UNIVERSITAT ROVIRA I VIRGILI

MATHEMATICAL MODELLING TO AID IN THE TRANSITION TOWARDS MORE SUSTAINABLE BUILDINGS

Alba Torres Rivas

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Mathematical modelling to aid in the transition towards more sustainable buildings

DOCTORAL THESIS

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Summary

The importance of the environment and sustainability is becoming an awareness for the policies and the society. For that reason, a new market of cost-effective, environmentally friendly and sustainable products. Methodologies and studies to evaluate the performance of those products can show new potentialities and improvement trends. The building sector is not an exception and multiples studies are evaluating new alternative technologies.

This sector represents one of the main energy consumers worldwide, with a 40% of the total annual energy consumption and being the responsible of a third part of the greenhouse gas emissions (GHG) [1]. Many countries have taken that into account and have dictate energy measures to reduce the energy demand and the GHG associated. To achieve those improvements, multiple strategies can be applied, such us energy efficient equipment, double-glazed windows, building insulation or renewable energy technologies, such as solar panels.

Building insulation has shown to be a promising alternative reducing the energy demand associated to heating and cooling, without compromising the thermal comfort inside the building. Following this trend, a wide range of insulation materials are available or have been developed, providing multiple alternatives. Despite the improvements that those materials provide in buildings demand, some materials have an important energy embodied that may counter effect the global energy consumption associated to the alternative (accounting the manufacture, installation, dismantling and disposal of the materials). Neglecting the associated impact of those materials may lead to sub-optimal solutions, which suggest that an initial evaluation of the alternatives would help in the early stages of building design or retrofit.

In this thesis we present several studies to analyse the possibilities of bio-based materials, as they provide good thermal properties and low embodied energy. Firstly, bio-based materials have been analysed in terms of cost, environmental impact and condensation risk, providing a systematic methodology to identify the possibilities of the different materials in different climate conditions. Secondly, a methodology to assess the combination of those materials in panels or fibre mats is carried out with an initial evaluation of the efficiency (in terms of cost and environmental impact) of the materials to identify the most promising alternatives to combine and systematically generate efficient combination of the materials. This promising alternative can propose materials with intermediate properties which could benefit in some applications (e.g., improving moisture buffering or acoustic insulation, among others).

To illustrate the possibilities of the methodology, a house-like cubicle has been considered, varying the insulation materials and thicknesses of the insulation with the objective to achieve the minimum cost and environmental impact without condensation risk. Despite that, the proposed methodology can be applied to other building models and with other variables or objective functions.

The first chapter of the thesis describes the methodology to asses a multi-objective optimization (MOO) with the evaluation of the moisture transfer to evaluate the condensation risk in different climates. It minimizes the cost and impacts associated during the whole life cycle, considering the construction materials and the energy consumed to achieve the comfort during the operational phase. The results provided are further evaluated to reduce optimal Pareto frontier alternatives to those without the condensation risk.

The environmental impact, is carried out following a life cycle assessment (LCA) methodology from cradle-to-gate (from extraction until end of life), based on the ReCiPe methodology [2]. ReCiPe has a total of 17 specific impact which are aggregated into three different damage groups (human health, ecosystem quality and resources), which are further clustered into a single indicator which is used in this approach.

This approach has shown important improvements with bio-based materials, achieving reductions in terms of cost and environmental impact comparing to a reference insulation material, polyurethane (PU). For the case of Lleida, the best economic alternatives are provided by 24cm of cotton and wool (a reduction of 28% compared to PU), whereas 86cm of corn is the best environmentally friendly alternative (with a reduction of 26% compared to PU). Despite being optimal solutions, any of those can be implemented without condensation risk, which proves the necessity of implement this further analysis for bio-based materials. Excluding those non-feasible solutions, other Pareto optimal solutions improve the performance of PU, 22cm of hemp is the most compromise solutions between cost and impact without condensation risk. All the solutions of PU are dominated by different bio-based materials.

The second chapter evaluates the efficiency of different combinations of insulation materials and thicknesses, with the objective to propose materials combination for sandwich panels or fibre mats which facilitate the installation process and provide materials with more balanced properties. For that reason, the material-thickness combinations have been evaluated in terms of cost and environmental impact, following a cradle-to-utilization variant (from the extraction until the use phase). The chosen LCA methodology used is ReCiPe with the 17 specific impacts which are considered inputs. Those inputs and the economic one are analysed with an objective reduction method to identify redundant objectives which are excluded from the further analysis without losing efficient solutions.

All the material-thickness combinations (from now DMUs) are evaluated with Data Envelopment Analysis, which provides for each alternative an efficiency score which divide the DMUs in efficient (efficiency score of 1) and non-efficient solutions (efficiency score < 1). Furthermore, for each non-efficient DMU an efficient alternative is provided, which are potential composites (materials-thicknesses combinations of different materials). All the composites are filtered to exclude non-feasible materials that are not attractive to the market, and the others are also evaluate to prove their performance. This methodology has been applied in a cubicle-like building, but can be carried out in other buildings or with different materials.

For the selected case study, 12 out of 42 solutions are efficient, while from the 30 proposed composites only 10 are finally retained due to their appealing properties. The methodology proposed also proved to properly predict composite performance generating a good methodology in the early stages of materials designs.

Furthermore, it is important to assess the benefits of adopting those methodologies at a larger scale. To evaluate such potential, a methodology to quantify and analyse the building residential sector stock of a region is tested. The proposed methodology quantifies and evaluates the whole stock of each municipality of the selected area, enabling to analyse the special characteristics, size of municipality and climate conditions. The main barrier for this methodology is the existence of a large amount of individualities in the building stock that makes it virtually impossible to gather all the information. For that reason, it is important to simplify and cluster the characteristics of the building stock, while maintaining as many individualities as possible. For that reason, the key parameters that define the residential stock, such as year of construction, amount of dwellings, the building typology and building surface, have been identified. It is important to note that the different categories of each of the key parameters may be different depending in the area selected, in this case, 12 clusters have been defined with specific energy demand and building characteristics.

The capabilities of this method have been assessed for the region of Catalonia (North-East area of Spain), where policies are encouraging the achievement of what they call an “Energetic transition agreement” coping with the idea of providing renewable energy by small suppliers (*i.e.*, building stock of the municipalities). In order to generate this energy, PV panels have been installed in the available roof area of the buildings. In this case study, a total of 947 municipalities of different sizes and characteristics have been analysed.

Following this methodology, we can conclude that, for the selected area, residential buildings can supply approximately a 20% of the electricity demand. According to the size of the municipality, this self-consumption rate decreases with the size of the municipality, with an important change of tendency for municipalities larger than 50000 inhabitants, where it decreases down to a self-consumption factor of 8% for the specific case of Barcelona (over 1,5 million habitants). Furthermore, this methodology enables the possibility to evaluate the effect of refurbishment of the actual building stock, which has been carried out in four different alternatives, reducing the energy demand by specific amounts (*e.g.*, energy reductions achieved by an insulation material). For this illustrative example, four different alternatives have been proposed, a reduction of 60% and 80% and fixing an energy demand of 30 kWh/m2 and 15 kWh/m2. The rationale is to illustrate the effect of building retrofit, varying from a 20% of self-consumption until more than 100% of self-consumption for the majority of municipalities with important building retrofit. Despite that, we can conclude that this measure of self-production is not able to produce all the energy required for the whole area in any case, which means that the building stock would always require an extra sources or energy (*e.g.*, solar farms and other renewable energies).

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I. Introduction

I.1.Background and motivation

1. Background and motivation

Society is facing an important challenge in terms of sustainability, due to the actual population, and its increasing tendency [3], and our society requirements, which are generating an important pressure in the planetary boundaries and in Earth's resilience [4]. Actually, four out of nine planetary boundaries have been crossed or are in high uncertainty risk, and another's one condition is under controversy. Those aspects suggest an obligation to switch into a more sustainable alternative; research can provide some information or guidelines to support the decision-making process for new policies.

To change the actual tendency, energy efficiency is a key objective in nowadays policies, to reduce greenhouse gas emissions, increase the renewable energy share and achieve important energy savings. Building sector is not an exception in this tendency. Being responsible of approximately a 50% of the total energy consumption and nearly 40% of the greenhouse gas (GHG) emissions in Europe [1], the window of opportunity is big. This energy comes mainly from lighting, heating and cooling if the entire building sector is accounted or heating and cooling and sanitary water for the residential part of the stock. Furthermore, if the residential sector is analysed, the room of improvement is large, with 50.7% of the buildings elder than 1969 (i.e., any thermal regulations), 30.6% of the buildings are between 1970 and 1989 and 18.7% after 1990 [5]. This shows that half of the residential stock was built before the application of thermal regulations [6], what leads into a high energy demand per surface (i.e. the average of energy consumption of residential sector (in normal climate) is 187.4 kwh/m2 [7].

The energy requirement implies several environmental impacts for the energy production (this sector responsible for more than 30% of the GHG emissions). Considering this, multiple policies are encouraging the construction and retrofit of buildings in a more sustainable way, reducing the energy demand of the buildings and implementing more sustainable materials with low embodied energy. To achieve those goals, multiple strategies can be applied which can include active and passive measures (i.e., efficient heaters or insulation, respectively). Those strategies should be analysed not only in terms of energy efficiency but also in terms of total cost and environmental impact in order to investigate the achievement of the corresponding targets with affordable measures.

To analyse those measures, tools that simultaneously assess the decision process in complex problems with multiple dimensions systematically could represent an important alternative to provide guidelines in the decision-making process of new policies.

2. General objectives

The general objectives of this thesis are:

1. To identify and evaluate the optimal building alternatives for bio-based materials that simultaneously minimizes cost and environmental impact without healthy risk.
2. To assess a systematic combination of insulation materials to generate more commercially appealing bio-based materials.
3. To evaluate the correlation between objectives to identify the possibility to reduce redundant objectives to simplify the systematic generation of composites.
4. To asses a regional analysis of the residential stock to evaluate the global effect of building retrofit.

3. Building simulation

In order to assess during the early stages design in buildings, coupling mathematical programming and building simulation is a promising alternative to evaluate the performance of the buildings and identify the more appealing alternatives. Optimization problems are usually carried out with mathematical programming, which is a widely method used in scientific or engineering problems and more recently in building modelling. This methodology has been widely used to evaluate the alternatives and minimize the cost, but more recently, multi-objective approaches have emerged to combine the optimization of other parameters, such as energy demand, thermal comfort and environmental impact [8,9] with the economic one.

In this thesis, we provide not only an optimization tool, but also a mathematic programming tool to assess the design of buildings with more environmental materials like bio-based insulation materials. Those tools focus on those materials and consider specific characteristics specific of them, which are the condensation risk and the limit of penetration in the market. In order to evaluate those characteristics, two different methodologies have been applied in the same case study. The first one evaluates the condensation risk using a multi-objective optimization methodology that minimizes the cost and the environmental impact, whereas the second one proposes a systematic generation of efficient alternatives of insulation materials with simple installation methods to increase the penetration of bio-materials in the market.

In order to achieve those objectives, the use of software tools is compulsory. Multiple software for building simulation have emerged in the last decades, handling complex engineering processes and improving the design steps. In terms of building simulation, a wide range of alternatives have emerged, covering Building Energy Modelling (BEM). Recently software tools that enlarge the scope are available, the so called Building Information Modelling (BIM). The first one couple with the objective to improve the energy efficiency process design, assessing the comparative between alternatives, economic optimization, among others, but those not cover the digital planning. On the other hand, the second methods also include information about the scheduling and delivering times, according to the Associated General Contractors of America definition.

Among the first group, the most commonly used are EnergyPlus and TRNSYS [10], whereas in the second category, IFC, Revit and ArchiCAD represent the state of the art in BIM [11]. In this thesis we are going to be focused mainly in the first group, given the fact that the main objective is to identify the optimal solution in terms of cost and environmental impact, especially focused on the early stages design. EnergyPlus and TRNSYS predict accurately building conditions and are able to use multi-zone model in thermal simulation. Building simulations are carried out with EnergyPlus (see chapters II and III for more details) which is more focused on the thermal performance of buildings and can be coupled/linked with moisture performance in building materials.

4. Environmental assessment methods

There are multiple methods to evaluate the environmental assessment, checklists and matrices, impact evaluation or life cycle assessment (LCA) among others. LCA has emerged as the prevalent approach [12], and is widely applied in decision-making contexts.

In order to evaluate the possibilities for the building retrofit, a LCA is perform in order to benchmark or optimize the different alternatives proposed. LCA is a data-based approach to define the environmental burdens associated with the different alternatives proposed independently of its nature, being an alternative for products, processes or activities. The idea is to transform those alternatives back into the initial raw materials and until the waste disposal, covering all the steps from cradle-to-grave [13]. This methodology is defined by the ISO 14040 and 14044 standards and is divided in four steps; goal and scope definition, inventory analysis, impact assessment and interpretation. A more detailed explanation can be found in following subsections for more details.

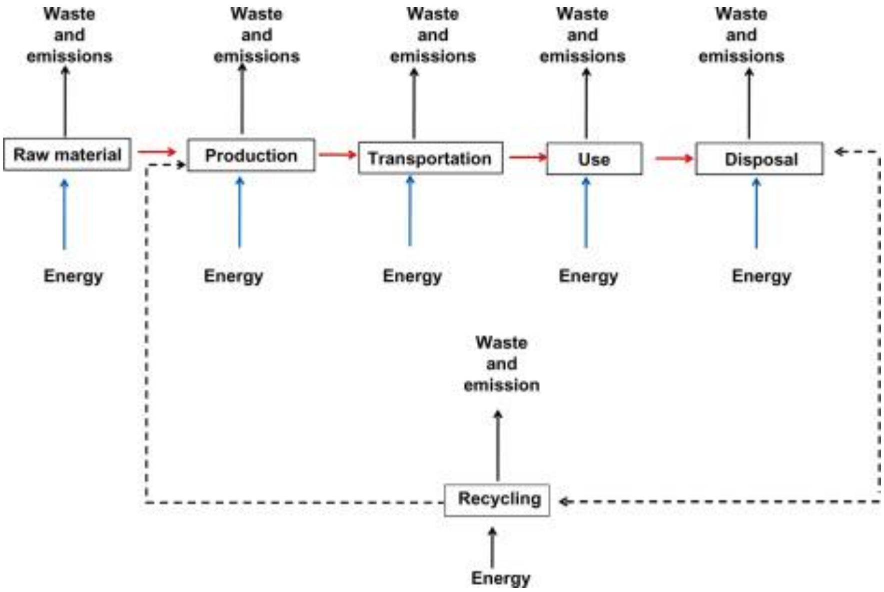

Figure I.1 Life cycle assessment in a production chain [14].

Perform a complete LCA is a complex and time consuming process, to reduce this process, several commercial software and methods have been developed, being SimaPro [15] and GaBi [16] the most employed ones. Despite the improvements of using those software the process is still a long and different databases have appear to speed up the process, such as Ecoinvent [17] database which has been used in this thesis to evaluate the environmental impact.

Integrate LCA and mathematical programming is a powerful tool to implement environmental assessment in decision-making processes, as it enables to quantitatively assess the environmental impact associated to different alternatives. Furthermore, when coupled with optimization it provides with useful insights to discriminate among different alternatives and strengthen and complement the policies resulted.

There are multiple variants of the LCA, which vary according to the areas of the life cycle included. Figure 2 provides an overview of the different options that vary from a whole cradle-to-gate until cradle-to-cradle. This is an important choice as it enables the comparison between the alternatives, in this thesis two different approaches are used, in the first case study a cradle-to-grave approach has be done accounting since the extraction of the raw materials until the end of life (see section 4.4.2 from the Chapter II). For the second case study a cradle-to-utilization, which include all the steps from the raw materials until the use phase (see section 2.4 from the Chapter III).

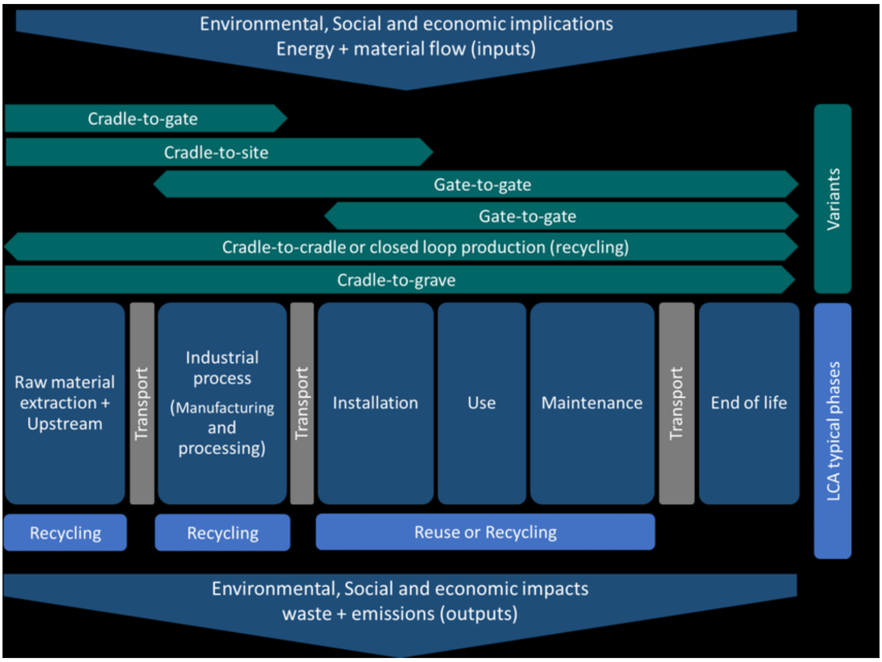

Figure I.2 Variants of life cycle assessment according to the steps included [14].

4.1. Goal and scope definition

This step will affect the results of the whole study. It defines the objective of the LCA and the boundaries of the study, with the corresponding functional unit. In this thesis, the system boundaries correspond to the cubicle with a specific comfort conditions for the corresponding climate conditions. In the first case study, we used a cradle-to-grave, starting from the raw materials necessaries for producing the equipment and the energy supplied to the system, until arriving to the conditions of comfort inside the building. In this case, the functional unit is the whole cubicle, due to the fact that different characteristics in the building would end in different results and the scope varies from a cradle-to-grave or cradle-to-utilization (including use phase but not end of life) perspective in the different chapters of the thesis (more details in Chapter II section 4.4.2 and Chapter III section 2.4 respectively).

4.2. Inventory analysis

In this step, it is necessary to analyse and quantify all the materials and energies used by the alternative under consideration. To do so, the energy and materials balances are carried out considering:

- Manufacturing and generation of utilities (e.g., industrial manufacturing and electricity production respectively) during the whole lifespan of the building.
- Materials and equipment transportation to the location of the building.
- Operational consumes during the whole lifespan (e.g., energy consumption for heating and cooling).

Those consumptions are transformed to elementary flows with Ecoinvent database (using v3.1 [18] in chapter II and v3.4 [19] in chapter III) (*i.e.,* recourses, emissions and wastes). Each contributor is quantified according to those three sources, according:

$$LCI_{tot} = LCI_{production} + LCI_{transport} + LCI_{operation} \quad (1)$$

Here, LCI tot corresponds to the total LCI for an elementary flow *i*, $LCI_{production}$ is the LCI of an elementary flow *i* of the manufacturing process and energies consumed, $LCI_{transport}$ accounts for the LCI for an elementary flow *i* associated to the transport steps and $LCI_{operation}$ is the elementary flow *i* of the operation step of the process.

4.3. Impact assessment

The objective of this calculation step is to transform those elementary flows into impact indicators according to the chosen methodology. Different methodologies are available and there is no general agreement on which one should be use. In this thesis, the methodology used is ReCiPe 2008, according to the EU Commission recommendation [20]. This methodology uses midpoints and endpoints levels of aggregation, where the first one correspond to the impact associated to a reference contributor for a category (*e.g.*, kg CO_2-equivalents for climate change measured in Global Warming Potential), and, on the other hand, endpoints are the damage resulting of a normalization and weighting process for the different impact categories (*e.g.*, ecosystem quality and human health have a corresponding impact associated to climate change category). The LCIA can be carried out either, using midpoints or endpoints with different connotations in each case; the main one is the consideration step in the cause-effect chain to calculate the impact, where endpoints evaluate the damage to human, species or resources (e.g., extinction of species due to a contaminant), midpoint considers the effect in the initial point of effect in environment (*e.g.*, the increase of a pollutant in the agricultural land) [21].

In this thesis, both levels of aggregation are used, following the next procedure (eq. 2 for midpoints calculations and from 3 to 5 for endpoint calculation):

$$LCIA_{mc} = \sum_i LCI_i \cdot C_{mi} \tag{2}$$
$$TI_m = \sum_m LCIA_{mc} \cdot Normalization_m \tag{3}$$
$$LCIA_{ec} = \sum_i LCI_i \cdot C_{ei} \tag{4}$$
$$TI_e = \sum_e LCIA_{ec} \cdot Normalization_e \cdot Weighting_e \tag{5}$$

4.4. Interpretation

The final step consists in the interpretation of the results, identifying the main sources of impact to provide information in order to suggest recommendations to improve the performance of the alternative or to discriminate between the different alternatives. In the following thesis, we couple the LCA assessment with MOO (Multi-Objective Optimization) and DEA (Data Envelopment Analysis) methodologies (see section 4.4.2 in chapter II and section 2.4 in chapter III for more information) in order to generate and evaluate these alternatives systematically, which results in a methodology that propose the best alternatives in terms of cost and environmental impact. Chapter II is based in a MOO algorithm that provides Pareto optimal solutions, whereas Chapter III is based in DEA and provide a set of efficient solutions, both of them propose a set of equally valid solutions that should be further analyse in order to identify the best alternative according to further constraints (*e.g.*, local resources availability).

5. Mathematical programming

Mathematical programming is a specific technique to reproduces real problems in mathematical algorithms to reproduce the reality. It is usually bonded with optimization, providing the possibility to evaluate the performance of the measures in order to minimize or maximize the key parameters of the problem, achieving feasible optimal solutions for a specific objective function. The objective function of the model is the equation that evaluates the quality of the solutions, which is optimized given a set of constrains or a particular set of variables. Those functions include economic, environmental, social or any other important parameter of the model (*e.g.,* maximizing the energy efficiency). This thesis is based on the first two cases, with the objective to minimize the cost and the environmental impact.

Depending on the optimization process, the models can be simultaneous or sequential, depending if the process is carried out globally or following a step-by-step approach. Mathematical optimization can be carried out coupled with simulation software to simplify the model, applying assumptions or numerical approximation specially with the objective of avoiding nonlinearities which imply more challenges to solve. In this thesis a simulation-optimization process is carried out in both case studies, dividing the model in different sub-problems. As previously explained, the simulation software used is EnergyPlus and the optimization is carried-out as a single-objective optimization and as a multi-objective optimization. For more detailed information on the models, see sections 4.4 and 4.5 of chapter II respectively.

5.1. Single-objective optimization

In mathematical models the single-objective optimization (SOO) problems can be simplified as an equation system of a main equation or objective function (which is minimized or maximized) and a set of constraints. The following model correspond to a minimization example:

$$\min f(x,y) \tag{6}$$

$$s.t.\, h(x,y) = 0 \tag{7}$$

$$g(x,y) =< 0 \tag{8}$$

$$x \in R, y \in Z \qquad (9)$$

here, f(x,y) represents the objective function to be minimized and x and y are the continuous and integer vectors of the decision variables (if any), respectively. The feasible set of solutions is defined by the set of constraints imposing restrictions on variables where h(x,y) represents equality constraints whereas g(x,y) refers to inequality constraints.

All points that satisfy all constraints are feasible solutions to the problem, conforming the feasible regions. The main objective of the problem is to optimize the model selecting from all the feasible solutions those which minimize (or maximize) the problem. In optimization problems all the solutions that minimize (or maximize) a feasible region are local minimum (or maximum), but only one takes the smallest (or the highest) value in the entire region, thus becoming the global minimum (or maximum).

5.2. Multi-objective optimization

Mathematical models usually consider multiple criteria simultaneously, generating a multi-objective optimization (MOO) problem that usually include conflicting objective functions. Those models are simplified in the following set of equations for a minimizing problem:

$$\min F = f_1, \dots, f_n \qquad (10)$$

$$s.t. \, h(x,y) = 0 \qquad (11)$$

$$g(x,y) =< 0 \qquad (12)$$

$$x \in R, y \in Z \qquad (13)$$

here, F corresponds to the objective function that ideally minimize all the individual functions, which it is usually a utopian point due to the conflicting nature of the objectives. Due to that reason, multi-objective problems usually results in a set of optimal solutions that usually provide of trade-off solutions between the different objectives (on the contrary, SOO achieves a single optimal solution). Those set of optimal solutions correspond to what is called a Pareto frontier. The following example correspond to an illustrative example for two objectives to minimize, where the Pareto frontier is represented by grey dots. All solutions that lies above this curve are feasible solutions, while the ones that lie under the line are infeasible solutions. The utopian point is the one that ideally minimizes both objectives at the same time and the nadir point is the worst point in both objectives. Those solutions that are above the Pareto frontier are suboptimal solutions and the extreme solutions of the Pareto frontier corresponds to the single-optimization for each objective.

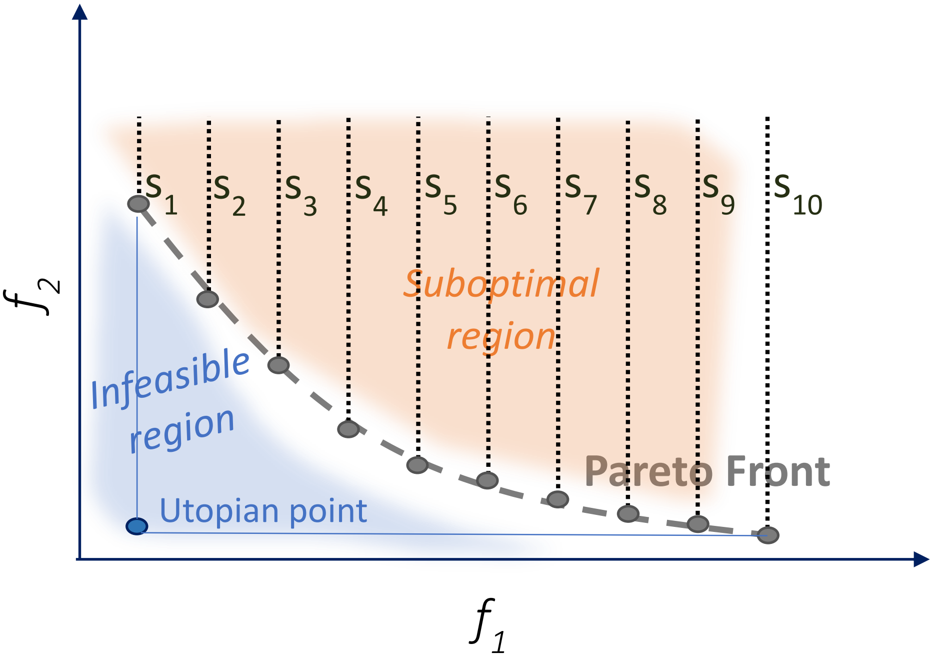

Figure I.3. Illustrative example for a multi-objective optimization of 2 objectives.

There are several approaches to obtain the whole set of Pareto optimal solutions for MOO, being weighted-sum and epsilon constrains the most used. The first one optimizes the weighted sum of all the objectives, while the second maintains one objective as the objective function and the rest are included as additional constrains to the main objective. Despite that, in this thesis we have incur to the brute force approach to achieve all the possible solutions and afterwards conform the Pareto frontier with the optimal ones.

5.3. Data Envelopment Analysis

Data Envelopment analysis (DEA) is a non-parametric linear mathematical programming method, that evaluates the performance of a different set of alternatives or decision-making units (DMUs). This performance is evaluated in terms of inputs and outputs, for each DMU DEA provides an efficiency score that varies between 0 and 1, which is calculated as the ratio of the weighted sum of their outputs and inputs. Efficient solutions are those that obtain and efficiency score of 1, while inefficient solutions are all the solutions that are strictly below 1. Between all the efficient solutions is formed the so-called efficient frontier where inefficient solutions are projected to obtain the reference set and the improvement targets to achieve efficiency. This efficiency score is the comparative between all the DMUs using the performance of ratio “output to input” (i.e., how much output provides the DMU for a specific amount of input). DEA also provides the information or the goals that a non-efficient DMU should be improved to became efficient. It also informs about the amount of similarities with each specific efficient DMU in order to provide information of the ideal composition alternative.

The standard DEA model was proposed by Charnes *et. al.* [22], CCR model, which considers that the changes in the outputs are proportional to the changes in the inputs, what is known as constant return to scale [23]. Lately, Banker *et. al.*, modified the original model with the property of variable return to scale (VRS), which is the model used in this thesis as all the materials insulation at different scale can have a difference performance and be still efficient (see section 1.2 in chapter III for more information). In terms of the improvement requirement of inefficient DMUs to achieve efficiency, two different orientations can be applied, an input-oriented or an output oriented-model, which is the reduction (or increase) in the inputs (or outputs) while the outputs (or inputs) are constant, for this thesis the input-oriented.

$$\min \quad \theta_0 - \varepsilon\left(\sum_i s_i^- + \sum_r s_r^+\right) \tag{14}$$

$$\text{s.t.} \quad \sum_j \lambda_j x_{ij} + s_i^- = \theta_0 x_{i0} \qquad \forall i \in I \tag{15}$$

$$\sum_j \lambda_j y_{jr} - s_r^+ = y_{r0} \qquad \forall r \in R \tag{16}$$

$$\sum_j \lambda_j = 1 \tag{17}$$

$$\lambda_j, s_i^-, s_r^+ \geq 0 \qquad \forall i, r, j \tag{18}$$

here, θo is the relative efficiency score of the DMU analysed, which can vary between 0 and 1, being one the maximum possible efficiency (which indicates efficient status) and 0 the minimum one; ε is a non-Archimedean value, which forces the strict positivity of the variables; s_i and s_r, correspond to the model slacks for inputs and outputs, respectively; and $λ_j$ is the weight assigned to each peer DMU_j in the creation of the virtual DMU.

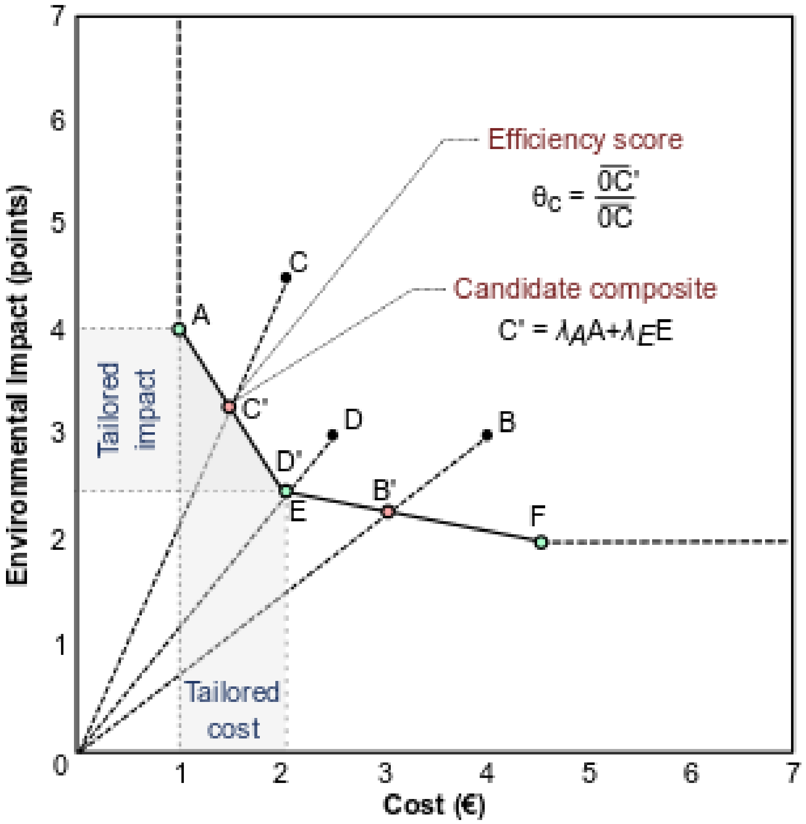

Figure I.4. Illustrative example of a DEA BCC model with radial projections.

Figure I.4. represents an illustrative example of a BCC model, where the efficient frontier is represented by green dots while non-efficient ones are blue and their radial projections are blue squares. As shown, the efficiency is the ratio between the distance of the projected DMU until the origin divided by the distance of the DMU until de origin. Furthermore, the projected DMU is the combination of the linear weights of the adjacent efficient DMUs. For those inefficient DMUs projected outside the efficient frontier can be projected to the weakly frontier (becoming weakly efficient) and become strongly efficient by the reduction of the corresponding input according to the slack (distance from the weakly projected DMU until the strongly projected DMU).

6. Case studies overview

Simulation-based optimization can assess in decision-making process, helping in the early stages of the design and providing guidelines for policy-makers. In this terms two different simulation-based optimization methods have been addressed in this thesis.

6.1. Case Study I: Bio-based insulation materials analysis

Bio-based insulation materials seem a promising alternative for both, building construction and building retrofit, due to the potential to reduce the energy demand in the operation phase of buildings. Despite that, it has further aspects to take into account compared to commercial materials. In order to assess the evaluation of those risks, we have proposed a methodology that combines building modelling optimization with condensation risk evaluation.

Our method combines EnergyPlus with total cost, life cycle assessment and condensation risk in a multi-objective optimization method. As a result of this connection, optimal insulation thickness for any climate and comfort conditions can be identified, considering economic and environmental criteria simultaneously and without condensation risk.

The capabilities of the proposed method are illustrated through its application in a case study based on a cubicle-like building in three different climate conditions (Lleida, Ouagadougou and Porto Velho). Numerical results show that bio-based materials can achieve improvements against commercial materials but an initial evaluation of the condensation risk is required to skip healthy problems due to condensation risk. In Figure I.5, we have graphically summarized the outline of the proposed approach of chapter II.

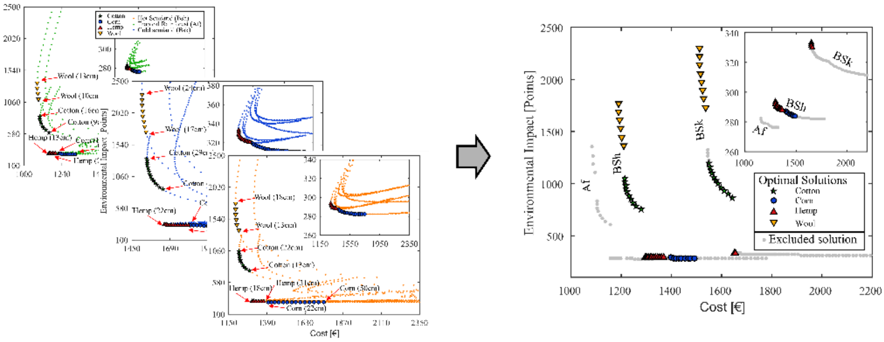

Figure I.5. Graphical abstract of "Multi-objective optimisation of bio-based thermal insulation materials in building envelopes considering condensation risk"

6.2. Case Study II: Bio-based composites generation

Despite bio-based materials are a promising alternative for building insulation, the market of those materials is still small and what suggest that some changes are required in the installation steps to became more appealing materials. In order to couple that proposal a methodology that combines materials into sandwich panels, rigid panels and fibre mats is proposed. The idea is to generate compensate materials with tailored properties and similar installation process as commercial materials.

To achieve that objective, a methodology that combines building simulation, Data Envelopment Analysis, total cost and life cycle assessment is proposed. This methodology identifies the efficient solution for different material-thicknesses combinations and provides composite proposals form the projected efficient alternatives.

We apply this tool to a case study of a cubicle-like building in Lleida, but it is general enough to integrate other buildings, climates or materials to the analysis. The methodology has proved its potential providing efficient composite alternatives with more balanced properties and simple installation. Figure I.6 summarizes the outline of the model of chapter III.

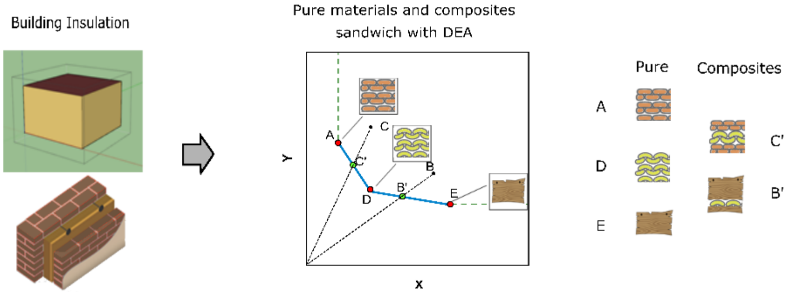

Figure I.6. Graphical abstract of "Systematic combination of insulation biomaterials to enhance energy and environmental efficiency in buildings"

6.3. Case Study III: Building stock quantification and analysis

We propose a methodology to assess a regional analysis of building retrofit, analysing the potential of roof installation of PV and the improvements in thermal envelope. The methodology has been assessed in illustrated in a case study in Catalonia, showing a global self-consumption potential of 20% for the residential sector, requiring an important retrofit (energy reduction of 80%) in order to achieve that the majority of municipalities achieve self-consumption in this sector.

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I.7.References

II. Case Study I

II.7.References

II. Multi-objective optimisation of bio-based thermal insulation materials in building envelopes considering condensation risk

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Abstract

The reduction in energy demand for heating and cooling with insulation materials increases the material related environmental impact. Thus, implementing low embodied energy materials may equilibrate this trade-off. Actual trends in passive house postulate bio-based materials as an alternative to conventional ones. Despite that, the implementation of those insulators should be carried out with a deeper analysis due to their hygroscopic properties. The moisture transfer, the associated condensation risk and the energy consumption for seven bio-based materials and polyurethane for a building-like cubicle are analysed. The performance is evaluated combining a software application to model the cubicle (EnergyPlus) and a tool to optimize its performance (jEPlus). The novelty of this optimization approach is to include and evaluate the effects of moisture in these insulation materials, taking into account the mass transfer through the different layers and the evaporation of the different materials. This methodology helps optimise the insulation type and thickness verifying the condensation risk, preventing the deterioration of the materials. The total cost of the different solutions is quantified, and the environmental impact is determined using the life cycle assessment methodology. The effect of climate conditions and the envelope configuration, as well as the risk of condensation, are quantified. The results show that cost and environmental impact can be reduced if bio-based materials are used instead of conventional ones, especially in semiarid climates. Condensation risk occurs for large thicknesses and in humid climates. In our case studies, hemp offered the most balanced solution.

1. Keywords

Multi-objective optimization; life cycle assessment (LCA); bio-based building materials; thermal insulation; condensation risk; moisture transfer.

2. Nomenclature

LCA	Life cycle assessment
GHG	Greenhouse gases
DEA	Data Envelopment Analysis
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
μ	Permeability resistance factor
CFT	Conduction Transfer Function

HAMT	Heat and moisture transfer
SOO	Single-objective optimisation
MOO	Multi-objective optimisation
CTE	Spanish building code
ITEC	Institute of technology of the construction
RH	Relative humidity
BSk	Cold semiarid climate
Af	Tropical rainforest climate
Bsh	Hot semiarid climate
COP	Coefficient of performance
PPD	Predictive percentage dissatisfied
C1	Insulation inside the air gap -core insulation
C2	Insulation interior surface of the wall -indoor insulation,
C2	
GLO	Average global impact
α	Thermal diffusivity (m2/s)
κ	Thermal conductivity (W/mK)
ρ	Density (kg/m3)
C	Specific heat (J/kg·K)
Cost_{cub}	Cost derived from the construction of the cubicle (€)

II.2.Nomenclature

$Cost_{elect}$	Cost of the electricity needed for heating and cooling the cubicle (€)
$Price_{mat}$	Cost of the materials used to build the cubicle (€/kg)
$Price_{elect}$	cost of the electricity (€/kWh)
$Price_{ins}$	market prices of the different insulators (€/kg)
$m_{(mat,n)}$	materials mass (kg)
m_{ins}	insulation mass (kg)
m	years
i	annual increment (%)
$Cost_{total}$	Total cost (€)
Imp_{cub}	Impact of the materials used in the construction of the cubicle (points)
Imp_{elec}	Impact of the electricity consumed during the operation time horizon (points/kWh)
Imp_{mat}	Impact of the construction materials of the cubicle (points/kg)
Imp_{ins}	Environmental impact per mass corresponding to the insulation material (points/kg)
$Cons_{elect}$	Consumption for heating and cooling (kWh)
$f_{Rsi,min}$	Minimum acceptable interior surface temperature
f_{Rsi}	Interior surface temperature
θ_{si}	Internal interstitial temperature

θ_e	Outside temperature
θ_i	Inside temperature and
$\theta_{si,min}$	Minimum interstitial temperature
P_{sat}	Saturation pressure
Pi	Vapour pressure
θ	Temperature
ϕ_i	Internal relative humidity
EMPD	Effective Moisture Penetration Depth
DB-HE	Basic document of Energy Efficiency

3. Introduction

Intervention in existing building stocks is a key strategy for tackling the objectives posed by the European Commission, which urge member countries to reduce the internal greenhouse gases (GHG) emissions by 80% in 2050 with respect to their 1990 emissions levels. This means that many buildings are and will be potentially renovated throughout Europe. It is estimated that about 10 million dwellings should be refurbished between now and 2050 only in Spain if the above mentioned EU challenges are to be achieved [24]. Among the multiple strategies that can be applied to reduce the energy consumption of buildings, the improvement of envelope thermal performance by the implementation of thermal insulation materials is one of the most extended. If properly implemented, higher insulation has been proved to reduce building energy demand and thus, the environmental impact and costs associated with energy production and consumption [25]. However, such intervention also requires an investment and involves an environmental impact derived from the manufacture, installation, dismantling and disposal of the materials [26,27]. If the so-called conventional insulation materials are used (organic foams and mineral wools), increasing the thermal performance of the envelope implies increasing the thickness of the insulation layer, which, in turn, translates into more materials and higher environmental impact [28]. Neglecting such environmental impact may lead to solutions that, even when effectively improving the operational energy efficiency, they result in a higher global impact on the environment [29–31].

Accordingly, the development of innovative insulation materials has gained the interest of the scientific community in the recent years. Two different approaches have been adopted: (1) the reduction of the amount of material used, that is, improving the thermal performance of the materials [32,33]; and (2) the reduction of the environmental impact associated to the material, that is, replacing conventional materials with “environmental friendly” ones[34,35]. Aerogels and vacuum insulation cells are examples of the former. Bio-based materials, such as hemp or wood mats, are examples of the latter. In the development of bio-based insulation materials, natural fibres and aggregates are used alone or combined to conform highly porous thermal insulation products [36–39]. Such products can compete with conventional materials in terms of thermal conductivity (which is about 0.040 $W \cdot m^{-1} \cdot K^{-1}$) but, also, offer additional environmental advantages [40].

Although bio-based insulation materials are increasingly commercially available, their market share corresponds only to a marginal fraction of the global thermal insulation market [41]. This is in part due to their relatively high economic cost when compared to mineral wools or polystyrene. However, as the environmental impact is beginning to be considered, a compromise between these two competing factors (*i.e.*, cost and environmental impact) will be increasingly sought. In such a context, the advantages offered by bio-based materials will probably boost their use. However, such speculation is merely intuitive. In order to discern which solutions, among the possible options, can simultaneously optimise these two factors a systematic optimisation process is required that uses adequate solution algorithms.

Optimisation algorithms have been proved to be a powerful tool in the disclosure of optimal solutions for the design of efficient building services. A wide range of possible optimisation methodologies are available [42], such as Data Envelopment Analysis (DEA) [40], TOPSIS decision-making methods [43,44], genetic algorithms [45–47], Particle Swarm Optimization algorithms [48] or Pareto based algorithms [49–51], each presenting their strengths and drawbacks [30]. In buildings, optimisation algorithms have been generally used focusing the optimisation of a single objective variables, which may either be the cost [52,53], the energy needed to operate the building [54], the CO_2 emissions or the environmental impact derived from the construction, use, and demolition of the building [55].

However, some authors also propose the use of such mathematical tools for the optimisation of two or more objective variables simultaneously. Fesanghary et al. [8] combined different genetic algorithms to generate inputs for the optimisation process which included the CO_2 emissions as an optimisation objective. More recently, Wu et al. [9] proposed a bottom-up methodology which optimises different characterised buildings for optimising a complete residential community, minimising the cost and the generation of GHG. Finally, Carreras et al. [29], proposed a multi-objective optimisation model capable of highlighting the optimum thermal insulation thicknesses that simultaneously minimised the cost and environmental impact associated with both the energy consumption over the operational phase and the manufacture of the construction material. The authors found that for the continental climate of Lleida (Spain), the use of different insulation thickness in each wall orientation does not represent an important reduction in the global cost of the solutions. From all the materials analysed (mineral wool, polystyrene, and polyurethane), the latter offered the best performance regarding economic cost, while mineral wool offered lower environmental impact and a more balanced compromise between both parameters. The study of Carreras et al. [29] showed that an informed choice of the insulation material and thickness might result in important cost savings and environmental benefits. It also pointed out the importance of the material choice in the total impact of the building.

In addition, within a wall system, the presence of thermal insulation materials can cause problems of condensation. Unlike conventional materials, bio-based insulation materials have low water vapour permeability resistance factors (μ about 3-6) and are highly vulnerable to mould growth [56]. Thus, they are more sensitive to humidity problems. Usually, interstitial condensation can be controlled with water vapour barriers. However, one of the advantages of bio-based materials is their hygroscopicity, which has been proved to contribute in the passive control of indoor air comfort conditions, both in terms of temperature and relative humidity [57–59]. In consequence, condensation risk assessments are even more crucial if bio-based insulation materials are to be used.

In the present work, seven bio-based materials are evaluated using the approach proposed by Carreras et al. [29], in order to determine how the optimal solutions achieved with these materials compare with the optimal solutions obtained with conventional ones. The novelty of this work is the implementation of the condensation risk combined with multi-objective optimisation, analysing the mass transfer through the construction layers and the evaporation capacity of the materials. It is carried out for the different solutions, which would generate optimal solutions without health problems due to the presence of mould in bio-based materials. The investigation is divided into two parts. In the first part, the materials are compared using EnergyPlus models based on an experimental cubicle from the University of Lleida [60]. Multi-objective optimisation is used to evaluate their cost and environmental impact performance simultaneously. In the second part, the effect of the position of the insulation layer in the building envelope and the effect of the climate on the results is also analysed. Moreover, the risk of condensation of each of the optimal solution obtained is evaluated with the intent to evaluate its feasibility.

4. Methodology

In this paper, seven bio-based building insulators (one of which is an experimental corn-pith based material) are evaluated and compared to a conventional polyurethane insulator. The materials are compared in terms of the total environmental impact and total cost resulting from their implementation in buildings.

To this aim, a case study was chosen, corresponding to an experimental cubicle built at the testing site at the University of Lleida. The building was modelled and calibrated before the analysis. Then, the materials were compared for three different climate conditions and two wall configurations by means of a multi-objective optimisation process, in which the risk of condensation was considered. A simplified algorithm describing the complete process is presented in Fig. 1. As shown in Fig. 1, the methodology proposed can be divided into three main optimisation loops: step 1, single-objective optimisation; step 2, multi-objective optimisation; and step 3, assessment of the risk of condensation. These optimisation loops are described in more detail in the following sections.

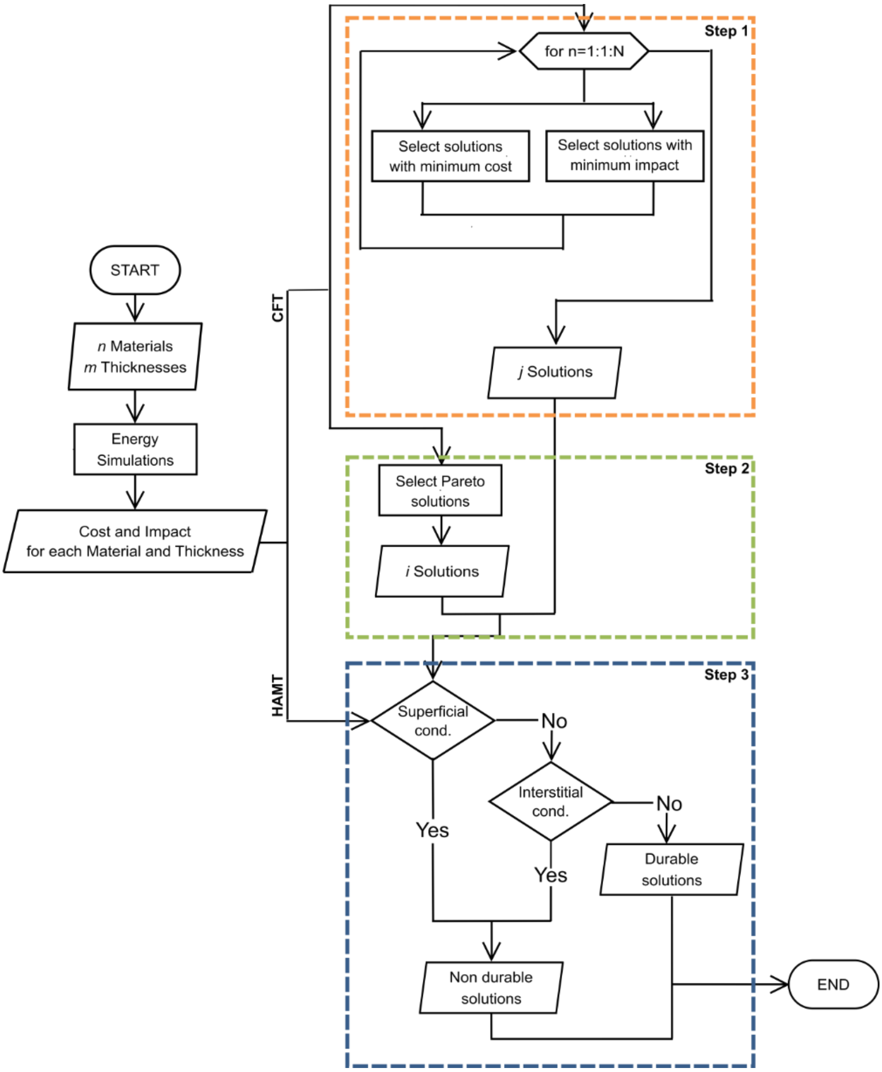

Figure II.1. Simplified algorithm for the optimisation process.

4.1. Description of the experimental cubicle

The model considered for calculation corresponds to an experimental cubicle built at the testing site of the University of Lleida in Puigverd de Lleida, Spain (see Fig. 2). This experimental cubicle has an external volume of 2.44 × 2.55 × 2.44 m with only one opening: a window of 0.8 × 1.2 m, situated on the south façade. The ratio wall/window at the south façade is 6. The construction profile, depicted in [60], represents a conventional

Mediterranean construction system. The wall of the cubicle is composed (from inside to outside) by a plaster finishing (1 cm), 14 cm thick perforated bricks, an air gap of 5 cm, and a finishing layer of hollow bricks (7 cm) rendered with 1 cm of cement mortar. The flat roof consists (from inside to outside) on plaster finishing (1 cm), a concrete beam and pot floor of 5 cm, a lightweight concrete layer in the form of slopes (3%), and a double asphaltic membrane for waterproofing. The foundations consist of a reinforced concrete slab of 3 × 3 m and 21 cm thickness.

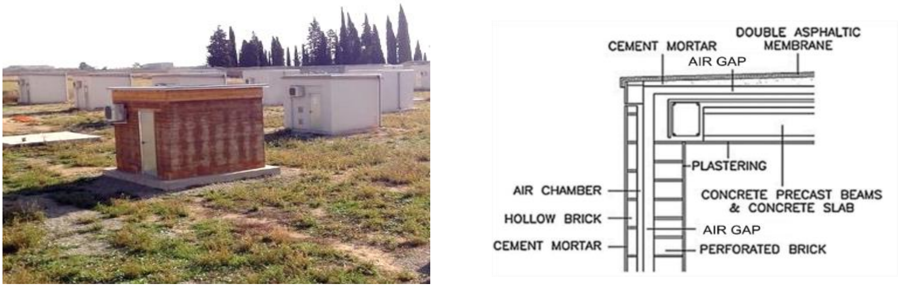

Figure II.2. Cubicles build at the testing site of University of Lleida and section showing the components of the envelope of the cubicle used for calibration [29].

4.2. Specifications of the energy model

The energy model of the cubicle was built using the OpenStudio [61] plug-in for SketchUp [62] and EnergyPlus [63] as the calculation engine. The model was built based on the characteristics of the experimental cubicle. The physical and thermal properties of the construction materials were obtained from the Spanish Building Code (CTE) [64], ITEC [65] and the technical sheets of the products [66–68], or were determined experimentally [69]. These are presented in Table 1.

Once the model is defined, the selected parameters are identified and specified (defining all the alternative values) in jEPlus [70] (a parametric tool), which generates a different model for each of the specifications proposed (m materials and n thicknesses). The output values of the simulation are selected in jEPlus, in our case, the energy demand for cooling and heating during a whole year. Finally, jEPlus generates a simulation request to EnergyPlus for each alternative modelled, and once the simulation is finished, jEPlus reads all the results files and combines them in a single file with the demands for all alternatives proposed. A scheme of the process is shown in Figure 3. The energy performance of the model was calculated following the hypothesis presented in Table 2. Then, the model was calibrated using the temperature and RH data yield in the monitoring of the experimental cubicle during a year [29,71].

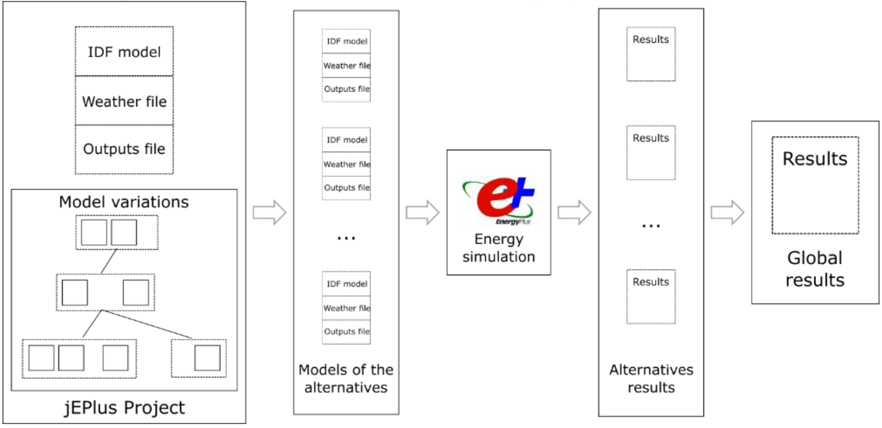

Figure II.3. Diagram of the connection between jEPlus and EnergyPlus.

II.4.2.Specifications of the energy model

Table II.1. Physical properties and market prices of the different building materials.

	Density (kg/m^3)	Thermal conductivity (W/m·K)	Specific heat (J/kg·K)	Thermal diffusivity (10^{-6} m^2/s)	Market price (€/kg)
CONSTRUCTION					
Plaster	1150	0.570	1000		-
Perforated brick	900	0.543	1000		-
Hollow brick	930	0.375	1000		-
Cement mortar	1350	0.700	1000		-
Asphaltic membrane	2100	0.700	1000		-
Concrete	2100*	0.472*	1000*		-
Steel bars	2100*	0.472*	1000*		-
Concrete tiles	1920	0.890	790		-
INSULATION					
Cotton	25	0.036	1800	0.80	1.024
Cellulose	45	0.035	1900	0.41	1.071
Cork	110	0.040	1700	0.21	0.909
Corn	50	0.038	1800	0.42	1.100
Hemp	30	0.041	1800	0.76	1.360
Wool	30	0.045	1800	0.83	0.947
Wood	250	0.050	1850	0.11	1.172
Polyurethane	45	0.027	1000	0.60	3.889

*Values for a precast reinforced concrete beam.

Table II.2. Hypothesis established for the calculation of the energy performance of the model.

	Hypothesis

External thermal loads	The cubicle is situated in a cold semiarid climate (BSk following the Köpen climate classification) which corresponds to the climate of Lleida, Spain, where the cubicle is physically built. The orientation of the building is the same as the physical cubicle.
	Infiltrations are set at 0.12 air renovations per hour.
	The envelope is homogenous, without any thermal bridge.
Internal thermal loads	Inexistence of internal gains (considering that the cubicle is not occupied).
Conditioning systems	The onset temperature is fixed for summer and winter, as described in ISO 7730 [72].
	The heating and cooling energy are supplied by a reversible heat pump with a COP of 3. The air exchange rate is dependent on temperature and fluctuates between 2 and 5 l/s.

The model was afterwards modified to analyse the performance of diverse bio-based thermal insulation materials. The variables analysed were:

(1) type of thermal insulator (7 bio-based materials and polyurethane). Their properties are presented in Table 1.

(2) thickness of the insulation layer, which was homogeneous all over the envelope, as previous studies showed that such assumption does not have a significant impact on the results [29], when compared to options in which the thickness of the insulation layer can vary from wall to wall.

(3) position of the insulation layer within the thermal envelope (either inside the air gap -core insulation, C1- or at the interior surface of the wall -indoor insulation, C2).

The aim was to find out which of the possible combinations resulted in a solution with simultaneously low environmental impact, low cost and low risk of condensation (that is, high durability). This analysis was performed for the original climate conditions (cold semiarid; BSk following the Köpen climate classification) and two other distinct climate regimes: tropical rainforest (Af), and hot semiarid (BSh). The setpoint temperature was fixed following the ISO 7730, Table A.5, limiting discomfort to < 10 PPD (category B) and considering a metabolic activity corresponding to an individual office. For the cold semiarid climate, the set-point was 20ºC during the heating season and 26ºC during the cooling season. For the two other climates, the set-point for the cooling season (26ºC) was used for the entire year. Fig. 4 summarises the different conditions analysed. The steps depicted correspond to those shown in Fig. 1.

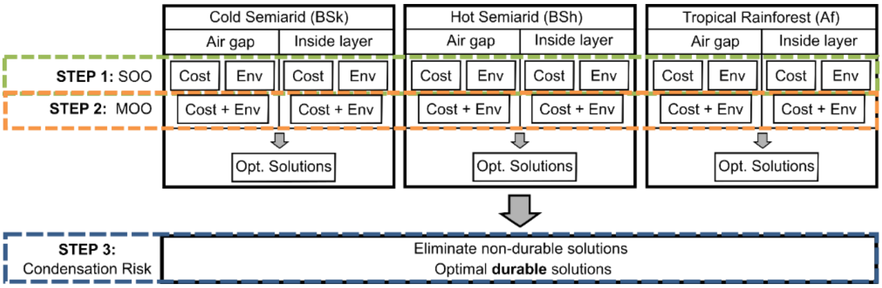

Figure II.4 Diagram depicting the process followed.

It should be noticed that the modifications imposed to the model are essentially influencing how heat (and moist) is transferred through the building envelope. Heat transfer in building envelopes can be expressed using Eq. 1:

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2}$$

(Eq.1)

which shows how heat transfer through a material is determined by the difference in temperature between its faces (which is different for each of the climates and wall compositions analysed) and the thermal diffusivity of the material (different for each of the insulators).

In turn, the thermal diffusivity of a material can be expressed as:

$$\alpha = \frac{k}{\rho C}$$

(Eq. 2)

Where: α is the thermal diffusivity (m2/s); κ is the thermal conductivity (W/mK); and ρC is the product of density (kg/m3) and specific heat (J/kg·K).

Usually, the performance of thermal insulators is determined by its thermal conductivity. However, as noticed before, density and heat capacity also play a role in their thermal performance, especially for bio-based materials, which are denser and with higher specific heat capacity than the conventional inorganic or petrol-based insulators.

To evaluate the transient energy performance of buildings, EnergyPlus allows for the choice between three different mathematical models: Conduction Transfer Function (CFT), Combined Heat and Moisture

Transfer (HAMT), and Effective Moisture Penetration Depth (EMPD). The CFT model was used in steps 1 and 2 and the HAMT one in step 3. Thus, in steps 1 and 2, heat transfer and storage within the materials were evaluated, but the effect of moisture content and moisture migration through the materials was not considered [73]. This choice derived from the need to reduce the complexity of the model. It was considered that such simplification did not affect the results considerably as preliminary tests performed by the authors had shown that, the annual results obtained with the CFT and the HAMT models were similar: with the HAMT model, energy consumption was higher in winter (due to the higher thermal conductivity), but this was compensated during summer, when the increased thermal inertia helped to reduce the need of refrigeration. In step 3, however, the HAMT model was used as, to assess the risk of condensation, the modelling on how moisture migrated within the materials was required.

4.4. Single-objective optimisation

4.4.1. Cost assessment

The economic indicator was determined as the sum of the cost derived from the construction of the cubicle ($Cost_{cub}$, €), which includes the cost of the construction materials and the thermal insulators, and the cost of the electricity needed for heating and cooling the cubicle along a lifespan of 20 years ($Cost_{elect}$):

$$Cost_{Cub} = \sum_n Price_{mat,n} \cdot m_{mat,n} + Price_{ins} \cdot m_{ins} \qquad \text{(Eq. 3)}$$

$$Cost_{elect} = \sum_m Price_{elect} \cdot kWh_{elect} \cdot (1+i)^m \qquad \text{(Eq. 4)}$$

$$Cost_{total} = Cost_{Cub} + Cost_{elect} \qquad \text{(Eq. 5)}$$

The cost of the materials used to build the cubicle ($Price_{mat}$) was 940 € [29]. The market prices of the different insulators ($Price_{ins}$) are presented in Table 1. The cost of the electricity ($Price_{elect}$) was assumed to be 0.22 €/kWh, with a yearly cost increment of 5%. The electricity mix considered was that of Spain for the year 2015.

4.4.2. Environmental impact

ReCiPe [2] indicator was used to determine the environmental impact of the materials. ReCiPe is a rating method in which 17 different impacts are aggregated into three different damage categories (human health, ecosystem quality, and resources) and translated into points using normalisation and weighting factors.

For the calculations, two main sources of impact were considered: the manufacture of the materials used in the construction of the cubicle, including the dismantling phase (Impcub), and the amount of electricity consumed during the operation time horizon, defined in 20 years (Impelec). The values corresponding to each component were obtained from Ecoinvent database (version 3.2.). Values for global market (GLO) were preferred. Where the specific material or component was not available, the most similar option was chosen. In order to cover the whole life cycle of the materials (cradle to grave) the impact of the waste processing was also included in the calculation.

The first source of environmental impact (Impcub) was determined as follows:

$$Imp_{cub} = \sum_n Imp_{mat \cdot n} \cdot m_{mat \cdot n} + Imp_{ins} \cdot m_{ins} \quad \text{(Eq. 6)}$$

Where: Impcub (points) is the total ReCiPe impact of the construction materials of the cubicle; Impmat (points/kg) is the coefficient of environmental impact per unit mass of a material n, which is taken from the Ecoinvent database [18]; mmat (kg) is the corresponding quantity of raw material n; Impins (points/kg) is the coefficient of environmental impact per mass corresponding to the insulation material evaluated; and mins (kg) is the total quantity of insulation used, which changes for each thickness analysed. The ReCiPe points attributed to each material are depicted in Table II..

For the second source, Ecoinvent data on the Spanish electricity production system is used to translate the electricity consumed over the operational phase into ReCiPe impact points as follows:

$$Imp_{elect} = Imp_{elect} \cdot Cons_{elect} \quad \text{(Eq. 7)}$$

Where: Impelect (points) is the total ReCiPe impact of the consumed electricity over the operational phase of the cubicle; Impelect (points/kWh) is the coefficient of environmental impact per kWh of electricity in Spain (0.0482 points/kWh); and Conselect (kWh) is the consumed electricity over the lifetime of the cubicle (20 years).

The global environmental impact is defined as the sum of the two sources (Impcub and Impelect).

Table II.3. Main sources of impact associated with the materials during the manufacturing and dismantling phases.

Component	Ecoinvent database item	ReCiPe (points /kg)	Amount (kg)	Total ReCiPe (points)
	CONSTRUCTION			
Plaster	Market for base plaster, GLO [kg]	0.0229	518	11.86
	Market for waste mineral plaster, GLO [kg]	0.0019	518	0.97
Brick	Market for brick, GLO [kg]	0.0285	5456	155.47
	Market for waste brick, GLO [kg]	0.0018	5456	9.65
Cement mortar	Market for cement mortar, GLO [kg]	0.0238	608	14.45
	Market for waste cement in concrete and mortar, GLO [kg]	0.0028	608	1.67
Reinforced concrete	Market for section bar rolling, steel, GLO [kg]	0.0200	262	5.24
	Market for concrete, normal, GLO [m^3]	28.3000*	0.57*	16.13
	Market for waste reinforced concrete, GLO [kg]	0.0025	1492	3.28
Concrete tiles	Market for concrete roof tile, GLO [kg]	0.0244	1770	43.16
	Market for waste concrete, not reinforced, GLO [kg]	0.0019	1770	3.28
Asphalt	Market for mastic asphalt, GLO [kg]	0.0378	153	5.78
	Market for waste asphalt, GLO [kg]	0.0021	153	0.32
	INSULATION			
Cotton	Market for cotton fibre [GLO] (kg)	3.3089	-	-
Cellulose	Market for cellulose fibre, inclusive blowing in [GLO] (kg)	0.0298	-	-
Cork	Market for cork slab [GLO] (kg)	0.5442	-	-

Corn	Market for maize silage, organic [GLO] (kg)	0.0157	-	-
Hemp	Market for kenaf fibre [GLO] (kg)	0.0993	-	-
Wool	Market for sheep fleece in the grease [GLO] (kg)	9.2190	-	-
Wood	Market for slab and siding, hardwood, wet, measured as dry mass [GLO] (kg)	0.0372	-	-
All bio-based insulation	Market for waste wood, untreated [GLO] (kg)	0.0043	-	-
Polyurethane	Market for polyurethane, rigid foam [GLO] (kg)	0.5195	-	-
	Market for waste polyurethane foam [GLO] (kg)	0.0581	-	-

*These values are given by volume unit.

Previous research showed that optimal solutions of low environmental impact materials require thicker insulation layers, whereas high embodied materials achieve thinner solutions. Beforehand, this implies that cellulose, corn and hemp would have thicker layers than other materials, while cotton and wool would have thinner ones. However, when energy consumption is taken into account, such trend may vary.

4.5. Multi-objective optimisation

After having identified the extreme solutions, that is, solutions minimising either cost or environmental impact, those solutions giving a better trade-off between these two competing objectives were identified by means of multi-objective optimisation (MOO). To this aim, the two objective functions presented in Sections 2.3.1 and 2.3.2 were considered. Then, the total cost and the total environmental impact of all the solutions (that is, all materials and thicknesses analysed) where plot together. When plotted on a chart where x axe corresponds to one of the optimisation objectives and y axe to the other, optimal solutions conform a Pareto front below which no solution exists which simultaneously improves both objectives. In other words, each point in the Pareto frontier minimises the total cost and the total impact. The rest of the solutions are so-called dominated solutions, that is, they have worse performance in one of the different objectives concerning the solutions forming the Pareto front, and thus can be dismissed.

4.6. Risk of condensation

The optimal solutions were evaluated in terms of the risk of condensation. The aim was to discard those options that were unfeasible due to the risk of superficial and interstitial condensations. This evaluation was made following the procedure described in the DB-HE of the Spanish Building

Code (CTE) [74]. This procedure is based on a comparison between indoor and outdoor conditions, which were output data from the energy simulations. The interstitial and superficial condensations were calculated for the most unfavourable month and the water evaporation for the rest of the year.

On a first step, the optimal cubicle configurations obtained previously were simulated using the HAMT model from EnergyPlus to obtain the temperatures and the humidity at each wall surface. From these results, the minimum acceptable interior surface temperature ($f_{Rsi,min}$), and the interior surface temperature (f_{Rsi}), were worked out following the method indicated at the DB-HE. Then, the superficial condensation risk was evaluated by comparing the $f_{Rsi,min}$ (Eq.8) against the f_{Rsi} (Eq. 9) and the interstitial condensation risk was determined by comparing the vapour pressure (Eq. 10) with the saturation pressure (Eq.11 and 12), which was calculated according to the DB-HE.

$$f_{Rsi,min} = \frac{\theta_{si,min} - \theta_e}{\theta_i - \theta_e} \qquad \text{(Eq. 8)}$$

$$f_{Rsi} = \frac{\theta_{si} - \theta_e}{\theta_i - \theta_e} \qquad \text{(Eq. 9)}$$

Where θ_{si} is the internal interstitial temperature, θ_e is the outside temperature, θ_i is the inside temperature and $\theta_{si,min}$ is the minimum interstitial temperature.

$$P_i = \phi_i \cdot 2337 \qquad \text{(Eq. 10)}$$

$$P_{sat} = 610.5 \cdot e^{\frac{17.259 \cdot \theta}{237.3 + \theta}} \qquad \theta \geq 0ºC \qquad \text{(Eq. 11)}$$

$$P_{sat} = 610.5 \cdot e^{\frac{21.875 \cdot \theta}{265.5 + \theta}} \qquad \theta < 0ºC \qquad \text{(Eq. 12)}$$

Where θ is the temperature and ϕ_i is the internal relative humidity.

If the result showed that condensation could probably take place, a further evaluation was performed, which considered the evolution of this condensation throughout the year. To this aim, the water content during the whole year of the layers that presented a risk of condensation was calculated following the EN ISO 13788, starting from the first month in which there was a risk of condensation. Such calculation allowed for the evaluation of the balance between the amounts of water condensed in a material surface and the water evaporated from that surface. For these solutions where the amount evaporated was higher than the condensed amount, it was considered that it would be naturally dried, and the solution was considered valid.

5. Results and discussion

As depicted in Fig. 4 at Section 2.2, the methodology proposed in this paper was applied to 6 different cases (resulting from the combination of 3 climatic conditions and two wall configurations). The results are presented in detail for one of the cases (insulation inside the air gap in a cold semiarid climate, BSk). The results of the other 5 cases are also shown but summarised in the tables presented below.

5.1. Single-objective optimisation

5.1.1. Cost assessment

As discussed in Section 2.3.1, a single-objective cost optimisation was conducted considering the market price of the insulations and construction materials, and the cost of the electricity needed to maintain the pre-set operative temperatures of the indoor air for 20 years by means of a reversible heat pump. Polyurethane, which in previous works was found to perform better than other inorganic and petrol-based insulation materials [6], was compared to seven different bio-based thermal insulation materials. Such comparison was done for six different configurations of the model, corresponding to the combination of three distinct climates and two wall arrangements. The optimal solution for each material is expressed in terms of the thickness of thermal insulation at which total cost is minimised. Fig. 5 depicts the kind of results obtained. For space limitation, only the results corresponding to PU and three of the bio-based materials (hemp, cork and wool), installed inside the air gap of the envelope (core insulation, C1) of a cubicle placed at a cold semiarid climate are presented. In the Figure, the red arrows show the optimal solution for each of the materials presented. The rest of the results are presented in Table 4.

As expected, the cost of the materials increases with thickness proportionally to their price per cubic meter, while the operative cost decreases faster at lower thicknesses and more gradually when a certain thickness is reached.

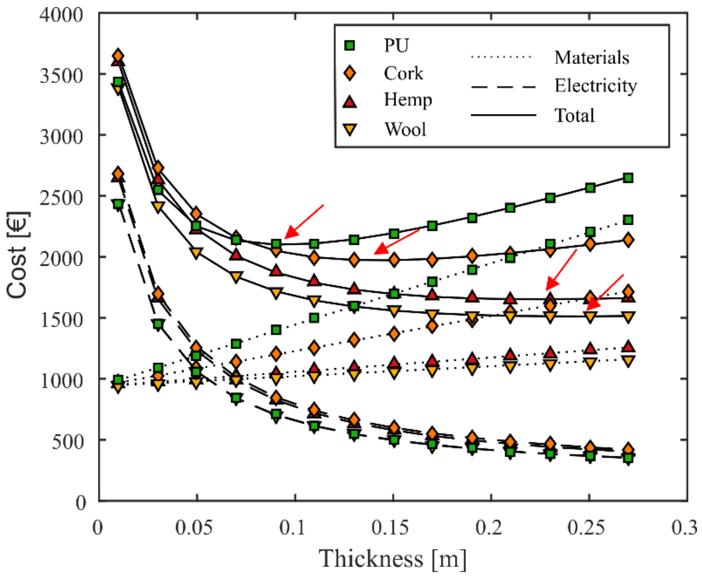

Fig. 1. Evolution of cost with insulation thickness for hemp, cork and wool. Polyurethane is included for comparison purposes.

From the results, it is noticeable that the performance of the materials is very similar in terms of energy savings (dashed line). Thus, the biggest difference between the materials, regarding total cost, is their purchase cost (dotted line). The materials having a higher cost per volume unit, that is, the most expensive and/or dense, show lower optimal thicknesses. In Fig. 5, polyurethane being the most expensive material, gives an optimal thickness of 9 cm, which means that the annual energy consumption is higher than for the rest of the cases. On the contrary, using wool would allow achieving higher energy savings, as its optimal thickness is 24 cm.

Table 4 presents, for each of the insulation materials and the three climates analysed, the optimal thickness, total cost and total environmental impact over 20 years. Only the wall arrangement in which the thermal insulation is placed in the air gap (core insulation, C1) is presented as this resulted in being the most optimal solution in all cases. The relative cost and environmental impacts of the bio-based cost-optimal solutions concerning those of polyurethane are also presented (values in brackets).

The results show that in the BSk and the Af climates, the use of bio-based materials is advantageous in all cases in terms of total costs with respect to the use of PU, with the exception of the wood insulation. The less expensive solution was the use of wool (24 and 13 cm at BSk and Af climates respectively), which supposed a total saving of 28% with respect to PU. However, when comparing the environmental impact, only cellulose, corn and hemp showed an improved behaviour compared to PU. It is noticeable that an informed choice of the insulation material can lead to cost savings up to 40% with respect to the most expensive option, which in this case was wood. Similarly, environmental impact reductions up to 85% with respect to the less performant option, which in this case was wool, can be achieved. In the hot semiarid climate (BSh), the trends differed from the other two climates. In this case, only cellulose and hemp resulted in lower cost and environmental impact than PU. It is important to note that the wood material chosen for this comparison is remarkably denser than the rest of the materials, which is highly affected by the cost per cubic meter of the solution.

Table II.4. Results from the single-objective optimisation of the cost in the three climates.

	Cold semiarid (BSk)			Tropical rainforest (Af)			Hot semiarid (BSh)		
	e (cm)	Cost (€)	EI (points)	e (cm)	Cost (€)	EI (points)	e (cm)	Cost (€)	EI (points)
Baseline	-	4966	772	-	3854	633	-	4674	735
PU	9	2100	422	6	1501	345	9	1676	368
Cotton	29	1544 (-26%)	1329 (+215%)	16	1102 (-27%)	833 (+141%)	22	2247 (+34%)	1051 (+186%)
Cellulose	21	1712 (-18%)	337 (-25%)	13	1195 (-20%)	284 (-18%)	17	1481 (-12%)	297 (-19%)
Cork	14	1971 (-6%)	525 (+24%)	9	1349 (-10%)	403 (+17%)	12	1711 (+2%)	455 (+24%)
Corn	19	1737 (-17%)	335 (-26%)	12	1209 (-19%)	282 (-18%)	14	1776 (+6%)	298 (-19%)
Hemp	22	1652 (-21%)	336 (-26%)	13	1158 (-23%)	283 (-18%)	18	1425 (-15%)	294 (-20%)
Wool	24	1512 (-28%)	2300 (+445%)	13	1085 (-28%)	1349 (+291%)	18	2381 (+42%)	1770 (+381%)
Wood	8	2677 (+27%)	428 (+1%)	6	1820 (+21%)	336 (-3%)	8	2487 (+48%)	374 (+2%)

5.1.2. Environmental impact

The environmental impacts (cradle to grave) of the insulation materials and the construction materials, together with the environmental impact of the electricity needed to maintain the pre-set operative temperature for 20 years were also considered for optimisation. The results are given in Fig. 6 and Table . For ease of understanding, only polyurethane and three of the materials (hemp, cork and wool) are presented in Fig. 6. Again, it was expected that a bigger insulation thickness resulted in a higher embodied environmental impact and a reduced operational environmental impact. It was also foreseen that the higher the environmental impact of a material, the lower the optimal thickness.

From the results it is noticeable that the optimal solutions for wool and cotton correspond to low thicknesses (1 to 3 cm) at the three climate conditions while, in contrast, the optimal solutions for cellulose, corn and hemp correspond to thicknesses between 20 and 86 cm, with a high variability depending on the outdoor climate conditions. This can be explained by the fact that for hot climates, the energy savings achieved with thicker layers do not compensate the embodied impact associated with the materials. This is even more remarkable for the tropical rainforest climate, where the thermal gap between day and night is moderate and which results in lower energy demand.

It is interesting to note that not all the bio-based materials have an improved environmental performance when compared to polyurethane. Wool and cotton showed a higher environmental impact than the rest of insulation materials, being agricultural land occupation the indicator that penalised the most their environmental profile. This resulted in lower optimal thicknesses (between 1 and 3 cm) and thus, in higher energy consumption. Using these two materials was also found to be more expensive, especially in the case of wool, which showed a cost between 42% and 61% higher than PU, depending on the climate. Although cork was able to compete with PU in terms of costs, it did not represent an advantage regarding the total environmental impact, probably due to its lower thermal performance when compared to PU. On the contrary, wood was competitive in terms of EI, but not regarding the cost. The experimental insulation (corn) resulted in being a good choice, but the results were sensitive to the climate regime. Hemp and cellulose were the best options in all cases. The use of these materials allowed for cost reductions between 5% and 20% and reductions of EI between 19% and 24% with respect to PU.

However, it should be noticed that the optimal thicknesses for cellulose, corn and hemp in the BSk and BSh climates are far much higher than those usually installed in buildings. This implies that in real situations these optimal solutions are unlikely to be implemented, as other limitations such as the occupation of the useful floor area, would come into play. In more realistic solutions in which the thickness of the insulator is limited to 20 cm, the EI would increase with respect to the optimal solutions shown here.

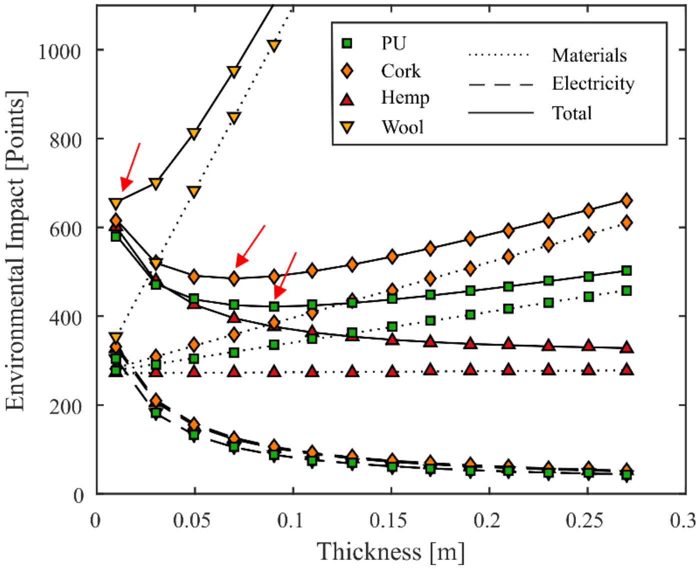

Fig. 2. Influence of the thickness on the environmental impact of cork, hemp, wool and polyurethane.

Table II.5. Results from the single-objective optimisation of the environmental impact in the three climates.

	Cold semiarid (BSk)			Tropical rainforest (Af)			Hot semiarid (BSh)		
	e (cm)	Cost (€)	EI (points)	e (cm)	Cost (€)	EI (points)	e (cm)	Cost (€)	EI (points)
Baseline	-	4966	772	-	3854	633	-	4674	735
PU	9	2100	422	6	1501	345	8	1677	368
Cotton	3	2643 (+26%)	585 (+38%)	3	1663 (+11%)	462 (+34%)	3	2247 (+34%)	536 (+46%)
Cellulose	56	2006 (-5%)	323 (-23%)	21	1255 (-16%)	280 (-19%)	34	1481 (-12%)	289 (-21%)
Cork	7	2154 (+3%)	485 (+15%)	5	1450 (-3%)	379 (+10%)	7	1711 (+2%)	430 (+17%)
Corn	86	2543 (+21%)	310 (-27%)	23	1325 (-12%)	276 (-20%)	50	1776 (+6%)	282 (-23%)
Hemp	56	1880 (-10%)	320 (-24%)	20	1200 (-20%)	279 (-19%)	36	1425 (-15%)	288 (-22%)
Wool	1	3386 (+61%)	657 (+56%)	1	2365 (+58%)	530 (+54%)	2	2381 (+42%)	614 (+67%)
Wood	17	3024 (+44%)	404 (-4%)	11	2020 (+35%)	324 (-6%)	15	2487 (+48%)	353 (-4%)

5.2. Multi-objective optimisation

A multi-objective optimisation was conducted following the methodology presented in Section 2.4, in order to identify the optimal solutions that lowered costs and environmental impacts simultaneously.

To depict the methodological process, all the results for a cubicle placed in a cold semiarid climate are presented first in Fig. 7, where the environmental impact is plotted against the cost for the two wall configurations and all the materials and thicknesses. Then, the optimal solutions constituting the Pareto front are highlighted in Fig. 8. Finally, in Fig. 9, these are compared to the optimal solutions obtained for the two other climates.

Plotting the environmental impact against the cost allows for the identification of both the extreme options (that is, the single objective optimum thicknesses) and the balanced options (that is, the options minimizing both values, which are to those situated in the areas of maximum curvature) corresponding to each of the insulation materials and wall configurations.

Note that some of the solutions in Fig. 7 are suboptimal since they are dominated by others (i.e., they can be improved in one objective without worsening the other). With this respect, and in consonance with the results from the single-objective optimisations, it was found that all the solutions in which the insulation layer was placed at the inner surface of the building envelope (C2) were dominated solutions.

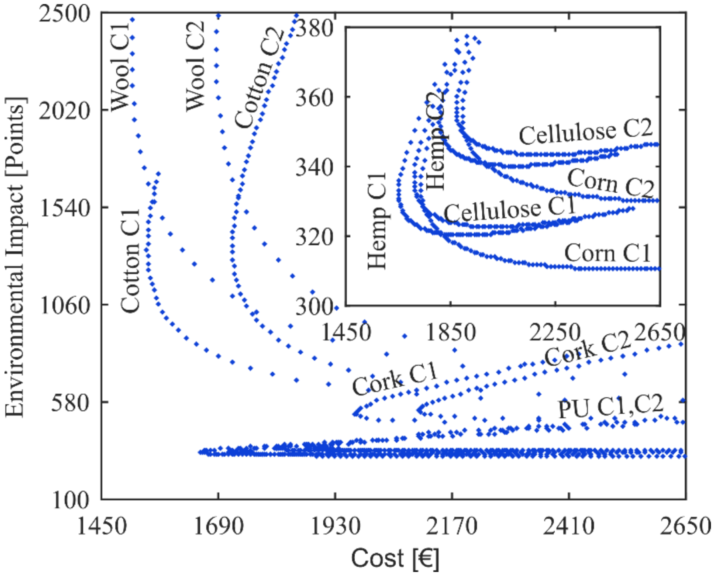

Fig. 3. Variation of the cost and the environmental impact with thickness for the materials and constructions.

Fig. 8 shows the Pareto frontier built from the results shown in Fig. 7. It was obtained that for the case under study, the Pareto frontier was constituted by the solutions of only four of the materials: cotton, cellulose, corn, and hemp. Two distinct parts of the Pareto frontier can be observed. The first part is built up with the results from wool and cotton. Here, reducing the thicknesses from 24 cm of wool to 15 cm of cotton results in only an 8% increase in cost, but in a dramatic decrease of environmental impact (62.3%). The second part combines the results from corn and hemp. Here, increasing the thickness has barely any effect on the environmental impact but leads to an important increase in the total cost. Such trend is in agreement with the results obtained by Carreras et al. [29], although the use of bio-based materials results in less polluting and less expensive solutions than the conventional ones (note that polystyrene is not among the solutions in the Pareto frontier).

The solution that falls in-between the two parts of the Pareto front, that is, 22 cm of hemp insulation (the knee point of the Pareto frontier), can be considered as the most balanced one for the case studied, since it is where the trend changes and from which any reduction of environmental impact results in an important increase of the cost. Compared to wool based solutions, the environmental impact is reduced by 85.5%, and the cost is increased by 16.7%. Thicker solutions represent only slight reductions in environmental impact while implying important additional costs. For instance, compared to 86 cm of corn, the environmental impact is increased by 3.22%, and the cost is reduced by 28.6%. However, it is important to notice that, as the optimal for hemp, cellulose and corn are very close, several solutions present similar advantages.

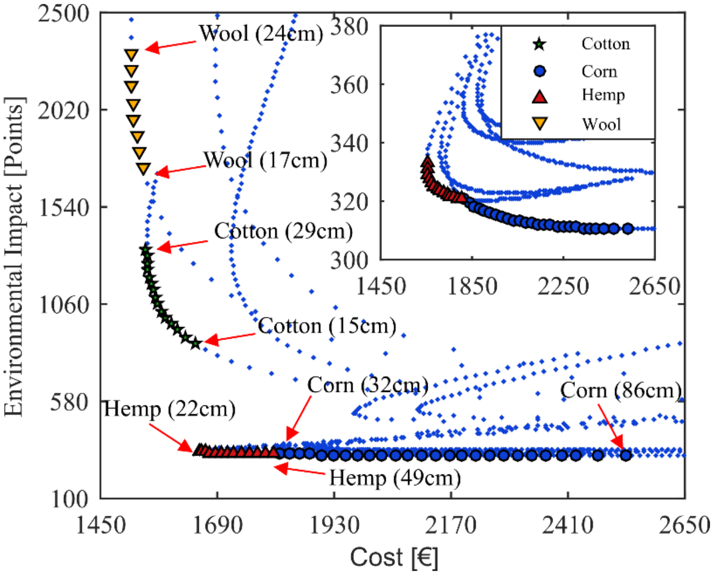

Fig. 4. Pareto frontier built from the overall optimal points.

All the suboptimal solutions and the Pareto frontiers obtained from the multi-objective optimisation analysis of the three climates are shown in Fig. 9. As expected,

The results show that the trends are similar for the three climates, although, as expected, the optimal thicknesses in the hot climates are lower than in the cold one. Moreover, it was observed that a significant reduction in the total cost was significantly reduced when the average outdoor temperatures increased, which is an expected result, too. The lowest cost for the optimal solutions is achieved in the tropical rainforest climate, where the temperatures do not decrease at night as much as in the hot semiarid one. The verticality of the first part of the Pareto frontiers indicates that although wool or cotton are better economic solutions, the use of hemp is more advantageous, as it allows for a significant reduction of the total environmental impact with only a slight increase in the total cost.

II.5.2.Multi-objective optimisation

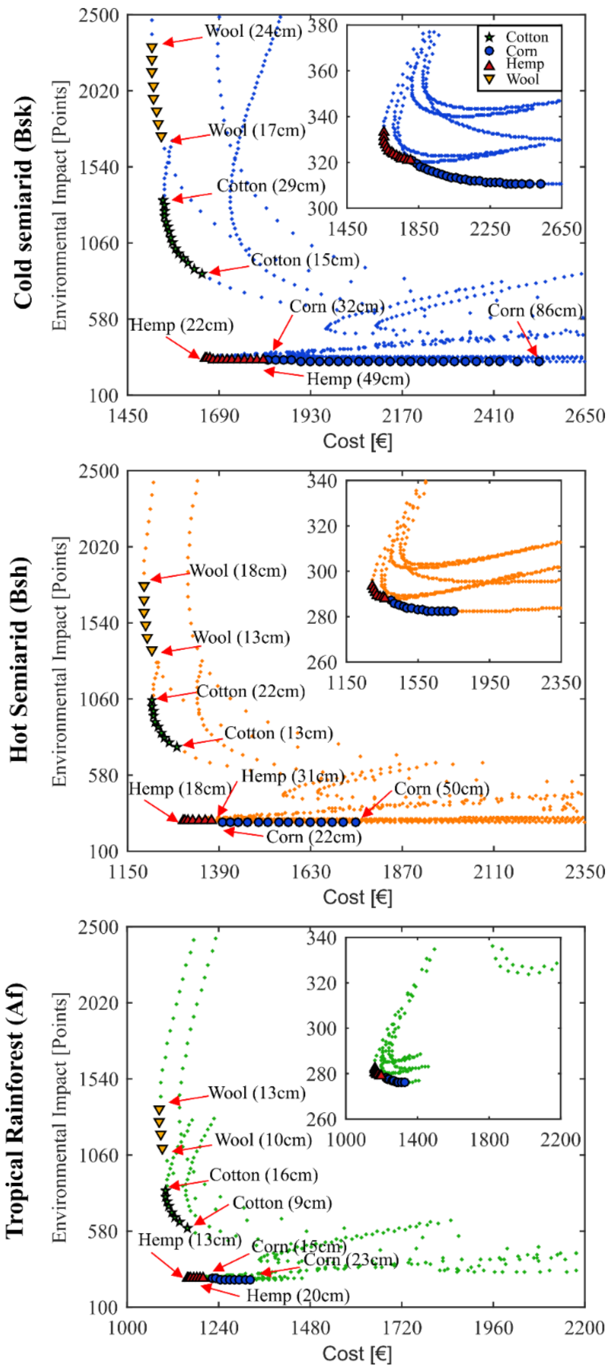

Fig. 5. Pareto frontier built from the overall optimal points for the three climates: cold semiarid (BSk), hot semiarid (BSh) and tropical rainforest (Af)).

The results showed that placing the insulation layer at the air gap (core insulation, C1) resulted in better results in all the cases. As an example, in the case of the cold semiarid climate, indoor insulation (C2) represented between 5% and 10% higher costs than core insulation (C1) and higher environmental impacts, too. This trend is maintained for all the climates. However, in the tropical rainforest climate, the differences between the two configurations are less significant. In the hot semiarid climate, core insulation results in cost savings between 4% and 7% with respect to indoor insulation, while in the tropical rainforest climate savings are reduced to between 2% and 4%. Similarly, the environmental impact of core insulation is 4% and 2% less than that of indoor insulation in the hot semiarid and the tropical rainforest climates, respectively. This can be explained by the fact that in the tropical rainforest climate, the diurnal difference temperature (i.e., different between day and night) is lower than in the other two cases. The envelope maintains a similar temperature all over the day, which prevents the activation of its thermal inertia. The results obtained show that the effect of the envelope configuration on the results of the multi-objective optimisation is more dependent on the diurnal temperature variation than to the mean daily temperature.

5.3. Risk of condensation

In order to verify the feasibility of the optimal solutions obtained, the risk of condensation for each optimal solution obtained previously (and presented in Fig. 9) was analysed, as described in Section 2.5, following the indications given by the CTE and the ISO 13788. All the optimal solutions of the Pareto frontiers, up to 30 cm of insulation were analysed.

II.5.3.Risk of condensation

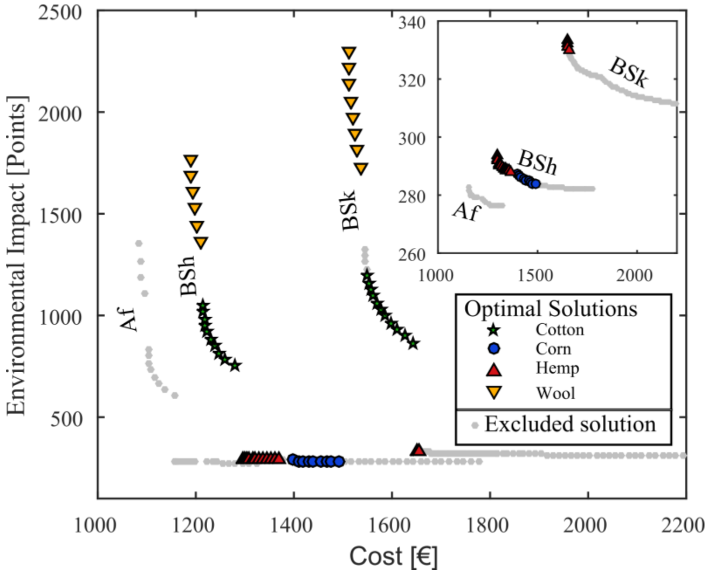

Fig. 10. Pareto frontier built from the overall optimal points without condensation risk

The results are presented in Fig. 10. It was observed that no risk of condensation exists in the hot semiarid climate (BSh), even for the thickest optimal thermal insulation solution. On the contrary, condensation occurs in all alternatives in the tropical rainforest climate (Af), where the air humidity is high all over the year. In the cold semiarid climate (BSk), where winters are humid and summers are drier, the risk of condensation exists from 25 cm of hemp upwards. As discussed before, sub-optimal solutions can be obtained using cellulose and corn as insulation materials. These were also evaluated obtaining comparable results. The envelope configuration did not show to have any impact on the results.

These results show that the use of bio-based insulation materials in climates with hot temperatures and high relative humidity (tropical rainforest) must be preceded by a detailed analysis of the construction solution in order to prevent interstitial condensation. Ventilated cavity walls and water vapour barriers will be needed. How such elements interfere with the hygrothermal performance of bio-based materials is an aspect to be analysed in detail in future studies.

The analysis of the risk of condensation resulted in the discard of 78%, 0% and 100% of the optimal solutions obtained in the multi-objective optimisation process for cold semiarid, hot semiarid and tropical rainforest climates respectively. The disparity in results among the distinct climates proves the importance of analysing the condensation risk in early stages of the design process. This implies that when using bio-based insulation materials, the risk of condensation should be taken into account in order to avoid structural damages and harmful effects on the health of occupants.

For the cold semiarid climate, despite reducing an important amount of solutions, the suggested solution for the MOO, 22cm of hemp (knee point) can be applied without risk, but thicker insulation layers should be avoided due to the condensation risk. In the case of hot semiarid, any of the solutions obtained with the optimisation could be applied without risk, but despite that, the solution in the knee point is preferable as it leads to an important reduction in environmental impact with a low increment in cost. Finally, this construction profile with bio-based material insulation should not be implemented in a tropical rainforest climate, due to the high risk of condensations. Different wall configurations and the use of water vapour barriers would prevent this risk but may play against the hygrothermal performance of bio-based materials.

6. Conclusions

Cost, environmental impact and risk of condensation resulting from the incorporation of seven bio-based insulation materials into an experimental cubicle were analysed using a multi-objective optimisation approach. The results were compared to a conventional polyurethane insulation. To this aim, an energy model of the cubicle was built and calibrated.

The results obtained indicate the use of bio-based materials may offer better solutions (in terms of cost and environmental impact minimisation) than the use of other conventional materials, such as polyurethane. Indeed, for the case study analysed, the optimal solutions obtained at each optimisation loop of the process corresponded to bio-based insulators. In particular hemp, cellulose and an innovative corn-pith based insulator were the materials that yield better results.

It was found that being the thermal properties and environmental impact of most of the materials rather similar (except for the sheep wool), the cost of the insulations had an important impact in their performance. This implies that finding a supplier offering competitive prices may represent the difference between a viable alternative and a no viable one, provided that the environmental impact is not increased. This is bonded with the concept of local green economy: the use of locally sourced and produced materials reduces both the cost and the environmental impact due to less transportation thus providing more optimal solutions.

The results showed that for the cold semiarid climate conditions of Lleida (Spain) and the considered building type, the best economic options were those including 24 cm of cotton or wool, achieving a cost reduction of about

28% when compared to the optimal solution using polyurethane. On the other hand, the best solutions in terms of low environmental impact was corn (86 cm) which offered an improvement of about 26% when compared to the optimal solution using polyurethane. Despite being optimal solutions, due to practical limitations, solutions of large thicknesses will not be applied in real life. The solution including 22 cm of hemp seemed to be the best compromise solutions when both objectives were considered. However, similar benefits can be achieved using corn and cellulose with less than 5% difference in total cost and less than 1% in terms of environmental impact. As expected, the optimal solutions in hot climates require less insulation. Again, the solutions including hemp were found to be the best ones when both objectives were minimised simultaneously.

The results were sensitive to the envelope configuration. The solutions in which the insulation layer was placed on the interior surface of the wall, instead of the air gap, resulted in higher cost and environmental impact. Such trend was less significant in a tropical rainforest climate, where the thermal gap between day and night is small thus annulling the effect of the thermal inertia of the envelope. Only in a tropical rainforest climate, the risk of condensation was found to be a concern. In such a climate, the hygrothermal performance of the whole envelope should be carefully evaluated previously to the implementation of bio-based materials. If water vapour barriers are needed, the effect of the hygroscopic nature of such materials might be reduced.

Bio-based materials represent a viable alternative to polyurethane and other conventional insulators, allowing for less expensive, more environmentally friendly solutions. However, these solutions usually represent higher thicknesses, and due to this fact, their use must be preceded by a deep analysis of their moisture behaviour.

The results obtained in the present study allow for a fair comparison between the different insulation materials. However, the models used have several simplifications which may have an impact on the results. In future works, the results will be verified using more complex models. Moreover, the effect of the hygrothermal performance of the materials on the multi-objective optimisation needs to be analysed.

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III. Case Study II

III. Systematic combination of insulation biomaterials to enhance energy and environmental efficiency in buildings

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Abstract

Achieving the 2050 EU goals requires reducing the energy demand of the actual building stock, for instance, through the deployment of thermal insulation based on bio-materials with low energy embodied. Despite their appealing properties, these materials are not widely available in the insulation market, which is dominated by glass wool due to the cost-effectiveness. To change this trend, this work introduces a systematic method to generate sandwich panels or fibre mats, similar to the commercial ones, but based on efficient combinations of bio-based materials with reduced cost and environmental impacts. For illustrative purposes, six bio-based materials, with varying thicknesses between 1 and 26cm, are used as the building blocks to obtain 30 composite candidates, from which only 17 are finally retained due to their appealing properties. These consists of 12 sandwich panels and five fibre mats made of different

quantities of cotton, corn and hemp. When compared against polyurethane, these composites demonstrate that they can be at least as efficient as commercial alternatives.

Keywords

Data Envelopment Analysis (DEA); life cycle assessment (LCA); bio-based building materials; thermal insulation, sandwich panels, fibre mats

1. Introduction

The building sector is responsible for approximately 50% of the total energy consumption and almost 40% of the greenhouse gas (GHG) emissions in Europe [75] [76], being a major contributor to global environmental pollution [1]. This sector has been at the heart of several energy efficiency policies, such as the ambitious 2020 Energy Strategy Plan enacted by the European Union (EU). With this policy, the EU aimed to reduce its greenhouse gas emissions by at least 20% from 1990 levels, increase the share of renewable energy to at least 20% of consumption, achieve energy savings of 20% or more [77] and reduce by 30% the use of primary energy by 2030 [78]. Objectives for 2030 are more strict [79] and they are expected to become even more ambitious by 2050 [80].

Various energy mitigation strategies must be put in place to achieve these targets. In the building sector, a relevant part of the energy is used for heating, cooling and air conditioning [81]. Therefore, insulation represents a promising option to achieve significant environmental and economic savings, with the capacity to decrease the cooling and heating demand of buildings [29]. However, while insulation can reduce the energy requirements of buildings during the use phase, this does not necessarily translate into savings along the whole lifecycle. This is because some insulation materials embody significant amounts of energy in their life cycle, as a result of their extraction, manufacturing and deployment phases [26].

According to different researchers [82][83][84], bio-based materials constitute a promising alternative in building insulation due to their low embodied energy. Despite this advantage, their penetration in the market is still rather low [85]. Acknowledging that prefabricated sandwich panels and fibre mats of conventional materials are showing an increasing demand [86], partially due the ease of their implementation, we argue that the production of composite solutions combining bio-based materials might be a promising strategy to improve their penetration in the market. The combination of different materials into a single panel has some intrinsic advantages such as the capacity to benefit from the properties of several individual materials at the same time (e.g., insulation properties, humidity transfer or water barrier). In this context, the question is how to combine bio-based materials in an optimal way to obtain a sandwich panel or another composite material.

To this end, we propose a systematic methodology for the generation of composite insulation materials. Our strategy combines building simulation, Data Envelopment Analysis (DEA) and Life Cycle Assessment (LCA) to automatically select insulation materials and their thickness according to their environmental and economic performance.

The combination of LCA and DEA into a single framework is not new. These two methodologies provide a powerful framework for eco-efficiency assessment (i.e., economic plus environmental performance) that has drawn the attention of researchers in the past due to its synergetic effects. On the one hand, LCA evaluates various aspects associated with the production and development of a product and its potential environmental impact throughout a product's entire lifecycle, that is, from the raw material acquisition, processing, manufacturing, use and finally its disposal, following defined principles and guidelines [12]. Therefore, it allows quantifying the impact of a product in several environmental categories along the product's life cycle, preventing burden-shifting among the different steps of the supply chain. Then, DEA allows combining this multidimensional (environmental and economic) information into a single efficiency score, without the need to define subjective weights. In particular, DEA evaluates the relative performance of a set of different alternatives (known in DEA as Decision Making Units, DMUs) according to any measurable indicator (inputs and/or outputs). This benchmarking tool assigns an efficiency score to each DMU, thus enabling the identification of the efficient and non-efficient solutions since the former are assigned an efficiency score of 1, while the latter receive a score strictly below 1.

In the last decade, several LCA+DEA approaches have been developed to link the economic and environmental performance of a system/product and identify efficient alternatives in different contexts [87][88]. More recently, DEA was combined with life cycle assessment (LCA) to assess the eco-efficiency and environmental efficiency in other sectors, like vine-growing exploitations [89], technologies for food waste management [90], electricity technologies [91] and solvents [92]. Note that these approaches based on DEA can be indistinctly applied to assess sustainability efficiency [93] (when the three dimensions of sustainability are considered), eco-efficiency [94] (only economic and environmental performance are included) and environmental efficiency (just environmental concerns). Furthermore, Vázquez-Rowe et al. [95] introduced a novel approach that relies on the integration of LCA and DEA with a simulation model for buildings. The interested reader is referred to recent surveys for further information on DEA application in environmental studies [96][97].

In the context of buildings, Iribarren et al. [40], used DEA to analyse 175 common external wall configurations belonging to the construction sector of Luxemburg in order to identify those which were environmentally sustainable. Each configuration was obtained by combining three different building blocks as follow: sixteen different bearing structures for external walls, sixteen different materials for insulation (six from renewable resources: cotton, hemp, cork, flax, wood wool panel and wood fibre insulation panel; two from recycling: cellulose fibres and cellulose fibre panel; four from mineral-based materials: mineral wool, glass wool, calcium silicate panel, and foam glass panel; and the remaining four from synthetic materials: EPS 032 and 040, XPS, and polyurethane panel). From these 175 configurations, only nine were identified as eco-efficient, and these resort to hemp, cellulose fibre, cotton and mineral wool, with thicknesses varying from 6 to 25 cm, as insulation materials.

In the pioneering approach by Iribarren et al., DEA was used as a benchmarking tool, providing efficiency scores for different candidate structures. However, here, we propose to use it in a radically different and novel way. Specifically, we exploit the fact that DEA constructs the so-called efficient frontier by performing convex combinations of efficient DMUs. For this propose, six different bio-based materials would be analysed in different thicknesses, to identify the efficient alternatives which would provide the reference set for the different proposed composites. Provided that such efficient DMUs correspond to different (pure) bio-based materials and that these materials can be physically combined into a sandwich panel [98] or any other commercial standard [84] (i.e., fibre mats), the facets of the efficient frontier can be used to systematically identify composites which are also eco-efficient. With the main propose to improve the applicability of those materials manufacturing requirements have been considered and a filtering section of the proposed composites has been included to skip non-feasible solutions.

2. Methodology

Our systematic approach to generate eco-efficient material combinations merges building simulation, LCA and DEA in a novel unified framework, where DEA lies at its core. In our framework, the starting point is a set of $|J|$ insulation alternatives, each corresponding to a possible combination between n thicknesses and m pure bio-based insulation materials considered (e.g., 20 cm of hemp). Each of these alternatives is modelled as a DMU with associated inputs and outputs that describe the performance of the alternative in different economic and environmental indicators. Note that, here, we do not use DEA in the traditional approach where DMUs are entities consuming inputs (resources) to produce outputs (products or services), but rather as a multicriteria decision-making tool allowing the use of any indicator as input or output [99]. In this new paradigm, the conventional choice, also used in this work, is to classify as inputs those indicators that should be minimized, and as outputs those that should be maximized [100].

Bearing this in mind, we proceed to describe briefly our approach, which consists of six different steps (see Figure 1). In this section, we focus on describing an overview of the methodology, while further details on each step are provided in the ensuing subsections.

The first step corresponds to data acquisition (i.e., obtention of the values for inputs and outputs) and is divided into two different sub-steps. In the first one, we simulate a building using the corresponding insulation alternative in order to estimate its energy requirements along the use phase. This step is necessary due to the lack of data about the energy demand of buildings with bio-based insulation. Then, in the second sub-step, we evaluate the total cost and life cycle impact associated with the alternative from cradle to gate, that is, including extraction, construction and use phases (note that sub-step one is required to assess the use phase). Note, however, that the methodology is general enough to accommodate other indicators if required.

Once the values of inputs and outputs have been obtained for each DMU, a dimensionality reduction method is used in the second step of the framework in order to identify potential redundant information between indicators, and ultimately diminish the number of inputs and outputs required to describe each DMU. This is carried out in such a way that redundant categories are eliminated without altering the dominance structure of the solutions: if the merely removal of a certain indicator would make any solution strictly worse than another, then these indicator is retained.

In the third step, DEA is performed to systematically identify potential combinations of bio-based materials. To this end, we use a DEA dual model that projects non-efficient solutions onto a given facet of the efficient frontier, thus (i) identifying candidate materials that could generate an eco-efficient composite (i.e., those lying at the vertexes) and, at the same time, (ii) the weights with which they have to be combined.

Some of these candidate composites might be infeasible from a practical point of view, either because they entail too many materials to guarantee proper manufacturing or simply because the selected materials cannot be combined in a single product (e.g., cellulose insulation with fibre materials). Therefore, in step number four, candidate solutions are filtered according to certain rules so that only those with practical value are

Candidate composites obtained through DEA are deemed eco-efficient assuming linear additive behaviour for the performance indicators of the individual insulation materials combined. The degree of correctness of such hypothesis is validated in step number 5 of the methodology. To this end, we proceed analogously as done in step 1 for original alternatives: composites are simulated in a building model to obtain their associated energy demand and then, this information is used together with lifecycle data to evaluate the associated cost and environmental impacts of the alternative.

The final step, number six, consists of validating the results by employing DEA again, but this time to benchmark the composites found in step four against the original "pure" eco-efficient solutions and also against other conventional insulation material (polyurethane).

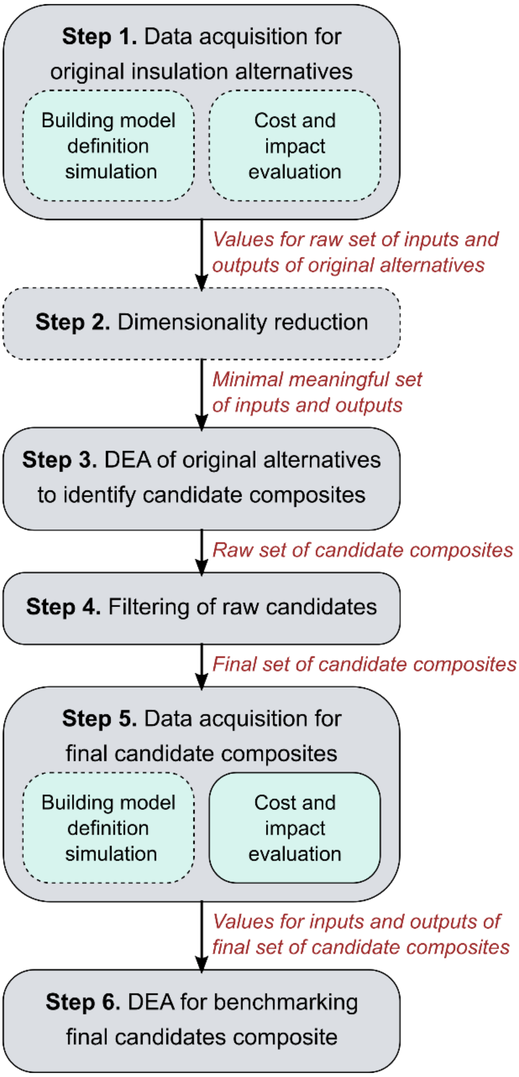


Figure 1: Simplified flow diagram of the proposed model showcasing the key steps (in grey), the sub-steps (in blue) and the optional steps (with dashed line). Products of each step are described in dark red font.

2.1. Model definition, energy simulation and economic and environmental assessment

The initial step in our approach is the acquisition of the data necessary to model each DMU, that is, the value of inputs and outputs. In our framework, inputs and outputs correspond to the cost and the environmental impact of each insulation alternative, as given by the contribution of two terms: (i) the energy demand of the building during the use phase and (ii) the manufacture of insulation materials. The former contribution corresponds to the amount of energy required during the whole lifespan of the building to achieve thermal comfort for each alternative, and can be estimated with an energy simulation. This involves the definition of the building structure and bearing materials as well as the operational and climate conditions of the selected siting. In the simulations of the different DMUs, all the parameters remain the same except for the insulation thickness and material, which vary from case to case. With the resulting energy consumption at hand, it is possible to calculate the associated lifecycle cost and environmental impacts assuming local data for energy production. Note that this sub-step could be skipped if these data were readily available in the literature or data repositories.

For the former contribution, the manufacture of insulation materials, environmental impacts are quantified following LCA, using a cradle to gate perspective due to the lack of data for the disposal phase, while the cost is quantified as an initial investment.

Note that we only take into account the contribution of the attributes changing from DMU to DMU, while discarding those that are equal for all DMUs such as the materials for the building structure (i.e., structural walls and roof). Further details on the calculations are provided in section 3.4.

2.2. Dimensionality reduction

Ensuring enough discriminatory power in DEA requires following a widely used rule of thumb which relates the number of DMUs assessed with the number of inputs and outputs considered [99]. According to this rule, the number of DMUs should be at least three times larger than the sum of inputs and outputs or than the number of inputs times the number of outputs.

Whilst not mandatory, meeting such criterion may require the implementation of a dimensionality reduction method in order to reduce the number of inputs and outputs, while retaining the essential information unaltered. This analysis can be done in the domain of inputs, outputs or in both, and is particularly useful when dealing with environmental impacts, which many times tend to be correlated [101].

Without loss of generality, we use a dimensionality reduction method based on measuring the delta approximation error [102], that is, the loss of information produced when certain indicators are omitted. This method will result in different indicators retained depending on the error that can be assumed, which gives some room to modellers to shape the methodology at their will. Further information on the specific setup used in this work is given in section 3.5.

It is to be noted that, sometimes, inputs and outputs may differ in orders of magnitude, which can lead to numerical issues when applying dimensionality reduction techniques. In order to avoid these problems, inputs and outputs are normalized between 0 and 1 with the min-max scaling [103] for the dimensionality reduction step (note that the normalization is only applied in the dimensionality reduction but not in DEA).

2.3. DEA fundamentals and projections

The proposed framework is underpinned by the DEA methodology, which is used twice along the whole procedure (each time with a different purpose). In step three, DEA is used to systematically obtain promising material combinations (i.e., composites) taking advantage of DEA projections. Later, in step five, DEA is used again, this time to verify the eco-efficiency of the proposed composite alternatives by benchmarking against some bio-based alternatives and a conventional insulator.

Conceptually, DEA is a mathematical programming methodology devised to benchmark a set of $|J|$ alternatives (DMUs), each consuming $|I|$ inputs to produce $|R|$ outputs. As previously commented, DEA was designed to assess production units, yet it has been widely implemented in the context of multicriteria decision making [104] to assess the performance of different technologies, systems, products or materials [105][106][107]. DEA assigns an efficiency score (θ) to each benchmarked DMU. Efficient DMUs are those that are not improved by any other DMU in all the inputs and outputs simultaneously. They receive an efficiency score of 1 and are convexly combined to form the so-called efficient frontier. Therefore, in the context of our problem, a DMU (combination of thickness and material) will be deemed inefficient if another one achieves comfort with lower environmental impacts and cost. Inefficient DMUs receive an efficiency score strictly lower than 1, and which is inversely proportional to the distance between the DMU and the efficient frontier: the lower the efficiency score, the longer the distance between them. Efficiency score is computed by projecting inefficient units onto the efficient frontier, giving rise to a virtual efficient DMU. This projection is particularly useful since it provides two additional valuable pieces of information. On the one hand, the inputs and outputs of the virtual DMU can be compared to those of the corresponding inefficient DMU to compute improvement targets (i.e., targets that if attained would turn the original DMU into efficient). On the other hand, it also allows to identify the so-called Reference Set (noted here by RS) of the inefficient DMU, which is composed by the efficient DMUs located at the vertexes of the facet of the efficient frontier where the virtual DMU lies. The DMUs at the RS can be used to guide the efforts of the inefficient DMU towards the achievement of its improvement targets.

There are several DEA models available in the literature, differing on the direction used project DMUs (i.e., the so-called orientation) and the returns to scale (i.e., constants *vs* variable) considered for building the efficient frontier, among other features [23]. The selection of the model orientation is particularly key in our approach, since it will drive the projection of inefficient DMUs, and therefore, the materials combinations that we obtain. In this case, we use an input-oriented model, whereby DMUs inputs are proportionally reduced while keeping the outputs constant. Regarding the returns to scale, the model considers variable returns to scale (VRS). The rationale behind the latter choice is the lack of proportionality between changes in the thickness of the insulation material and the resulting indicators (i.e., impacts and cost). Specifically, we use the radial input-oriented dual BCC model (Banker, Charnes, Cooper) [23], as shown in Eq. 1-5, yet our framework is general enough to accommodate any other DEA formulation.

$$\min \quad \theta_0 - \varepsilon\left(\sum_i s_i^- + \sum_r s_r^+\right) \tag{1}$$

$$\text{s.t.} \quad \sum_j \lambda_j x_{ij} + s_i^- = \theta_0 x_{i0} \qquad \forall i \in I \tag{2}$$

$$\sum_j \lambda_j y_{jr} - s_r^+ = y_{r0} \qquad \forall r \in R \tag{3}$$

$$\sum_j \lambda_j = 1 \tag{4}$$

$$\lambda_j, s_i^-, s_r^+ \geq 0 \qquad \forall i, r, j \tag{5}$$

here, θ_o is the relative efficiency score of the DMU analysed, which can vary between 0 and 1, being one the maximum possible efficiency (which indicates efficient status) and 0 the minimum one; ε is a non-Archimedean value, which forces the strict positivity of the variables; s_i and s_r, correspond to the model slacks for inputs and outputs, respectively; and λ_j is the weight assigned to each peer DMU$_j$ in the creation of the virtual DMU.

2.3.1. Composites via DEA projections

In this section we further illustrate the use of DEA in the context of our problem, with particular emphasis on how its projections can be used to derive eco-efficient candidate composites. To this end, we present the following motivating example. Consider six insulation alternatives (DMUs A, B, C, D, E and F), each corresponding to a different combination of thickness (5 or 10 cm) and material (M1, M2 or M3), as given in Table 1. The eco-efficiency of these insulations is to be assessed considering two inputs (i.e., the environmental impact and the cost) and one output (i.e., achieving comfort requirements, modelled as a dummy output of one), whose values are also provided in the table.

Table 1. Data for the motivating example.

			Inputs		Output
DMU	Thickness (cm)	Material	Cost (€)	Impact (points)	Comfort
A	5	M1	1.0	4.0	1.0
B	10	M1	4.0	3.0	1.0
C	5	M2	2.0	4.5	1.0
D	10	M2	2.5	3.0	1.0
E	5	M3	2.0	2.5	1.0
F	10	M3	4.5	2.0	1.0

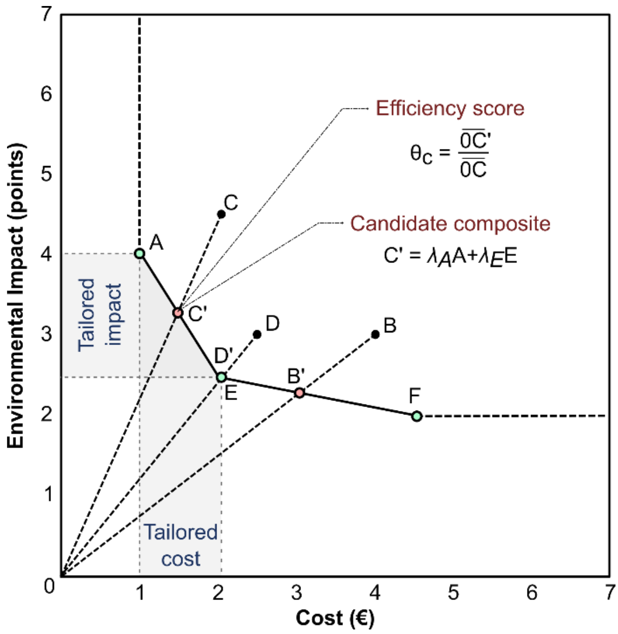


Figure 2: DEA illustrative example for an input-oriented model of two inputs and a **dummy output.**

In order to address this problem, DEA is applied as shown in Figure 2. Insulation alternatives (i.e., thickness-material combinations) represented by DMUs A, E and F have the lowest input values for the same level of outputs and, for this reason, they are identified as efficient DMUs (green dots in the figure). The line that connects those solutions determines the piecewise linear efficient frontier ($\overline{AEF}$). Contrarily, DMUs B, C and D are inefficient because they require higher inputs for the same output, that is, they have to incur a higher cost and/or cause more environmental impact, to provide the same comfort level (black dots). These second group of DMUs (i.e., the inefficient ones) are projected radially towards the origin (i.e., radial input-oriented projection), as illustrated by the black dashed lines in the figure, giving rise to virtual DMUs B', C' and D' (red dots) at the intersection with the efficient frontier. As illustrated for DMU C in the figure, the efficiency score of inefficient alternatives corresponds to the ratio of the distance from the origin to the projected DMU (i.e., $\overline{OC'}$) to the distance from the origin to the original DMU (i.e., $\overline{OC}$).

Additionally, virtual DMUs provide information about the reference set (RS) of each inefficient DMU, that is, which DMUs have to be combined (RS) and in which proportion (λ_j) to form each virtual DMU. In the case of DMU D, the RS is only composed of DMU E, and therefore, this projection does not give any hint on potential efficient composites. The same happens with DMU B, whose ERS contains DMUs E and F, both employing insulation material M3. These two examples illustrate why it is necessary to include a filtering step to discard projections that do not lead to a feasible composite. Finally, virtual DMU C' is based on efficient DMUs A and E, which employ insulation materials M1 and M3, respectively. Therefore, virtual DMU C' corresponds indeed to a candidate composite material. From a manufacturing point of view, the amount of materials M1 and M3 that have to be combined to produce C' can be obtained from the corresponding linear coefficients λ_j, which must be applied to the original thicknesses of the alternatives (i.e., λ_j times the original thickness of *j*). In this particular case, C' will consist of 2.5 cm of M1 (i.e., 0.5 times 5 cm of M1) and 2.5 cm of M3 (i.e., 0.5 times 5 cm of M3). In mathematical terms, the total thickness of the insulation composite is given by Eq. (6), while the share of each material that must be included in the composite is computed *via* Eq. (7):

$$Total\ composite\ thickness = \sum_j \left(\lambda_j Thickness_j\right) \tag{6}$$

$$Share\ of\ material\ j\ in\ composite = \frac{\lambda_j Thickness_j}{Total\ composite\ thickness} \tag{7}$$

Where $Thickness_j$ is the insulation thickness of alternative j. Individual material shares from Eq. (7) are obtained on a thickness basis, which is very convenient for the preparation of sandwich panels since manufacturing depends directly on these data. In this case, it suffices with dividing by two the thickness value obtained for the material that will be placed at the two sides of the panel in order to have ready-to-use information. Conversely, in the case of fiber mats, weight fractions (rather than thickness fractions) might be required; these are easily computed from thicknesses and the apparent densities of the corresponding individual materials.

Furthermore, there is an additional observation, with practical implications, that can be exploited to generate new materials with tailored performance: any linear combination of DMUs in an RS necessarily lies on the efficient frontier and is therefore efficient. In essence, this means that it is not strictly necessary to combine alternatives in an RS using the linear weights provided by DEA solution (noted by λ_j*), but rather that these materials can be combined in any proportion to obtain composites with specific values of inputs and outputs within the boundaries defined by the vertexes of the corresponding facet (see gray shadowed regions in the figure). Following with the example of C', it is possible to obtain a composite with lower cost but higher environmental impact by increasing the amount of M1 (i.e., larger λ_A), or a composite with lower impact but higher cost by resorting to more M3 (i.e., larger λ_E). In any case can the cost of the composite be lower than 1 € or the environmental impact lower than 2.5 points, as these limits are dictated by the pure materials are the vertexes of the facet $\overline{AE}$. At the same time, it is not possible to obtain a composite with the lowest cost and impact simultaneously since cost-impact pairs are given by the values of λ_j (i.e., there is only one degree of freedom in this two-dimensional case). This is illustrated in Eq. (8) for any performance indicator p:

$$Composite\ expected\ performance_p = \sum_j \left(\lambda_j Indicator_{j,p}\right) \quad (8)$$

where, $Indicator_{j,p}$ is the value of performance indicator p (inputs or outputs) of insulation alternative j. This estimation of expected performance assumes a linear behavior for the combination of materials, which might not hold for some indicators (e.g., thermal resistances are not linearly additive), making it necessary to resort to a validation step later in the overall methodology (see section 2.5).

Finally, it is to be noted that the identification of efficient DMUs is not enough to obtain efficient composites. For instance, DMUs A and

F are both efficient and employ different materials (M1 *vs* M3), however, their combination (segment $\overline{AF}$) would be inefficient assuming linear additive performance. In conclusion, DEA projections can be used to systematically obtain combinations of materials which do have the potential to be eco-efficient as well as a range of available combinations for the manufacturer to choose from in order to customize the material performance to some extent.

2.4. Filters

As aforementioned, not all virtual DMUs qualify to be manufactured into real final products, which calls for the use of a filtering step with a set of rules in order to discard solutions with no practical application. Some of these filtering rules might be useful for all cases, yet others might depend on the particular application addressed or simply reflect the manufacturer’s preferences. Even in the case of rules with wide applicability, there might be some aspects of the rule that have to be specifically setup for each particular case study. These aspects will be discussed later in the article in the context of the case study (see section 3.6), while in this section only general issues will be addressed.

There are mainly two rules with very wide applicability in the generation of composites. The first aims to exclude combinations of alternatives made of the same material, regardless of their potential different thicknesses (recall DMUs B’ and D’ in Figure 2). The second involves discarding solutions entailing too many materials since this has the potential to hinder the manufacturing process. The threshold for what can be considered “a reasonable number of different materials” is a modeler’s choice and will, again, depend on the particular application and manufacturing process addressed. However, it is important to note that, even when the candidate composite satisfies such threshold regarding the number of materials, it might still be impossible to combine these materials into a single product due to their different nature. As an example, cellulose, which is one of the most common bio-based materials, is usually implemented by blowing it up into the walls or filling air gaps, making it impossible to combine it in an insulating mat or a sandwich panel [108].

2.5. Validation

The final step of the methodology consists of a verification of the performance of the proposed composites. In DEA, the inputs and outputs of a virtual DMU are obtained as a convex combination of the inputs and outputs of the DMUs at RS, which might give rise to a spurious performance. This is because nonlinear behavior is expected between some properties such as the thickness of the insulation material and the energy requirements, which could in turn affect the cost and impact associated with the use phase of the building.

In order to guarantee that this is not the case, we simulate the candidate alternatives obtained using DEA by introducing the corresponding layers of materials (i.e., those obtained with Eqs. (6-7)) in the energy simulation model and obtain the “real” (*in silico*). values for the different inputs and outputs.

Once verified the consistency of the solutions, a second application of DEA is carried out, comparing those hybrid-materials with those that just contain one insulation material.

3. Case study

In this contribution, six bio-based building insulation materials (wool, wood, cork, corn, hemp and cotton) are considered as candidates for combination in sandwich panels and insulation mats, with the ultimate aim of facilitating the penetration of these materials in the insulation market. Each of these materials is available in six different thicknesses screening the range between 1 and 26 cm with increments of 5 cm. This generates a total of 36 bio-based insulation alternatives, each modelled as a DMU for the initial DEA.

Additionally, the performance of the bio-based insulators will be compared against a conventional insulation material (polyurethane, PU, available also in six different thicknesses) in terms of the total environmental impact and cost. This makes a total of 42 DMUs, with 7 materials and 6 thicknesses for each material.

The performance of these alternatives is assessed in experimental cubicles built at the testing site of the University of Lleida (Spain) [60]. In the following sections, we present further details of the case study in the context of our framework.

We assume these alternatives are implemented in a cubicle with the bearing structure described in section 3.2, but any other building structure could be used in our framework. The advantage of using the cubicle is that its corresponding thermal simulation has already been validated in a testing site of the University of Lleida with experimental data [36].

3.1. DMU definition

As explained, we model each insulation alternative for the cubicle (i.e., combination of thicknesses and insulation material) as a DMU, whose eco-efficiency is quantified according to a series of indicators, modeled as inputs and outputs. In terms of environmental performance, the 18 different midpoint categories of the ReCiPe indicator are considered. These indicators represent the generation of pollutants and should in principle be considered as undesirable outputs in DEA (i.e., they are outputs of the process but are not desired [100,109]). Despite this, we follow here the approach by Korhonen and Luptacik [110]) according to which undesirable outputs can be modeled as inputs in a benchmarking problem. Meanwhile, the economic performance of the DMU is assessed via the total cost, which is another input of the DMU.

Standard DEA requires DMUs to have both inputs and outputs, yet so far only inputs have been selected for our DMUs. To amend this, we follow a widely extended practice in DEA [40], which consists in including one dummy output in the analysis. This dummy output can be understood as the fulfilment of certain conditions; in our case, the thermal requirements of the building as given by a fixed temperature limit during the year. This comfort requirement is imposed in all the simulations and for this reason, all the modeled DMUs (both original pure materials and candidate composites analyzed later) achieve a value of 1 for the dummy output, resulting in a total of 19 inputs and 1 output per DMU. Note that the framework could accommodate any (non-dummy) output, if required.

3.2. Building description

The capabilities of our framework are illustrated through a case study considering the insulation of experimental cubicles of the University of Lleida, located in a testing site in Puigverd de Lleida, Spain. The envelope of this cubicle has an external volume of 2.44×2.55×2.44 m with one window in the south facade, with dimensions of 0.2×1.2 m, with a wall/window ratio of 6. The materials used have a conventional Mediterranean profile, formed by a plaster layer (1 cm), 14 cm thick perforated bricks, an air gap of 5 cm, and a finishing layer of hollow bricks (7 cm) rendered with 1 cm of cement mortar. The roof consists (from inside to outside) of a plaster finishing (1 cm), a concrete beam and pot floor of 5 cm, a lightweight concrete layer in the form of slopes (3%), and a double asphaltic membrane for waterproofing. The foundations consist of a reinforced concrete slab of 3 × 3 m and 21 cm thickness. Insulation is then placed inside the air chamber as shown in the scheme of the construction shown in Figure 3.

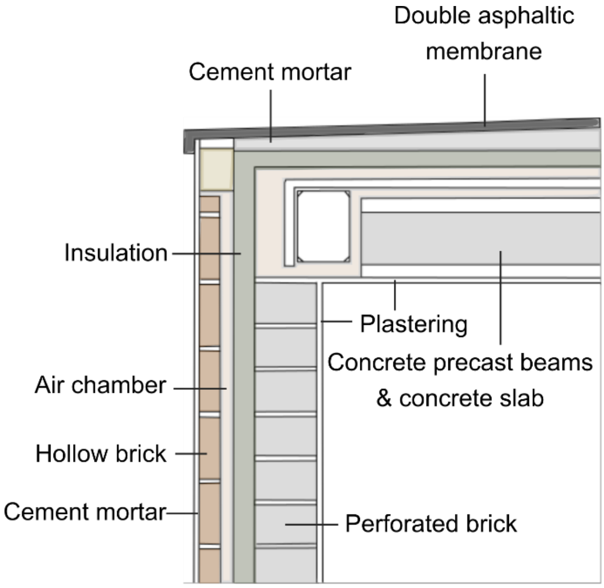


Figure 3: Construction profile of the experimental cubicles of the University of Lleida (adapted from [29]).

3.3. Specifications of the energy model

The development of the energy model of the cubicle requires a combination of three different type of software: a 3D modeling software, a modeling tool for providing building information and a simulation engine. The initial step is carried out with SketchUp [62], which is used to provide dimensional information for the building envelope. Within this software environment, the building consists of a set of walls and the roof, which might have windows, but no thickness or structural information.

Then, OpenStudio [61], which is a SketchUp plugin, enables the introduction of additional information into the initial sketch: walls and roof thicknesses, construction materials, internal human occupation, use of appliances and daily schedules for their use and occupation. This model is built to replicate the characteristics (i.e., dimensions and materials) of the experimental cubicle described in section 4.2, as well as the climate conditions of Bsk – Koppen climate, and has been validated in a previous work for some insulation materials [82]. Note, however, that a different model, based on any other construction profile, could be used without compromising the methodology proposed.

This task has to be repeated for all 42 insulation alternatives (and later candidate composites), generating models which are identical in all aspects except for the insulation material and thickness. This process can be automated *via* a fourth software, jEPlus [70] (a parametric tool), which can read EnergyPlus files and generate modified replicates (M materials in a range of T thicknesses, including a predefined minimum and maximum thicknesses and steps) to be inputted into the simulation engine.

Data for the physical and thermal properties of the construction materials are obtained form the Spanish Building Code (CTE) [64], ITEC [65] and the commercial products [66–68], or experimental data [69]. These data are presented in Table 2, along with the price used for the cost calculation. Recall also that, since structural materials are the same for all the alternatives, their cost and environmental impacts are omitted from the assessment and therefore, from Table 2 as well.

Finally, all this information is sent to EnergyPlus [111], which is used as the simulation engine to run the thermal simulation. EnergyPlus includes the set of equations describing the energy balances of the building, taking into account climate conditions as well as heat and mass transfer balances, and provides the heating and cooling requirements of the building. These requirements are then translated into the corresponding electricity demand, assuming a reversible heat-pump with a COP of 3. that. This electricity demand, together with the materials stock used in the building, are used later to evaluate the economic and environmental impact of the different alternatives.

Table 2. Building characteristics of the model and their cost.

	Density (kg/m^3)	Thermal conductivity (W/m·K)	Specific heat (J/kg·K)	Thermal diffusivity (10^{-6} m^2/s)	Market price (€/kg)
CONSTRUCTION					
Plaster	1150	0.570	1000	-	-
Perforated brick	900	0.543	1000	-	-
Hollow brick	930	0.375	1000	-	-
Cement mortar	1350	0.700	1000	-	-
Asphaltic membrane	2100	0.700	1000	-	-
Concrete	2100	0.472	1000	-	-
Steel bars	2100	0.472	1000	-	-
Concrete tiles	1920	0.890	790	-	-
INSULATION					
Cotton	25	0.036	1800	0.80	1.024
Cellulose	45	0.035	1900	0.41	1.071
Cork	110	0.040	1700	0.21	0.909
Corn	50	0.038	1800	0.42	1.100
Hemp	30	0.041	1800	0.76	1.360
Wool	30	0.045	1800	0.83	0.947
Wood	250	0.050	1850	0.11	1.172
Polyurethane	45	0.027	1000	0.60	3.889

3.4. Inputs and outputs assessment

The 19 inputs (one economic plus 18 environmental) are quantified following a life cycle perspective (from cradle to gate), where only the elements varying from DMU to DMU (insulation material and energy consumption) are considered. Therefore, the cost and impact associated to the rest of the building walls, roof and foundation are omitted, which is a usual procedure in comparative LCA studies

[112].

The total cost of each DMU j results from two contributions: the cost of the insulation material (a one-time investment) plus the cost of the electricity consumed during the whole use phase of the building (Eq. (9)). The former is obtained from the amount of insulation material (i.e., kg) and its unitary cost (i.e., €/ kg), and is supposed to be invested during the first year of the building life. Unitary costs for conventional materials have been retrieved from the iTEC database, whereas those for bio-based materials have been gathered from the corresponding suppliers (see Table 2). On the other hand, the electricity cost is given from the annual electricity demand obtained in the corresponding simulation and the unitary cost of electricity, which assumes a 5% increment during lifetime.

$$Cost_j^{TOT} = Mass_{ins,j}Cost_{ins}^{MAT} + \sum_m Elec_j Cost^{ELE}(1 + i)^m \qquad \forall j \tag{9}$$

Here, $Cost_j^{TOT}$ is the total cost DMU j (€), $Mass_{ins,j}$ is the amount of insulation material ins (e.g., cork) in insulation alternative j (kg), $Cost_{ins}^{MAT}$ is the unitary cost of insulation material ins (€/kg), m correspond to each year in the lifespan of the building, $Elec_j$ is the amount of electricity required insulation alternative j to achieve the thermal comfort of the building (kWh), $Cost^{ELE}$ is the unitary cost of electricity (in Spain, in this case) (€/kWh) and i is the annual increment of the electricity cost.

Similarly, the environmental impact for the 18 different categories of the ReCiPe indicator is quantified for all the alternatives j taking into account the contribution of the insulation materials and the electricity from the reversible heat pump (Eq. (10)). Unitary impacts for all materials and electricity have been retrieved from Ecoinvent database version 3.4 (2017), using entries listed in Table 3 (note that the impact of electricity has been evaluated assuming Spanish mix).

Table 3. Unitary impacts of the insulation materials an electricity.

	ALO (m^2a)	GWP (CO_2-eq)	FD (kg oil-eq)	FET (kg 1,4-DCB-eq)	FE (kg P-eq)	HT (kg 1,4-DCB-eq)	IR (kg U_{235}-eq)	MET (kg 1,4-DCB-eq)	ME (kg N-eq)	MD (kg Fe-eq)	NLT (m^2)	OD (kg CFC-11-eq)	PMF (kg PM_{10}-eq)	POF (kg NMVOC)	TA (kg SO_2-eq)	TET (kg 1,4-DCB-eq)	ULO (m^2a)	WD (m^3)
Market for slab and siding, hardwood, wet, measured as dry mass [GLO] (kg)	0.713	0.02	0.007	$2\cdot10^{-5}$	$6\cdot10^{-7}$	0.003	0.001	$4\cdot10^{-5}$	$5\cdot10^{-6}$	0.001	$9\cdot10^{-6}$	$3\cdot10^{-9}$	$5\cdot10^{-5}$	$2\cdot10^{-4}$	$9\cdot10^{-5}$	$2\cdot10^{-5}$	0.016	$6\cdot10^{-5}$
Market for sheep fleece in the grease [GLO] (kg)	82.25	34.55	1.18	0.567	0.009	0.718	0.164	0.045	0.155	0.467	0.001	$4\cdot10^{-7}$	0.12	0.041	0.791	0.11	0.656	1.263
Market for kenaf fibre [GLO] (kg)	1.725	0.781	0.135	0.026	$3\cdot10^{-4}$	0.032	0.017	0.002	0.003	0.041	$8\cdot10^{-5}$	$4\cdot10^{-8}$	0.002	0.003	0.012	$2\cdot10^{-4}$	0.011	0.505
Market for maize silage, organic [GLO] (kg)	0.225	0.054	0.008	$6\cdot10^{-4}$	$1\cdot10^{-5}$	-0.01	0.002	$9\cdot10^{-5}$	0.001	0.004	$7\cdot10^{-6}$	$3\cdot10^{-9}$	$3\cdot10^{-4}$	$2\cdot10^{-4}$	0.002	$-3\cdot10^{-5}$	0.001	0.009
Market for cork slab [GLO] (kg)	16.81	1.771	0.549	0.002	$1\cdot10^{-4}$	0.221	0.079	0.002	$3\cdot10^{-4}$	0.052	$3\cdot10^{-4}$	$1\cdot10^{-7}$	0.004	0.006	0.009	$2\cdot10^{-4}$	0.02	0.005
Market for cotton fibre [GLO] (kg)	8.509	3.175	0.757	0.037	$6\cdot10^{-4}$	0.463	0.124	0.006	0.014	0.181	$4\cdot10^{-4}$	$3\cdot10^{-7}$	0.01	0.013	0.031	0.197	0.05	1.989
Market for polyurethane, rigid foam [GLO] (kg)	0.21	5.775	2.447	0.027	$5\cdot10^{-4}$	2.032	0.265	0.021	0.006	0.339	$7\cdot10^{-4}$	$1\cdot10^{-6}$	0.012	0.026	0.028	0.002	0.041	0.03
Market for electricity, low voltage [ES] (kWh)	0.026	0.353	0.096	$1\cdot10^{-4}$	$3\cdot10^{-5}$	0.039	0.081	$3\cdot10^{-4}$	$6\cdot10^{-5}$	0.015	$5\cdot10^{-5}$	$5\cdot10^{-8}$	$9\cdot10^{-4}$	0.001	0.003	$2\cdot10^{-5}$	0.003	0.002

$$Imp_{cat,j}^{TOT} = Mass_{ins,j} Imp_{ins,cat}^{MAT} + \sum_{m} Elec_j Imp_{cat}^{ELE} \qquad \forall j \qquad (10)$$

Here, Imp_{cat}^{TOT} is the total impact of DMU j in ReCiPe category *cat* (e.g., impact in agricultural land occupation, in category-dependent units), $Mass_{ins,j}$ is the amount of insulation material *ins* in the DMU j (kg), $Imp_{ins,cat}^{MAT}$ is unitary impact of insulation material *ins* in ReCiPe category j (category-dependent units/kg), m correspond to each year in the lifespan of the building, $Elec_j$ is the amount of kWh to achieve the thermal comfort of the building (kWh) and Imp_{cat}^{ELE} is the unitary impact of electricity in Spain for ReCiPe category *cat* (category-dependent units/kWh).

As explained in section 3.4, for this research, a dummy output of 1 is used. This output represents the capacity of each alternative to maintain the building with a scheduled set-point for winter and summer. The conditions selected corresponds to 20ºC during the heating season and 26ºC during the cooling season, based on the requirements of the ISO 7730 and considering a metabolic activity corresponding to an individual office. This result in an energy consumption that is used in the calculation of the inputs.

3.5. Dimensionality reduction

At this point, the case study consists of a total of 42 DMUs with 19 inputs and one output each. As explained in section 2.2 [23], these figures suggest the necessity to resort to a dimensionality reduction technique in order detect redundant inputs and ensure the discriminatory capabilities of DEA. These methods allow to reduce the number of indicators in multidimensional problems (inputs and outputs in our case) without altering the dominance structure of the alternatives, which is crucial to maintain the dichotomic classification between efficient *and* inefficient alternatives in DEA (see [113] for the similarities between DEA and Pareto-Koopmans efficiency concepts [114]).

It is advised to carry out this procedure using normalized data in order to avoid numerical issues due to differences in the order of magnitude of input and output values, which ultimately stem from their distinct nature. Without loss of generality, in this contribution, inputs and outputs are normalized using min-max scaling.

Once data is normalized, we apply a dimensionality reduction method based on the calculation of the so-called delta error [102], which has been previously used to identify redundant metrics in sustainability optimization [31], yet the proposed framework is flexible enough to accommodate other dimensionality reduction methods. The method is applied only to inputs, therefore yielding the smallest subset of inputs necessary to keep unaltered the later classification of alternatives between efficient and inefficient. Whilst this step is not mandatory, it simplifies the analysis and increases DEA's discriminatory power.

3.6. Filtration of the systematic combinations

Despite the fact that all the suggested solutions are in principle efficient alternatives, not all of them might be implemented in practice. As described in section 2.5, the reason for this might be technological limitations in combining some materials. Therefore, filtering rules will depend on the materials assessed and might vary from case to case. In this case study, the following rules are applied:

1. A minimum of 2 different materials needs to be combined.
2. A maximum of 3 different materials can be combined.
3. Composites require layers of a minimum of 1cm of each individual material.
4. A minimum of 5% of difference from a reference single-material material is necessary.
5. For the manufacture of fibre mats, only long flexible fibres can be combined; in this case these are wool, cotton or hemp.
6. The manufacture of sandwich panels must involve two different kinds of materials: on the one hand, densely packed short fibres or aggregates like corn, wood and cork, and, on the other hand, long fibres like wool, cotton or hemp.
7. For the manufacture of rigid panels, two or three materials like corn, wood and cork must be combined.
8. PU is only used for comparison; composites must be formed by bio-based materials only.

Here, the first rule ensures that a hybrid material is obtained, while the remaining rules aim at ensuring a feasible manufacturing process, firstly by keeping the number of different materials low (second rule), simplifying the manufacturing process by excluding combinations that differ little from a single-layered material or have thin layers (rules third and fourth) and then by limiting the combinations of materials taking into account the properties of the resulting products (rules from fifth to eighth). Note that, while the threshold for the second rule could be altered at will by the modeller, the remaining rules might have practical implications in the manufacturing process of the composite material. If different materials and/or performance indicators were considered, further filtering rules could be included (i.e., ensuring a flame retardant layer, mechanical resistance, acoustic insulation [115] or a vapour barrier, etc.).

The above depicted filtration plays a key role in the methodology, enabling the feasibility of the materials proposed. Together with the projection method it helps to it helps to discard combinations that would not be feasible in an applied context, as resulting products would not be competitive in the market due to higher manufacturing effort or to the fact that resulting products would not be suitable for the conditions of application. The proposed filters could be completed by a subsequent step evaluating the performance of suggested composites in vitro tests.

4. Results and discussion

In this section, we discuss the results obtained by applying the proposed methodology to the case study described in section 3.

4.1. Inputs and outputs assessment

The environmental and economic performance of the different DMUs is obtained following the procedure detailed previously. Specifically, environmental impacts are computed for all the categories of the ReCiPe indicator, whereas the total cost is computed as in Eq. (9). Both impacts and cost include the contribution of the electricity consumed in conditioning the building and that of the materials. This yields a total of 19 inputs: agricultural land occupation, ALO (m^2a); climate change, GWP (CO_2-Eq); fossil depletion, FD (kg oil-eq), freshwater ecotoxicity, FET (kg 1,4-DCB-eq), freshwater eutrophication, FE (kg P-eq), human toxicity HT (kg

1,4-DCB-eq), ionizing radiation, IR (kg U_{235}-eq), marine ecotoxicity, MET (kg 1,4-DCB-eq), marine eutrophication, ME (kg N-eq), metal depletion, MD (kg Fe-eq), natural land transformation, NLT (m^2), ozone depletion, OD (kg CFC-11-eq), particulate matter formation, PMF (kg PM_{10}-eq), photochemical oxidant formation, POF (kg NMVOC), terrestrial acidification, TA (kg SO_2-eq), terrestrial ecotoxicity, TET (kg 1,4-DCB-eq), urban land occupation, ULO (m^2a), water depletion, WD (m^3) , and total cost, $Cost_j^{TOT}$ (€), respectively.

Results for the 18 life cycle impacts and cost (inputs and outputs) corresponding to each of the 42 insulation alternatives, as well as their energy consumption, are shown in the supplementary material. Additionally, the first two pieces of information are depicted here in a Parallel Coordinates Plot, PCP, (Figure 4), where each input has been normalized across the different DMUs to a range between 0 and 1. This plot allows to identify the existence of non-conflicting objectives and, therefore, spot opportunities for dimensionality reduction techniques that simplify the subsequent analyses. In a PCP, these conflicts are identified through the intersections of the polylines: if there are no intersections between a subset of objectives, or if intersections are repetitive, these objectives are said to be non-conflicting or harmonic. This means they provide redundant information and thus, some can be excluded from further analysis. As an example, let us turn our attention to the four inputs in the shadowed region of Fig 4. The behavior of all the DMUs is similar across this region, with some of the polylines being parallel and others intersecting with each other, but both trends being maintained along these four inputs. This suggests that it might suffice to retain some of these inputs in order to explain existing discrepancies among the four of them. Similar patterns are also observed in other regions of the figure, showing a plethora of opportunities for dimensionality reduction.

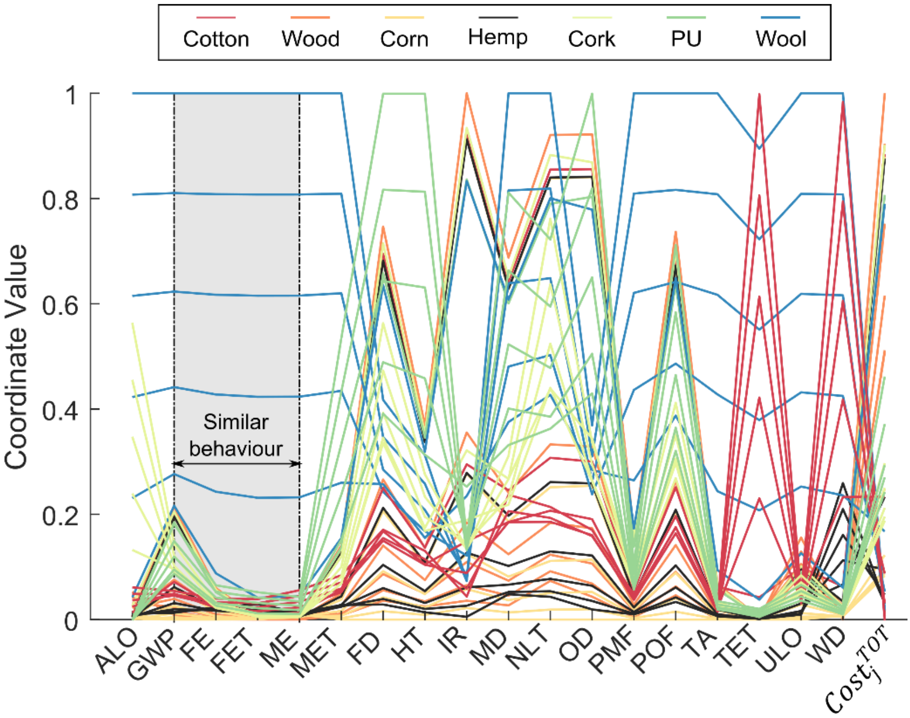


Figure 4: Parallel Coordinates Plot of the normalized inputs for all the DMUs. For each of the seven materials, six different polylines appear, each corresponding to a different thickness (from 1 to 26 cm, with a 5 cm step).

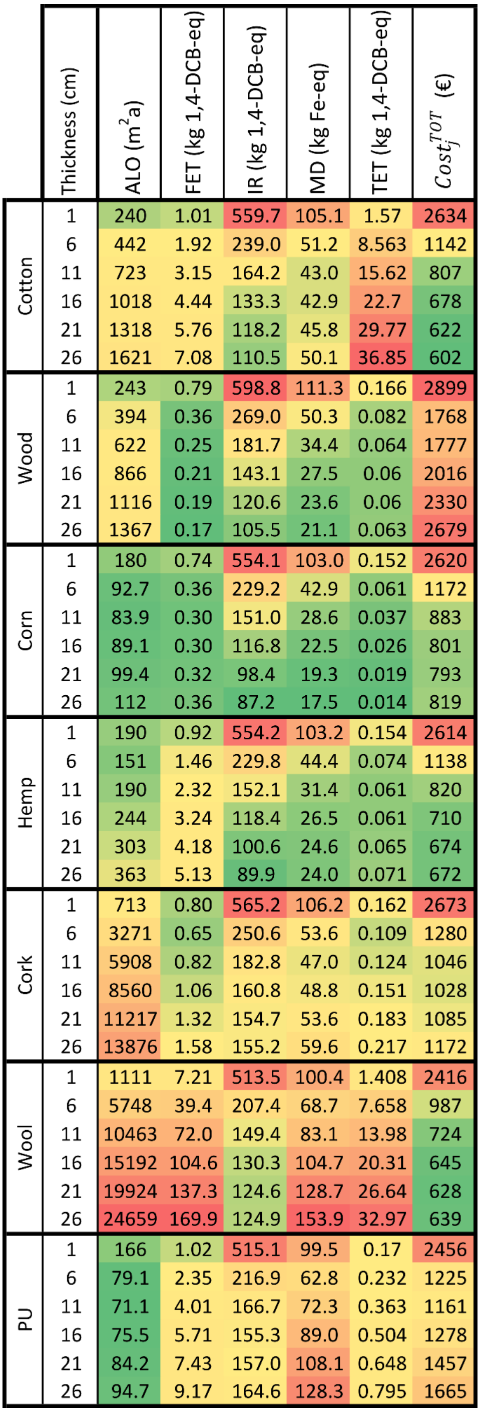
However, differences can still be observed among the them and some other DMUs show a clearly distinct trend with high amount of conflicts. These tendencies among the inputs suggest that they would benefit from an objective reduction. It can be noted that the first five inputs (ALO (agricultural land transformation), GWP (global warming potential), FE (freshwater eutrophication), FET (terrestrial ecotoxicity), ME (metal depletion)) present a similar trend, with few DMUs showing a conflict between adjacent inputs. For example, insulation alternatives involving high thicknesses of cork (0.11-0.26m) present low impacts in most environmental categories, but high impacts in ALO (agricultural land transformation). These high impacts are explained by the amount of land necessary to grow cork oaks, from which cork can only be extracted every 10 years approximately. Conversely, wool has high environmental impact in the first five inputs (ALO (agricultural land transformation), GWP (global warming potential), FE (freshwater eutrophication), FET (terrestrial ecotoxicity), ME (metal depletion)) and in the majority of the impacts. A deep analysis shows that wool has a relevant environmental impact, especially the high amount of land required for its production, the impact in soil salinity and erosion and the high amount of greenhouse gases involved in its production.

In conclusion, it is expected that a high amount of inputs, such as GWP (global warming potential), FE (freshwater eutrophication), ME (metal depletion), FD (fossil depletion), NLT (natural land transformation) will be reduced. In contrast, those showing more conflicts (ALO (agricultural land transformation), IR (ionizing radiation), MD (metal depletion), PMF (particulate matter formation), ULO (urban land occupation) and $Cost_j^{TOT}$) will probably remain after objective reduction.

4.2. Dimensionality reduction

The dimensionality reduction method described in section 3.5 is applied imposing an accepted delta error of 0%. This means that inputs are only eliminated if this causes no information to be lost. Results reveal that only six inputs are required in order to maintain the dominance structure of the problem, and that these six inputs are unique (i.e., there are no other combinations of six inputs producing the same result). Retained inputs are ALO (agricultural land occupation), FET (fresh water ecotoxicity), IR (ionizing radiation), MD (metal depletion), TET (terrestrial ecotoxicity) and $Cost_j^{TOT}$. Their values for the 42 DMUs are represented in a heatmap in Figure 5; these are the data that will be used in the following step of the methodology.

III.4.2.Dimensionality reduction



	Thickness (cm)	ALO (m^2a)	FET (kg 1,4-DCB-eq)	IR (kg 1,4-DCB-eq)	MD (kg Fe-eq)	TET (kg 1,4-DCB-eq)	$Cost_j^{TOT}$ (€)
Cotton	1	240	1.01	559.7	105.1	1.57	2634
	6	442	1.92	239.0	51.2	8.563	1142
	11	723	3.15	164.2	43.0	15.62	807
	16	1018	4.44	133.3	42.9	22.7	678
	21	1318	5.76	118.2	45.8	29.77	622
	26	1621	7.08	110.5	50.1	36.85	602
Wood	1	243	0.79	598.8	111.3	0.166	2899
	6	394	0.36	269.0	50.3	0.082	1768
	11	622	0.25	181.7	34.4	0.064	1777
	16	866	0.21	143.1	27.5	0.06	2016
	21	1116	0.19	120.6	23.6	0.06	2330
	26	1367	0.17	105.5	21.1	0.063	2679
Corn	1	180	0.74	554.1	103.0	0.152	2620
	6	92.7	0.36	229.2	42.9	0.061	1172
	11	83.9	0.30	151.0	28.6	0.037	883
	16	89.1	0.30	116.8	22.5	0.026	801
	21	99.4	0.32	98.4	19.3	0.019	793
	26	112	0.36	87.2	17.5	0.014	819
Hemp	1	190	0.92	554.2	103.2	0.154	2614
	6	151	1.46	229.8	44.4	0.074	1138
	11	190	2.32	152.1	31.4	0.061	820
	16	244	3.24	118.4	26.5	0.061	710
	21	303	4.18	100.6	24.6	0.065	674
	26	363	5.13	89.9	24.0	0.071	672
Cork	1	713	0.80	565.2	106.2	0.162	2673
	6	3271	0.65	250.6	53.6	0.109	1280
	11	5908	0.82	182.8	47.0	0.124	1046
	16	8560	1.06	160.8	48.8	0.151	1028
	21	11217	1.32	154.7	53.6	0.183	1085
	26	13876	1.58	155.2	59.6	0.217	1172
Wool	1	1111	7.21	513.5	100.4	1.408	2416
	6	5748	39.4	207.4	68.7	7.658	987
	11	10463	72.0	149.4	83.1	13.98	724
	16	15192	104.6	130.3	104.7	20.31	645
	21	19924	137.3	124.6	128.7	26.64	628
	26	24659	169.9	124.9	153.9	32.97	639
PU	1	166	1.02	515.1	99.5	0.17	2456
	6	79.1	2.35	216.9	62.8	0.232	1225
	11	71.1	4.01	166.7	72.3	0.363	1161
	16	75.5	5.71	155.3	89.0	0.504	1278
	21	84.2	7.43	157.0	108.1	0.648	1457
	26	94.7	9.17	164.6	128.3	0.795	1665

Figure 5. Heatmap with retained input values for each DMU. Higher impacts are represented in red while lower impacts are depicted in green.

A preliminary analysis of the data shows that wool has the highest environmental impact in ALO (agricultural land transformation) due to the high feed crop area required by sheep [116]. On the other hand, hemp, corn and PU have a much lower impact in this category, with the former two being high-yielding, fast-growing crops, and the latter being obtained from fossil fuels. It is noticeable that thinner layers of insulation result in high IR (ionizing radiation). This is because the thinner the insulation material, the more energy is required to maintain the comfort within the dwelling and therefore, the higher the contribution of the electricity mix on the total impact of that alternative. In the case of Spain, where the share of nuclear energy is approximately 20% of the total mix, this results in a noticeable increase in IR (ionizing radiation)[117]. Similarly, cost is also high in all the alternatives involving thin layers of insulation as a result of the electricity cost in the Spanish retail market (0.23€/MWh, 15% higher than the average in the EU in 2016 [118]). In cork and PU, the high cost of the material carries more weight, which explains the increase of cost with thickness.

In brief, hemp and wood have the lowest environmental impacts, while cork and cotton present the largest impacts due to their manufacturing processes [119] and the amount of pesticides and water used to farm [120]. Wool has the worst environmental impact in most of the categories as a result of livestock farming and wool treatment during manufacture [121]. Regardless of the material, all the combinations between 1 and 6 cm thick, show high $Cost_j^{TOT}$ and IR (ionizing radiation), , due to the amount of electricity needed for heating and cooling the building.

4.3. Initial DEA results: efficiency assessment

At this point, DEA is applied to the 42 DMUs considering the reduced set of inputs in order to identify efficient alternatives and candidate composites. Efficiency scores are presented in Figure 6, where efficient solutions are those achieving an efficiency score of 1. Results reveal that 12 out of 42 insulation alternatives are efficient, with 11 of them involving bio-materials and one PU. This means that some bio-based alternatives show a performance at least as good as that of PU and even better if any non-optimal thickness of insulation of the later is used (i.e., different from 11 cm). This result is in agreement with previous observations by Torres-Rivas et al.[82]. The alternative entailing 11 cm of PU is efficient mainly because it shows the lowest impact in ALO (agricultural land occupation). In the case of bio-based alternatives, optimal thickness range 21 to 26 cm since energy savings surpass impacts and costs incurred during material manufacturing. Exceptions to this rule are corn, which become efficient from 11 cm onwards (due to its low environmental impact and the reuse of a by-product [38]), and wood, which is efficient starting at 16 cm (mainly owing to its low impact in FET (freshwater ecotoxicity)). As expected for a climate as the chosen for the case study (Bsk - Koppen classification, with a temperature range between 1 and 12 ºC on average in the coldest month, and between 19 and 33 ºC in the warmest), insulation layers below 10 cm are never efficient regardless the insulation material employed, which supports the advantage of insulating buildings in such cold climates.

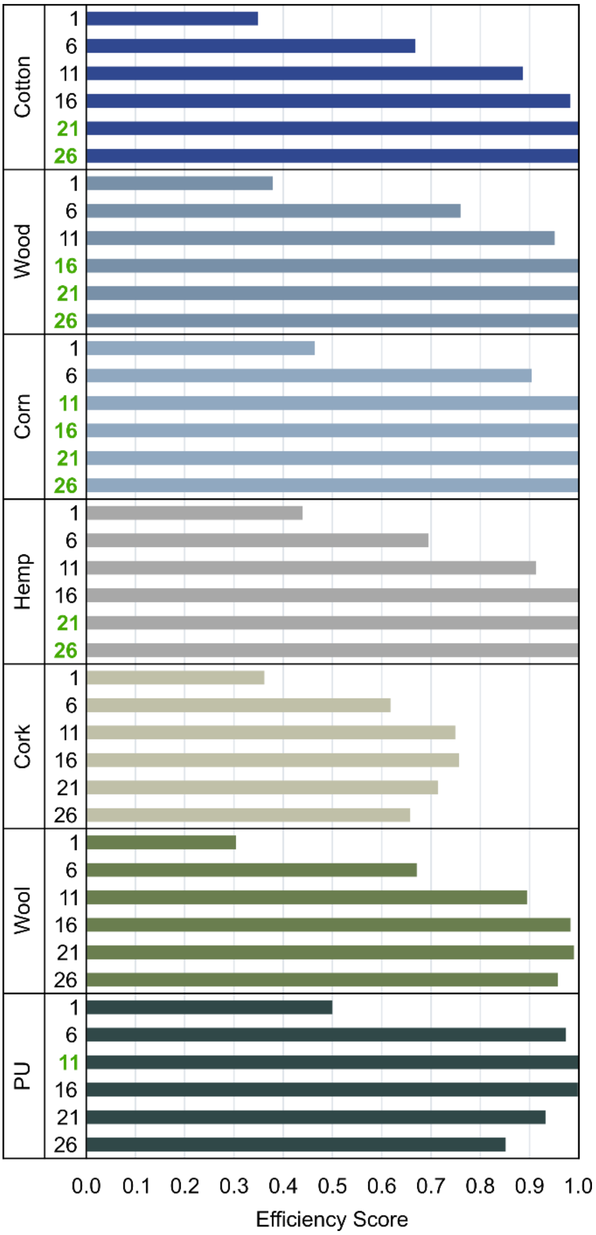
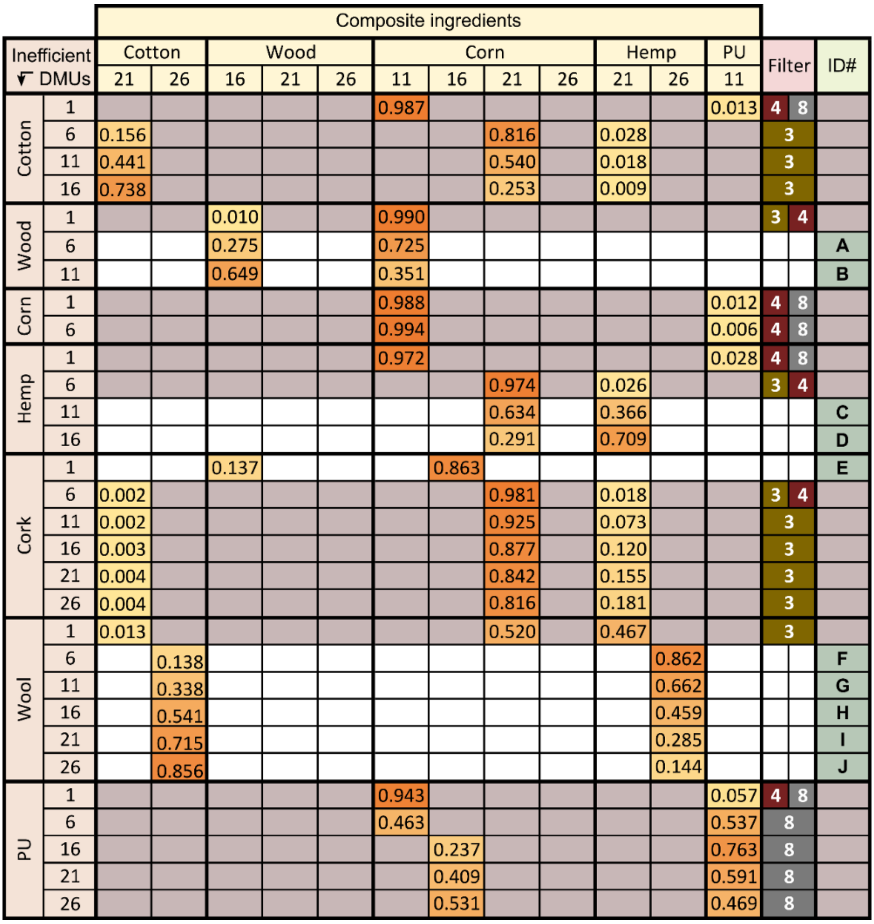


Figure 6: DEA efficiency scores. The numbers beside the materials provide the thicknesses of the insulation layers, with green labels indicating an efficient alternative.

The 30 inefficient alternatives contain all of the alternatives involving cork and wool. This is because these two materials never achieve the best performance in any input, being always inferior to other alternatives. Despite this, wool is close to achieving an efficient status with layers of 16 and 21 cm, due to their low cost. Conversely, cork is always far from being efficient despite having lower values than wool in most of the inputs. In a traditional DEA, one would now analyse the reason of the inferior performance of inefficient alternatives in an attempt to spot opportunities for improvement. However, in the proposed framework, we use these alternatives as a source for potential candidate composites, as described in the next section.

4.4. Identification of potentially efficient composites

Inefficient DMUs were projected onto the efficient frontier, giving rise to virtual DMUs with the potential to become feasible building products (fiber mats, sandwich panels or rigid panels). Results from these projections are shown in Figure 7, where each row corresponds to an inefficient solution and inner cells provide the contribution of each efficient alternative (i.e., material and thickness, as indicated by the columns) required to produce the corresponding virtual DMU. As an example, when the first inefficient DMU (1 cm of cotton) was projected onto the efficient frontier, the resulting virtual DMU was obtained by combining 11 cm of corn with 11 cm of PU, with relative weights of 98.7%-1.3%, respectively.



		Composite ingredients														
Inefficient DMUs		Cotton		Wood			Corn				Hemp		PU	Filter		ID#
		21	26	16	21	26	11	16	21	26	21	26	11			
Cotton	1						0.987						0.013	4	8	
	6	0.156							0.816		0.028			3		
	11	0.441							0.540		0.018			3		
	16	0.738							0.253		0.009			3		
Wood	1			0.010			0.990							3	4	
	6			0.275			0.725									A
	11			0.649			0.351									B
Corn	1						0.988						0.012	4	8	
	6						0.994						0.006	4	8	
Hemp	1						0.972						0.028	4	8	
	6								0.974		0.026			3	4	
	11								0.634		0.366					C
	16								0.291		0.709					D
Cork	1			0.137				0.863								E
	6	0.002							0.981		0.018			3	4	
	11	0.002							0.925		0.073			3		
	16	0.003							0.877		0.120			3		
	21	0.004							0.842		0.155			3		
	26	0.004							0.816		0.181			3		
Wool	1	0.013							0.520		0.467			3		
	6		0.138									0.862				F
	11		0.338									0.662				G
	16		0.541									0.459				H
	21		0.715									0.285				I
	26		0.856									0.144				J
PU	1						0.943						0.057	4	8	
	6						0.463						0.537	8		
	16							0.237					0.763	8		
	21							0.409					0.591	8		
	26							0.531					0.469	8		

Figure 7: Heatmap of the candidate composites systematically obtained from DEA projections. Rows correspond to inefficient DMUs and columns to efficient alternatives that can be used as ingredients to obtain candidate composites. Inner cells provide the contribution of each efficient DMU in the composite, with light color (yellow) corresponding to low contributions and dark ones (bright orange) corresponds to high contributions. The second to last column corresponds to the filtering rules excluding a given alternative (if the alternative is discarded, the whole row is shadowed). The last column assigns an identifier to retained candidate composites.

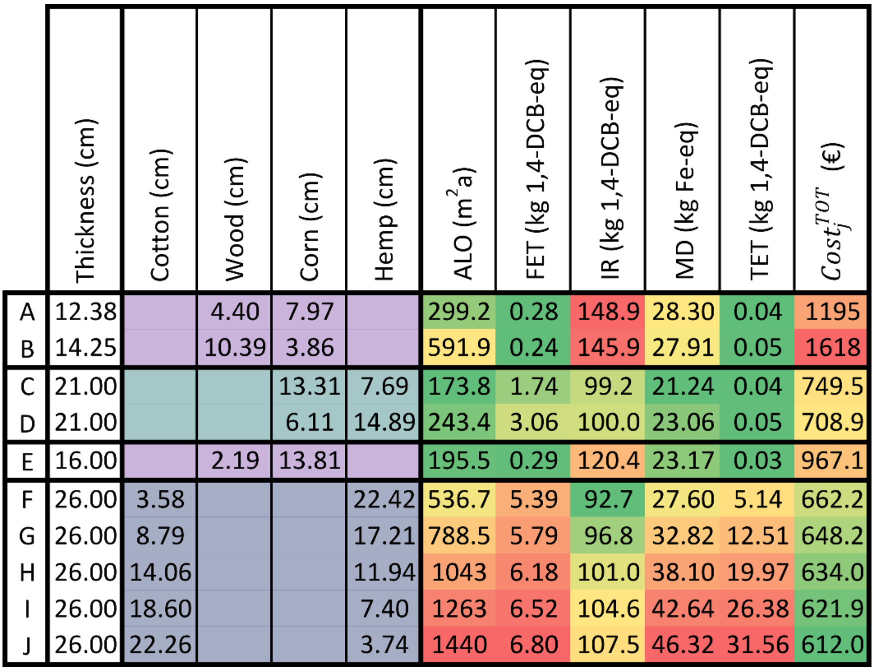
From Figure 7, it can be observed that corn is the main material in most of the candidate alternatives identified with DEA (linear weight larger than 0.500), due to having the lowest impact on most of the environmental categories. A deeper analysis reveals that there are two main types of composites involving corn. Ones are thin rigid panels where corn is combined with wood or PU. These composite alternatives assume a higher energy demand during the use phase which is compensated with a low embodied impact. The second type of corn-based composites are thicker sandwich panels combining corn and hemp or cotton. Their embodied impact is higher but energy demand during use phase is reduced. Other combinations not including corn were also efficient. This was the case of thick fibre mats combining cotton and hemp, also maximizing energy savings during the use phase.

After this, the 30 candidate composites (one per each inefficient DMU) went through the filtration described previously, where eight filtering rules are applied to avoid combinations considered unattractive to the insulation market. The result of this process is also shown in Figure 7, precisely in the second to last column, where the filtering rule(s) violated by each alternative (if any) are depicted using the same numeric code as presented in Section 3.6. Following with the example of the first candidate composite, it violates two of the filters, namely, the difference between the composite and the "single-material" alternative involving 11 cm of corn lies below 5% (rule number 4), and it also contains PU, which is not a bio-based material (rule number 8). Therefore, it must be discarded (note the shadowed row in the figure).

The filtering step resulted in the exclusion of a total of 20 out of 30 efficient combinations: nine including PU (identified with number 8 in Figure 7), 12 including layers of less than 1 cm (rule number 3) and eight whose composition differed less than 5% from the single-material alternative (number 4), since those materials will not benefit from the tailored performance of the composites. In this case study, single-material alternatives or combinations with more than three materials did not arise through DEA projections.

The other 10 composites meet all the requirements and therefore, are retained for subsequent analysis (see the last column in Figure 7 for reference to their identifier). Among them, we can identify three rigid panels combining corn and wood (A, B and E); two sandwich panels formed by two rigid surface layers (wood or corn) and a soft inner layer (cotton or hemp) (C and D); and five fibre mats combining cotton and hemp (F-J).

To obtain the amount of each material that should be implemented in the final composite, linear weights should be used in combination with the thickness of the material in the efficient alternative associated with that weight. For example, in candidate A, the linear weight of the efficient alternative involving 16 cm of wood is 0.275, which would correspond to a layer of wood of 4.4 cm thick. In the case of sandwich panels, this is directly thickness of layer on the final panel (or half the thickness of each external layer in case the material corresponds to the external support), whereas, for fibre mats, this layer should be understood as the quantity of material to be combined with the other fibres. All combinations are shown in Figure 8. The combinations suggested are more balanced solutions than single-material alternatives, as the weaknesses of one material in a particular category are compensated by the addition of a second material. For example, if cost is a barrier for the implementation of a material, a combination with cotton (i.e., the cheapest bio-based insulation materials) would decrease the cost of the final composite, bearing in mind that the composite cost has been assumed to be the same as the layers of the material individually. Similarly, if, for instance, a more constraining environmental regulation on FET (fresh water ecotoxicity) appears, composites involving wood would constitute promising alternatives to bring the final impact on this category down.



	Thickness (cm)	Cotton (cm)	Wood (cm)	Corn (cm)	Hemp (cm)	ALO (m^2a)	FET (kg 1,4-DCB-eq)	IR (kg 1,4-DCB-eq)	MD (kg Fe-eq)	TET (kg 1,4-DCB-eq)	$Cost_j^{TOT}$ (€)
A	12.38		4.40	7.97		299.2	0.28	148.9	28.30	0.04	1195
B	14.25		10.39	3.86		591.9	0.24	145.9	27.91	0.05	1618
C	21.00			13.31	7.69	173.8	1.74	99.2	21.24	0.04	749.5
D	21.00			6.11	14.89	243.4	3.06	100.0	23.06	0.05	708.9
E	16.00		2.19	13.81		195.5	0.29	120.4	23.17	0.03	967.1
F	26.00	3.58			22.42	536.7	5.39	92.7	27.60	5.14	662.2
G	26.00	8.79			17.21	788.5	5.79	96.8	32.82	12.51	648.2
H	26.00	14.06			11.94	1043	6.18	101.0	38.10	19.97	634.0
I	26.00	18.60			7.40	1263	6.52	104.6	42.64	26.38	621.9
J	26.00	22.26			3.74	1440	6.80	107.5	46.32	31.56	612.0

Figure 8. Summary of the different composites, the first part corresponds to the thickness and composition of the alternatives, where the colour of the alternative corresponds to the typology of the material (purple, light blue and blue corresponds to rigid panels, sandwich panels and fibre mats respectively). The second part of the

figure corresponds to a heatmap of the inputs of the proposed composites, the higher inputs are represented in red while the lowers are green.

The performance of these composites in terms of inputs, as provided by DEA projections, is shown in Figure 8. For instance, the comparison of composites C and D reveals that increasing the share of hemp with respect to corn reduces environmental impacts at the expense of incurring in a higher cost. Recall that while only two particular combinations (i.e., set of shares) of these materials were identified through DEA projections, their combination in any proportion would in principle be efficient and lie on the efficient frontier. Finally, we can see that composites C and D are the most balanced solutions, as they provide solutions with low inputs in the majority in of the categories.

As aforementioned, input values shown in Figure 8 are those obtained in DEA by linearly combining the performance of the individual materials forming the composite. However, it could be the case that this hypothesis would not hold in practice since impacts or costs might experience a non-linear behaviour due to heat transfer laws. Therefore, we next simulate the 10 composite alternatives retained in the same building model as described in section 3.1 in order to reassess their performance in the space of impacts and cost.

4.5. Validation of the retained composites

In the absence of more detailed information regarding the physical properties of the composites, these are implemented in the simulation by adding a separate layer for each material of the composite, even in the case of fibre mats. The output of the model is energy demand along the building’s lifespan, which is used to calculate the corresponding environmental impact and cost of the composite alternative as described in 3.4.

In Figure 8, results obtained from the simulation are compared with those provided directly by DEA’s virtual DMUs. Specifically, there are six pairs of bars for each candidate composite; each of these pairs provides the normalized value for a given input as obtained from DEA projections (plain bar) or from the simulation (patterned bar) (values to be read in the left-hand side axis). The relative error between the two assessment alternatives (DEA *vs* simulation), obtained prior to normalizing, is represented with square markers (to be read in the right-hand side axis). Results evidence that inputs of virtual DMUs and those obtained from the simulation are almost the same, with relative errors lower than 1% in all the cases and with an average error of 0.025%. We can conclude that, at least for the materials involved in this case study, the performance of the composite materials can be accurately predicted from DEA projections, making it possible to avoid the modelization and simulation of the composites proposed.

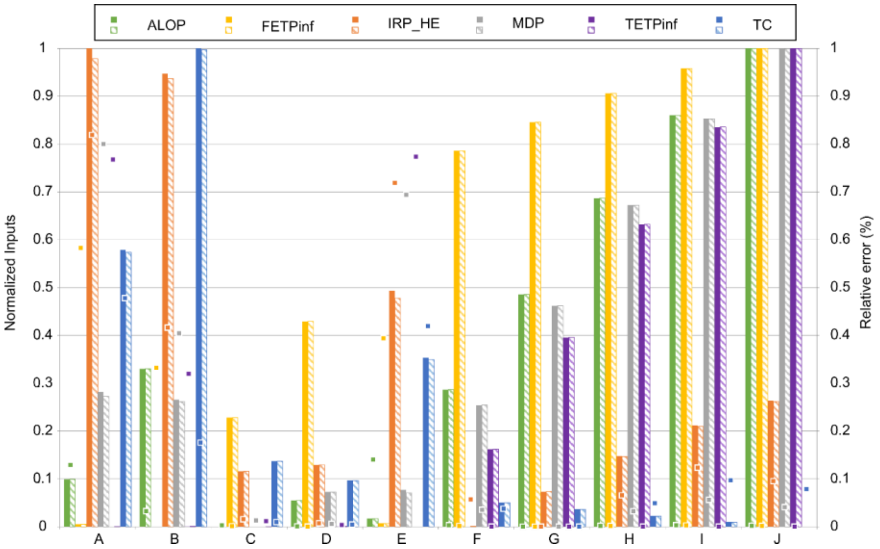


Figure 9: Comparison of the composites' performance between DEA prediction (plain) and simulation results (patterned). Bars correspond to the normalized inputs (as read on the left-hand side axis) while the squares markers represent the relative error (as given by the right-hand side axis). The composition of each composite is shown underneath.

With impacts and costs from simulation at hand, we finally assess the efficiency of the composite alternatives using DEA and including as well the 11 (single-material) alternatives found efficient in the previous DEA analysis (section 3.4). Results (Figure 9) evidence, that seven out of the ten proposed composites achieve an efficiency score of 1, with the remaining ones lying really close to the efficient status (i.e., efficiency scores always above 0.999). Hence, the proposed methodology has proven to provide eco-efficient composites in a systematic manner and, perhaps more importantly, aid in the penetration of the bio-based insulation alternatives.

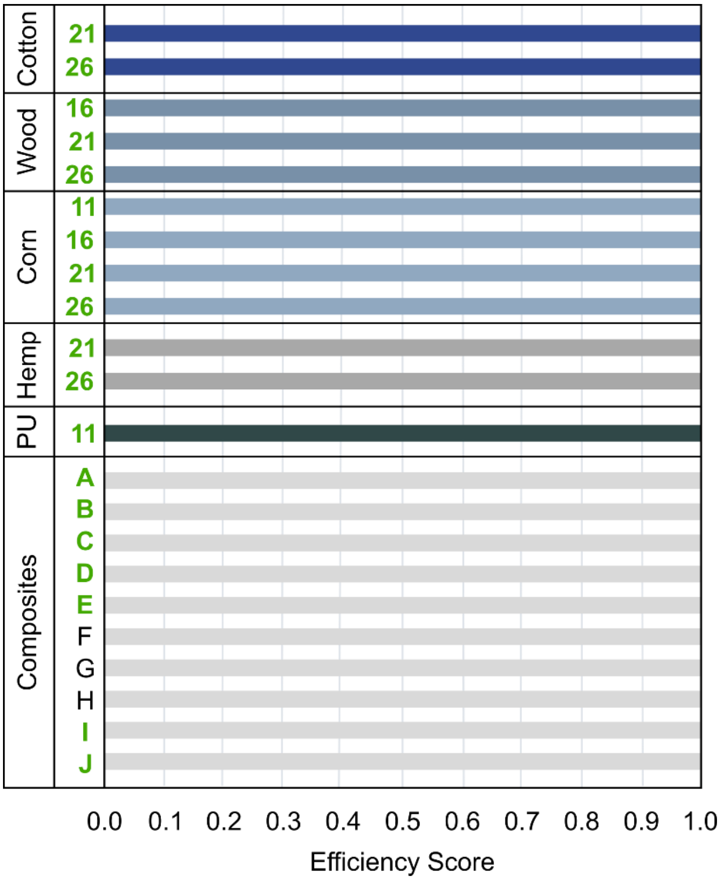


Figure 10: Efficiency score of the composite materials and the efficient one-component materials.

5. Conclusions

In this contribution, a systematic methodology to generate eco-efficient insulation composites has been put forward. The methodology takes advantage of DEA projections to identify promising combinations of single-material insulation alternatives. These candidate combinations hold the property of being eco-efficient, but require additional filtering to disregard those which are unappealing from a commercial point of view.

As a testbed, we have illustrated the performance of the methodology considering six bio-based insulation materials and a conventional one (polyurethane) to be implemented in a cubicle-like building. All these materials are available in seven different thicknesses, yielding a total of 42 insulation alternatives that are available as building blocks for the composites.

We found that 12 insulation alternatives were efficient (29% of the total) and, therefore, qualified for becoming part of the final composites. For each of the other 30 (inefficient) alternatives, we generated a particular combination of efficient alternatives using DEA projections. These eco-efficient alternatives were later filtered, resulting in only ten candidate composites retained: two sandwich panels made of corn and hemp, three rigid panels combining wood with corn, and five fiber mats entailing different shares of cotton and hemp.

Without loss of generality, other DEA models or projections could be used to generate different composite alternatives than the ones identified here.

The formed composites have achieved efficiency in almost all alternatives, (seven with an efficiency of 1 whereas the rest of the composites achieve efficiencies higher than 0.999). We can conclude that DEA properly predicts the performance of the insulation materials of the composites, generating a good methodology of the early stages of materials design of composites.

It is important to emphasize that, here, results were obtained using simulation tools and, therefore, should be complemented with in vitro tests in order to obtain accurate estimates of both composite properties as well as manufacturing costs. Only then the promising results from this study could be confirmed. Meanwhile, perhaps the proposed methodology can motivate further interest in the development of commercial products based on bio-materials and increase this way their deployment as insulation solutions in the building sector.

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IV. CASE STUDY III

IV.7.References

IV. Building stock quantification approach for building retrofit analysis. A case study for PV potential and Energy demand reduction.

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1. Introduction

It is estimated that 50% of the total final energy consumption in EU is used in heating and cooling of buildings, and less than 10% of such energy is produced using renewable sources [122]. There is, thus, a wide potential for the development of renewable energy sources. European Union policies are encouraging the implementation of renewable energies as an alternative to the fossil fuels dependency (https://ec.europa.eu/eurostat/cache/infographs/energy/bloc-4c.html). This change has become a necessity due to the global warming effects as the increase of temperatures, especially in the cities. Those new tendencies have generated changes in local policies [123], in the cities strategies [124] and in consumers' perspective.

A wide implementation of a solar energy network for heating and cooling of buildings have several advantages. On one hand, it contributes to the resilience of the energy system, thanks to the diversification of energy sources and the reduction of the pressure on existing electric lines, especially in pick hours. On the other, it enhances the efficiency of the system, as energy losses due to transport are reduced. To carry out this implementation, Nault et al. [125] identified solar potential methods into three categories: (1) geometry-based metrics; (2) external solar and geometry-based metrics; and (3) full climate and geometry-based metrics. For each metric, two kinds of performance criteria are identified: passive solar and active solar. Then, the authors apply these metrics to two case studies: an area with different urban planning options and a planning with different parameter options, modelling with Rhinoceros and Grasshopper plugin and climate files from Meteonorm.

To estimate the solar potential of the existing building stock, the available roof area (Aa) needs to be worked out. The available roof area corresponds to the part of the built-up area in which the implementation of solar panels is feasible. This excludes poorly oriented or shaded areas, areas perforated for natural lighting or ventilation and areas occupied by competing uses (such as HVAC installations, terraces, elevators), among others. As such aspects are highly case specific, the assessment of the available roof area on a large scale (a city or a region) is hampered. Once the available area is known, the solar potential can be easily calculated using available irradiation maps and climate databases.

Most of the attempts made for the evaluation of available roof area (and the consequent solar potential) follow a bottom-up strategy. This approach consists on analysing in detail a comprehensive urban area to determine what ratio of the total roof area is available and then extrapolate the results to a larger territory.

Following a bottom-up approach, Izquierdo et al. [126] sampled areas of about 450 x 450 m of urban areas in Spain. Using available cartographic maps, they estimated the available roof area in each sample. They defined the available roof area (Aa) as the total roof area (Ar) modified by two coefficients ranging from 0 to 1 (Cs and Cf) that accounted for the effect of shadows from other buildings and for the areas occupied by competing uses respectively. Then, they classified urban areas into Representative Building Typologies (RBT). RTB were function of population density and building density, which were both divided into quartiles (Low, Medium, High and Very High). Thus, the RBT "L-L" included, for instance, rural areas (low population density) with disseminated single family houses (low building density), while the "VH-L" included suburban areas (very high population density) with single-family houses in row (low building density), etc. Ar per area unit, Cs and Cf were extrapolated from the sampling assuming that they were characteristic to each RBT.

Their results showed that the total available roof area in Spain is 517 ±183 km2 and 14.0±4.5 m2/habitant (confidence level of 95%). This agrees with the figures previously published by IEA (393.7 km2) and Greenpeace (595 km2). The authors also reported that Catalonia is the region in Spain with the highest potential, with about 100 km2 of available roof area. The authors also pointed out that solar potential is concentrated rather than distributed in the territory: 3.5% of the municipalities contribute to half of the total solar potential of the country.

Hofierka et Kanuk [127] proposed a three-step methodology to assess photovoltaic potential at a neighbour or mid-sized town level. Their methodology includes (1) the creation of a 3D model of the city and its implementation in a GIS database; (2) the modelling of solar radiation using r.sun model; and (3) the calculation of potential energy production using PVGIS. They applied their methodology to a town in Slovakia. In order to allow for an extrapolation of the results obtained, the authors divided the urban area into four zones according to the predominant building typologies: residential houses (767.5 buildings/km2), blocks of flats (230.2 buildings/km2), industrial areas (258.2 buildings/km2) and other facilities (212.0 buildings/km2). Their results show that the ratio of available roof area with respect to the total and roof area (Aa/Ar) varies from 0.35 to 0.75 among the zones. The authors point out that higher photovoltaic potential and lower connection and maintenance costs should be expected in zones with bigger buildings, such as blocks of flats or facilities.

Li et al. [128] evaluated the effect of building aspect ratio, orientation and density (which was depended on building high and floor occupation) on solar potential. Their analysis was not restricted to roofs but accounted for all the building façades. They took into account the "exploitable solar radiation", that is, the radiation above the minimum threshold from which solar technologies are feasible.

The authors modelled an urban arrangement of 9 pavilion dwellings in TRNSYS to estimate the total building surface with "exploitable solar radiation" and then applied a corrective factor (0.75) that accounted for any other aspect restricting the available area (such as areas occupied by competing uses, etc.). Their results show that solar potential in roofs can be reduced in 60% at high-density configurations

The concept of "exploitable solar radiation" is also used by Santos et al. [129], who exclude surfaces with a solar irradiation lower than 800 kwh/m2year in their calculations. Moreover, the authors also consider the size of the roof area and exclude those roofs of less than 24 m2, as these are supposed too small for any solar technologies to be economically viable.

Those models are computational demanding and they are not coupled with the demand of those buildings. Following this objective and with the perspective to achieve a methodology which analyse the possible self-consumption of the residential sector we propose a novel methodology that enables to estimate the roof potential and the energy demand at the same time, what allows to calculate the covering potential of the buildings applying the chosen technology, in this case PV. The methodology consists in quantify the residential stock and characterise it in order to distribute those dwellings in the total of buildings. This enables to quantify the energy demand of the dwellings, depending on the characteristics of the buildings and to quantify the roof potential of the buildings. Furthermore, this model provides the possibility to analyse the effect of energy efficiency measures in the whole building stock which can provide guidelines for policy makers to justify future trends.

2. Methodology

We proposed a methodology that quantifies the solar potential of the residential building stock and the energy demand corresponding to the corresponding regional stock. This is important in order to verify the potential of the residential stock and to generate a methodology that quantifies the potential of improvement required in the building stock in order to achieve a regional balance between the potential of generation and the demand of all the buildings. To achieve these aim, the current stock of a region has to be quantified and characterized, in order to know the building's characteristics and the quantity of each profile specified. This would allow analysing the different style of municipalities and the effect of the local climate conditions.

This methodology is divided into three steps, the first one is the corresponds to the building stock, the next one is the solar potential and finally the improvement targets in the residential sector. The following figure summarize the key steps and the necessary data to carry out this methodology.

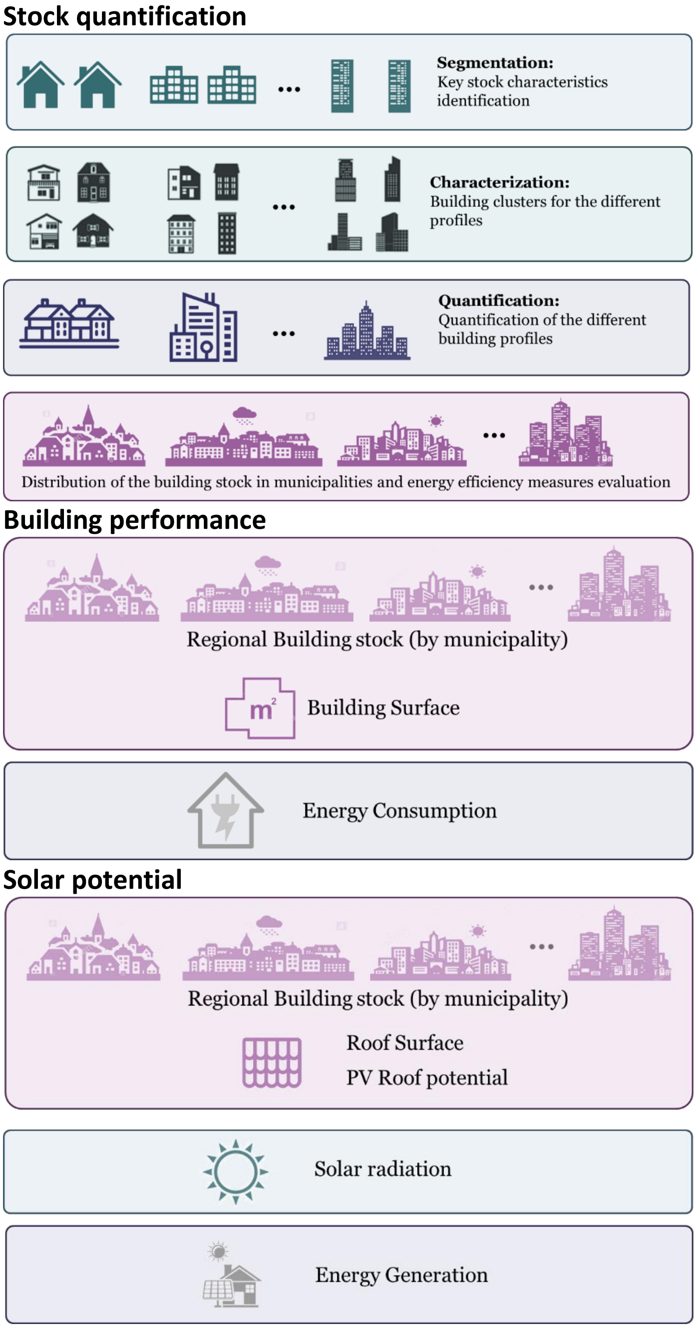

Figure 0: Methodology scheme of the different steps and the different sub-steps of the proposed methodology, starting with the building stock quantification and distribution in the different municipalities. Energy demand calculation based on the building stock, the characterization of the buildings and the building surface by typology of the

building. The energy generation based on the same calculation but implementing the PV potential roof and the solar radiation.

This methodology can be applied to all the different solar potential studies, but is mainly focus on wide areas, decreasing the computational demand with an important clustering of the building stock, which could be coupled with building modelling or bibliographic data. In the following section we would detail the methodology in a general view going more in deep in the details of the model in the Case Study section.

2.1. Building stock

The most important part of the model is to quantify and characterize the building stock properly, taking into account that it is impossible to define each particular building characteristics of a regional area, clustering properly the buildings stock should decrease the computational demand of the model and make it feasible without compromising the final results. In this case, the most important characteristics to define the building stock correspond to the year of construction, the number of dwellings and the typology of the buildings, as all the building characterizations include those characteristics (ref cuchi, episcope and tabula). The year of construction is important because old buildings trend to have less insulation and worse enclosure than newer buildings, which affects the thermal conductivity in the roof and walls and specially the infiltrations of the building, which are two key parameters in the energy demand of a building. The number of dwellings is important because it decrease the amount of roof for each housing and also reduces the effects of outside conditions in the energy demand. Finally, the typology of construction is important to quantify properly the energy demand of the building, single family houses have more enclosure that multi-family houses and are more exposed to all climatic conditions, especially solar radiation in the roof for Mediterranean climates [130]. Taking into account this three key factors, the regional area selected would be analysed and clustered.

The total building stock of the area is divided according to the selected clusters, achieving for each of the municipality the amount of buildings that correspond to each typology of building and the total building surface of each typology. With this information, the total roof and the energy demand can be calculate.

2.2. Solar potential

The solar potential is quantified for each municipality, applying the specific climate conditions to the total roof available. For this roof potential, the total stock of each municipality divided in the different profiles of buildings is used to calculate the total roof available, applying a corresponding relation between the building surface and the total roof of the building, which is influenced by the amount of dwellings and the type of the roof (flat or gable roof). With this method we ensure that all the roof analysed is only from the residential sector and available for PV panels.

This total roof does not correspond to the potential roof, according to the fact that it is affected by the orientation, the architectonical effects and the shadings, among others, the whole area should be reduced to ensure a profitable installation of solar panels. To quantify those effects, a vectorial GIS map methodology can provide the information required to discriminate the profitable roof from the non-profitable one, for this research, as there is some bibliography which already provides results of this methodology [126] for the selected region the final proportion of those research would be applied, for other regions without information provided, a GIS recognition of the roofs of the area could be applied in substitution of this step.

Izquierdo et al. classified the municipalities according to the population density and the building density, and for each combination they suggest an available roof factor and a global available factor. For this study, the range of factors would be used in order to analyse the sensibility of the roof availability in the energy generation.

The solar potential of each municipality can be evaluated with any software simulation, mathematical calculation or just simplify the calculation coupling the roof surface and a bibliographic data of the energy generated. This can provide the energy generation in the chosen time step, which can go from hourly generation to annual one in order to match the generation with the energy demand, which is an important parameter when the energy cannot be absorbed by the grid or when coupled with batteries for example. Finally, the potential of self-consumption would be calculated based on the energy demand and the energy generation in each municipality.

3. Case study

The geographical area of study was limited to Catalonia, which is located in the north-east of Spain. The area includes a total of 947 municipalities and more than 7.5 million of habitants, which correspond to approximately 3.8 million of dwellings in 1.1 millions of buildings [131]. This area is interesting due to the interests of the corresponding government of the area to achieve what they call Energetic transition agreement [123], creating small suppliers of energy that provide electricity in local area. The model proposed would help to analyse the possibilities of the proposed transition or identify the requirements to achieve this model in the residential sector (i.e. building retrofit, small electricity generators (i.e. solar farms), electricity grid improvements, etc.).

The total amount of the municipalities, were divided according to the total population in eleven groups, less than 100 inhabitants, between 101 and 500, between 501 and 1000, between 1001 and 2000, between 2001 and 5000, between 5001 and 10000, between 10001 and 20000, between 20001 and 50000, between 50001 and 100000, between 100001 and 500000 and more than 500000, this division has been carried out using statistical data from INE (the National Statistics Institute of Spain)[132]. After that, the dwellings of each municipality were classified according to the year of construction, the number of flats, the typology of the building (single family house or multi-family house), this is shown in more detail in section 3.

The following figure shows the quantity of each of the nine municipalities size of the different provinces of the region (Tarragona, Barcelona, Lleida and Girona). It is important to remark the high amount of small villages (less than 1000 inhabitants) of the region, the total amount of municipalities is divided in the previous categories with an amount of 458, 113, 142, 89, 58, 40, 13, 9 and 1 case respectively.

In the following figure there are quantified all the different municipalities un each of the region, according to the size of the municipalities. We can see that Lleida (West) and Tarragona (South) have a similar distribution of the type of municipalities, while Barcelona (Middle East) and Girona (North-East) have different profiles. Apart from that, we can see that the all the regions have a good amount of municipalities between 5001 and 10000 habitants, which would help us to compare the climate conditions in those municipalities.

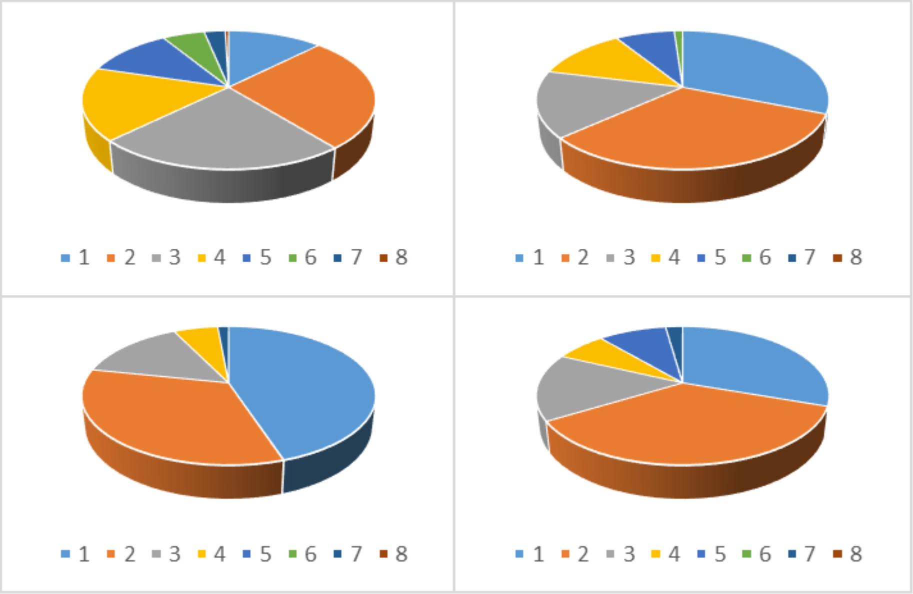

Figure 1: Municipalities distribution for the different size of municipalities (less than 100 inhabitants, between 101 and 500, between 501 and 1000, between 1001 and 2000, between 2001 and 5000, between 5001 and 10000, between 10001 and 20000, between 20001 and 50000, between 50001 and 100000, between 100001 and 500000 and more than 500000).

Once the stock is quantified for each municipality, the total built area is quantified and transformed to the total roof area and energy demand at municipality scale, clustering the existing stock into distinctive typologies. To this aim, the clustering proposed by Cuchí et al. [24]was adopted and actualised up to 2011, assuming the worse scenario possible, where new buildings have the same envelope has the buildings of 2001. Existing buildings were classified into 16 building typologies according to the number of dwellings (single-family and multi-family blocks), number of floors (up to 3 and more than 3 storeys) and the year of construction (before 1960, between 1960 and 1980, between 1981 and 2001 and between 2002 and 2011). The total roof area of the buildings was calculated from the total built area and the number of buildings in each municipality, using the ratios given by Cuchí et al. for each building typology, those typologies without information where extrapolated from Cuchí et al.

information and are shown in table 1. Estimations on the energy demand for each building typology were also taken from Cuchí et al. The authors analysed the main features of the buildings in each category (surface area per dwelling, roof area per usable area, etc.) and determined the average energy demand in each category by building an energy model representative of each category. On the other hand, the stock provided by INE (Instituto Nacional de Estadística) was used to determine the total built area and the number of buildings corresponding to each category in each municipality.

Table 1: Building profiles taken from Cuchí et al. and actualized up to 2011.

	Year of const.	< 1960		1961-1980		1981-2001		2002-2011$^{(1)}$	
	Floors	≤3	≥4	≤3	≥4	≤3	≥4	≤3	≥4
Single family	kWh/ m^2 year	180.5	100.1	175.7	99.5	142.7	85.3	142.7	85.3
	m^2 roof/ m^2 dwelling	0.69	0.5	0.69	0.5	0.69	0.18	0.69	0.18
Multy family	kWh/ m^2 year	180.5	100.1	175.7	99.5	142.7	85.3	142.7	85.3
	m^2 roof/ m^2 dwelling	0.69	0.18	0.69	0.18	0.69	0.18	0.69	0.18

(1) Extrapolated from GTR

Once the total roof and energy demand is quantified for the different municipalities, the roof potential is extracted according to the coefficients of Izquierdo et al. They suggest a different coefficient depending on the population density and the building density of the municipalities. In this article, the maximum range of coefficients and the mean value are used in order to analyse the effect of those coefficients in municipality level. The corresponding value is 0.19±0.06, take into account that 0.19 is the suggested value for Spain, which include the selected area of this article, which means that this range provides the mean value and the worst and best cases.

Finally, the roof potential is transformed to PV potential with the climate conditions of the municipality. This climate conditions influence the solar radiation required for the solar potential of the municipality, for the selected area, there are six different climatic areas according to Köppen classification, Cfb (Temperate oceanic climate), Csa (Hot-summer Mediterranean climate), Cfa (Humid subtropical climate), BSk (Cold semi-arid climate) and Dfb (Warm-summer humid continental climate). This makes it really interesting in order to be able to analyse if this conditions influence the PV generation in the different municipalities, the solar radiation of the different municipalities is shown in the following table.

The solar potential of each municipality can be evaluated with any software simulation, mathematical calculation or just simplify the calculation coupling the roof surface and a bibliographic data of the energy generated. This can provide the energy generation in the chosen time step, which can go from hourly generation to annual one in order to match the generation with the energy demand, which is an important parameter when the energy cannot be absorbed by the grid or when coupled with batteries for example. Finally, the potential of self-consumption would be calculated based on the energy demand and the energy generation in each municipality.

With this radiation the energy produced by the roofs is quantified with an annual numerical calculation (ref). This is carried out with the assumption that the grid is able to absorb the energy produced and supply the same amount when the building demand is required.

4. Results and discussion

We next discuss the results obtained when applying the methodology to the chosen case study. First we will analyse the municipalities characteristics and the initial conclusions that can be obtained from them.

The building stock of each municipality individually is quantified, divided by the year of construction, the amount of dwellings and the type of building. Furthermore, the total constructed area, total roof and PV available roof is also quantified.

IV.4.Results and discussion

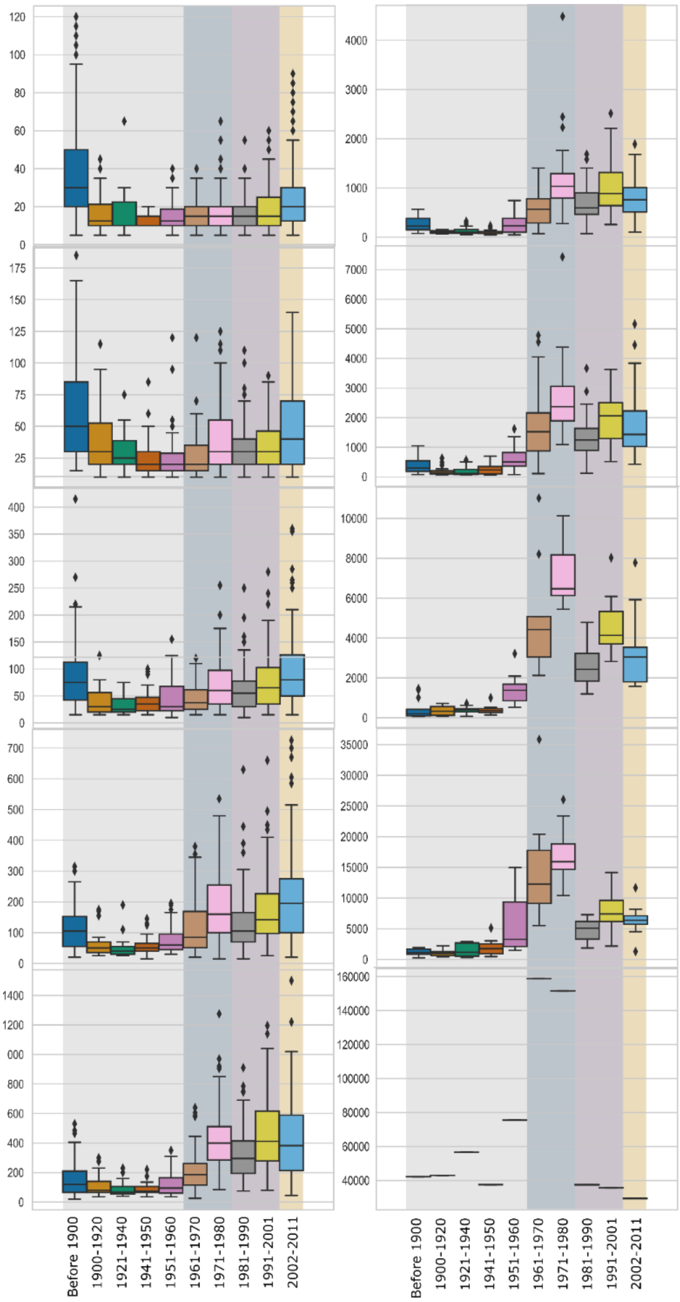

Figure 2: Box plot of the distribution of the buildings according to the municipality size and the year of construction. Starting with the municipalities from 101 to 500 inhabitants until more than 500000 inhabitants, increasing the size from top to the bottom and from left to right.

Figure 2 summarizes the building stock of the municipalities based on the year of construction and the size of the municipality. This plot helps us to analyse the main characteristics of the municipalities. The figure is divided in ten subplots, one for each size of municipality (except municipalities less than 100 inhabitants), furthermore, each subplot contains ten boxplots, one for each range of year of construction. According to Guchi et al., there is a high amount of old dwellings in Spain, which have really high consumption in heating and cooling, which is especially important in buildings built before 1900. According to this plot we can go in more detail about it, identifying that those old dwellings are especially common in small municipalities, less than 10000 inhabitants, which are a total of 86.8% of the municipalities but only a 16.7% of the whole inhabitants, and those buildings correspond to 4.4% of the whole stock. If we analyse all the buildings without insulation, which corresponds to buildings until the 80s (Ref Tabula), the amount of buildings affected is especially important in big municipalities bigger than 20000 inhabitants, which corresponds to 6.8% of the municipalities, but a total of 72% of the whole inhabitants. This is clearly explained by the transition of the people from the rural areas to cities and the high growth that they had during this period. Those buildings correspond to 63.5% of the whole stock of the selected area. The buildings constructed after that period include some insulation, which reduces the energy demand of those buildings.

According to the figure, we can identify 3 different groups of municipalities, B, C and D are the first group, with an intermediate amount of buildings of all ages and with an important amount of really all ones, built before 1900. E, F, G have low amount of all buildings (built before 1960) and with an increase of buildings built after that year. Finally, the last group corresponds to H, I, J and K, with low amount of old buildings, an important increase between 50/60s and 80s with a decrease of buildings after 1981.

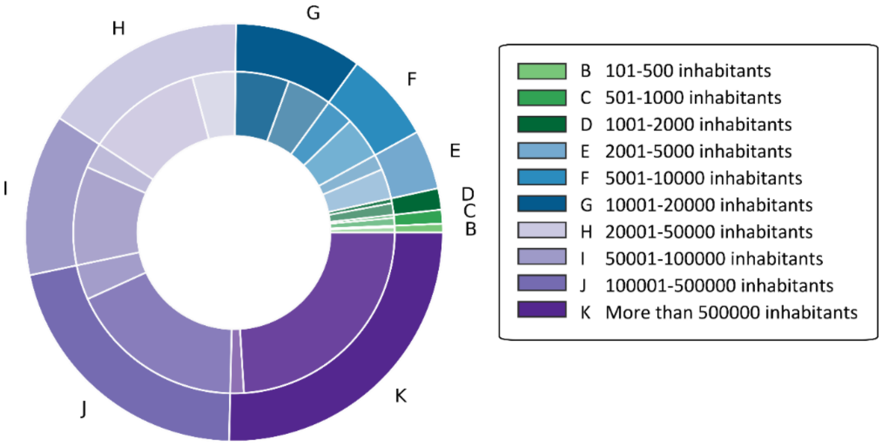

Figure 3. Amount of dwellings divided in single-family houses and pluri-family houses for the different size of the municipality.

Another important reduction in energy consumption is the one provided by the construction typology, comparing multifamily houses with single-family houses. This trend benefits big cities compared to small villages, as it is shown in figure 3, where it is shown clearly that municipalities with less than 20000 inhabitants have more single-family houses than multifamily houses. The increase of multifamily houses has a counterpart with the roof surface by habitant, which is drastically reduce if multifamily houses increase (more details in figure 4). We can see that the groups identified in figure 2 are also identified in this one, where they show the change of tendency the first group has an important amount of single-family houses, the second group has intermediate amount of each type, and the third one has mainly multi-family houses.

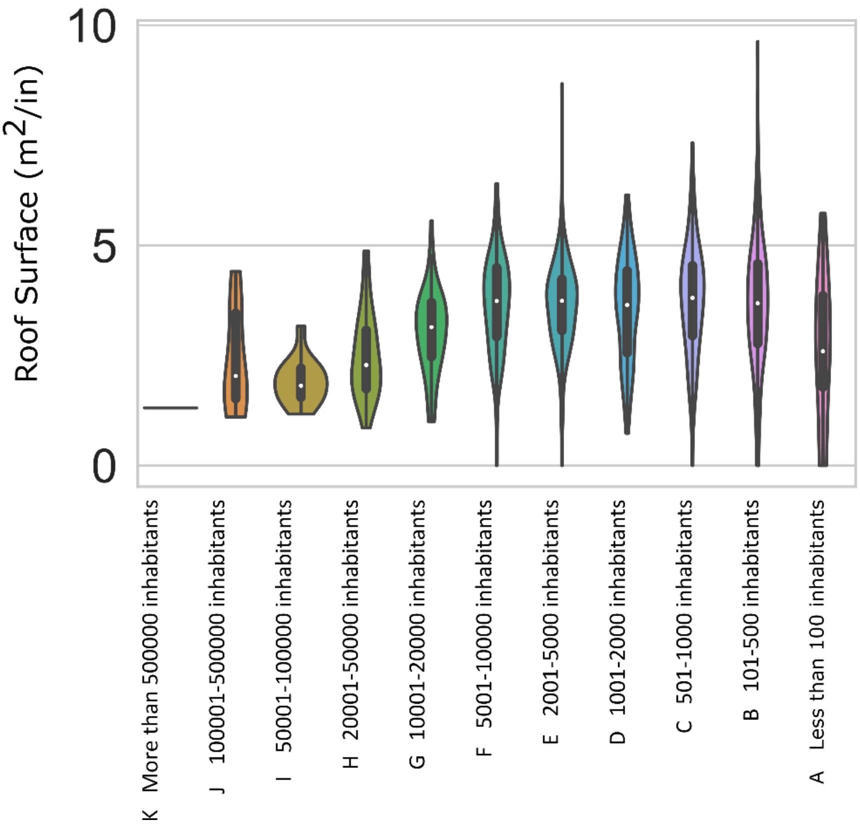

Figure 4: Roof surface per habitant for the different municipalities size.

In the previous figure, the roof surface by habitant is represented for all the municipalities size with a violin plot representation, where the white dot corresponds to the mean value, the black rectangular correspond to the first and third quartiles and the lateral shape wide correspond to the distribution of the municipalities of the different sizes. According to the figure, we can see that all the small municipalities (until 10000 inhabitants), except A category, have a similar roof surface by habitant, between 3.6 and 3.9 m2/h, and it starts to decrease as the size of the municipality increases, reaching decreasing values of 2.9, 2.2, 1.9, 1.65 and 1.3 respectively.

According to this trade-off between the energy reduction of heating and cooling of multifamily houses and the reduction of roof surface per habitant of those houses, a correlation matrix has been carried out in order to identify which are the correlation between the different parameters. In this case, the different characteristics included are: the total amount of dwellings, total roof available, total surface constructed, the total amount of dwellings of each typology selected in section 3, the total of dwellings of single-family houses, the total of dwellings of buildings lower than 3 flats, the energy consumed, the energy produced and the mean surface of the dwellings. The following figure corresponds to a correlation matrix, where the colour represents the relation between row and column characteristics. Apart from that, the specific values of the correlation are displayed in each square to provide the exact value of the correlation, where the sing of the value is positive for a positive correlation and negative if there is a negative correlation, in contrast,

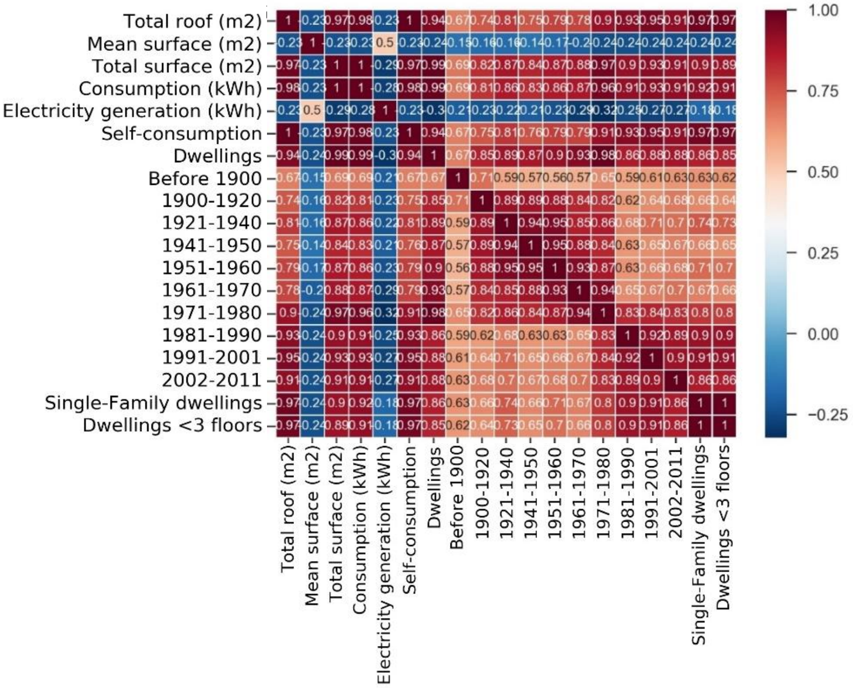

Figure 5. Correlation matrix between the different variables of the model.

As the previous figure shows, the energy generated is highly related with the amount of buildings, especially with the total amount, the single family houses proportion, the buildings with more than three flats, the number of buildings of 1981-1990 and 1991-2001, and the total built surface of the municipality and the roof surface. On the other hand, the energy demand is related with the amount of buildings also, but with the number of buildings of 1971-1980 especially and the total amount of buildings and with the total built surface and roof surface. We can see that they are also correlated between them, as the methodology used is based on building surface coefficients in both cases.

Finally, it is important to analyse the potential of self-consumption of the different municipalities to analyse if the residential sector is able to produce enough energy to cover their energy consumption. In order to analyse this, the three following plots quantify for the whole region the amount of energy provided by PV, the energy consumption of the residential buildings and the self-consumption factor.

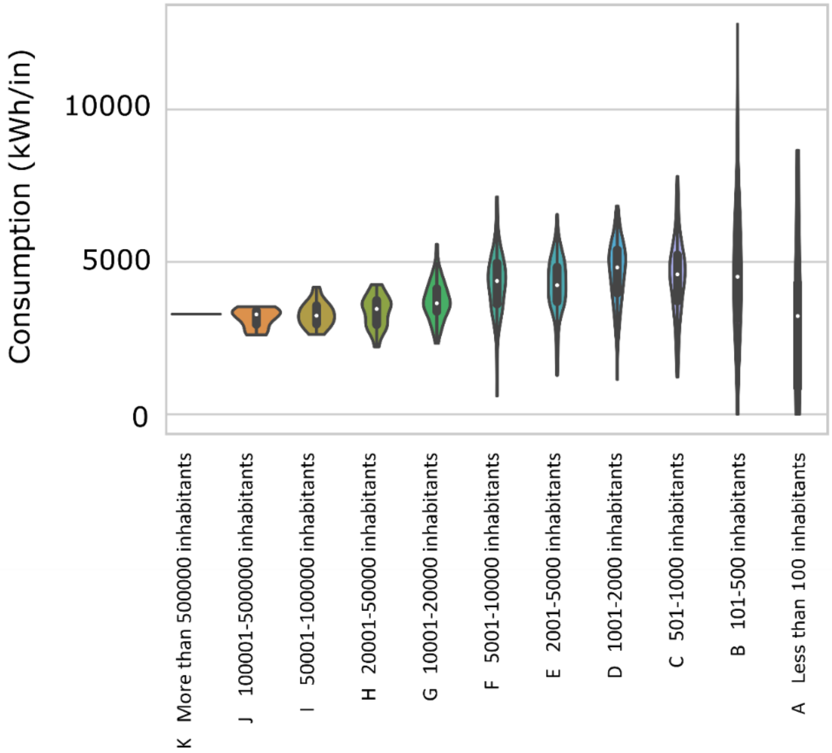

Figure 6. Consumption per habitant for the different municipalities size.

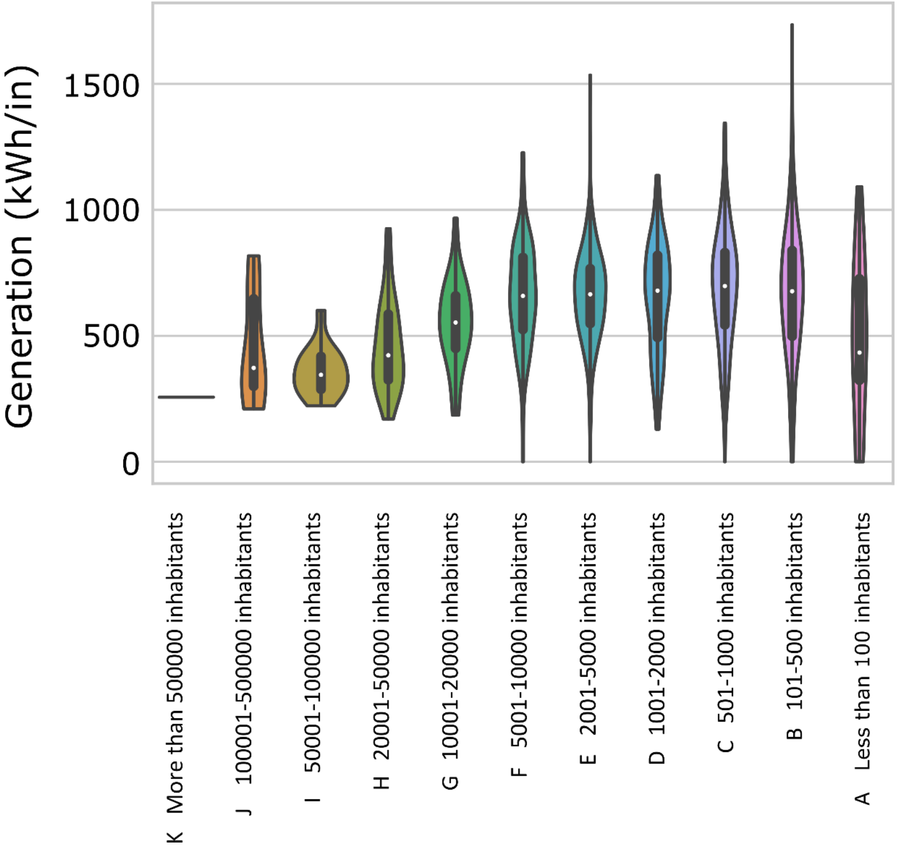

Figure 7. PV generation per habitant for the different municipalities size.

As it is clearly shown in the two first plots, there is not a municipality that the energy produced is close to the energy demand which anticipates that the self-consumption factors are going to be lower than 1. As it is shown, the maximum value of those factors are 0.3, which means that the municipalities are really far from self-consumption. In order to visualize the effect of the size of the municipality in the self-consumption, the following figure is a representation of the distribution in terms of self-consumption and municipalities size.

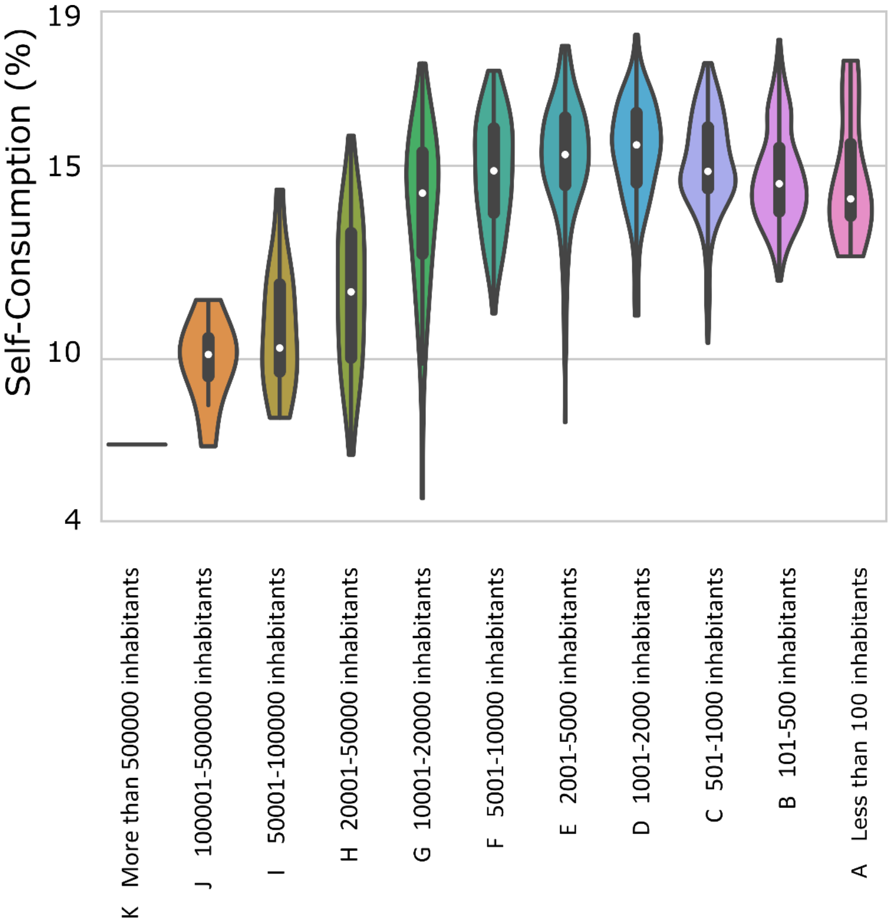

Figure 8. Self-consumption for the different municipalities size.

All the municipalities achieve self-consumptions lower than 20%, with especially lower values for big municipalities, this is relevant from sizes bigger than 20000 inhabitants, where the mean factor is 12%. It is also important to show the case of Barcelona (the only municipality of more than 500000 inhabitants, where the self-consumption factor is 8%, approximately three times lower than small municipalities.

These factors suggest that important refurbishment should be carried out in the actual building stock, in order to analyse the effect of these refurbishments. Four different scenarios are analysed, reduction of 50% and 80% of the energy demand and a demand of 15 and 30 kwh/m2.

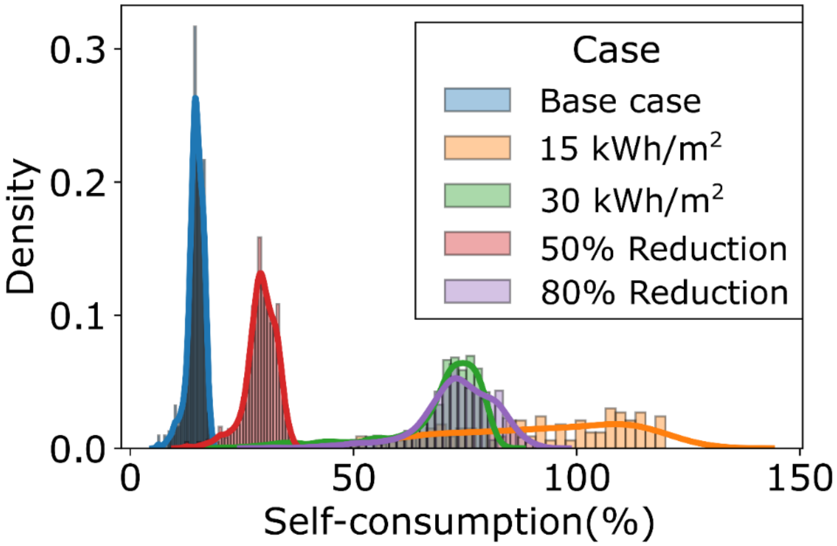

Figure 9: Different scenarios to evaluate the effect of building retrofit in self-consumption with PV.

We can see that building retrofit provides an important improvement in the self-consumption possibilities of the area of study. Furthermore, the retrofit should be carried out to the whole stock, as only improvements of the whole stock and with reductions higher than 80% are required to achieve self-consumptions closer to 100% and only in the case of the whole stock close to Net Zero Energy Building self-consumption can be provided by the residential stock. We have to take into account that the retrofit required is really demanding, and can a further evaluation of the environmental impact and cost should be evaluated to analyse the global effectiveness of the measures. A further optimization of the measures should be realized to identify the retrofit possibilities and identify if exists the optimal amount of retrofit required.

5. Conclusions

A methodology to analyse the building stock is assessed, which enables to couple PV generation and energy demand. Furthermore, this methodology provides an alternative to evaluate the building retrofit for a whole regional area.

After analyse the whole stock, 3 different styles of municipalities are identified, according to the size of the municipality and the year of construction of the whole stock. Small municipalities have mainly old buildings, medium municipalities have a majority of the stock built after 1960 and big municipalities have a big amount of the stock of buildings constructed between 1950/60 and 1980.

For the selected area, the maximum self-consumption that can be achieved for the residential stock is around 20%, and decreases drastically when the size of the municipality is bigger than 20000 inhabitants. This effect is also complemented with the building typology, as those municipalities have an important amount of multi-family houses.

Finally, the four different scenarios of building retrofit have been analysed, showing important improvements with deep building retrofits. Achieving important self-consumption factors with reductions of the energy demand of more than 80%.

6. Acknowledgment

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V. General conclusions

This work has been dedicated to developing simulation-based optimization models to asses early building design and capable of assisting decision-making steps in building construction and retrofit or in policy-making steps. Different models of bio-based insulation alternatives have been developed and evaluated with different objectives to evaluate the bio-based alternatives, to improve their market share and a global model to identify regional potentialities for building retrofit. Find below the summary of the knowledge achieved from the different studies assessed in this thesis and the general conclusion obtained. Note that in the individual sections there are detailed discussions and conclusions in each case study.

The general conclusions are presented herein.

- We present a tool, which can be adapted to other MOO problems with similar characteristics, which enables to combine MOO with condensation risk assessment. It has proved to be an essential tool to assess early stages on building design with bio-based materials when optimizing cost and environmental impact. Illustrating the example in a cubicle-like building located in three different climates, it has provided improvements against commercial materials (e.g., Polyurethane) without risk of condensation in Lleida and Ouagadougou.

- In the second case study we provide a methodology that systematically provides efficient composite alternatives with tailored properties potential (more balance solutions compared to single-materials). An illustrative example in a cubicle-like building has provide ten different composites proposals to improve market scalability of bio-based materials with materials with simple installation.
- Finally, we have provided a methodology to assess a regional analysis of building retrofit, analysing the potential of roof installation of PV and the improvements in thermal envelope. The methodology has been assessed in Catalonia, showing a global self-consumption potential of 20% for the residential sector, requiring an important retrofit (energy reduction of 80%) in order to achieve that the majority of municipalities achieve self-consumption in this sector.

VI. Challenges and future directions

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

- Implement the third pillar of sustainability, assessing the social concerns in the methodology, implementing social indicators for more sustainable buildings design. Despite this task may seem challenging, due to the lack of standard and quantified information on social aspects, some new initiatives are emerging and may be implemented in new lines of research.
- The proposed methodologies are general enough to implement other variables, designs or conditions. Those

methodologies could be extended to more complex or real scenarios (*e.g.*, building design, thermal loads,….).

- Future work could consider the analysis of multiple retrofit measures, evaluating their efficiency and propose combination alternative measures (e.g., thermal insulation, double glazed windows,…).
- Evaluate the optimal alternatives in a whole stock, providing more information for policy-makers and provide knowledge of the retrofit steps for countries (i.e., priority buildings to improve or initial retrofit measures).

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VIII. Appendices

1. Publications

1.1. Research articles

Alba Torres-Rivas, Mariana Palumbo, Assed Naked Haddad, Laureano Jiménez Esteller, Luisa F. Cabeza, Dieter Boer, Multi-objective optimisation of bio-based thermal insulation materials in building envelopes considering condensation risk, Applied Energy Volume 224, 15 August 2018, Pages 602-614.

Alba Torres-Rivas, Mariana Palumbo, Carlos Pozo, Anna Ewertowska, Laureano Jiménez Esteller, Dieter Boer, Systematic combination of insulation biomaterials to enhance energy and environmental efficiency in buildings, Construction and building materials, Under review.

2. Scientific conference participations

2.1. Oral communications

A. Torres-Rivas, C. Pozo, A. Ewertowska, D. Boer, L. Jiménez-Esteller, Systematic Generation of Hybrid Insulation Materials Via Data Envelopment Analysis, American Institute of Chemical Engineers, Minneapolis (USA), 2017

Alba Torres-Rivas, Mariana Palumbo, Assed Haddad, Laureano Jiménez, Dieter Boer, Multi-objective optimization comparative of bio-based and conventional insulation materials, 10ª edición del Congreso Internacional de Ingeniería Termodinámica (CNIT), Lleida, 2017

Alba Torres-Rivas, Mariana Palumbo, Assed Haddad, Laureano Jiménez, Dieter Boer, MULTI-OBJECTIVE OPTIMIZATION OF BIO-BASED THERMAL INSULATION MATERIALS IN BUILDING MODELING, 2nd International

Conference on Bio-Based Building Materials, Clermont-Ferrand (France), 2017

Alba Torres-Rivas, Alex Ximenes Naves, Mariana Palumbo, Assed Naked Haddad, Laureano Jiménez Esteller, Luisa F. Cabeza, Dieter Boer, Low impact building insulation materials: Modelling of condensation risk in different climates, 1st LA SDEWES Conference, Rio de Janeiro (Brazil), 2018

Alex Ximenes Naves; Ahmed Mostafa Abdelmoaty; Alba Torres-Rivas; Mariana Palumbo; Assed Haddad; Luisa Cabeza; Laureano Jimenez and Dieter, Energy Efficiency Optimization of Cooling Systems Using Thermal Energy Storage: Towards Zero Energy Balance in Buildings, 1st LA SDEWES Conference, Rio de Janeiro (Brazil), 2018

3. Co-supervision of Master thesis and Internship report

Ilenia Campo, Improvement of the refrigeration system of Mercagranada: Technical, Economic and Environmental Analysis, 2016, Master's degree in Environmental Engineering and Sustainable Production

Samar Sherif, Improvement of the energy efficiency in buildings considering environmental aspects. MERCA-GRANADA BUILDINGS AS A CASE STUDY, 2016, Master's degree in Environmental Engineering and Sustainable Production

Martin Ivanov, Design of a solar assisted refrigeration system for Mercagranada: Economic and environmental analysis, 2016, Master's degree in Environmental Engineering and Sustainable Production

David Campoy Díaz, Modelación energética de edificios integrando superficies reflectantes y de cambio de fase, 2017, Máster en Ingeniería Industrial

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