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.

Keywords

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

Nomenclature

Abbreviations

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)
Costcub	Cost derived from the construction of the cubicle (€)
Costelect	Cost of the electricity needed for heating and cooling the cubicle (€)
Pricemat	Cost of the materials used to build the cubicle (€/kg)
Priceelect	cost of the electricity (€/kWh)

Priceins	market prices of the different insulators (€/kg)
m(mat,n)	materials mass (kg)
mins	insulation mass (kg)
m	years
i	annual increment (%)
Costtotal	Total cost (€)
Impcub	Impact of the materials used in the construction of the cubicle (points)
Impelec	Impact of the electricity consumed during the operation time horizon (points/kWh)
Impmat	Impact of the construction materials of the cubicle (points/kg)
Impins	Environmental impact per mass corresponding to the insulation material (points/kg)
Conselect	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
Psat	Saturation pressure
Pi	Vapour presure
θ	Temperature
ϕ_{i}	Internal relative humidity
EMPD	Effective Moisture Penetration Depth
DB-HE	Basic document of Energy Efficiency

1. 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 [1]. 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 [2]. However, such intervention also requires an investment and involves an environmental impact derived from the manufacture, installation, dismantling and disposal of the materials [3,4]. 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 [5]. 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 [6–8].

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 [9,10]; and (2) the reduction of the environmental impact associated to the material, that is, replacing conventional materials with "environmental friendly" ones[11,12]. 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 [13–16]. 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 [17].

Although bio-based insulation materials are increasingly commercially available, their market share corresponds only to a marginal fraction of the global thermal insulation market [18]. 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 [19], such as Data Envelopment Analysis (DEA) [17], TOPSIS decision-making methods [20,21], genetic algorithms [22–24], Particle Swarm Optimization algorithms [25] or Pareto based algorithms [26–28], each presenting their strengths and drawbacks [7]. In buildings, optimisation algorithms have been generally used focusing the optimisation of a single objective variables, which may either be the cost [29,30], the energy needed to operate the building [31], the CO_2 emissions or the environmental impact derived from the construction, use, and demolition of the building [32].

However, some authors also propose the use of such mathematical tools for the optimisation of two or more objective variables simultaneously. Fesanghary et al. [33] 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. [34] 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. [6], 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. [6] 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 [35]. 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 [36–38]. 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. [6], 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 [39]. 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.

2. 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.

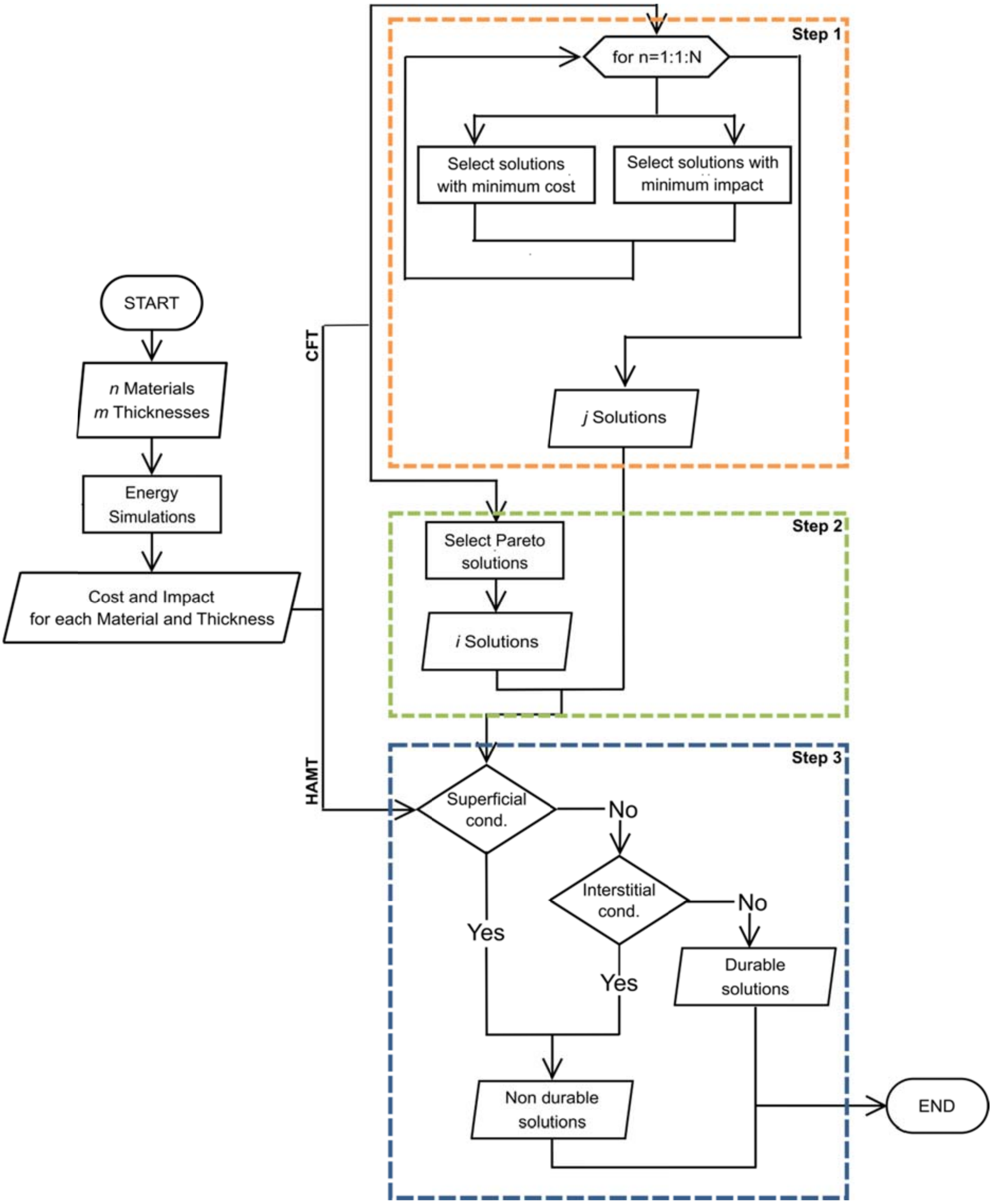

Fig. 1. Simplified algorithm for the optimisation process.

2.1. 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, 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 Fig. 2, 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.

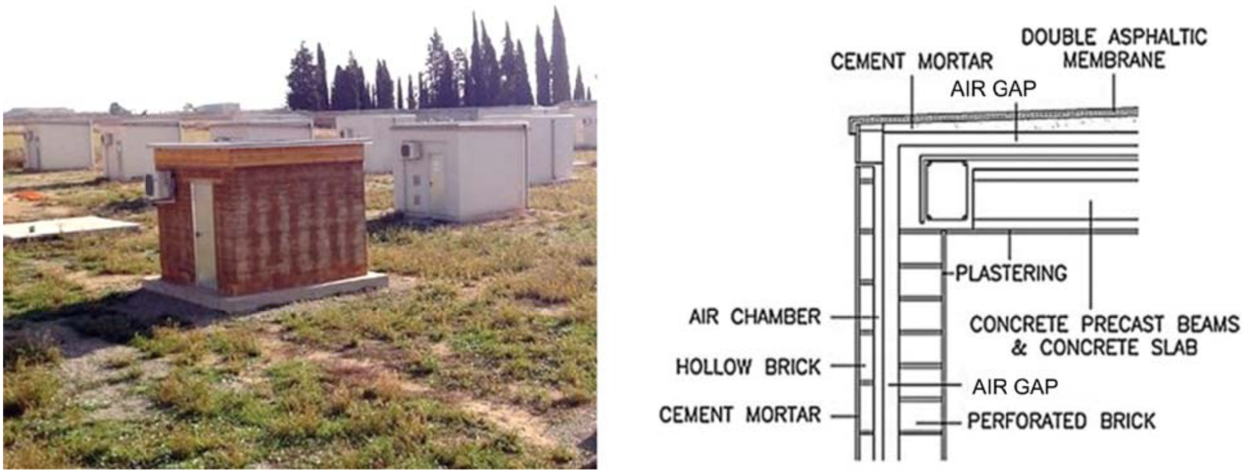

Fig. 2. Cubicles build at the testing site of University of Lleida and section showing the components of the envelope of the cubicle used for calibration [6].

2.2. Specifications of the energy model

The energy model of the cubicle was built using the OpenStudio [40] plug-in for SketchUp [41] and EnergyPlus [42] 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) [43], ITEC [44] and the technical sheets of the products [45–47], or were determined experimentally [48]. 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 [49] (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 [6,50].

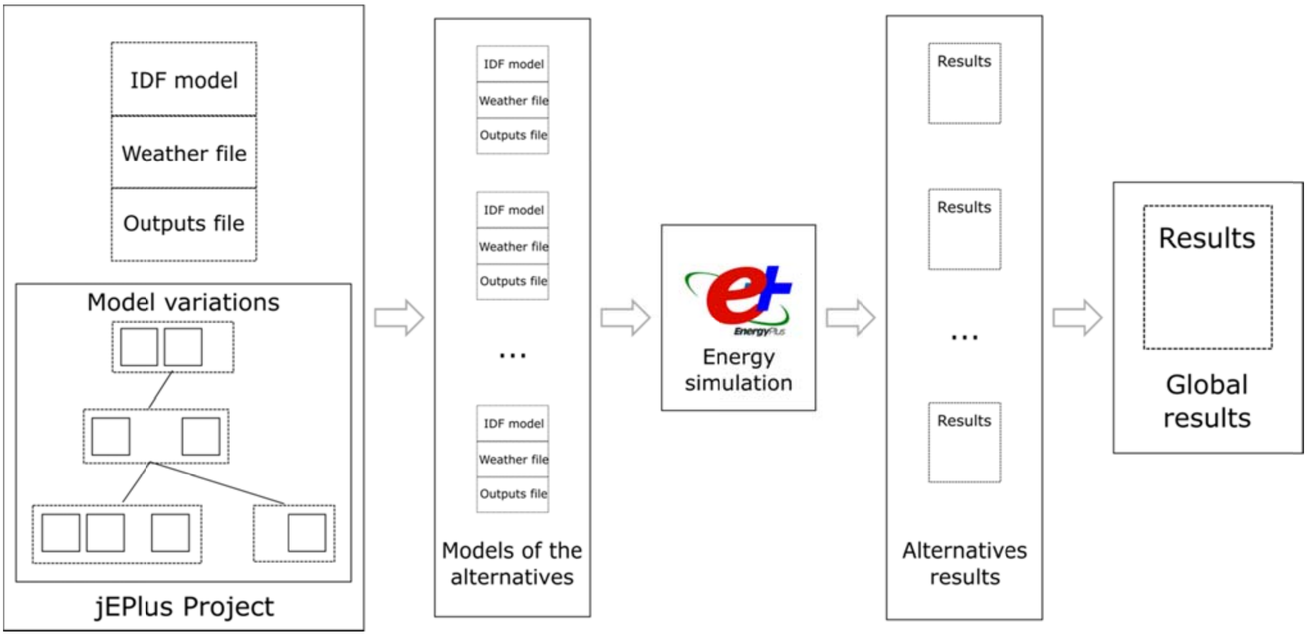

Fig. 3. Diagram of the connection between jEPlus and EnergyPlus.

Table 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 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 [51].
	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 [6], 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.

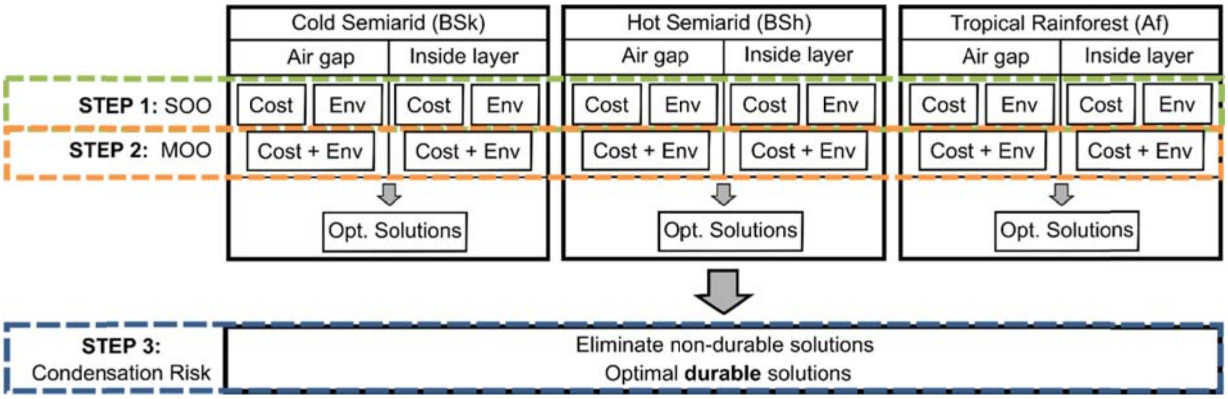

Fig. 4. Diagram depicting the process followed.

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:

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2} \quad \text{(Eq.1)}$$

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:

$$\alpha = \frac{k}{\rho C} \quad \text{(Eq. 2)}$$

Where: α is the thermal diffusivity (m^2/s); κ is the thermal conductivity (W/mK); and ρC is the product of density (kg/m^3) 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 [52]. 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.

2.3. Single-objective optimisation

2.3.1. 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 ($Cost_{elect}$):

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

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

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

The cost of the materials used to build the cubicle ($Price_{mat}$) was 940 € [6]. 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.

2.3.2. Environmental impact

ReCiPe [53] 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 (Imp_{cub}), and the amount of electricity consumed during the operation time horizon, defined in 20 years (Imp_{elec}). 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 (Imp_{cub}) 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: Imp_{cub} (points) is the total ReCiPe impact of the construction materials of the cubicle; Imp_{mat} (points/kg) is the coefficient of environmental impact per unit mass of a material n, which is taken from the Ecoinvent database [54]; m_{mat} (kg) is the corresponding quantity of raw material n; Imp_{ins} (points/kg) is the coefficient of environmental impact per mass corresponding to the insulation material evaluated; and m_{ins} (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 3.

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: Imp_{elect} (points) is the total ReCiPe impact of the consumed electricity over the operational phase of the cubicle; Imp_{elect} (points/kWh) is the coefficient of environmental impact per kWh of electricity in Spain (0.0482 points/kWh); and $Cons_{elect}$ (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 (Imp_{cub} and Imp_{elect}).

Table 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.

2.4. 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.

2.5. 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) [55]. 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.

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

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

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

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.

3. 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.

3.1. Single-objective optimisation

3.1.1. 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.

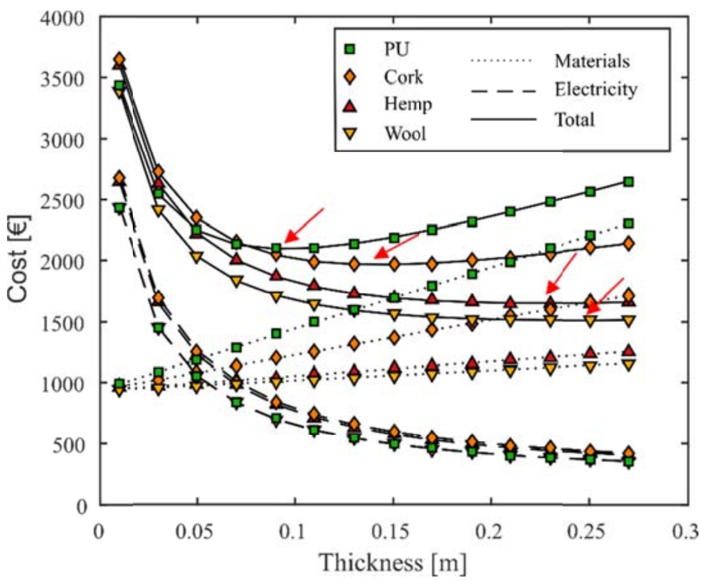

Fig. 5. Evolution of cost with insulation thickness for hemp, cork and wool. Polyurethane is included for comparison purposes.

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 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%)

3.1.2. 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 5. 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.

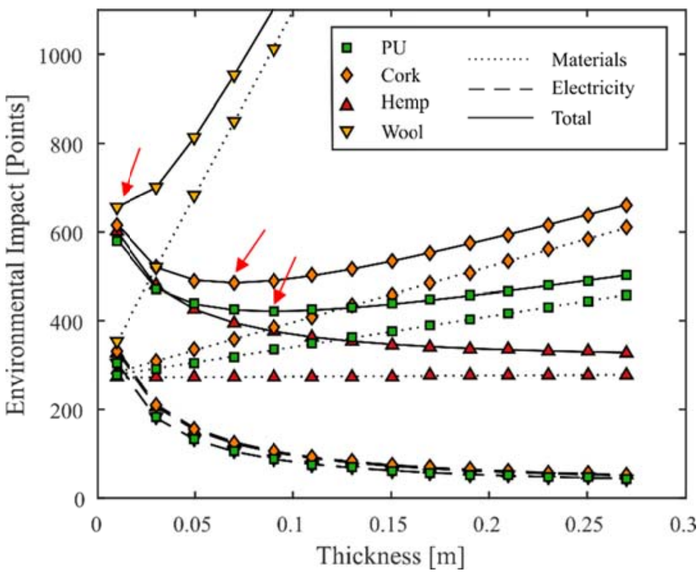

Fig. 6. Influence of the thickness on the environmental impact of cork, hemp, wool and polyurethane.

Table 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%)

3.2. 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.

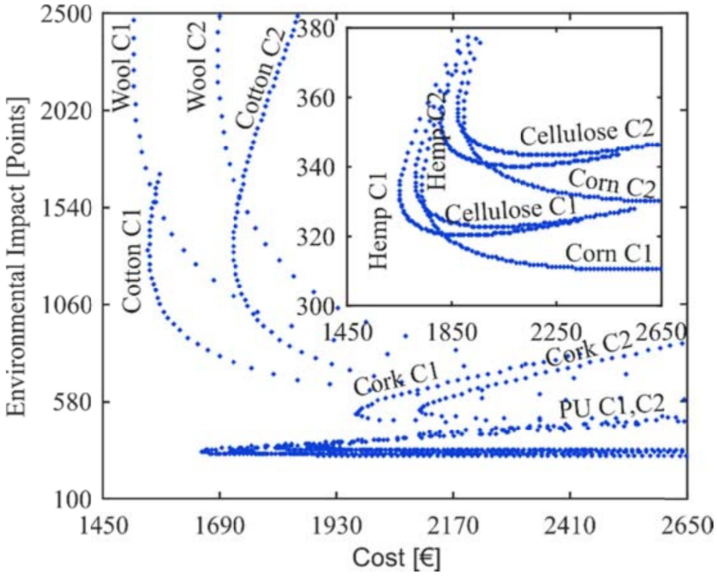

Fig. 7. Variation of the cost and the environmental impact with thickness for the materials and constructions.

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. [6], 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.

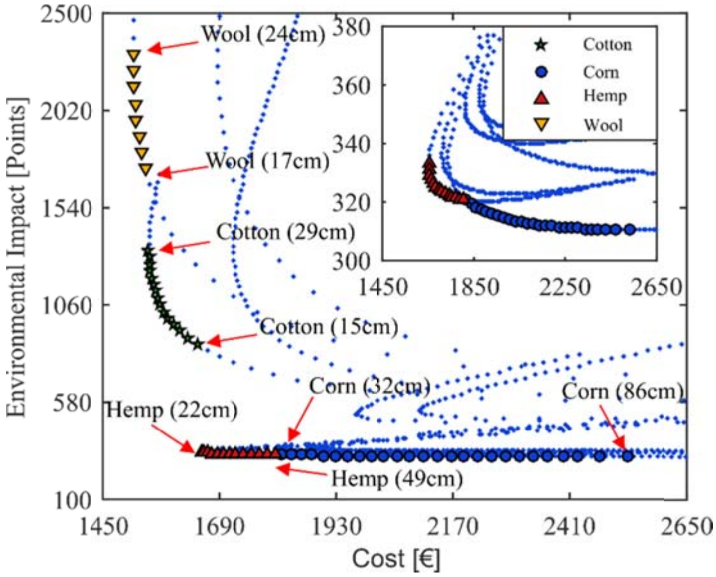

Fig. 8. Pareto frontier built from the overall optimal points.

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.

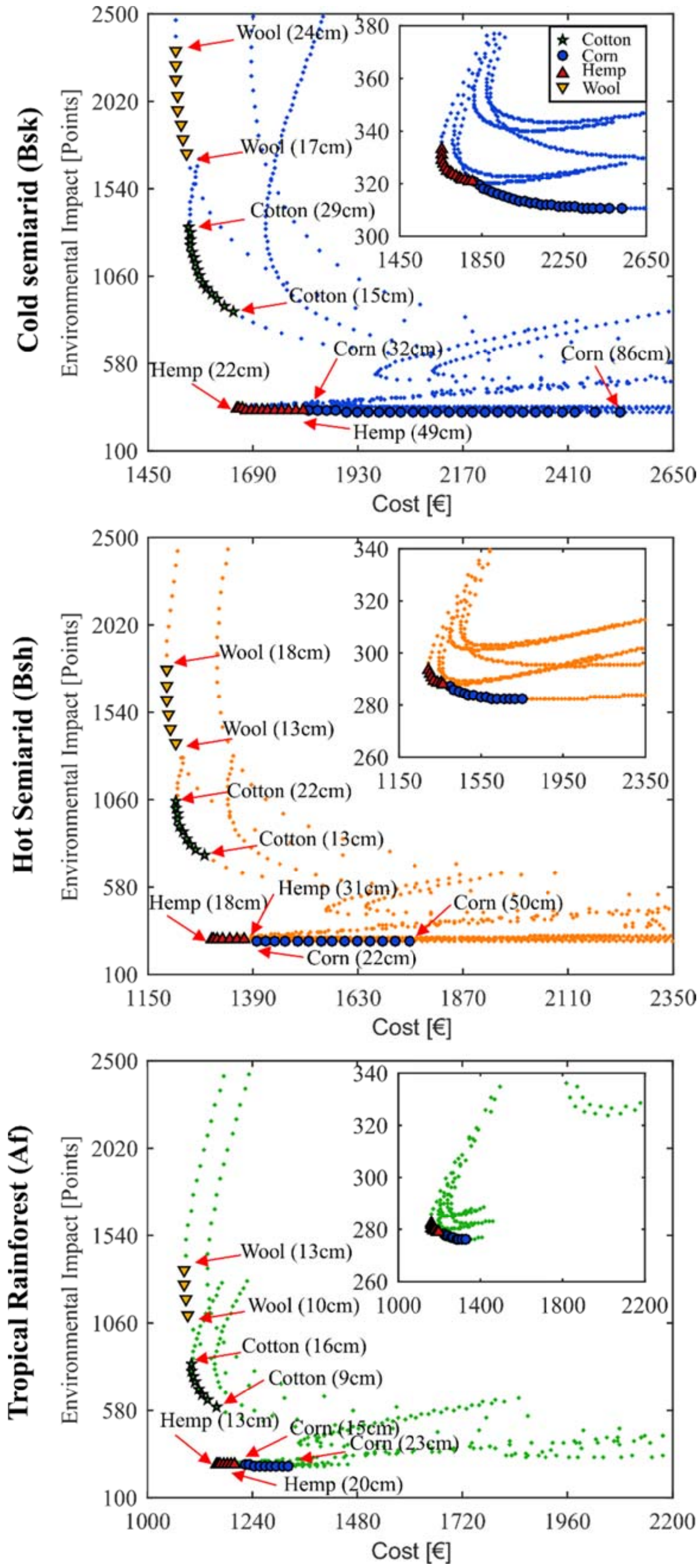

Fig. 9. Pareto frontier built from the overall optimal points for the three climates: cold semiarid (BSk), hot semiarid (BSh) and tropical rainforest (Af)).

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.

3.3. 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.

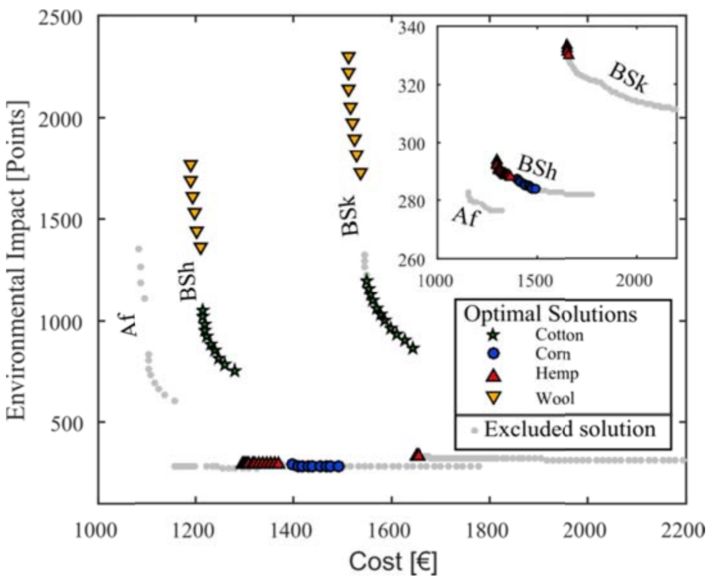

Fig. 10. Pareto frontier built from the overall optimal points without condensation risk

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.

4. 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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