3.1. Mathematical model” and in Article 3 section “4.2. Model specifications” for further details).

These software can measure the influence of many different variables in the building energy performance. For example to evaluate the consequence of modifying the implemented construction system, materials, geometry and internal distribution and also the result of using different HVAC equipment, power, efficiency and the operation scheduling for the set points or the influence of the people occupation. To evaluate the effect of a specific variable (*e.g.*, thickness of thermal insulation) on the objective functions, one can resort to a parametric study. This analysis might lead to large calculations that will not even ensure convergence to an optimal solution. Hence, when the search space is huge, it is more convenient to resort to complex rigorous optimization algorithms. With these approaches the building model is usually interrogated iteratively attaining progressively better approximations to an optimal solution and avoiding the task of evaluating the whole space of possible solutions (see in Article 1 section "3.1. Mathematical model" for more details). At present, the prevalent approach to solve problems with more than one objective function (*e.g.*, economic cost and environmental impact) is multi-objective optimization (MOO) [18–21]. Note that the minimum cost solution will differ, in general, from the minimum impact one, as in most cases these are conflicting objectives. 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 (see in Article 1 section "3.3. Solution procedure" for more details).

In this thesis we resort to simulation-based optimization methods for the optimal design of buildings. The developed tools are intended to promote optimal economic solutions for energy efficiency in buildings, while also minimizing their environmental impact. These tools can guide decision-makers towards the adoption of more sustainable designs as well as policy-makers during the development of more effective regulations for improving the economic and environmental performance of the building sector.

The document is organized as follows. Section 2 states the motivation of the thesis. Section 3 provides information about the available building simulation software to evaluate the energy performance and insights into the simulation program implemented in this thesis. The methods to assess the environmental impact of a building are presented in section 4. Section 5 describes the mathematical programming approach to the building design. In section 6 some case studies are presented illustrating the capabilities of the aforementioned techniques. Results and general conclusions are summarized in Section 7. In Sections 8 challenges and future work are presented. Section 9 presents the used bibliography. Section 10 comprises the articles composing the thesis. And section 11 summarizes the scientific work developed during the PhD.

1.1. General objectives

The objectives of this thesis are:

1. To identify optimal building solutions that simultaneously minimizes the economic cost and the environmental impact.
2. To incorporate explicitly the environmental impact into the economic performance assessment.
3. To expedite the resolution of the multi-objective optimization (MOO) problems.
4. To identify and remove redundant objectives from the multi-objective model to simplify its resolution and interpretation.

More specific objectives are listed in Section 6.1.

2. Simulation-based optimization methods to assess and optimize the economic and environmental performance of the buildings

Mathematical programming is widely used in many scientific and engineering problems. The application of these mathematical models is especially appealing for optimization problems. The use of optimization methods applied to building performance is reviewed in many different works [17,22]. Many studies have resorted to simulation-based optimizations techniques to evaluate the performance of a building focusing on minimizing exclusively the economic criteria. More recently other approaches used multi-objective optimization to incorporate more objective functions in the stated problem as the minimization of carbon dioxide equivalent (CO_2-eq) emissions of the buildings [23] or the maximization of the thermal comfort [24].

In this thesis we resort to optimization techniques to develop systematic tools to obtain buildings with the minimum economic cost but also presenting low environmental impact. As a case study to illustrate the capabilities of the developed tools we consider a house-like cubicle [25,26]. The main goal is to optimize the insulation strategy of the building envelope in order to minimise its cost and environmental impact simultaneously.

The economic performance is quantified through the cost, which accounts for the insulation material and the electricity consumed for heating and cooling over the lifetime of the building. The objective is to achieve the minimum total cost. For the assessment of the environmental impact, the impact of the consumed energy and the impact of the materials are quantified, the objective is again to achieve the minimum environmental burden (for more details see Section 4. Environmental Assessment methods).

3. Building simulation

3.1. Building performance simulation tools

Until the mid-1960s only hand-calculation methods were available for estimating energy use in buildings. The degree-day method [27,28] was commonly used to calculate heating energy requirements. Although these methods were useful when computational resources were limited and expensive, they simplified and neglected some important factors such as transient thermal storage in building materials, solar gains, internal gains, variations in outdoor air ventilation and infiltration rates, and non-steady operation of heating equipment.

In recent decades, applications of computer simulation for handling complex engineering systems have emerged. Designers often use dynamic thermal simulation programs to analyse thermal and energy behaviour of a building and to achieve specific targets (*e.g.*, reducing energy consumption, environmental impacts or improving indoor thermal environment). Among these building simulation programs the more commonly used are [29]: EnergyPlus, TRNSYS, DOE-2, ESP-r, EQUEST, ECOTECT, DeST, Energy-10, IDE-ICE, Bsim, IES-VE, PowerDomus, HEED, Ener-Win, SUNREL and Energy Express, BLAST, TAS, TRACE and HAP. Despite the wide range of software available more than 70% of the studies resort to EnergyPlus (37.2%) and TRNSYS (35.3%) [17].

TRNSYS [30] is a transient system simulation program with a modular structure that implements a component-based approach. TRNSYS components (referred to as ‘‘Types’’) may be as simple as a pump or pipe, or as complex as a multi-zone building model. The components are configured and assembled using a fully integrated visual interface known as the TRNSYS Simulation Studio, while building input data is entered through a dedicated visual interface (TRNBuild). The simulation engine then solves the system of algebraic and differential equations that represent the whole energy system.

In the present thesis the building simulation program used is EnergyPlus [31]. TRNSYS and EnergyPlus are both widely used and validated software, however in the present thesis EnergyPlus was selected since it is shareware and it is more oriented to the analysis of building thermal behaviour.

3.2. EnergyPlus

EnergyPlus is a modular, structured code based on the most popular features and capabilities of BLAST [32] and DOE-2.1E [33]. It is a simulation engine with input and output text files. Loads calculated (by a heat balance engine) at a user-specified time step (15 minutes by default) are passed to the building systems simulation module at the same time step. The EnergyPlus building systems simulation module, calculates heating and cooling system and plant and electrical system response. This integrated solution provides accurate space temperature prediction, crucial for system and plant sizing, occupant comfort and occupant health calculations. Integrated simulation also allows users to evaluate realistic system controls, moisture adsorption and desorption in building elements, radiant heating and cooling systems, and interzone air flow.

4. Environmental assessment methods

To quantify the environmental impact of the building, we resort to Life-Cycle Assessment (LCA) methodology. LCA is a technical, data-based and holistic approach to define the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and material usage and waste discharges, assessing the impact of those wastes on the environment. The basic idea of LCA is that all environmental burdens connected with a product or service have to be assessed, back to the raw materials and down to waste disposal [34,35].

In our case studies the environmental impact accounts for the generation of the electricity consumed and the manufacture of the construction materials and we asses these impacts through the use of Eco-indicator 99 (EI99) methodology which is based on LCA principles. EI99 is an indicator whose value is determined from the life cycle inventory of inputs and outputs of a process, a set of damage factors, and several normalizations and weighting parameters (see in Article 1 section “3.2.2. Environmental indicators” and in Article 3 section “3.1.4. Environmental indicators” for more details). EI99 quantifies the damage in ten specific impacts, which are grouped into three different damage categories (ecosystem quality, human health and resources depletion) and finally aggregated in a single score. The environmental assessment can be performed using the group of specific impacts, using the damage categories or the aggregated indicator. A higher aggregation of the indicators implies more uncertainty but facilitates significantly the analysis of the results. Other recent techniques are emerging in order to convert the environmental impact into monetary terms. In the present thesis Eco-cost, one of these approaches, is implemented to include the environmental cost into the economic function (see in Article 2 section “3.2.2. Environmental indicators (eco-costs)”for more details).

5. Mathematical programming

5.1. Multi-objective optimization

To optimize problems considering more than one criterion (*i.e.*, economic and environmental) multi-objective optimization (MOO) techniques are required.

$$
\begin{aligned}
MOO \quad \min \quad & F = \{f1, \dots, fN\} \\
s.t. \quad & h(x) = 0 \\
& (x) \leq 0 \\
& x \in \Re
\end{aligned}
$$

In MOO problems usually there is not only one optimal solution but rather a set of Pareto solutions that represent the optimal trade-off between the conflicting objectives considered in the analysis. A solution is said to be Pareto optimal when it cannot be improved simultaneously in all the objectives without necessarily worsening at least one of them. Therefore, all the Pareto solutions are considered to be equally optimal (see [36] for further information).

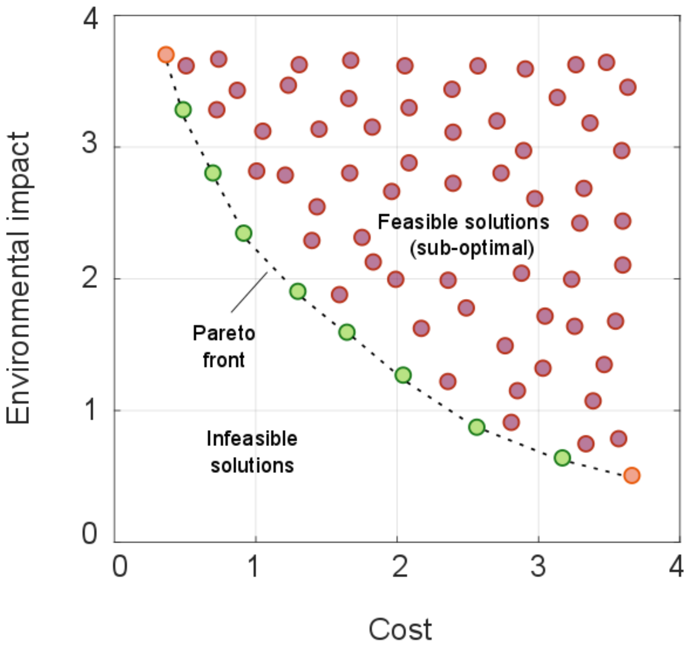

Figure 2. Example of a bi-criteria Pareto optimal frontier for two conflicting objectives.

For the calculation of the Pareto optimal solutions in MOO problems, two main methods exist in the literature: the weighted-sum and ε constraints. The weighted-sum method is only rigorous for the case of convex problems, whereas the ε constraint method is rigorous for convex and non-convex problems. However in the present thesis an Evolutionary Algorithm (EA), one of the most widely used optimization methods in engineering, has been used. This is *a posteriori* method that produces all the Pareto optimal solutions with one run of the algorithm. The main advantage of evolutionary algorithms is the fact that they typically generate sets of solutions, allowing computation of an approximation of the entire Pareto front. The main drawback of evolutionary algorithms is their lower speed and that the Pareto optimality of the solutions cannot be mathematically guaranteed (see in Article 1 section “3.1. Mathematical model” for more details).

There are many different tools to optimize building designs. GenOpt [37] and MatLab environment [38] are the widely-used tools. In the present thesis JEPlus+EA, a multi-objective optimization tool based on a customized non-dominated sorting genetic algorithm-II (NSGA-II), is used to perform the optimization (see in Article 1 section “3.1. Mathematical model” for further details).

5.2. Objective reduction

The simultaneous optimization of several objectives might lead to highly complex models that would be very hard to solve. This is because MOO is rather sensitive to the number of objectives and the generation and analysis of the Pareto points of a model becomes more difficult as we increase the number of objectives. The prevalent approach to overcome this problem is to use aggregated metrics that translate several environmental metrics into a single indicator defined by assigning weights to them [39,26,40]. Following this approach, most authors have developed bicriteria models where the economic performance is traded off against a single environmental indicator obtained as a weighted sum of individual impacts. This method simplifies the analysis to a large extent, but has two main weaknesses. The first is that the weights used may not necessarily reflect the preferences of decision-makers. The second is that their optimization might alter the structure of the problem by eliminating Pareto solutions potentially appealing for decision-makers. Multidimensionality reduction methods can overcome these limitations removing redundant objectives from the multi-objective model while still preserving its structure. Several dimensionality reduction methods have been proposed in the literature. Particularly, Deb and Saxena [41] were the first to investigate dimensionality reduction in MOO. They developed a statistical method based on principal component analysis (PCA) for eliminating nonessential objectives in MOO problems, thereby simplifying the associated calculations. Brockhoff and Zitzler [42] presented another approach based on the minimization of an approximation error (*i.e.*, delta error) resulting from the elimination of objectives. More recently, Guillén-Gosálbez [43] introduced a multi-dimensionality reduction method based on a mixed-integer linear program (MILP) that minimizes the delta error proposed by Brockhoff and Zitzler [42] (see in Article 3 section "3.2.2. Dimensionality reduction method" for more details).

5.3. Surrogate modelling

The necessity of resorting to dynamic simulation for estimating the energy performance of a building makes the optimization computationally challenging as this requires solving a system of partial differential equations (PDE) many times. Some studies [44–46] have attempted to reduce the complexity of the PDE model by streamlining the simulation process. Other authors resorted to surrogate models to expedite the optimization process [47–49]. A surrogate model is a method used when an outcome of interest cannot be easily directly measured, so a model of the outcome is used instead. To create a surrogate model first a sample of the total possible results is created. Based on this set of solutions the surrogate model is conformed and validated. This is a black box model fitted with rigorous simulation points that provides approximated results but it is faster to solve than the original model (see in Article 3 section "3.2.3 Building the surrogate model" for more details).

6. Case study

The capabilities of our approaches are illustrated through its application to the optimization of real cubicles located in an experimental installation in Puigverd de Lleida (Lleida, North-East Spain) [50]. The cubicles have identical dimensions (five plane walls with 2.4 m × 2.4 m × 0.15 m), but implement different insulation materials. 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 m × 3 m with reinforcing bars. The walls consist of six material layers (enumerated from outside to inside): a cement mortar finish, a hollow bricks structure, an air chamber of five cm, a layer of an insulation material, perforated bricks and a plaster plastering layer. The roof was constructed using concrete precast beams and five cm of concrete slab. The internal finish is plaster plastering. The insulation material is placed over the concrete, and it is protected with a cement mortar roof with a slope of 3% and a double asphalt membrane.

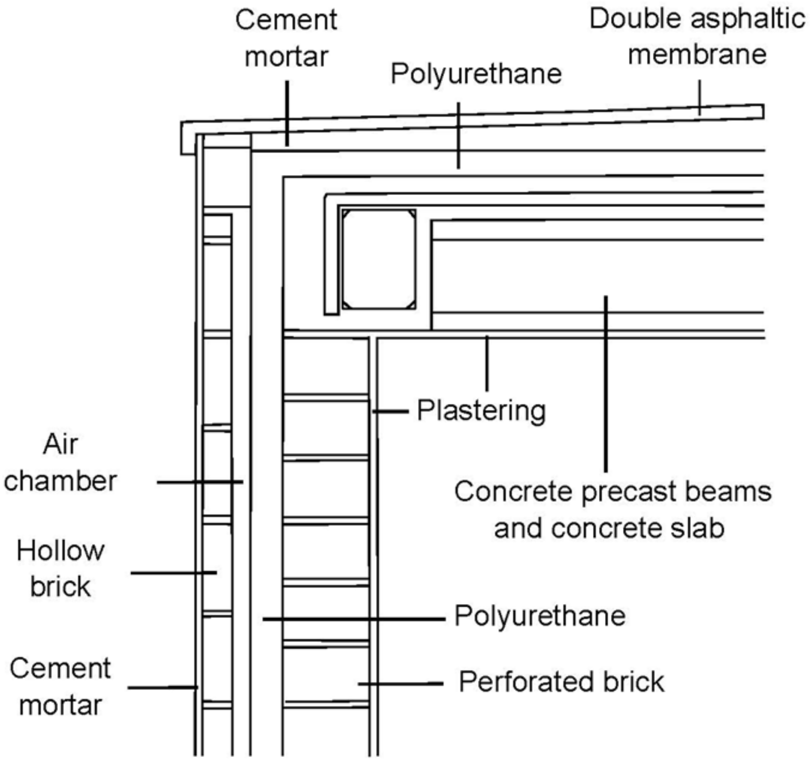

Fig.3. Construction profile of the experimental cubicles in Puigverd de Lleida (Spain).

The model presents some specifications 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 [50,51].
- 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 three.
- A fixed infiltration rate of 0.12 ACH (air changes per hour) [52] 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 analyse 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 [53,54].
- The total investment for the construction materials takes places the first year of the time horizon.

6.1. Specific objectives

The general objectives of this thesis are listed in Section 1.1. However in this section other specific objectives are enumerated:

Article 1:

1. To identify the insulation solutions (considering different materials and thicknesses) for the case study that presents better performance from the economic and environmental perspectives
2. To identify the optimal designs when considering both objectives (*i.e.*, Pareto Frontier).
3. To identify the relative importance of the consumed energy and the construction materials when the environmental impact is measured and also when the economic cost is quantified.
4. To quantify the improvement of the optimal building models (from the environmental and economic points of view) compared to a model without insulation.
5. To evaluate the relevance of considering different insulation thicknesses for the building external surfaces. This is, to evaluate if the construction effort of implementing heterogeneous insulation is justified for the energy savings.
6. To check if the optimal solutions obtained are in accordance with the recommendations of buildings directives in Spain.

Article 2:

1. To evaluate the Eco-costs for the optimal design of buildings with lower environmental impact following the LCA principles.
2. To identify the insulation solution (considering different materials and thicknesses) for the case study model that presents better environmental and economic performance through the use of Eco-costs indicator.
3. To identify the optimal insulation solutions when considering different locations (*i.e.*, different weather conditions and different electricity prices and impacts associated to the electricity generation).
4. To quantify the improvements of the optimal building designs (from the environmental and economic points of view) compared to a design without insulation.
5. To test the robustness of the optimal solutions obtained through the development of a sensitivity analysis of the Eco-cost indicator.
6. To compare the optimal solutions obtained using Eco-cost with those obtained evaluating the economic and environmental impact performance separately.

Article 3:

1. To identify the insulation solutions (considering different thicknesses) for the case study that presents better environmental and economic performance using different environmental impact indicators to assess the environmental impact.
2. To identify, through the use of a dimensionality reduction analysis, the redundant objectives that can be eliminated while still preserving the structure of the problem.
3. To develop a surrogate modelling approach that expedites the optimization task by reducing the time required to estimate the energy consumed by the building.
4. To test if working with the set of individual indicators according to the EI99 provides better results than working with the EI99 aggregated indicator.
5. To quantify the improvement of the optimal building designs (from the environmental and economic points of view) compared to a design without insulation.

7. General conclusions

This doctoral thesis focuses on the development of systematic methods for the identification of optimal designs for building insulation under different criteria. A brief summary of the results and conclusions obtained is provided below. Further details can be found in the original publications attached to this document.

In the first study we developed 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). Taking as a basis a standard cubicle without insulation, our approach identifies solutions that reduce both, the cost and environmental impact by around 40%.

In the second work we resort to Eco-costs, a method that translates the environmental impact of a product or activity into monetary units, which can then be incorporated explicitly into the economic performance assessment. Hence, a unique optimal solution is attained, thereby avoiding the task of deciding among different optimal alternatives. Our approach identifies building insulation designs that improve significantly the environmental performance at a marginal increase in cost.

Finally in the third paper we propose a systematic framework for the design of buildings that combines a rigorous objective reduction method (which removes redundant objectives from the analysis) with a surrogate model (which simplifies the calculation of the energy required by the building), both of which expedite the identification of alternative designs leading to environmental improvements. As in the other papers the variables considered are the insulation materials and their thicknesses. Results show that significant economic and environmental improvements can be achieved compared to the base case (cubicle without insulation) while the computational time required to solve the problem is reduced. Furthermore, it is clearly illustrated how the minimization of an aggregated environmental metric, like the Eco-Indicator 99, as unique environmental objective may overlook some Pareto solutions that may be appealing for decision-makers.

8. Challenges and future directions

We present a set of potential research lines to be addressed in future work on this domain:

- A sustainable analysis might include social concerns in the assessment. Therefore, social indicators should be considered in the identification of more sustainable building solutions. Obtaining data reliable is bottlenecking those studies.
- The presented systematic tools are general enough to work with other variables and designs. The systematic methodologies presented in this thesis could be easily extended to deal with new scenarios considering more complex and realistic building models (*i.e.*, dimension, internal distribution, occupation…).
- Future work could consider the analysis of the main sources at uncertainty sources in the problem (*e.g.*, insulation cost, energy cost, inflation rate, emissions data, etc…).

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10. Research articles

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

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Highlights

- We present a methodology to determine the optimal building insulation thickness.
- Multi-objective optimization reduces at once economic and environmental impact.
- Optimization reduces the cost and impact of the base case (no insulation) by 40%.
- Environmental impact of materials and not only energy impact has to be considered.
- In the future an uncertainty analysis and more complex models will be studied.

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
$Cost_{elec\_n}$	Electricity cost over n years
$Cons_{elec}$	Electricity consumption
$PCost_{elec}$	Present cost of the electricity
n	Years
Inf	Year electricity inflation rate (%)
$Cost_{total}$	Total cost
Imp_{cub}	Cubicle impact
Imp_{k}	Coefficient of damage per kilogram of raw material
Imp_{elec}	Electricity impact
Imp_{kWh}	Coefficient of damage per kWh of electricity in Spain
$Quant_{kWh}$	Consumed electricity over the lifetime of the cubicle
Imp_{total}	Total impact
$\vec{z}$	Objective function
X	Space of feasible solutions
z_1 to z_j	Components of the objective function
x_1 to x_i	Decision variables

1. Introduction

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

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.

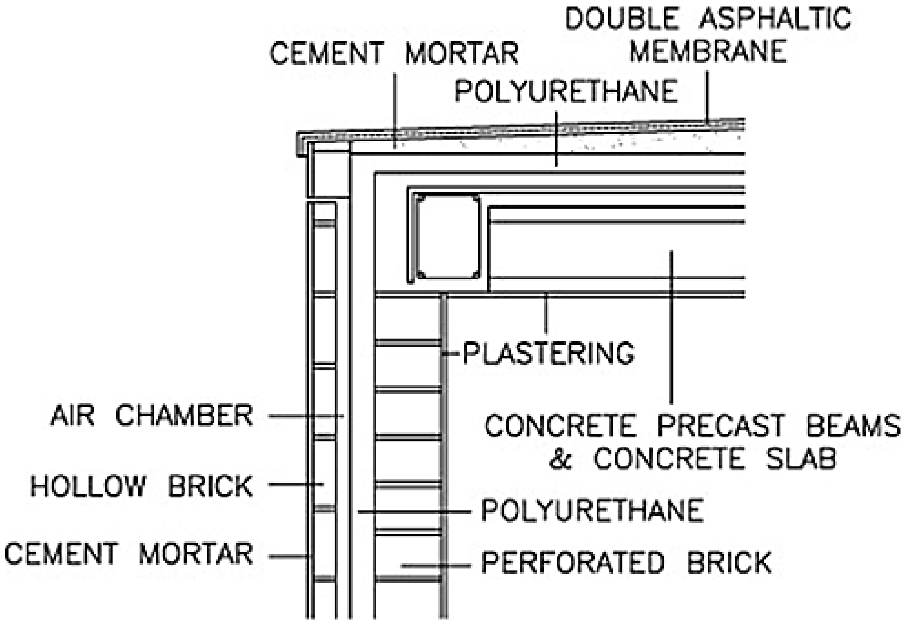

Fig.1. Construction profile of the experimental cubicles in Puigverd de Lleida (Spain).

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 absorbance. 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].

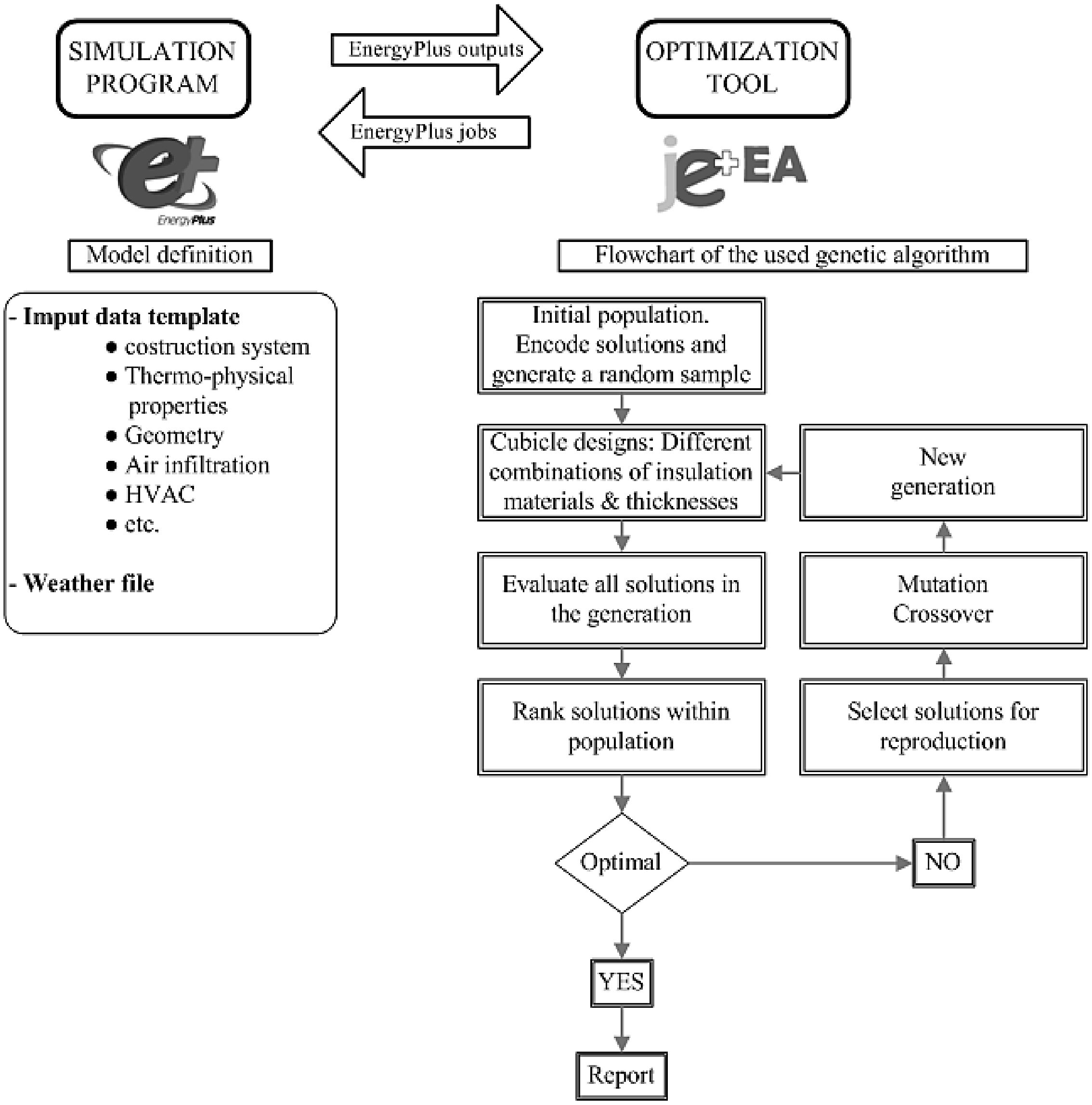

Fig.2. JEPlus+EA optimization process coupled with EnergyPlus.

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:

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

Where Costcub is the total cost of the materials for the construction of the cubicle, Pricek is the price per kilogram of raw material k and Quantk is the correspondent quantity in kilograms of raw material k used in the construction (i.e. kg of concrete).

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/m3)	Thermal conductivity (W/(m·K))	Specific heat (J/(kg·K))	Cost (€/m3)
Polyurethane	45	0.027	1,000	175
Polystyrene	30	0.038	1,000	131
Mineral Wool	40	0.04	1,000	122

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:

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

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:

$$Cost_{total} = Cost_{cub} + Cost_{elec\_n} \tag{3}$$

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 use 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:

$$Imp_{cub} = \sum_{k} Imp_k \cdot Quant_k \tag{4}$$

Where Impcub is the total EI99 impact of the construction materials of the cubicle, Impk , is the coefficient of damage per kilogram of raw material k (an information that is available in the EcoInvent database[72]), and Quantk 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.

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

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:

$$Imp_{elec} = Imp_{kWh} \cdot Quant_{kWh} \tag{5}$$

Where Impelec is the total EI99 impact of the consumed electricity over the operational phase of the cubicle, ImpkWh 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}):

$$Imp_{total} = Imp_{cub} + Imp_{elec} \tag{6}$$

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:

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

That is, the vector (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 , which contains the values of the thickness of each wall. The resulting multi-objective optimization model can be expressed in compact form as follows:

$$\min_{\vec{x}\in X}\left(z_1,...,z_j\right) = \min_{\vec{x}\in X} f^{MOD}\left(x_1,...,x_i\right) \tag{8}$$

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 x 2.4 x 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.

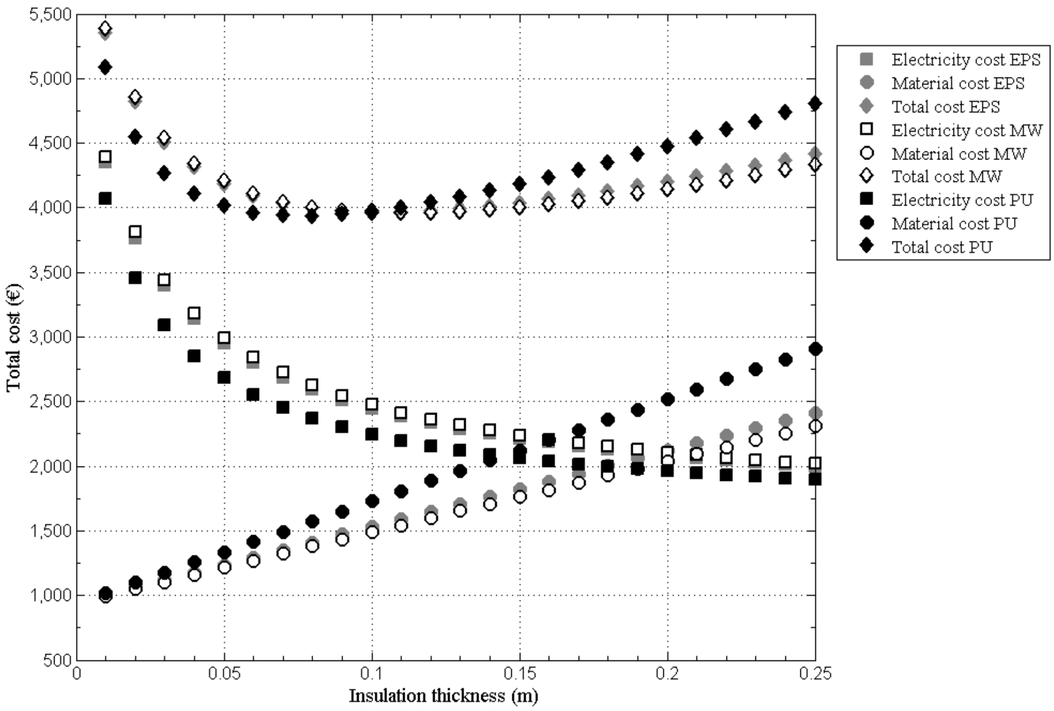

Fig. 3. Simulations obtained from the variation of the cubicle cost with the insulation thickness for PU, MW and EPS for case study I.

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.

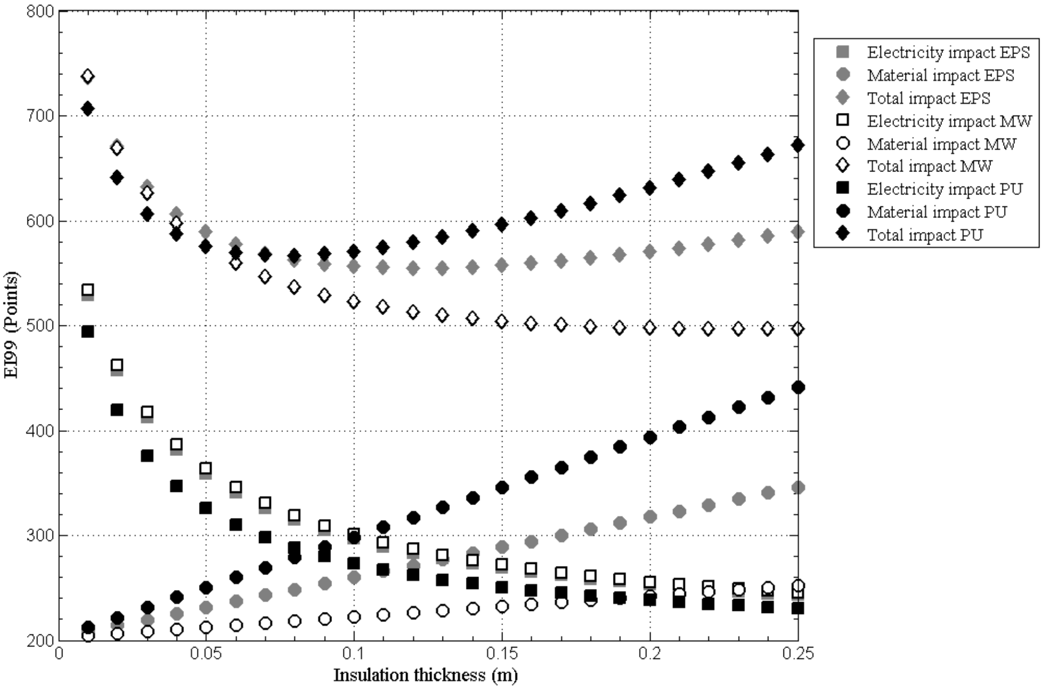

Fig. 4. Simulations obtained from the variation of the cubicle EI99 scores with the insulation thickness for PU, MW and EPS for case study I.

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 11cm (economic) and 23 cm (environmental).

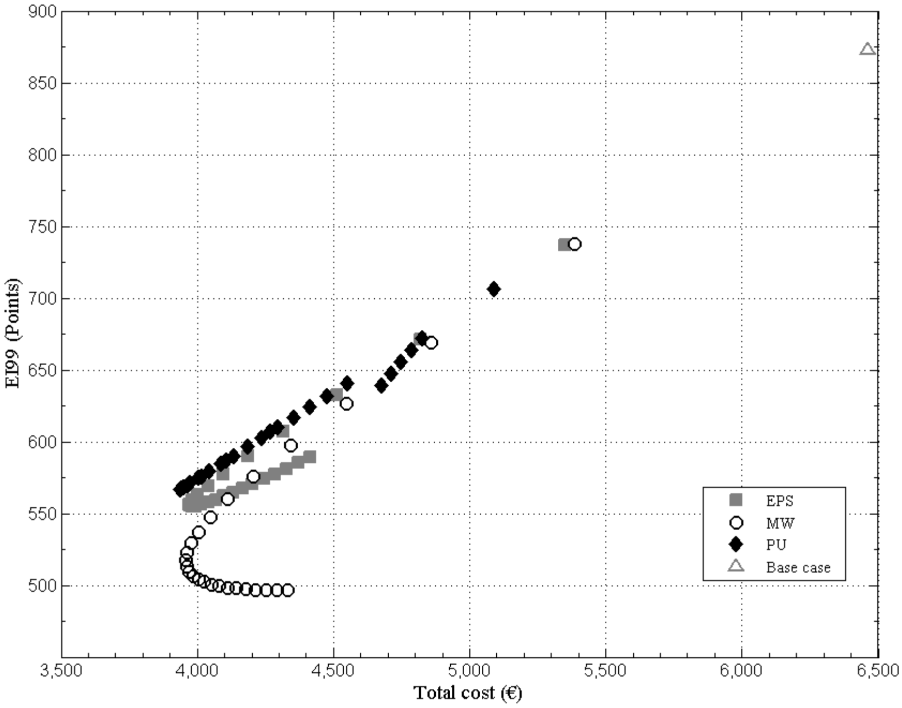

Fig. 5. Solutions obtained from the simultaneous variation of all of the thickness values in the 2-D space environmental impact (Eco-indicator 99) vs total cost for case study I.

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 %.

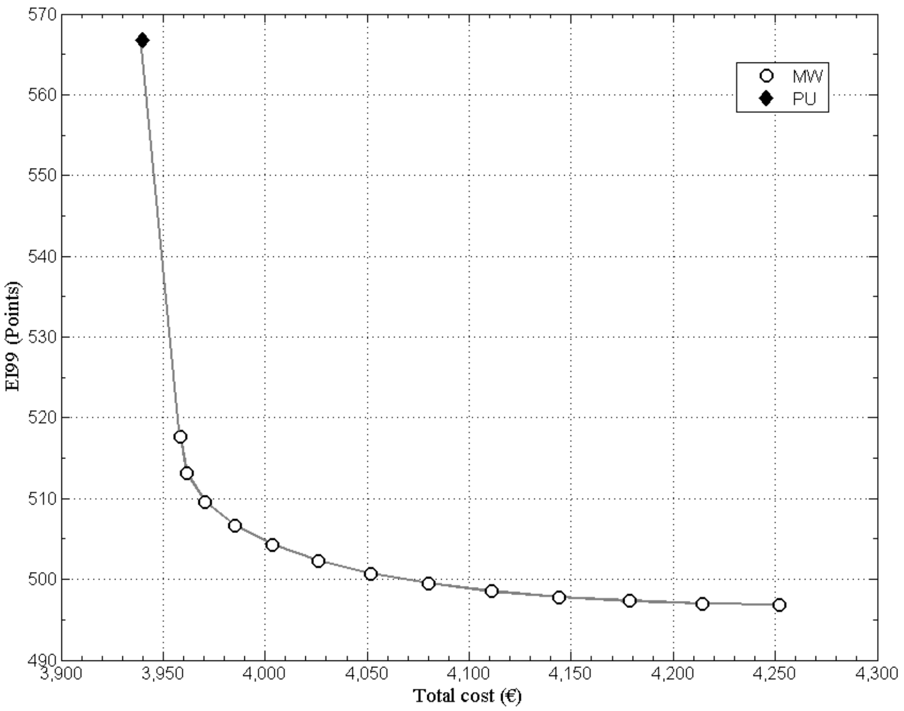

Fig. 6. Projection of the Pareto frontier with the optimal points obtained from the simultaneous variation of all of the thickness values in the 2-D space environmental impact (Eco-indicator 99) vs total cost for case study I.

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.

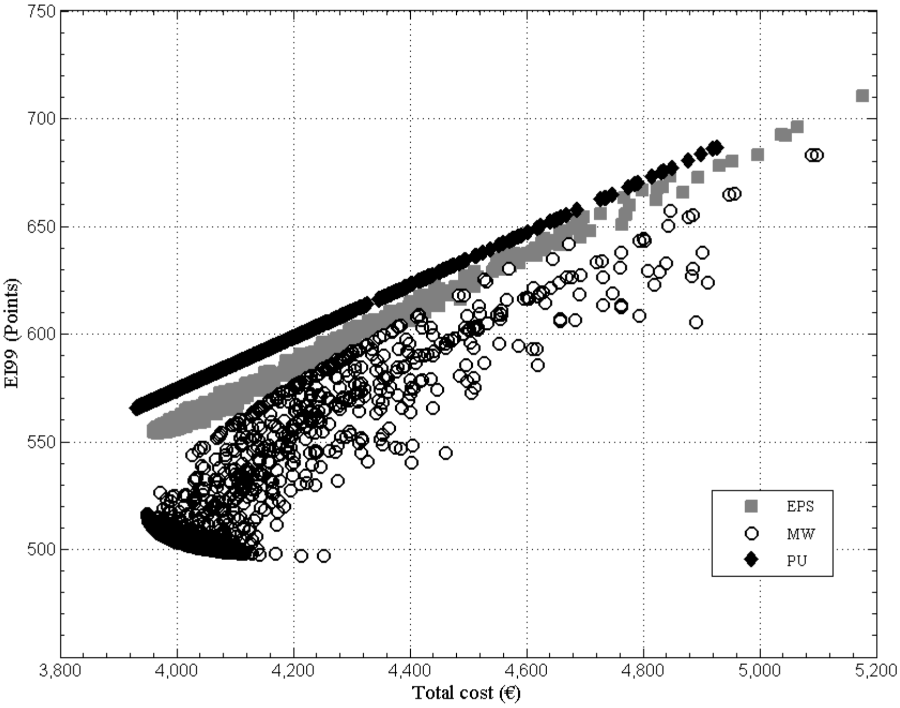

Fig. 7. Solutions obtained from the simultaneous variation of all of the thickness values in the 2-D space environmental impact (Eco-indicator 99) vs total cost for case study II.

Fig. 8 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 an East, and 9 cm in the roof.

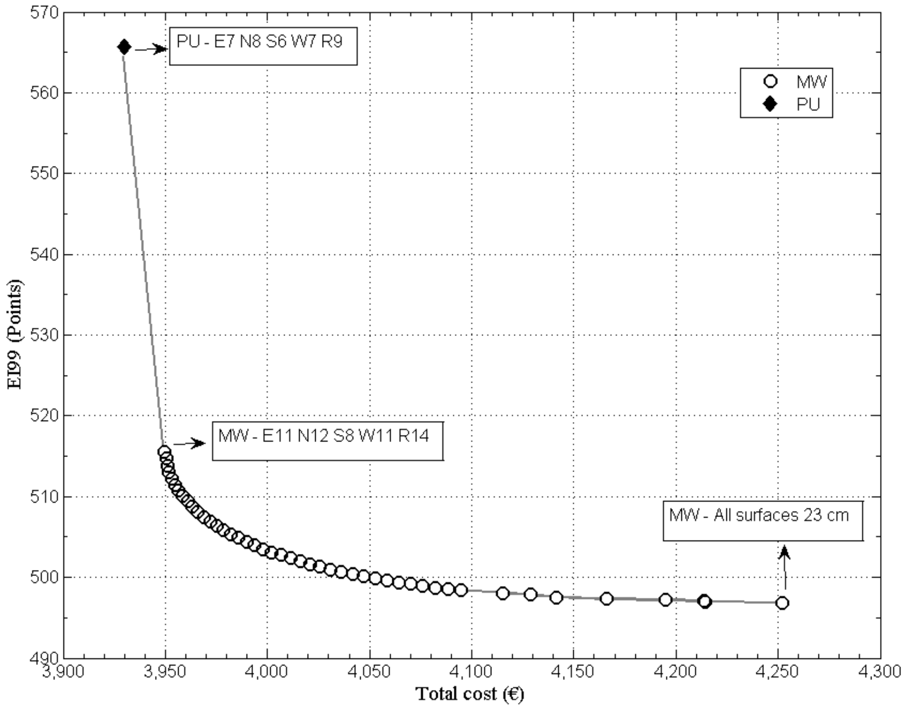

Fig. 8. Projection of the Pareto frontier with the optimal points obtained from the simultaneous variation of all of the thickness values in the 2-D space environmental impact (Eco-indicator 99) vs total cost for case study II.

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.

Table 4. 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	Improvement (%) 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

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.

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
Çomaklı et al. [42]	Erzurum (Turkey)	Stropor (Expandable polystyrene)	0.105	0.105	0.105	0.105
	Kars (Turkey)		0.107	0.107	0.107	0.107
	Erzincan (Turkey)		0.085	0.085	0.085	0.085
Axaopoulos et al. [43]	Athens (Grecee)	Extruded polystyrene	0.101	0.071	0.1	0.1
Hasan [44]	West Bank (Palestine)	Rock wool	0.068	0.068	0.068	0.068
		Polystyrene	0.052	0.052	0.052	0.052
	Gaza (Palestines)	Rock wool	0.035	0.035	0.035	0.035
		Polystyrene	0.026	0.026	0.026	0.026
Daouas [45]	Tunis (Turkey)	Expanded polystyrene	0.101	0.101	0.117	0.116
Al-Sanea et al. [46]	Riyadh (Saudi Arabia)	Molded polystyrene	0.088	0.087	0.092	0.092
Ozel [47]	Elâzığ (Turkey)	Extruded polystyrene	0.06	0.055	0.06	0.06

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 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 $W/m^2 \cdot K$ for the external facade walls in the location of Lleida, but our results suggest lower values between 0.35 and 0.26 $W/m^2 \cdot K$ for the best economic solution and 0.135 $W/m^2 \cdot K$ to achieve the best environmental performance. For the roof, the same situation is observed, since the law requires a thermal transmittance of 0.38 $W/m^2 \cdot K$, and our analysis suggests values of 0.285 $W/m^2 \cdot K$ for the best economical solution and of 0.135 $W/m^2 \cdot K$ 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 an 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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10.2. Eco-costs evaluation for the optimal design of buildings with lower environmental impact

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Highlights

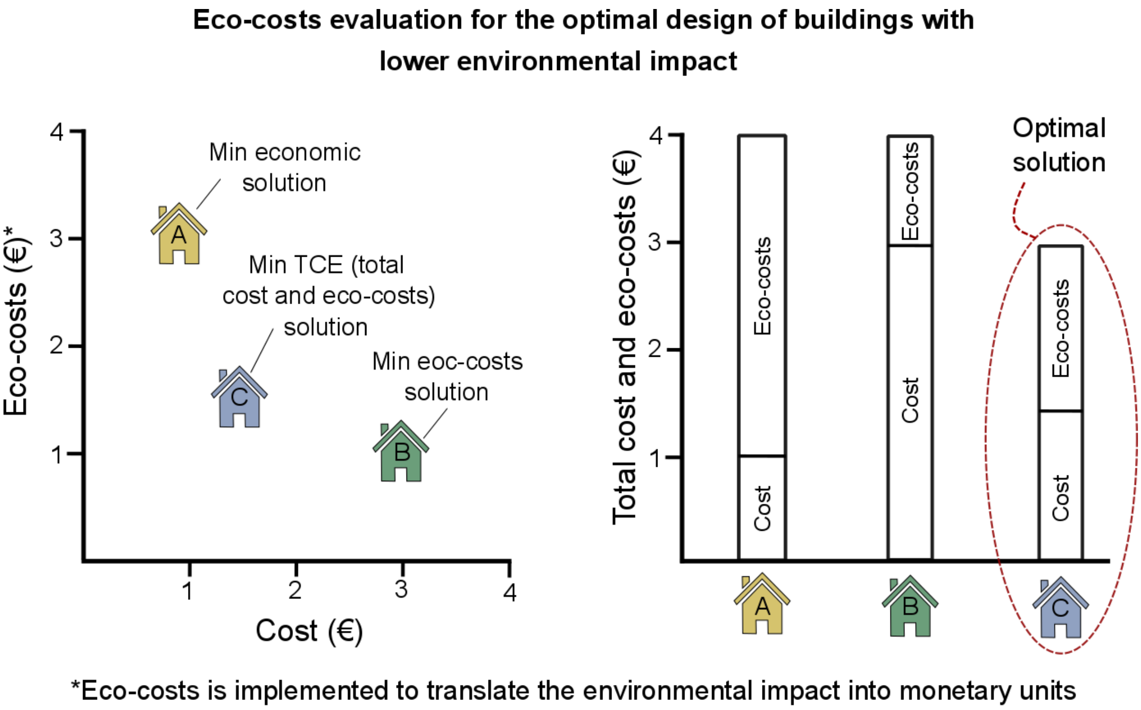
- Eco-costs is implemented to determine the optimal building insulation thickness.
- Optimal designs simultaneously reduce the cost and associated environmental impact.
- Eco-costs is used to translate the environmental impact into monetary units.
- A unique optimum is reached avoiding having to decide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

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. The prevalent method to include the environmental impact as a key aspect in decision-making relies on the use of multi-objective optimization. Following this approach, the environmental and the economic performance are quantified separately as two different objectives, and the final result is given by a set of Pareto optimal solutions. In this study, we resort to eco-costs, a method that translates the environmental impact of a product or activity into monetary units, which can then be incorporated explicitly into the economic performance assessment. Hence, a unique optimal solution is attained, thereby avoiding the task of deciding among different optimal alternatives. The approach presented is illustrated through a case study where we test the eco-costs capabilities in the building sector. The objective is to optimize the thermal insulation of a building envelope in different climate zones. Our approach identifies building solutions that improve significantly the environmental performance at a marginal increase in cost.

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

Graphical abstract



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 the engineering domain, which is at present striving 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], and because of this improving its energy efficiency, particularly in new and existing buildings, is becoming a priority objective in the EU and US [2,3]. One of the most promising energy efficiency strategies, among the options available, 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 of the building simultaneously. This is because the environmental impact embodied in the insulation material can be significant, to the extent that it might 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 have shown that the impact embodied in these construction materials contribute very significantly to the total environmental impact of a building [8,9]. To assess in a rigorous manner the environmental impacts of buildings, it is therefore required 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]. The final result of a MOO typically consists of a set of Pareto optimal solutions, each achieving a unique combination of objective function values. When several players take part in the decision-making process and/or many conflicting criteria need to be analysed, it might be difficult to generate the Pareto points and identify from them 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). Similarly, some may prefer the solution with minimum global warming impact, while others might go for the one with minimum eco-toxicity, and so on.

To overcome this limitation, this work explores the use of monetization techniques as an effective manner 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 an approach for building design that relies on a single-objective optimization (SOO) formulation in which all of the environmental objectives are expressed in monetary terms. By doing so, the trade-offs between economic and environmental objectives are explicitly considered via economic penalties, thereby enabling the formulation of a 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 the amount of wellness losses due to the impacts of a product or activity in monetary terms. 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 latter 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 therefore based on the cost of additional impacts reduction measures that will keep the environmental damages within some allowable limits. These political targets, theoretically, reflect the collective preferences of society [22,23].

The Eco-costs approach, which is the one followed in this work, is a prevention based method. 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 several applications in the assessment of products. Vogtländer et al. [25] used eco-costs to compare the environmental impact of bamboo materials shipped to Western Europe versus commonly used materials such as timber. Morales-Mora et al. [26] evaluated the marginal prevention cost associated with the capacity expansion 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 the environmental burden of a product or activity plus its environmental credits (i.e. unburden on the environment). These credits assume that some products or activities may have a positive impact (i.e. environmental benefit) 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, mainly because product quality plays as well a key role in the assessment procedure. The EVR overcomes this problem by adding the “value” to the eco-costs indicator. This is defined as 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 the eco-costs methodology in the context of finding the optimal thermal insulation for building envelopes. We find that the use of eco-costs identifies 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

To illustrate the capabilities of our approach, 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 minimises the total cost, considering the design, operation and associated environmental impact.

3. Methodology

Our methodology integrates several ingredients: (i) a rigorous model of the building implemented in a standard simulator, (ii) the eco-costs approach that allows quantifying the environmental performance in monetary terms, and (iii) an optimization algorithm that looks for the optimal solution that minimises the total cost objective function. The ensuing sections describe each of these parts of the methodology in detail.

3.1. Mathematical model

We start by developing a model of the building in 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 decision variables to be optimized are the type of insulation materials and their thicknesses, while the objectives to minimise are the economic cost and the environmental impact. Note, however, that our general methodology can work with different decision variables and objective functions.

3.2. Objective functions

3.2.1. Economic indicators

One of the pursued objectives is to minimise 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 percentage increment 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], which quantifies the cost of preventing a certain amount of environmental burden related to a product or activity. These are regarded as virtual costs, since they are not yet integrated into the real costs of the product under study, and are calculated considering the cradle to grave environmental impact of a material (including all the phases in its life cycle). The eco-costs account for the following 5 elements (see [38] for further details), which are calculated following LCA principles (as established in the ISO 14041):

- The virtual pollution prevention costs '99. The virtual pollution prevention costs ‘99 are calculated from the life cycle inventory (LCI) of the emissions associated with a specific activity (here the building design and operation). The LCI emissions (expressed in equivalent kilograms) are quantified in first place, and then multiplied with the corresponding “prevention cost”, which corresponds to the marginal costs (per kilogram of emission) related to bringing back the pollution to a level deemed “in line with earth's carrying capacity” [38,39].
- The eco-costs of energy .The eco-costs of energy correspond to the cost of replacing conventional systems (i.e. fossil fuels or nuclear) by sustainable energy sources. These are calculated using data from the database MARKAL developed by ECN (Energy research Centre of the Netherlands) [40]. These eco-costs might change (very likely declining over time) as renewable energy sources replace gradually nonrenewable ones.
- The material depletion costs. The eco-costs of materials 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 depreciation. The eco-costs related to the depreciation of the product facilities are those indirect costs that consider the reduction in the value of a product arising from its use over time. In this study, no depreciation is considered because the cost of the building is agreed to be paid the first year.
- The eco-costs of labour. 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.

Note that 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 in this database, including the ones widely used in the construction of buildings [37].

Hence, in mathematical terms 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 of the countries. The total eco-costs of the consumed energy (ECO_COSTS^{EN}) is calculated as follows:

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

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

Expressing the environmental impact into monetary terms enables us to formulate a single-objective problem with the following objective function:

$$TCE = COST^{TOT} + ECO\_COSTS^{TOT} \tag{7}$$

Where TCE is the total cost, which includes both, the conventional cost ( ) and the eco-costs ( ). Thus, we seek to minimise the value of TCE.

3.3. Solution procedure

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

$$z = f^{MOD}(x) \tag{8}$$

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 equality constraints of the model, which are solved implicitly in the simulation package, result from the application of first principles to our system (*e.g.*, mass and energy balances). The only explicit inequality constraint handled externally (by the optimization algorithms instead of the simulation package) imposes lower and upper bounds on the insulation thickness.

Without loss of generality, in this work the model of the building is optimized with a genetic algorithm-II (NSGA-II) called JEPlus+EA [32], which is combined with EnergyPlus in a manner similar as we did before in a previous work [33]. Note, however, that any other optimization algorithm could be used for the same purpose.

4. Case study

4.1. Cubicle description

The capabilities of our approach are illustrated through its application to the optimization of real cubicles located in an experimental installation in Puigverd de Lleida (Lleida, North-East Spain). These 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 bituminous membrane which covers a cement mortar coating with a 3% slope. The insulation material, located under the cement mortar, is connected with the insulation of the walls, thereby avoiding possible thermal bridges. The internal finishing 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 buffer 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 structure of perforated bricks and a plaster layer [41,42]. The thermal transmittance of the roof and the walls without considering the insulation (which varies among the alternative designs) is respectively 1.18 $W/m^2{\cdot}K$ and 1.21 $W/m^2{\cdot}K$. Whereas a cubicle of i.e. 10 cm of polyurethane in all external surfaces presents a thermal transmittance of 0.19 $W/m^2{\cdot}K$ in the roof and 0.22 $W/m^2{\cdot}K$ in the walls.

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

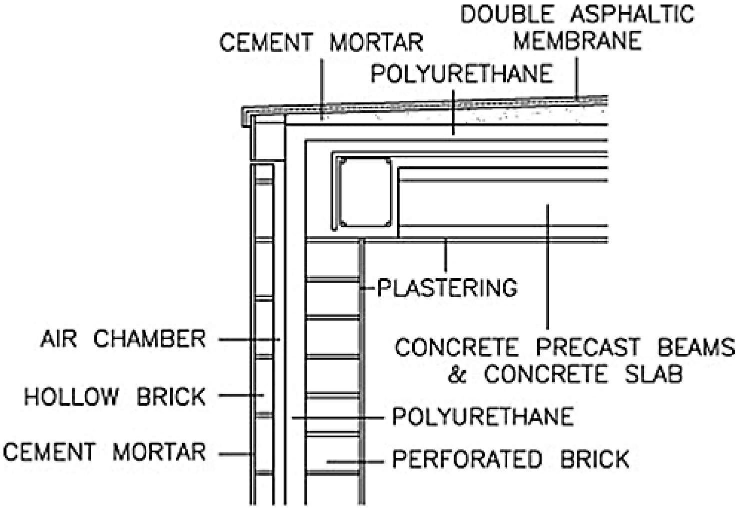


Fig.1. Construction profile of the experimental cubicles in Puigverd de Lleida (Spain).

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·K))	Specific heat (J/(kg·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 for illustrative purposes an example of the eco-costs values associated with a cubicle with 1 cm of insulation thickness in all of its 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 [kg]	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 assumptions were made in the simulation of the cubicles in order to reach a better agreement between the model predictions and 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 considered in the model. We assume a building lifespan of 20 years [36,47]. The implemented materials for the construction of the building are fully paid the first year of the project (i.e. no credit is used to cover the associated expenses). 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. Combinations of different insulation materials in the same design are not allowed.

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. 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], its environmental impact from [52], and its 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	0.210	0.010	0.002
Berlin (Germany)	Dfb	0.292	0.030	0.009

5. Results and discussions

A preliminary analysis is first performed (Section 5.1.) that considers cubicles located in Lleida and with homogeneous insulation thickness in all their external surfaces (from 1 to 30 cm). 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, 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 simultaneously (TCE). In this section, we also present a sensitivity analysis for the eco-costs values.

Finally (Section 5.3), we compare the optimal solution of each case with those generated with a MOO model that optimizes the economic cost (€) and the environmental impact simultaneously. In this MOO, the environmental performance is assessed via the Eco-Indicator 99 (EI99) [11,53], a metric calculated following LCA principles.

5.1. Preliminary 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 of the surfaces, the cubicle solution presenting a better economic performance (without considering the eco-costs) is the one with 9 cm of PU.

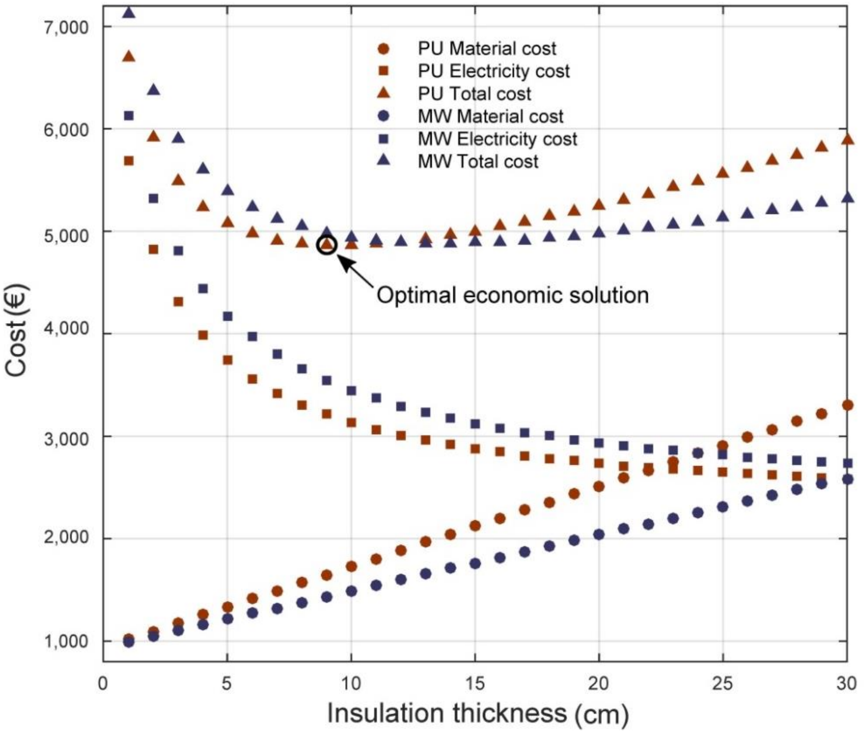


Fig. 2. Variation of the cubicle cost with the insulation thickness for PU and MW considering a cubicle with homogeneous insulation thickness in roof and walls. Results for Lleida, Spain.

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 of the surfaces, the cubicle with minimum eco-costs has 21 cm of MW.

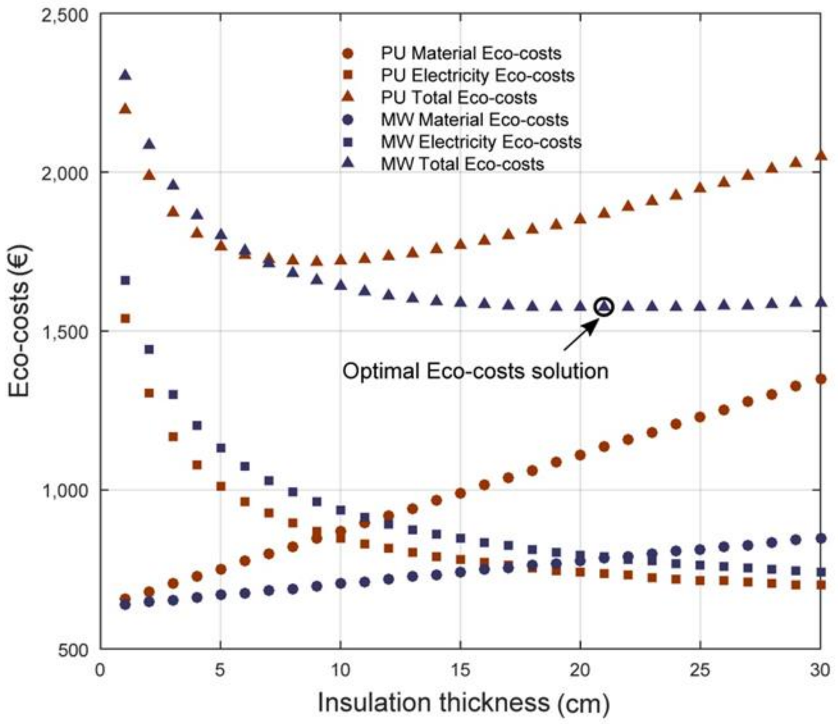


Fig. 3. Variation of the cubicle eco-costs with the insulation thickness for PU and MW considering a cubicle with homogeneous insulation thickness in roof and walls. Results for Lleida, Spain.

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 both 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 minimises the TCE (conventional cost plus eco-costs). For the particular case of Lleida, the solution with minimum TCE has an insulation thickness of 15 cm of MW (Figure 4).

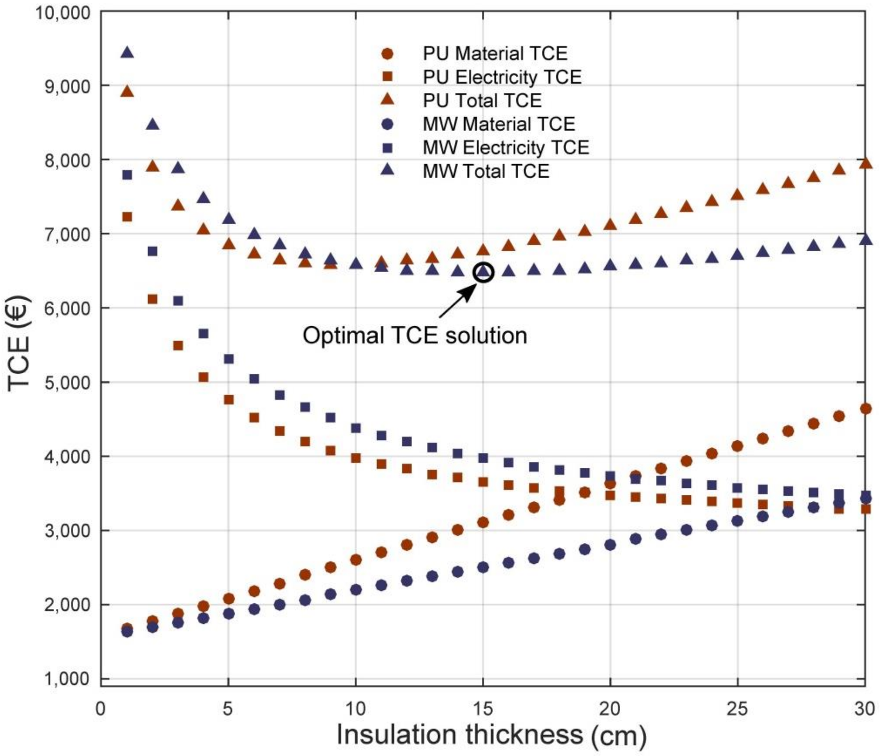


Fig. 4. Variation of the cubicle TCE with the insulation thickness for PU and MW considering a cubicle with homogeneous insulation thickness in roof and walls. Results for Lleida, Spain.

5.2. Optimization results using the proposed approach

5.2.1. Minimisation of the cost using the optimization algorithm

In this section we optimize the cubicles considering different insulation thicknesses for the roof and the walls for the five locations (Table 4). This first analysis considers only the cost of the construction materials and the electricity, but disregards the eco-costs.

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 of the locations, the insulation thickness of the walls is slightly thinner than the one in the roof (2 or 3 cm difference). The differences between the optimal economic solutions in each location depend on the climate conditions and on the electricity cost in each location. Athens is the location achieving the solution with the lowest cost. This is because it presents a moderate climate as well as the lowest electricity price. Meanwhile Berlin presents the most expensive cubicle solutions due to the harsh climatic conditions of the city and the high electricity cost.

5.2.2. Minimisation 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. In this case the conventional cost is not included in the analysis, since in this subsection the goal is to find the cubicles with minimum environmental impact (and for this reason the eco-costs are minimised as single objective).

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 of the 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 for Athens, where the thickness is the same. Athens, despite showing mild weather conditions, leads to the largest insulation thickness due to the high impact of its electricity mix. On the other hand, in Stockholm we would expect a thicker insulation because of the harsh climate conditions. In practice, however, Stockholm shows the smallest thickness because the impact of its electricity mix is rather low (9 times lower than in Athens).

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

Table 6 shows the optimal TCE solutions for the five locations. In this subsection the economic and environmental performance are both considered, and the goal of the analysis is to find those solutions with minimum total cost (conventional cost plus eco-costs).

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 of the locations, the insulation material implemented is MW. In all of the 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 low 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).

Comparing the optimal TCE results with the optimal economic solutions, we observe the following. First, Athens leads to the lowest economic cost (without environmental penalties), but in this location the minimum total cost solutions with and without eco-costs included differ the most (71% of increment when the eco-costs are accounted for in the objective function compared to the case when they are not). Dublin, with an increase of 41% (when we include eco-costs compared with the case when eco-costs are omitted) is the country with the second largest difference between the minimum cost (without eco-costs) and minimum total cost (with eco-costs) solutions, followed by Lleida with a 33%, and Berlin with a 28%. Stockholm shows the smallest difference (only a 15% increment), mainly due to its lower electricity eco-costs.

Table 7 shows the solutions with minimum TCE for the different case studies and their percentage improvements comparing with a cubicle without insulation (base case). In all of the scenarios, the percentage improvements are similar and very significant in magnitude. Berlin presents the highest improvement, since the harsh climatic conditions penalize the cubicle with no insulation. In the case of Stockholm, a location with similar climatic conditions as Berlin, the improvement is lower, since in this location the impact of electricity generation is low and so is its eco-costs. In Athens, the cost in the base case cubicle increases significantly when eco-costs are included due to the high impact of electricity generation. However, this effect is offset to a large extent by the low electricity price. Lleida and Dublin present similar electricity cost and eco-costs, but still lead to different results due to their different climate conditions.

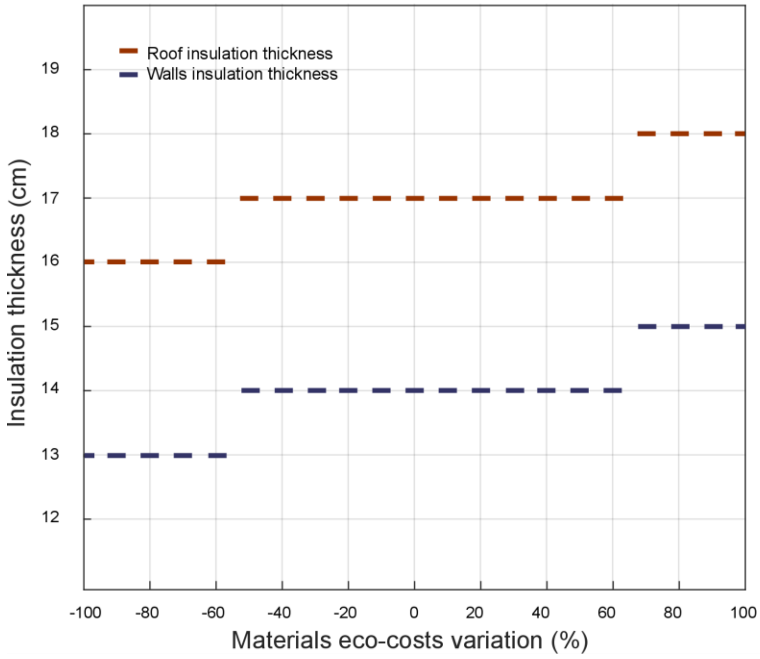
Table 7. Comparison of the base case results and the optimal TCE solutions.

		Cubicle model	TCE (€)	Improvement (%)
Athens	Base case	No insulation	9,943	0
	TCE optimal	MW - Walls 13 cm, Roof 17 cm	5,988	40
Lleida	Base case	No insulation	11,111	0
	TCE optimal	MW - Walls 14 cm, Roof 17 cm	6,468	42
Stockholm	Base case	No insulation	13,527	0
	TCE optimal	MW - Walls 18 cm, Roof 22 cm	8,167	40
Dublin	Base case	No insulation	15,783	0
	TCE optimal	MW - Walls 19 cm, Roof 21 cm	8,739	45
Berlin	Base case	No insulation	19,994	0
	TCE optimal	MW - Walls 22 cm, Roof 25 cm	10,238	49

5.2.4. Eco-costs sensitivity analysis

Different approaches have been developed to quantify the environmental impacts in monetary terms [20–22]. These approaches follow different methodologies, and there is no consensus on how to perform these calculations. Hence, a sensitivity analysis is performed next for evaluating how the uncertainty of the input data (i.e. electricity eco-costs) affects the outcome of the optimization (i.e. optima thermal insulation thickness). First, we study the uncertainty in the materials eco-costs and then the uncertainty in the electricity eco-costs. For these evaluations we will consider the conditions of Lleida.

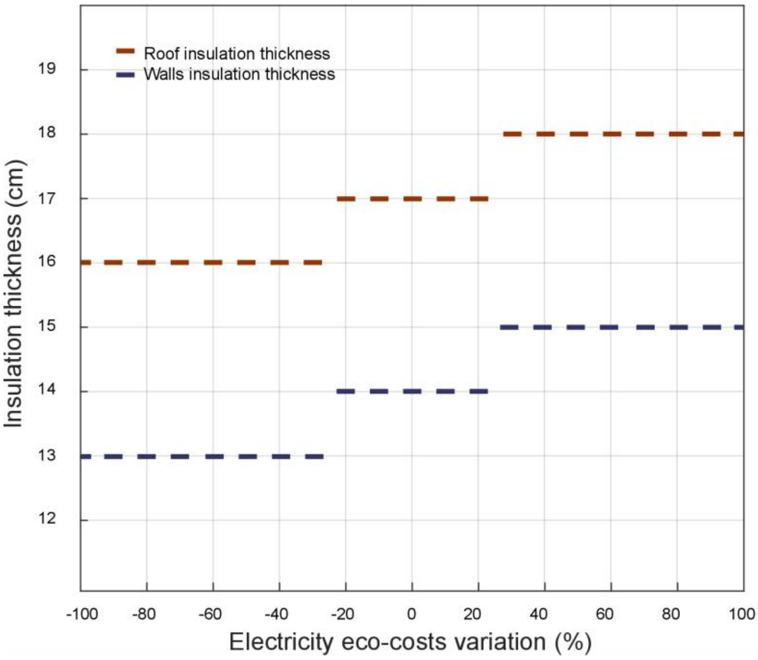
Figure 5 shows that the uncertainty in the materials eco-costs values has little impact on the optimal solution. The materials eco-costs has to increase or decrease up to 60% so as to modify the optimal insulation thickness. Furthermore, the new optimal solutions increase/decrease the insulation thickness in the walls and the roof by only 1 cm, respectively. These new solutions remain optimal for scenarios in which the materials eco-costs are either doubled or neglected. Thus, these results show that the optimal solution is quite robust.



Materials Eco-costs variation (%)	Eco-costs (€)
100	7,202
90	7,129
80	7,056
70	6983
60	6,910
50	6,837
40	6,763
30	6,689
20	6,615
10	6,542
0	6,468
-10	6,394
-20	6,320
-30	6,247
-40	6,173
-50	6,098
-60	6,024
-70	5,949
-80	5,875
-90	5,801
-100	5,726

Fig. 5. Optimal insulation thicknesses in roofs and walls under alternative materials eco-costs values.

Figure 6 shows how the uncertainty in the electricity eco-costs affects the final optimal insulation solutions. In this case a different optimal insulation thickness is attained when the electricity eco-costs is increased or decreased by 30 % (with the new solutions differing from the original ones as much as 1 cm in roof and walls). The new solutions remain optimal for variations of up to 30 to 100% from the nominal case. Again, these results reinforce the robustness of the optimal solutions found in the nominal scenario.



Electrcity Eco-costs variation (%)	Eco-costs (€)
100	7,309
90	7,225
80	7,142
70	7,058
60	6,974
50	6,890
40	6,806
30	6,723
20	6,638
10	6,553
0	6,468
-10	6,383
-20	6,298
-30	6,212
-40	6,126
-50	6,039
-60	5,953
-70	5,866
-80	5,780
-90	5,693
-100	5,606

Fig. 6. Optimal insulation thicknesses in roofs and walls under alternative electricity eco-costs values.

5.2.5. Summary results

Figure 7 shows the optimal economic, environmental and TCE solutions for each location. PU is the material achieving better economic results, while MW leads to better environmental performance in all of the locations. When resorting to the optimal TCE solutions, in all of the locations the building designs with better performance use MW. In all of the 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 of the 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).

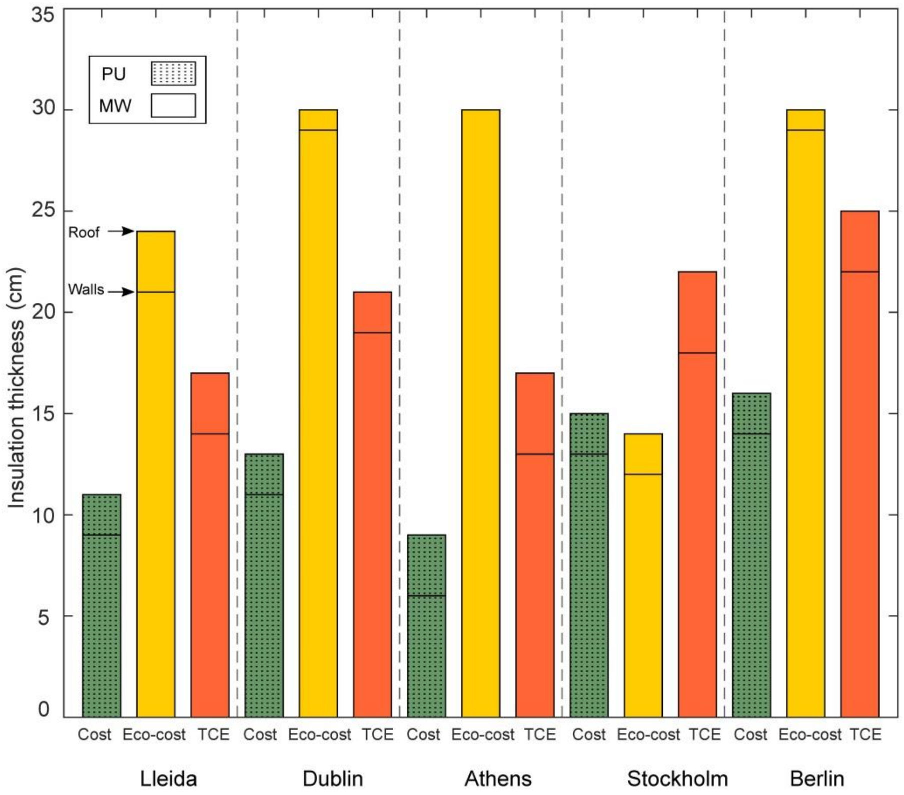


Fig. 7. Optimal economic, environmental and TCE cubicle solutions for the five locations considering different insulation thicknesses in walls and roof.

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 an 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 quantified via the EI99 (instead of using eco-costs) are expressed in terms of a set of Pareto optimal points. Thus, each point depicted in Figure 8 represents a cubicle with a specific insulation and economic cost and environmental impact. There are two extreme optimal solutions, the minimum cost (A) and minimum environmental impact alternatives (B), and a set of intermediate optimal solutions lying in between them (Figures 8).

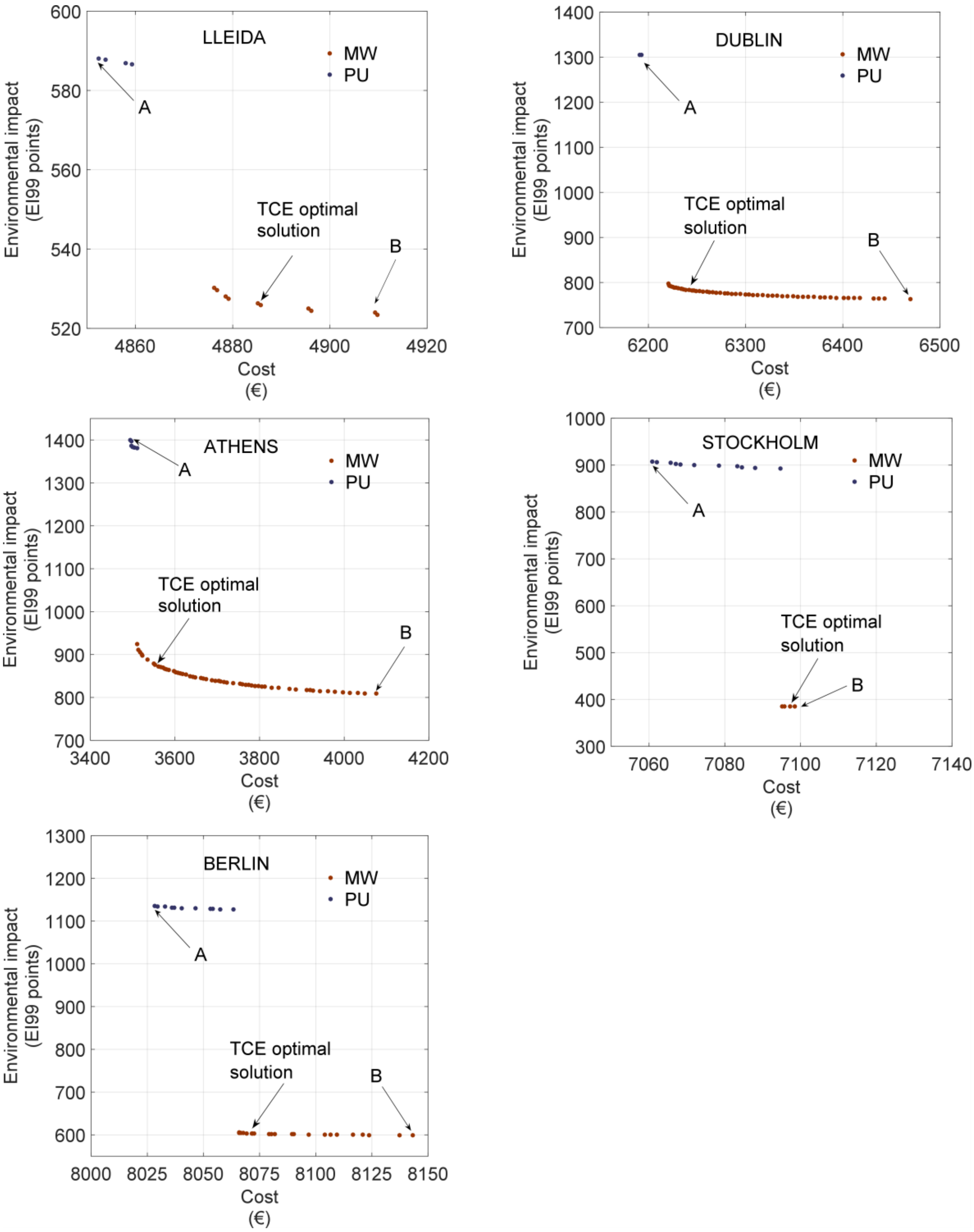


Fig. 8. Each plot in the figure depicts the Pareto frontiers of optimal solutions of the corresponding MOO problems. The points represent cubicles with different insulation configurations going from the best economic solution (A) to the solution with minimum environmental impact (B). A set of intermediate

solutions lie between the extremes A and B. These are optimal solutions considering both objectives simultaneously, yet they do not attend the minimum value in any objective separately. In each plot, the TCE optimal solution is highlighted, which corresponds to one specific intermediate Pareto point. Note that the cubicle with maximum economic performance (considering the eco-costs) corresponds to one optimal intermediate solution of the MOO problem.

Figure 8 shows that the optimal economic solutions that consider the eco-costs (minimum TCE optimal solutions) are intermediate solutions of the MOO problems cost vs EI99 for all of the locations. In all of the cases, TCE solutions implement MW and are close to the extreme economic optimal solution (but with a clear improvement in environmental performance with respect to the minimum cost design). 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, society is becoming more aware of the importance of being environmentally conscious. As a result, many companies and consumers seek products that are cost efficient but also environmentally friendly.

This work explores the use of eco-costs, a monetization technic, to incorporate environmental aspects into the optimization of buildings. Eco-costs quantify the cost related to the environmental burdens of an activity or a product considering the expenditures of preventing 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 implementing eco-costs in the building sector are illustrated through a case study, where the main goal is to optimize the insulation thickness of the envelope of a building in order to minimise 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 those associated with 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 specific cost and 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 an environmentally friendlier 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 simplifies the task of selecting a Pareto optimal solution, thereby facilitating the decision-making process. Through a sensitivity analysis it was shown that the uncertainty in the eco-costs values has little effect on the optimal insulation solutions.

In all of the scenarios analysed, the minimum TCE solution (conventional cost plus eco-costs) 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

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10.3. Systematic approach for the life cycle multi-objective optimization of buildings combining objective reduction and surrogate modeling

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Highlights

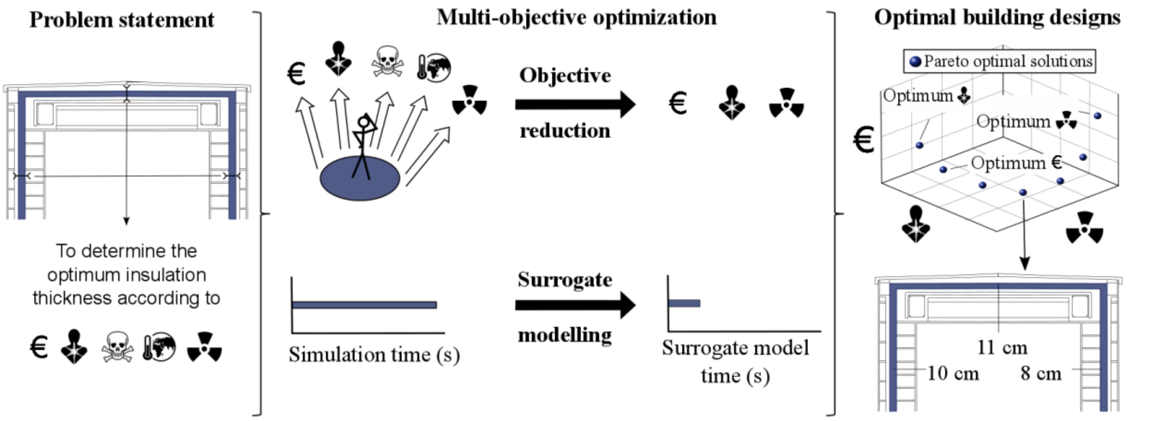
- We present a systematic approach to optimize the thermal insulation of a building.
- The optimization reduces simultaneously the cost and several environmental impacts.
- We resort to an objective reduction method to simplify the problem resolution.
- We built a surrogate model to expedite the search for Pareto optimal solutions.
- Significant improvements compared to the base case (no insulation) are achieved.

Abstract

With the recent trend of moving towards a more sustainable economy, the interest on designing buildings with lower cost and environmental impact has grown significantly. In this context, multi-objective optimization has attracted much attention in building design as a tool to study trade-off solutions ("cost" vs "environmental impact") resulting from the optimization of conflicting objectives. One major limitation of this approach (as applied to building design) is that it is computationally demanding due to the need to optimize several objectives using complex models based on differential equations (which are required to model the energy required by a building). In this work, we propose a systematic framework for the design of buildings that combines a rigorous objective reduction method (which removes redundant objectives from the analysis) with a surrogate model (which simplifies the calculation of the energy requirements of the building), both of which expedite the identification of alternative designs leading to environmental improvements. The capabilities of our methodology are illustrated through a case study based on a thermal modelling of a house-like cubicle, in which we optimize the insulation thicknesses of the building envelope. Results show that significant economic and environmental improvements can be achieved compared to the base case (cubicle without insulation). Furthermore, it is clearly illustrated how the minimization of an aggregated environmental metric, like the Eco-Indicator 99, as unique environmental objective may overlook some Pareto solutions that may be appealing for decision-makers.

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

Graphical abstract



Nomenclature

Abbreviations

ACH	Air changes per hour
COP	Coefficient of performance
EI99	Eco-indicator 99
GLO	Average global impact
LCA	Life cycle assessment
MILP	Mixed-integer linear programming
moNLP	Multi-objective non-linear programming
MOO	Multi-objective optimization
NLP	Nonlinear programming
OECD	Organisation for Economic Co-operation and Development
PCA	Principal component analysis
PDE	Partial differential equations
PU	Polyurethane

Indices

c	Impact category
k	Construction material
n	Year

Sets

C	Set of impact categories

I	Set of solutions
K	Set of construction materials
RSO	Reduced set of objectives
SOO	Set of objectives to be optimized

Variables

$CONS^{EN}$	Energy consumption [kWh]
$COST^{EN}$	Energy cost [€]
$COST^{MAT}$	Materials cost [€]
$COST^{TOT}$	Total (material and energy) cost of the building [€]
IMP_c^{EN}	Energy impact in each impact category *c* [Points]
IMP_c^{MAT}	Material impact in each impact category *c* [Points]
IMP_c^{TOT}	Total (material and energy) impact of the building in each impact category *c* [Points]
M_k	Mass of material *k* [kg]

Parameters

ir	Yearly electricity inflation rate [%]
$UCOST^{EN}$	Cost per kWh of energy [€/kWh]
$UCOST_k^{MAT}$	Cost per kilogram of component k [€/kg]
$UIMP_c^{EN}$	Impact in category *c* per kWh of energy [Points/kWh]

$UIMP_{kc}^{MAT}$	Impact in category *c* per kilogram of component *k* [Points/kg]

Other symbols

$g_I(\cdot)$	Implicit inequality constraints (i.e., embedded in the building simulation)
$h_E(\cdot)$	Explicit equality constraints (i.e., computed offline)
$h_I(\cdot)$	Implicit equality constraints (i.e., embedded in the building simulation)
It	Iterations
x_D	Vector of decision variables
z	Vector of objective functions

1. Introduction

In both developed and developing countries, the building sector is responsible for approximately 40% of the total annual worldwide consumption of energy [1], and for one third of global greenhouse gas emissions [2]. Many OECD countries have dictated measures for minimizing energy consumption in the building sector. In March 2007, the European Parliament approved a binding legislation comprising several goals: i) to achieve a 20% reduction in EU greenhouse gas emissions from 1990 levels; ii) to increase the share of EU energy consumption produced from renewable resources to 20%; and iii) to improve the EU's energy efficiency by 20% [3]. To meet these targets, several energy strategies must be put in place. Among them, building insulation appears as a promising option, since it has the potential to decrease the cooling and heating demand without compromising comfort and can be applied in both, new and refurbished buildings [4–6].

Nowadays the current trend is to implement high insulation thicknesses, given the fact that a thicker insulation reduces energy consumption and therefore the associated environmental impact. This strategy might be suboptimal, as the cost and environmental impact embodied in the insulation materials can be quite large. Blengini et al. [7] analysed the impact produced in all the phases of the life of a low energy house, finding that the impact embodied in the construction materials represented the greatest contribution towards the total impact. Following a similar approach, Stephan et al. [8] concluded that up to 77% of the total energy (embodied and operational) used by a passive house over 100 years can correspond to the energy embodied in the construction materials. Hence, the impact embodied in the insulation materials needs to be accounted for a proper optimization of the whole system.

At present, multi-objective optimization (MOO) [4,9–14] has become the prevalent approach to solve problems with more than one objective function (e.g. economic cost and environmental impact). This mathematical approach is widely employed in many areas of science and engineering for studying trade-off solutions and for optimizing several objective functions simultaneously [15–18]. Unfortunately, MOO is rather sensitive to the number of objectives considered in the analysis, mainly because both the calculation of the Pareto solutions and their visualization and analysis become more complex as we increase the number of criteria. To overcome this problem, the optimization is typically restricted to two or three objectives [19] by either removing objectives or by aggregating some of them into a single indicator based on subjective weights [20–22]. Both approaches are inadequate; the former because it omits objectives that might be relevant, and the later because it alters the structure of the problem by eliminating Pareto solutions potentially appealing for decision-makers. These drawbacks can be bypassed by means of dimensionality reduction methods, which remove redundant objectives from the multi-objective model while still preserving its underlying structure. Several dimensionality reduction methods have been proposed in the literature. In a seminal work, Deb and Saxena [23] introduced a statistical method based on principal component analysis (PCA) for removing redundant objectives in MOO problems. Brockhoff and Zitzler [24] presented another approach based on the minimization of an approximation error (i.e., delta error) resulting from the elimination of objectives. More recently, Guillén-Gosálbez [25] introduced a multi-dimensionality reduction method based on a mixed-integer linear program (MILP) that minimizes the delta error proposed by Brockhoff and Zitzler [24].

Unfortunately, applying multi-objective optimization to building design is further complicated by the fact that estimating the energy performance of a building through simulation is computationally challenging. That is, even if the optimization is performed in a reduced domain of objectives, it might yet be difficult to evaluate the objective functions, as this requires solving a system of partial differential equations (PDE). Some approaches have attempted to reduce the complexity of the PDE model by streamlining the simulation process [26–28]. Other authors have explored the use of surrogate models to accelerate the optimization process [29–31]. These methods simulate first a set of sample points, to then use the output to construct a surrogate model. This is a black box model fitted to data points (generated with the rigorous simulation), which is faster to solve than the original model (which requires solving a system of PDEs), yet it provides approximated results. The use of surrogate models is particularly appealing when they are coupled with an optimization algorithm, as the latter needs to interrogate the simulation model many times during the optimization task. Caballero et al. [29,32] presented a methodology for the rigorous optimization of nonlinear programming (NLP) problems in which the objective function and some constraints are represented by noisy implicit black box functions. The black box modules are replaced by kriging meta-models, an interpolating method based on basic functions with adjustable parameters. Costas et al. [31] applied a surrogate-based multi-objective optimization technique to car crashworthiness problems, while Eisenhower et al. [30] presented a method to optimize building energy models using a meta-model generated from a set of design and operation scenarios of the building around its baseline.

This work introduces a novel approach for the multi-objective optimization of buildings that integrates multidimensionality reduction and surrogate modelling. To the best of our knowledge, this is the first time that these two methodologies have been combined within a single framework. We illustrate the capabilities of our approach through a case study based on a house-like cubicle where the goal is to determine the optimal insulation thickness (for the building envelope) according to economic and environmental criteria.

The article is structured as follows. The problem statement is presented in Section 2. The methodology, which includes the description of the objective functions and the solution procedure, is introduced in Section 3. Details of the case study are given in Section 4, whereas in Section 5, the results are presented and discussed. Finally, the conclusions of the work are drawn in Section 6.

2. Problem statement

The problem we aim to solve can be formally stated as follows. Given is a building (i.e., cubicle) that will be retrofitted through the installation of insulation materials. The detailed cubicle configuration, along with cost and environmental data associated with different insulation materials and energy demands are provided. The goal of the analysis is to determine the optimal insulation material and thickness of the insulation layer so as to optimize simultaneously the economic and the environmental performance of the overall system.

3. Methodology

Our approach is based on building a surrogate model of the building that is optimized in a reduced domain of objectives. The model of the building is described first before presenting in detail our algorithmic framework.

3.1. Mathematical model

The optimization of a building considering economic and environmental criteria can be mathematically posed as a multi-objective non-linear programming problem (moNLP) such as problem *SIMMOD*:

$$\begin{aligned} (SIMMOD) \quad min_{x_D} \quad & z = \{z_1(x, x_D), \dots, z_p(x, x_D)\} \\ s.t. \quad & h_I(x, x_D) = 0 \\ & g_I(x, x_D) \leq 0 \\ & h_E(x, x_D) = 0 \\ & g_E(x, x_D) \leq 0 \\ & x, x_D \in \Re \end{aligned} \qquad (1)$$

Here, z_1 corresponds to the economic objective whereas z_2 to z_p are the p-1 environmental objectives. Regarding the constraints, we can distinguish between implicit and explicit constraints. Implicit equality and inequality constraints, denoted by $h_I(\cdot)$ and $g_I(\cdot)$ respectively, are the equations implemented in the building simulator to describe the energy balances through the building walls and roof (refer to the next section for further details). Conversely, explicit constraints, referred to by $h_E(\cdot)$ and $g_E(\cdot)$, are equations computed externally (i.e., outside of the building simulator), and which are mainly used to evaluate the objective functions in the point determined by the simulator as well as to establish bounds on the variables. Finally, x_D are the independent decision variables of the problem (i.e., the insulation thicknesses of the external surfaces of the building), whereas x account for the remaining dependent variables. That is, we distinguish between independent decision variables x_D (independent variables) whose values must be optimized, and dependent variables x whose values are given once the decision variables (corresponding to the degrees of freedom of the problem) are fixed.

3.1.1. Simulation software encoded equations

The energy loads of the building are calculated using EnergyPlus v.8 [33–35], which is a commercial simulator that models energy and water use in buildings. EnergyPlus includes a set of simulation properties, calculated via user-configurable modular systems, that are integrated with a heat and mass balance-based simulation environment that considers variable time steps and input/output data structures oriented to facilitate third party module and interface development [34]. In mathematical terms, EnergyPlus contains a system of partial differential equations (PDE) that describe a set of energy balances. These PDEs model the energy consumption during a given time horizon.

The simulator requires the decision variables $\mathrm{x_D}$ to be fixed to a given value and then runs the calculations to provide as output the value of the remaining variables x (mainly, the energy consumed). Note that the simulator does not perform the optimization, but rather determines the value of x for a given value of $\mathrm{x_D}$.

3.1.2. Objective function equations

In the ensuing sections, we describe each block of objective function equations in detail. Note that the objective functions considered in this study are encoded externally (i.e., outside of the simulation program), which provides more flexibility to the approach.

3.1.3. Economic indicators

The economic performance of each building design alternative is quantified through the cost of the construction materials and the cost of the energy consumed for heating and cooling over the operational phase of the building. Hence, the final goal is to minimize the total cost ($COST^{TOT}$) [36–39] which is calculated as in Eq. (2).

$$COST^{TOT} = COST^{MAT} + COST^{EN} \tag{2}$$

Here, $COST^{MAT}$ denotes the cost of the materials, whereas $COST^{EN}$ accounts for the cost of the energy consumed over the operational phase of the building:

The cost of the construction materials, which is assumed to be paid the first year of the time horizon, is given by Eq. (3).

$$COST^{MAT} = \sum_{k \in K} UCOST_k^{MAT} \cdot M_k \tag{3}$$

Here $UCOST_k$ is the unitary cost of raw material k (belonging to the set of raw materials K) and M_k is the corresponding mass of raw material k.

The total economic cost of the energy required to cover the heating and cooling requirements of the building is given by:

$$COST^{EN} = \sum_{n \in N} CONS_n \cdot UCOST^{EN} \cdot (1+\text{ir})^n \tag{4}$$

where $CONS_n$ is the energy consumed for heating and cooling (which is considered to be constant for all the years) in year n (belonging to the set of years N), $UCOST^{EN}$ is the current unitary energy cost (i.e., the unitary cost of energy at the start of the simulated time horizon) and *ir* is the yearly increase in the energy cost.

3.1.4. Environmental indicators

The environmental impact caused by the energy consumed and the construction materials is assessed through the Eco-indicator 99 (EI99) methodology [40,41], which is based on LCA principles. The EI99 covers three different damage categories (human health, ecosystem quality and resources), which include a total of 10 specific impact indicators. In this study, we consider individual indicators according to the EI99 report [40], which carry less uncertainty than the aggregated indicator. This is because the aggregated indicator suffers from the added uncertainty resulting from the weighting process of converting the individual indicators into an aggregated metric. We also report the values of the aggregated impact calculated according to the average weighting set and the hierarchic perspective. Particularly, the following impacts are considered: acidification & eutrophication, ecotoxicity, land occupation, carcinogenics, climate change, ionising radiation, ozone layer depletion, respiratory effects, fossil fuel extraction and mineral extraction. The total impact of the building in each impact category *c* (e.g. carcinogenics belonging to the set of categories *C*), denoted by IMP_c^{TOT}, is calculated from the impact in category *c* associated to the construction materials of the building, which is given by IMP_c^{MAT}, and the impact of the energy consumed over the operational phase, which is represented by IMP_c^{EN}:

$$IMP_c^{TOT} = IMP_c^{MAT} + IMP_c^{EN} \qquad \forall c \in C \qquad (5)$$

The total impact of the building materials in impact category *c* is determined via Eq. (6),

$$IMP_c^{MAT} = \sum_{k \in K} UIMP_{kc}^{MAT} \cdot M_k \qquad \forall c \in C \qquad (6)$$

where $UIMP_{kc}^{MAT}$ is the impact in category *c* per kilogram of component *k* (an information available in environmental databases, such as the ecoinvent database version 3 [42]), and M_k is the mass of material *k*.

The impact of heating and cooling is calculated using the following equation:

$$IMP_c^{EN} = UIMP_c^{EN} \cdot \sum_{n \in N} CONS_n \qquad \forall c \in C \tag{7}$$

Here $UIMP_c^{EN}$ is the impact in category *c* per kWh of energy and $CONS_n$ is the energy consumed in the building in year *n* for heating and cooling requirements.

3.2. Solution procedure

We solve problem *SIMMOD* combining dimensionality reduction and surrogate modelling. First, we apply sampling techniques to generate an initial set of solutions. This initial sample serves two main purposes, as it is used to: (i) apply the dimensionality reduction method, which will reduce the number of objectives in the original model; and (ii) build a surrogate model, which will expedite the optimization task. Finally, the surrogate model is optimized in the reduced set of objectives, yielding a set of optimal building designs (Pareto solutions). These Pareto points can be used in turn to improve the performance of the dimensionality reduction algorithm and the quality of the surrogate model, thereby leading to better solutions.

The algorithm (see Fig. 1) we propose is summarized next. Let *SOO* be the set of objectives to be optimized.

0) Initialize the reduced set of objectives $RSO = \emptyset$, and the iteration counter $it = 0$.
1) Simulate a given number of building designs. Let *I* be the set of solutions resulting from these simulations.
2) If $|RSO| = |SOO|$, stop: further reductions in the number of objectives are not possible and hence *I* is the final set of optimal building designs. Else:
    1) If $it \neq 0$, make $SOO = RSO$, $it = 0$ and return to 2.1. Else, make $it = 1$ and:

      1) Apply the objective reduction method to set *I*. Update *RSO* eliminating the redundant objectives.
      2) Build a surrogate model *SURMOD* from solutions in set *I*.
      3) Use a MOO method to optimize the surrogate model *SURMOD* considering objectives in *RSO* (i.e., optimize model *RSUMOD*). Update *I* so that it containts the resulting set of optimal solutions.
   2) End if.
3) End if.

Note that steps 2.1.1 and 2.1.2 can be applied in parallel. Each of the steps of the previous approach is explained in detail in the ensuing sections.

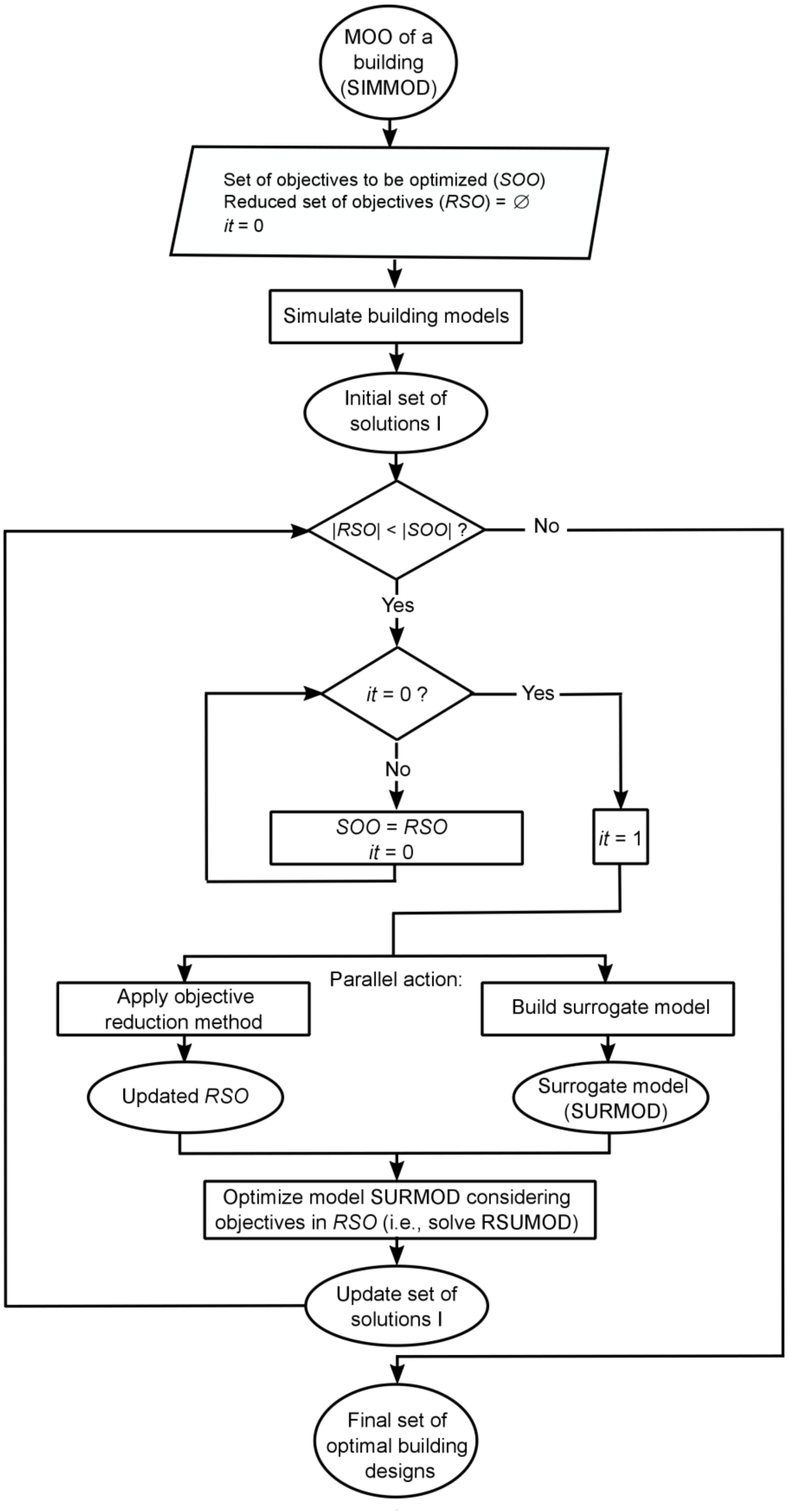


Fig.1. Algorithm summarizing the proposed optimization strategy.

3.2.1. Generation of an initial sample

A set of solutions I is generated by running different simulations with EnergyPlus using a parametric tool called JEPlus [43]. Specifically, JEPlus is used to generate a sample composed of $|I|$ different combinations of values of the decision variables x_D. These values of the decision variables are then fixed in EnergyPlus, which simulates the corresponding building designs and provides the values of the remaining variables x (note that this is accomplished by solving the energy balances implemented in the simulator). Finally, the values of the objective functions $z_1(x, x_D)$ to $z_p(x, x_D)$ are determined from the values of the variables.

The samples serve two different purposes: (i) reduce the dimensionality of the problem; and (ii) construct a surrogate model that approximates the PDEs implemented in the building simulator.

3.2.2. Dimensionality reduction method

A dimensionality reduction analysis is carried out to eliminate redundant objectives. The model objectives are different in nature and their values may differ in several orders of magnitude, thereby causing numerical problems during dimensionality reduction. To overcome this, the solutions in the set I are first normalized so they fall in the range 0-1. Then, a dimensionality reduction method is applied to eliminate redundant objectives. The overall strategy presented in section 3.2. can work with any dimensionality reduction method available in the literature [23,25]. Without loss of generality, however, we apply here an exhaustive exploration based on the work by Brockhoff and Zizler [24]. This method seeks to replace the original set of objectives *SOO* by a reduced subset of objectives *RSO* that shows minimum delta approximation error (δ). This concept is further clarified by means of Fig. 2, which depicts 4 Pareto optimal solutions (A,B,C,D) (i.e., no solution is dominated by any of the others). Assume that objective 4 is removed from the original set of objectives (*SOO* = {1, 2, 3, 4}), thus yielding a new reduced set of objectives (*RSO* = {1, 2, 3}). If we do this, the original dominance structure of the problem will be modified (i.e., solution C is dominated by solution B in the reduced set of objectives *RSO*, whereas in the original one this does not happen). In this context, it is possible to define a delta error associated with the approximation made (when removing subsets of objectives), which is given by the largest difference between the objective values (before and after removing objectives) that would prevent a change in the dominance structure (i.e., that would prevent that a Pareto optimal solution in the original set of objectives is dominated in the reduced set). In the case of *RSO*, the delta error is given by the difference between the value of objective 4 in solution B, and the value required to dominate solution C in the original space of objectives (i.e., $\delta = 0.25$). Now consider the reduced set resulting from removing objectives 2 and 3, while maintaining objectives 1 and 4 (*RSO'*= {1, 4}). As seen, this reduced set does not modify the dominance structure, since all the solutions are also Pareto optimal in the reduced domain *RSO'*. In this case, we say that the reduced objective set (*RSO'* = {1, 4}) is non-conflicting with the original one (*SOO* = {1, 2, 3, 4}). Hence, the goal of objective reduction is to identify the minimum number of objectives entailing a zero delta error, or the minimum delta error for a given number of objectives.

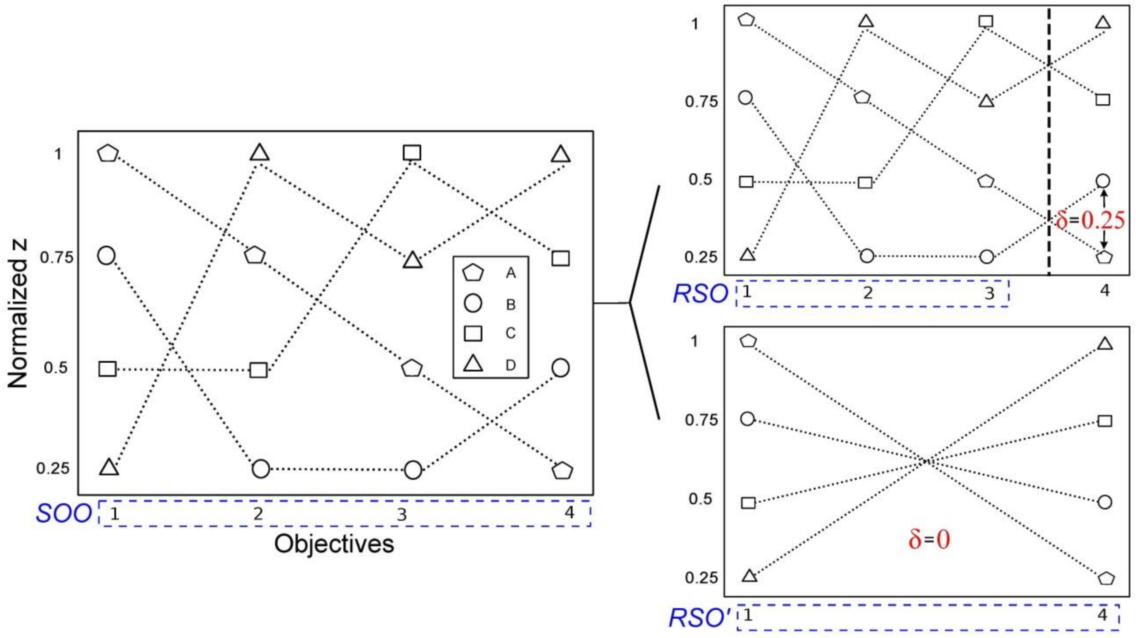


Fig.2. Dominance structure for the original set of objectives *SOO*. No solution dominates any of the others in the space of all the objectives, thus they are weakly efficient. *RSO* modifies the dominance structure ($\delta = 0.25$), however *RSO'* does not (all the solutions are still optimal in the reduced set of objectives).

3.2.3. Building the surrogate model

The PDE model *SIMMOD* is complex and leads to large CPU times associated with the solution of the PDEs. Furthermore, when this model is coupled with an optimization algorithm, we need to calculate its derivatives. This is a very time consuming task that can show inherent numerical noise, thus leading to poor numerical performance [44]. In order to simplify the calculations and enhance the robustness of the optimization algorithm, we build a surrogate model *SURMOD* to approximate the original model *SIMMOD* and to estimate the p explicit objective functions. Hence, the optimization algorithm minimizes the decision variables by interrogating the surrogate model (rather than the original model) as follows:

$$(SURMOD) \quad min_{x_D} \quad z = \left\{f_1^{SUR}(x_D), \dots, f_p^{SUR}(x_D)\right\} \tag{8}$$

The functions of the surrogate model, $f_{ob}^{SUR}(\cdot)$, are obtained from the initial sample I generated, as described in Section 3.2.2. In particular, and without loss of generality, the interpolated value at a query point is based on a cubic spline interpolation (using not-a-knot end conditions) of the values at neighbouring grid points in each respective dimension. Interpolation by cubic splines ensures C^2 continuity, which is very important when optimizing the resulting model. Other interpolation approaches (i.e. linear interpolation is just C^0, nearest point is discontinuous and cubic only ensure C^1 continuity) could be also applied in this step of the method.

In order to get an accurate interpolation, it is necessary to generate a 5-dimensional grid. A sufficient number of points are required to ensure a satisfactory level of accuracy in the predictions while at the same time improving the numerical performance of the optimization algorithm by avoiding the direct use of the simulation model.

3.2.4. MOO of the surrogate model in the reduced domain

In this step of the algorithm, we aim to identify the optimal building designs that minimize simultaneously the objective functions in vector z. For this, the MOO problem *SURMOD* is solved in a reduced domain of objectives $RSO \subseteq SOO$, thus giving rise to problem *RSUMOD*:

$$(RSUMOD) \quad min_{x_D} \quad z' = \{f_{ob}^{SUR}(x_D) | ob \in RSO\} \tag{9}$$

Note that model *RSUMOD* makes use of both, the surrogate model *SURMOD* obtained in step 2.1.2 of the algorithm and the reduced set of objectives *RSO* identified in step 2.1.1.

The solution of multi-objective optimization problems like *RSUMOD* is given by a set of Pareto points representing the optimal trade-off between conflicting objectives [9,45]. These Pareto solutions feature the property that it is not possible to find another solution that improves any of them in one objective without worsening at least one of the others. In mathematical terms, $x^* \in X$ is a Pareto optimal solution if there does not exist any $x' \in X$ such that $f_{ob}^{SUR}(x') \leq f_{ob}^{SUR}(x^*)$ for all *ob* ∈ *RSO*, and $f_{ob'}^{SUR}(x') < f_{ob'}^{SUR}(x^*)$ for some *ob'* ∈ *RSO*. If x^* is Pareto optimal, then $z'(x^*)$ is called non-dominated point or efficient point.

In order to solve problem *RSUMOD* and obtain a set ot Pareto optimal solutions, one can use any MOO method available in the literature [46–49]. Without loss of generality, here we use the epsilon constraint method [50,51], which consists of calculating a set of auxiliary single-objective problems in which one objective is kept as main criterion while the others are transferred to auxiliary constraints and limited within allowable bounds.

3.2.5. Remarks

- The initial sample *I* is not the result of any optimization process, but rather the outcome of evaluating model *SIMMOD* in different points of the space of the decision variables.
- The CPU time of the objective reduction approach is rather sensitive to the number of solutions, but the outcome itself does not change significantly with an increasing number of points (i.e., sample size).
- Different surrogate models might be used to approximate the solution of the simulation model *SIMMOD*, including kriging or linear, thin-plate and splines interpolations [52,53].

4. Case study

The capabilities of the proposed approach are illustrated through the optimization of the insulation thickness of a house-like cubicle considering both economic and environmental concerns. The decision variables of the problem are the insulation thicknesses of the external surfaces of the building.

4.1. Cubicle description

The model of the cubicle is based on real life cubicles built by the research group GREA in Puigverd, (Lleida, Spain). Several studies before are based on these cubicle models [20,54,55]. The cubicles considered in the present study show identical dimensions (five plane walls with 2.4×2.4×0.15m), and the same construction systems, but differ in the insulation thickness implemented (polyurethane in this case study, see Table 1 for its physical properties).

The cubicles show a conventional Mediterranean construction system (Fig. 3). Four mortar pillars with reinforcing bars allocated in each corner of the building configure the structure of the cubicle. The walls of the cubicle, which are identical from one model to the other except for the insulation thickness, are configured with 6 layers of different materials: an exterior cement mortar cover (0.1m), a hollow bricks structure (0.07m), a 0.05m air chamber, the polyurethane layer (insulation) whose thickness varies depending on the case, a perforated bricks structure (0.14m) and the interior cover, which is a plaster plastering layer (0.01m). A concrete base of 3×3m with reinforcing bars configure the floor, which is in contact with the ground. On the other hand, the roof contains a structure of concrete precast beams (0.05m) and 0.05m of concrete slab. The internal finish is a plaster plastering layer (0.01m). The insulation material is placed over the concrete, and it is protected with a cement mortar layer (0.1m) with a slope of 3 % and a double asphalt membrane (0.05m). The construction materials of the cubicles are displayed in Table 2. Data for the case study were retrieved from the LIDER [56] and ITeC [57] databases. A reference cubicle with no insulation is also considered [54,58] for comparison purposes.

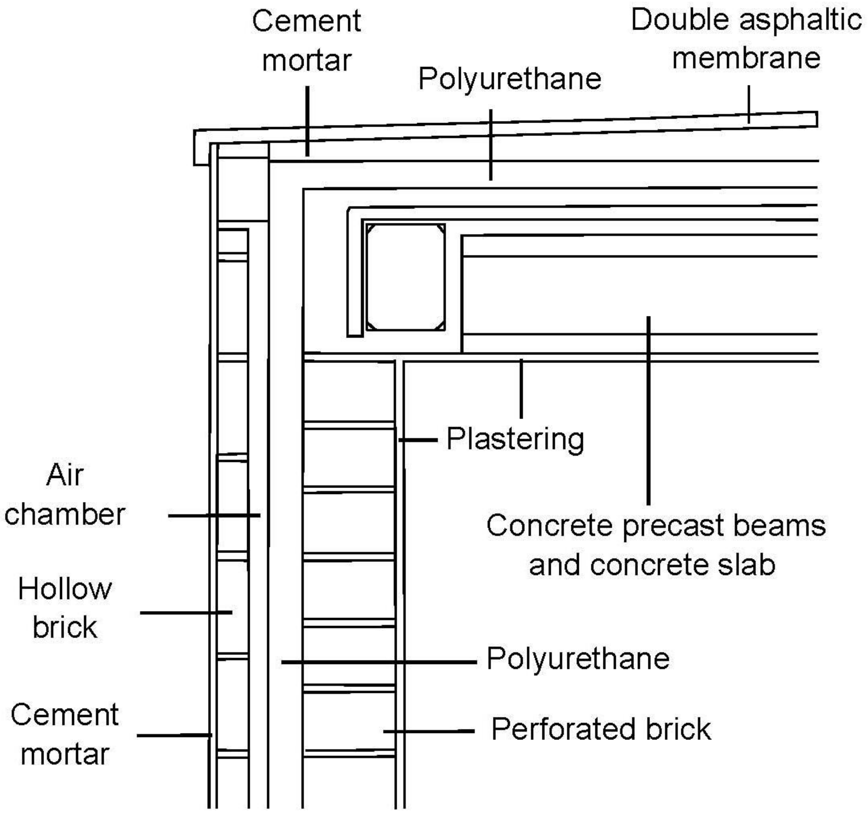


Fig.3. Construction profile of the experimental cubicles in Puigverd de Lleida (Spain).

Table 1. Properties of the insulation material.

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

Table 2. Inventory list of the materials and quantities used for the building construction and their corresponding cost. Since the amount of polyurethane (insulation material) varies from one case to another as a result of the value of the decision variables, a cubicle with 0.01m of polyurethane in all exterior surfaces is considered and included in the inventory list for illustrative purposes.

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 (0.01m)	20	79

Heating and cooling demands are supplied by a heat pump with a COP of 3. The electricity consumed is calculated by dividing the demand by the COP of the heat pump.

4.2. Model specifications

For the physical modelling EnergyPlus is implemented. This software mainly requires four modelling modules. The first one includes the building physical description (construction system, materials, geometry and internal distribution), and for the energy simulations the operational spaces can be defined as thermal units. The second module defines the HVAC systems including the selection of the equipment, power, efficiency and the operation scheduling for the set points. The third module defines the internal loads (people occupation and activity, electronic devises and miscellaneous). Finally, module four allows to define the weather conditions including temperature, solar radiation, wind speed and direction and humidity (defined using time steps per hour). For more details see [34].

For the cubicle simulation, the following specifications are used. The construction system is the one defined in Section 4.1. The range of insulation thickness considered varies from 0.01 to

0.21m of insulation. As will be later discussed in more detail, the insulation thickness is first varied uniformly (i.e., all the walls with the same thickness), and then considering different thicknesses for the five external surfaces of the cubicles. Heating and cooling demands are supplied by a heat pump with a COP of 3, and an internal set point temperature of 24°C is fixed for the whole year [54,55]. Neither doors nor windows are included in the model. No mechanical or natural ventilation is used, but a fixed infiltration rate of 0.12 ACH (air changes per hour) [59] is assumed. There is no internal mass, and no human occupancy is considered. A building lifetime of 20 years is assumed [60,61]. The investment in construction materials is paid the first year of the time horizon. As for the electricity, a cost of 0.16 €/kWh [62] is considered with a yearly increase in cost of 5%.

The weather conditions of the simulations are given by the location of the cubicles, which corresponds to a continental Mediterranean climate characterized by moderate cold winters, dry hot summers and significant daily temperature oscillations between day and night [63].

The environmental impact of each cubicle alternative, quantified via LCA principles, takes into account the manufacturing, operational and dismantling phases. In particular, the 10 impact categories considered in the EI99 methodology, along with the EI99 itself, are studied. Table 3 summarizes the impact per kilogram of material used, whereas Table 4 presents environmental data of the Spanish electricity market. This information has been retrieved from the ecoinvent database [42].

Table 3. Inventory list of the materials and quantities used for the building construction and their corresponding environmental impacts. As an illustrative example, the amount of polyurethane (PU) used in a cubicle with 0.01m of insulation thickness in all of their surfaces is also displayed.

		Ecosystem quality (PDF*m2*yr/kg)			Human Health (Daly/kg)					Resources (MJ/kg)	
Component	Name in the data base Eco Invent	Acidification & eutrophication	Ecotoxicity	Land occupation	Carcinogenics	Climate change	Ionising radiation	Ozone layer depletion	Respiratory effects	Fossil fuels	Mineral extraction
Brick	market for brick, at plant,GLO [kg]	$3.73\cdot10^{5}$	$2.1\cdot10^{5}$	$3.6\cdot10^{5}$	$1.9\cdot10^{10}$	$6.3\cdot10^{10}$	$5.2\cdot10^{12}$	$2.1\cdot10^{13}$	$1.0\cdot10^{9}$	$4.1\cdot10^{9}$	$3.7\cdot10^{11}$
Base plaster	market for base plaster, GLO [kg]	$5.3\cdot10^{5}$	$4.9\cdot10^{5}$	$7.1\cdot10^{5}$	$2.9\cdot10^{10}$	$8.2\cdot10^{10}$	$4.0\cdot10^{12}$	$1.8\cdot10^{13}$	$1.9\cdot10^{9}$	$2.2\cdot10^{9}$	$3.3\cdot10^{11}$
Cement mortar	market for cement mortar, GLO [kg]	$6.0\cdot10^{5}$	$6.5\cdot10^{5}$	$8.3\cdot10^{5}$	$3.3\cdot10^{10}$	$8.2\cdot10^{10}$	$4.3\cdot10^{12}$	$2.1\cdot10^{13}$	$2.1\cdot10^{9}$	$2.6\cdot10^{9}$	$4.3\cdot10^{11}$
Steel bars	market for section bar rolling, steel, GLO [kg]	$3.1\cdot10^{5}$	$1.3\cdot10^{4}$	$5.1\cdot10^{4}$	$9.5\cdot10^{10}$	$6.2\cdot10^{10}$	$5.1\cdot10^{12}$	$2.5\cdot10^{13}$	$1.9\cdot10^{9}$	$1.6\cdot10^{9}$	$1.5\cdot10^{10}$
Concrete	market for concrete, normal, GLO [m3]	$7.5\cdot10^{2}$	$7.8\cdot10^{2}$	$5.5\cdot10^{2}$	$3.9\cdot10^{7}$	$1.1\cdot10^{6}$	4.2·109	$2.6\cdot10^{10}$	$1.2\cdot10^{6}$	$3.2\cdot10^{6}$	$7.1\cdot10^{8}$
In-floor bricks	market for concrete roof tile, GLO [kg]	$5.8\cdot10^{5}$	$8.6\cdot10^{5}$	$5.8\cdot10^{5}$	$5.7\cdot10^{10}$	$8.1\cdot10^{10}$	$4.2\cdot10^{12}$	$2.3\cdot10^{13}$	$2.2\cdot10^{9}$	$2.9\cdot10^{9}$	$1.5\cdot10^{10}$
Asphalt	market for mastic asphalt, GLO [kg]	$7.4\cdot10^{5}$	$8.0\cdot10^{5}$	$1.4\cdot10^{4}$	$4.5\cdot10^{10}$	$7.1\cdot10^{10}$	$8.3\cdot10^{12}$	$8.1\cdot10^{13}$	$3.1\cdot10^{9}$	$9.7\cdot10^{9}$	$3.3\cdot10^{11}$
Polyurethane	market for polyurethane, rigid foam, GLO [kg]	$8.9\cdot10^{4}$	$8.4\cdot10^{4}$	$2.4\cdot10^{4}$	$5.2\cdot10^{9}$	$1.2\cdot10^{8}$	$3.1\cdot10^{11}$	$8.8\cdot10^{13}$	$4.1\cdot10^{8}$	$1.5\cdot10^{7}$	$7.6\cdot10^{10}$
Disposal bricks	market for waste brick, GLO [kg]	$9.3\cdot10^{6}$	$2.4\cdot10^{6}$	$-4.9\cdot10^{6}$	$5.7\cdot10^{12}$	$3.5\cdot10^{11}$	$9.4\cdot10^{14}$	$4.0\cdot10^{14}$	$6.9\cdot10^{10}$	$5.3\cdot10^{10}$	$2.6\cdot10^{12}$
Disposal plaster	market for waste mineral plaster, GLO [kg]	$6.7\cdot10^{6}$	$8.0\cdot10^{6}$	$-1.1\cdot10^{7}$	$1.8\cdot10^{11}$	$3.1\cdot10^{11}$	$3.7\cdot10^{13}$	$3.8\cdot10^{14}$	$6.5\cdot10^{10}$	$4.7\cdot10^{10}$	$4.0\cdot10^{12}$
Disposal mortar	market for waste cement in concrete and mortar, GLO [kg]	$1.1\cdot10^{5}$	$3.5\cdot10^{5}$	$1.4\cdot10^{5}$	$1.5\cdot10^{9}$	$5.1\cdot10^{11}$	$6.0\cdot10^{13}$	$5.3\cdot10^{14}$	$8.0\cdot10^{10}$	$6.5\cdot10^{10}$	$7.4\cdot10^{12}$
Disposal concrete + steel bars	market for waste reinforced concrete, GLO [kg]	$9.4\cdot10^{6}$	$3.5\cdot10^{4}$	$5.8\cdot10^{6}$	$3.3\cdot10^{10}$	$3.9\cdot10^{11}$	$5.0\cdot10^{13}$	$4.6\cdot10^{14}$	$7.3\cdot10^{10}$	$4.6\cdot10^{10}$	$6.2\cdot10^{12}$
Disposal in-floor bricks	market for waste concrete, not reinforced, GLO [kg]	$7.9\cdot10^{6}$	$1.1\cdot10^{5}$	$4.0\cdot10^{6}$	$2.6\cdot10^{10}$	$3.2\cdot10^{11}$	$4.3\cdot10^{13}$	$3.4\cdot10^{14}$	$6.8\cdot10^{10}$	$4.0\cdot10^{10}$	$4.0\cdot10^{12}$
Disposal asphalt	market for waste asphalt, GLO [kg]	$7.9\cdot10^{6}$	$1.8\cdot10^{5}$	$2.7\cdot10^{5}$	$5.6\cdot10^{11}$	$5.0\cdot10^{11}$	$4.7\cdot10^{13}$	$4.4\cdot10^{14}$	$2.5\cdot10^{10}$	$5.6\cdot10^{10}$	$8.1\cdot10^{12}$
Disposal PU	market for waste polyurethane, GLO [kg]	$1.0\cdot10^{4}$	$7.1\cdot10^{4}$	$3.7\cdot10^{5}$	$2.7\cdot10^{8}$	$2.8\cdot10^{9}$	$1.6\cdot10^{12}$	$1.6\cdot10^{13}$	$2.0\cdot10^{9}$	$2.1\cdot10^{9}$	$2.7\cdot10^{11}$

Table 4. Environmental data per kWh of electricity in Spain (this dataset has been extrapolated from year 2008 to the year 2014).

	Ecosystem quality (PDF*m2*yr/kWh)			Human Health (Daly/kWh)					Resources (MJ/kWh)	
Component	Acidification & eutrophication	Ecotoxicity	Land occupation	Carcinogenics	Climate change	Ionising radiation	Ozone layer depletion	Respiratory effects	Fossil fuels	Mineral extraction
Electricity (Spain)	1.13310^{4}	$4.03\cdot10^{4}$	$9.47\cdot10^{5}$	$1.28\cdot10^{9}$	$1.30\cdot10^{9}$	$6.47\cdot10^{11}$	$8.92\cdot10^{13}$	$3.99\cdot10^{9}$	$9.87\cdot10^{9}$	$1.99\cdot10^{10}$

5. Results and discussions

5.1. Initial simulation results

An initial sample of solutions is first obtained by simulating different cubicle designs. We define 6 insulation thicknesses (i.e. 0.01, 0.03, 0.06, 0.09, 0.15 and 0.21m) and generate 7776 points by means of JEPlus (number of alternatives raised to the number of walls, that is, 6^5), each with a different combination of external building surfaces. We then simulate the resulting cubicles in EnergyPlus to obtain sample *I* containing 7776 solutions. Note that for these solutions the building properties and weather conditions are the same, but the insulation thicknesses and consequently the energy consumption and objective functions values are different.

Fig. 4 shows a parallel coordinates plot corresponding to the solutions (belonging to *I*) with the same insulation thicknesses in all their external surfaces (i.e., that is, the solution with all the thickness values equal to 0.01 m, the one with all of them equal to 0.03 m, and so on). Each line in the plot represents a different solution. As seen in the figure, impacts related with ecotoxicity, land occupation, ionizing radiation, ozone layer depletion and mineral extraction tend to decrease with the insulation thickness of the cubicles, while the other impacts behave in an opposite manner. This suggests the existence of objectives showing similar behavior and which might be removed from the pool without altering the dominance structure of the problem.

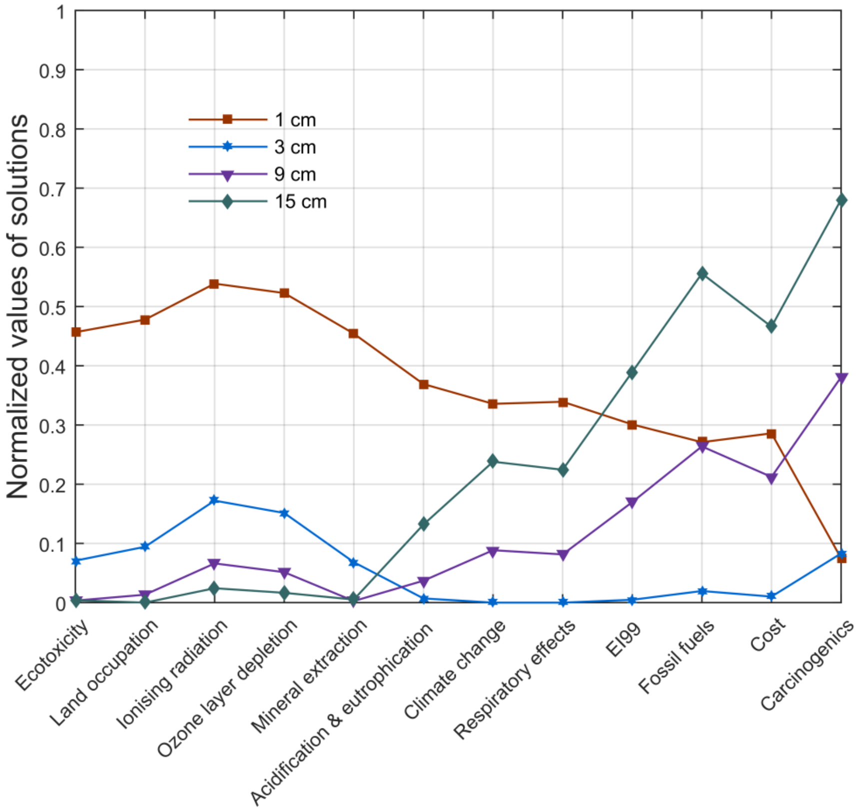


Fig. 4. Parallel coordinate plot where the different objectives are presented in the horizontal axis and in the vertical one there are the normalized values of each solution in each objective. Only solutions of sample *I* entailing the same insulation thickness in all the external surfaces are depicted.

5.2. Objective reduction

The cubicle solutions generated in the previous step (i.e., solutions in the set *I*) are normalized and then used to identify redundant objectives by means of the exhaustive exploration dimentionality reduction approach presented in Section 3.2.2. In this particular case, we force the economic performance to be always part of the reduced set of objectives *RSO*. The approach was implemented in GAMS in a computer HP Compaq Pro 6300 SFF with an Intel Core Processor 3.30 GHz and 3.88 GB of RAM. The required CPU time was around 120 seconds.

Fig. 5 shows the minimum delta error achieved for a decreasing number of objectives retained. Note that different combinations of objectives can be removed for a given reduction in size (for a given cardinality of the set |*RSO*|), and each such combination will lead to a different delta error. As seen, 3 objectives suffice to keep the original Pareto structure unaltered (i.e., delta error = 0).

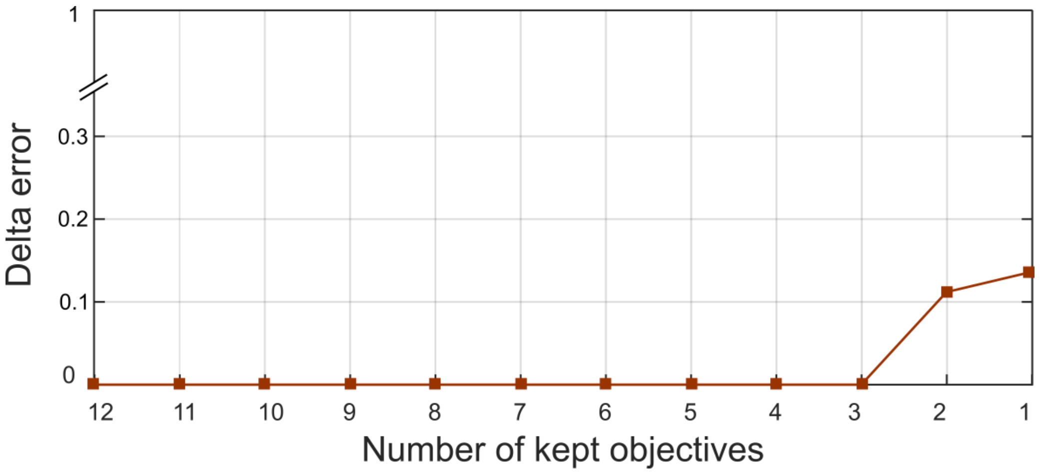


Fig. 5. Minimum delta error achieved by sets with a given number of objectives.

Table 5 displays the delta error (expressed in %) for all possible sets of three objectives kept sorted in lexicographic order. As seen, two out of 55 combinations (i.e., the triples: economic objective, carcinogenics, ionising radiation; and economic objective, carcinogenics, ozone layer depletion) present a delta error of 0. These results are consistent with Fig. 4, where we already observed that several indicators behave similarly.

Table 5. Delta error for all possible combinations of three objectives. These combinations are always formed by the economic objective (i.e., cost, Obj. 1) and two environmental objectives (Obj. 2 and Obj. 3). Here, 1 is total cost, 2 is acidification & eutrophication, 3 is ecotoxicity, 4 is land occupation, 5 is carcinogenics, 6 is climate change, 7 is ionising radiation, 8 is ozone layer depletion, 9 is respiratory effects, 10 is fossil fuels, 11 is mineral extraction and 12 is the EI99 aggregated.

Obj 1	Obj 2	Obj 3	Delta error [%]
1	2	3	11.19
1	2	4	11.19
1	2	5	23.51
1	2	6	13.63
1	2	7	11.19
1	2	8	11.19
1	2	9	13.63
1	2	10	13.63
1	2	11	11.19
1	2	12	13.63
1	3	4	11.19
1	3	5	7.3
1	3	6	11.19
1	3	7	11.19
1	3	8	11.19
1	3	9	11.19
1	3	10	11.19
1	3	11	11.19
1	3	12	11.19
1	4	5	6.33
1	4	6	11.19
1	4	7	11.19
1	4	8	11.19
1	4	9	11.19
1	4	10	11.19
1	4	11	11.19
1	4	12	11.19
1	5	6	23.51
1	5	7	0
1	5	8	0
1	5	9	23.51
1	5	10	23.51
1	5	11	7.3
1	5	12	23.51
1	6	7	11.19
1	6	8	11.19
1	6	9	23.51
1	6	10	23.51
1	6	11	11.19
1	6	12	23.51
1	7	8	11.19
1	7	9	11.19
1	7	10	11.19
1	7	11	11.19
1	7	12	11.19
1	8	9	11.19
1	8	10	11.19
1	8	11	11.19
1	8	12	11.19
1	9	10	23.51
1	9	11	11.19
1	9	12	23.51
1	10	11	11.19
1	10	12	23.51
1	11	12	11.19

Carcinogenics and ionising radiation are finally selected along with the cost as the reduced set of objectives to be minimized (i.e., *RSO* = {*Cost, Carcinogenics, Ionising radiation*}). Note that the delta error of the couple “EI99 - Economic cost” is 10.64. Hence, it is clear that the use of the aggregated EI99 as unique environmental objective may leave Pareto points out of the analysis. This is an important finding that highlights the need to avoid aggregated metrics and work instead with disaggregated environmental metrics in the optimization. In fact, even when considering a third environmental indicator along with the EI99 and cost, the delta error is still above zero (Table 6).

Table 6. Delta error for all combinations of three objectives considering cost (Obj. 1) and the EI99 (Obj. 2) along with different environmental midpoint indicators (Obj. 3). Here, 1 is cost, 2 is EI99, 3 is acidification & eutrophication, 4 is ecotoxicity, 5 is land occupation, 6 is carcinogenics, 7 is climate change, 8 is ionising radiation, 9 is ozone layer depletion, 10 is respiratory effects, 11 is fossil fuels and 12 is mineral extraction.

Obj 1	Obj 2	Obj 3	Delta error
1	2	3	13.63
1	2	4	11.19
1	2	5	11.19
1	2	6	23.51
1	2	7	23.51
1	2	8	11.19
1	2	9	11.19
1	2	10	23.51
1	2	11	23.51
1	2	12	11.19

5.3. Optimization with a surrogate model

The surrogate model SURMOD is implemented in Matlab R2015a [62] using the 7776 cubicle solutions of sample I generated in the first step. A multivariate cubic spline interpolation, which uses piecewise cubic polynomials, is applied to build this surrogate model, for which analytical derivatives can be obtained. The use of low-order polynomials is especially attractive for surface fitting because they reduce the numerical instabilities that arise with higher degree polynomials. The most compelling reason for their use is their C2 continuity, which guarantees continuous first and second derivatives across all polynomial segments. To optimize the surrogate we access the state-of-the-art NLP solvers through the MATLAB-TOMLAB [63] optimization environment. TOMLAB allows us to standardize the model definition and interfaces with the main optimization solvers regardless of the different syntax (i.e., it is not required a specific inter-face routine for each optimization solver). In addition, for the definition of the optimization problem we have developed a homemade modeling system with indexing capacities and interfaced with the MATLAB-TOMLAB optimization environment. Building the SURMOD takes approximately 77,760 seconds in a computer HP Compaq Pro 6300 SFF with an Intel Core Processor 3.30 GHz and 3.88 GB of RAM. Some of the objectives in SURMOD are eliminated according to the output of the objective reduction algorithm. This gives rise to multi-objective surrogate model RSUMOD, which is then solved using the epsilon-constraint method. 25 epsilon parameters values were defined for each objective, leading to 625 NLPs (i.e., 25|RSO|-1 = 252), which were solved by CONOPT version 3.10. The algorithm takes 2,500 seconds to solve the 625 NLPs, which leads to a total CPU time of 80,260 seconds (around 1 day), considering also the time required for the construction of the surrogate model. Note that the time required to optimize the system using EnergyPlus would be much higher than the one associated to the surrogate model. More precisely, using CONOPT, each NLP requires on average 17 iterations to be solved, each of which needs 6 evaluations of the objective functions. If we consider 625 NLPs, 17 iterations per NLP, 6 evaluations per iteration and a simulation time of 10 seconds for each simulation in EnergyPlus, the whole process would take 637,500 seconds (around 1 week). Hence, the CPU time is reduced more than 7 times (i.e., approximately 8 times), compared to the direct optimization of the simulation software. Moreover, this reduction in time in the optimization task might be much more significant for more complex building models. Note also that in addition to the reduction in time, we benefit from a simplified analysis of the Pareto solutions that focuses on key environmental metrics, thereby avoiding the need to study all of them simultaneously.

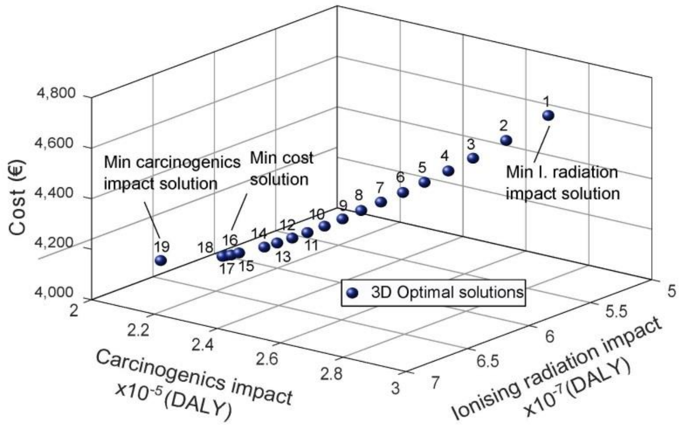
At this point of the overall algorithm, the Pareto solutions obtained can be used in both, the dimensionality reduction and the construction of the surrogate model, in an attempt to further improve the quality of the final set of solutions. However, in this case study this step is not required, since a significant reduction in the number of objectives is achieved in the first iteration (i.e. RSO contains only 3 objectives).

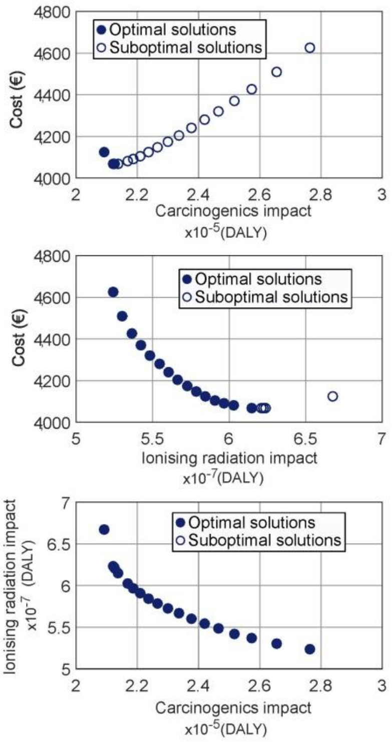
5.4. MOO solutions

After conducting the optimization with the surrogate model we obtain 19 different Pareto solutions (Fig.6) (we solve 625 NLPs, 48 render feasible, and within this group of solutions there are 29 repeated solutions and 19 unrepeated points). In these solutions, the insulation thickness of North, East and West walls vary from 0.06 to 0.21 m, that of the South from 0.04 to 0.2 m and that of the roof from 0.07 to 0.21 m.

The minimum cost solution has 0.08 m of insulation thickness in the North, East and West walls, and 0.07 and 0.09 m in the South and roof, respectively. The optimal solution from the perspective of carcinogenic effects on humans has thinner insulation thicknesses in all of the external surfaces (0.06 m in the North, East and West and 0.04 and 0.07m in the South and the roof, respectively). The solution with minimum impact on human health caused by ionizing radiation shows thicker insulation thicknesses (i.e., 0.20 m in the South facade and 0.21 m in all the other surfaces). This solution is the worst from the standpoints of impact in carcinogenics and economic performance.

For a better understanding of the tradeoff between the objectives, Fig. 6 shows the 19 optimal solutions of the problem in a three dimensional space along with the two dimensional projections onto 2-D subspaces. When solutions are projected onto the bi-criteria space considering objectives “carcinogenics” and “cost”, only 4 of them keep their Pareto optimality condition (i.e., the remaining 15 solutions that are Pareto optimal in the 3 dimensional space are dominated when only these two objectives are considered). In the bi-criteria space “cost” vs “ionising radiation”, 16 solutions keep their Pareto optimality condition and 3 become dominated. Finally, the original 19 Pareto optimal solutions (in the 3 dimensional space) are also Pareto optimal in the space of the two environmental impacts (i.e., “carcinogenics” and “ionising radiation”). These results reinforce the idea that selecting a proper set of objectives in the objective reduction step is crucial to avoid losing potential Pareto optimal solutions.





SOLUTIONS		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Insulation thickness (cm)	East	21	19	18	17	16	14	13	12	11	11	10	10	9	9	8	8	8	8	6
	North	21	20	19	18	17	16	16	15	13	11	11	10	10	9	9	8	8	8	6
	South	20	17	11	11	10	10	10	10	9	9	8	8	8	7	7	7	6	7	4
	West	21	19	18	17	15	14	13	12	11	11	10	10	9	9	8	8	8	8	6
	Roof	21	20	19	18	18	17	17	17	16	15	14	12	11	10	9	9	8	8	7

Fig. 6. Pareto optimal solutions in the three dimensional space (3 objectives) and their corresponding projections on the different two dimensional spaces (2 objectives). As the insulation thickness of the optimal solutions increases, the cost and the impact of carcinogenics on human health tend to decrease, while the impact of ionising radiation on human health tends to increase.

Table 7 shows the different extreme optimal solutions and their improvements with respect to the base case (without insulation). For instance, the use of insulation can lead to savings between 800 and 1400€ (i.e., between 16 and 26%) in total cost. This means that the cost of the insulation material is compensated by the savings in the energy consumed. Regarding the impact in ionising radiation, the use of appropriate insulation allows for an improvement between 38 and 51%. In our case study, this impact is strongly dependant on the electricity consumption, and thus, on the electricity mix of the country. Consequently, the minimum ionising radiation solution (which consumes less electricity) reduces more than twice this indicator compared to the base case solution (with high electricity consumption). Conversely, not all the extreme solutions improve the base case in terms of carcinogenics impact. In particular, the minimum ionising radiation solution involves an impact 9% higher than that of the base case in this category. The carcinogenic impact caused by the polyurethane is relatively important. Thus, when considering cubicles with thick insulation like this one (i.e., between 0.2 and 0.21 m in each external surface), the carcinogenics impact increases when compared to the base case. Despite this, the results reinforce the general idea that selecting a proper insulation thickness leads to significant reductions in economic cost and environmental impact.

Table 7. Comparison of the base case and the extreme optimal solutions. In the table, E, N, S, W, R are East, North, South, West and Roof and the attached numbers denote the thickness of insulation of the corresponding surface in cm (i.e. E8 is 0.08m of polyurethane in the East wall).

	Cubicle model	Economic cost (€)	Carcinogenics (DALYS)	Iionising radiation (DALYS)	Improvement (%)		
					Economic	Carcino-genics	Ionising radiation
Base case	No insulation	5,485.24	$2.53\cdot10^{-5}$	$1.08\cdot10^{-6}$	0	0	0
Economic	E8_N8_S7_W8_R9	4,067.27	$2.13\cdot10^{-5}$	$6.21\cdot10^{-7}$	25.9	15.7	42.4
Carcinogenics	E6_N6_S4_W6_R7	4,123.63	$2.09\cdot10^{-5}$	$6.68\cdot10^{-7}$	24.8	17.3	38.0
Ionising radiation	E21_N21_S20_W21_R21	4,625.71	$2.76\cdot10^{-5}$	$5.24\cdot10^{-7}$	15.7	-9.2	51.4

The recommended insulation values of the regulatory framework about buildings basic requirements of safety and habitability are not close to the optimal results obtained in the present study [7]. In the location of Lleida, the Spanish law requires a thermal transmittance of 0.66 $W/m^2\cdot K$ for the external facade walls and 0.38 $W/m^2\cdot K$ for the roof. However, the results of the present study suggest lower thermal transmittance values of between 0.33 and 0.26 $W/m^2\cdot K$ for the best economic solution in the facades and 0.285 $W/m^2\cdot K$ in the roof. The solution showing better environmental performance from the point of view of ionising radiation suggests an insulation with a thermal transmittance of 0.133 $W/m^2\cdot K$ in facades and roofs. To attain the solution with lower values of carcinogenics, the results of the present study suggest thermal transmittances of between 0.37 to 0.44 $W/m^2\cdot K$ in facades and 0.33 in the roof.

A cubicle constructed according to the Spanish law requirements and evaluated through the sated methodology presents a higher price compared to the optimal solutions attained (between a 3% and 10% higher depending on the solution). This cubicle also presents higher values of ionizing radiation compared to the optimal solutions of the present study (between a 10 and a

24% higher depending on the solution) and also higher values of carcinogenics (between a 2% and a 7%).

6. Conclusions

In this work we have presented a systematic tool to effectively identify optimal building designs according to economic and environmental criteria that combines: (i) an objective reduction method that identifies redundant environmental metrics; and (ii) a surrogate modelling approach that expedites the optimization task by reducing the time required to estimate the energy consumed by the building.

The tool presented, which can be easily adapted to solve other MOO problem with similar features, was applied to a case study of a house-like cubicle where the insulation thicknesses of the external surfaces were optimized in order to minimize the cost and several environmental impacts assessed through LCA principles. Numerical results show that 3 objectives suffice to optimize the system while keeping its original dominance structure. We showed as well that the bi-objective optimization of the cost together with the widely used aggregated EI99 might change the problem’s structure, with the associated potential risk of losing solutions that are Pareto optimal in the original space of objectives.

Results also demonstrate that the surrogate model notably reduces the computational burden of the optimization task, thereby expediting the overall solution time (i.e., 8 times). This reduction in time may become more significant as the complexity of the building model considered increases.

The results of the case study illustrate how significant improvements can be achieved with respect to the base case (cubicle without insulation), when the appropriate insulation is used. In particular, the cost can be reduced by 26%, the carcinogenics impact can be mitigated by 17%, and the ionising radiation impact can be decreased by 51 %.

The methodology presented here is intended to promote optimal economic solutions for energy efficiency in buildings, while also minimizing their environmental impact. This tool can guide decision-makers towards the adoption of more sustainable designs as well as policy-makers during the development of more effective regulations for improving the economic and environmental performance in the building sector.

7. Acknowledgments

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11. Appendices

11.1. Publications

11.1.1. Research articles

J. Carreras, D. Boer, G. Guillén-Gosálbez, L.F. Cabeza, M. Medrano, L. Jiménez, Multi-objective optimization of thermal modelled cubicles considering the total cost and life cycle environmental impact, Energy and Buildings. 88 (2014) 335–346. doi:10.1016/j.enbuild.2014.12.007. Impact factor: 2,973. Journal 7 of 135 in Civil Engineering.

J. Carreras, D. Boer, L.F. Cabeza, L. Jiménez, G. Guillén-Gosálbez, Eco-costs evaluation for the optimal design of buildings with lower environmental impact, Energy and Buildings. 119 (2016) 189–199. doi:10.1016/j.enbuild.2016.03.034. Impact factor: 2,973. Journal 7 of 135 in Civil Engineering.

J. Carreras, C. Pozo, D. Boer, G. Guillén-Gosálbez, J. A. Caballero, R Ruiz-Femenia, L. Jiménez, Systematic approach for the life cycle multi-objective optimization of buildings combining objective reduction and surrogate modeling. Energy and Buildings. 130 (2016) 1–13. doi:10.1016/j.enbuild.2016.07.062. Impact factor: 2,973. Journal 7 of 135 in Civil Engineering.

J. Mazo, A.T. El Badry, J. Carreras, M. Delgado, D. Boer, B. Zalba, Uncertainty propagation and sensitivity analysis of thermo-physical properties of phase change materials (PCM) in the energy demand calculations of a test cell with passive latent thermal storage, Applied Thermal Engineering. 90 (2015) 596–608. doi:10.1016/j.applthermaleng.2015.07.047. Impact factor: 1.718. Journal 7 of 135 in Mechanics.

11.1.2. Book chapters

J. Carreras, D. Boer, G. Guillén-Gosálbez, L.F. Cabeza, M. Medrano, L. Jiménez, Chapter No 28: Reducing the Life Cycle Environmental Impact of Buildings Following a Simulation-Optimization Approach. Springer book *Advances in Energy Systems Engineering*. doi:10.1007/978-3-319-42803-1_28.

11.2. Scientific conference participations

11.2.1. Oral communications

J. Carreras, D. Boer, G. Guillén-Gosálbez, L.F. Cabeza, M. Medrano, L. Jiménez, Multi-objective optimization applied to thermal modelling of cubicles. Eurotherm Seminar No99: Advances in Thermal Energy Storage. May 2014. Lleida, Spain.

J. Carreras, D. Boer, G. Guillén-Gosálbez, L.F. Cabeza, M. Medrano, L. Jiménez, Optimización multi-objetivo de cubículos: minimización del coste y del impacto ambiental. 9ª edición del Congreso Nacional de Ingeniería Termodinámica. June 2015. Cartagena, Murcia. Spain.

J. Carreras, C, Pozo, , D. Boer, G. Guillén-Gosálbez, J.A. Caballero, R. Ruiz-Femenia, L. Jiménez, Uso combinado de métodos de reducción de objetivos y “modelos sustitutos” para acelerar la optimización en el diseño de edificios. 9ª edición del Congreso Nacional de Ingeniería Termodinámica. June 2015. Cartagena, Murcia. Spain.

J. Carreras, D. Boer, G. Guillén-Gosálbez, L.F. Cabeza, L. Jiménez, Aplicación de ECO-COST en el diseño de edificios, 9ª edición del Congreso Nacional de Ingeniería Termodinámica. June 2015. Cartagena, Murcia. Spain.

11.2.2. Invited conference

J. Carreras, S. Colclough, D. Boer, G. Guillén-Gosálbez, L.F. Cabeza, M. Medrano, L. Jiménez, Multi-objective optimization applied to minimize the cost and the environmental impact of a building: An Irish case study. See the Light Conference. November 2015. Dublin, Ireland.

11.2.3. Poster presentations

J. Carreras, A. el Badry, D. Boer, G. Guillén-Gosálbez, L.F. Cabeza, M. Medrano, L. Jiménez, Multi-objective optimization applied to minimize the economic cost and the environmental impact of building insulation. 13th Mediterranean Congress of Chemical Engineering (13MCCE). October 2014 Barcelona, Spain.

J. Carreras, C, Pozo, , D. Boer, G. Guillén-Gosálbez, J.A. Caballero, R. Ruiz-Femenia, L. Jiménez,Combined use of a dimensionality reduction approach and a surrogate model for accelerating building design optimization. American Institute of Chemical Engineers (AIChE) Annual Meeting. November 2015, Salt Lake City, USA.

J. Carreras, C, Pozo, , D. Boer, G. Guillén-Gosálbez, J.A. Caballero, R. Ruiz-Femenia, L. Jiménez, Modelling and optimization framework for the multi-objective design of buildings. 26th European symposium on computer aided process engineering (ESCAPE26). June 2016. Portorož, Slovenia.

11.3. Co-supervision of Master thesis

A. el Badry, Multi-objective optimization to minimize the cost and environmental impact of building. Application to cubicles. 2014. Universitat Rovira i Virgili. Master of Environmental Engineering and Sustainability Production.

M. Martinez, Avaluació del consum energètic d’un edifici i optimització de l’aïllament. (Evaluation of energy consumption of a building and isolation optimization) 2015. Universitat Rovira i Virgili. Master of Industrial Engineering.

H. Estévez, Evaluación del consumo energético de un edificio y optimización de diseño y control de sombreado (Evaluation of energy consumption of a building and shading control design and optimization). 2015. Universitat Rovira i Virgili. Master of Industrial Engineering.

A. Torres, Multi-objective optimization applied to buildings. Life Cycle Assessment. 2015. Universitat Rovira i Virgili. Master of Environmental Engineering and Sustainability Production.

Samar Sherif, Improvement of the energy efficiency in buildings considering environmental aspects. 2016. Universitat Rovira i Virgili. Master of Environmental Engineering and Sustainability Production.