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

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HIGHLIGHTS

- The performance of seven bio-based building insulation materials is evaluated.
- Multi-objective optimization is used to reduce economic and environmental impact.
- For the optimal solutions, the condensation risk in 3 distinct climates is evaluated.
- Compared to polyurethane, bio-based optimal solutions offered better results.

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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. 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

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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
GLO	average global impact
α	thermal diffusivity (m^2/s)
κ	thermal conductivity (W/m·K)
ρ	density (kg/m^3)
C	specific heat (J/kg·K)
$Cost_{cub}$	cost derived from the construction of the cubicle (€)
$Cost_{elect}$	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 (€/kW·h)
$Price_{ins}$	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/kW·h)
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 (kW·h)
$f_{Rsi,min}$	minimum acceptable interior surface temperature (°C)
f_{Rsi}	interior surface temperature (°C)
θ_{si}	internal interstitial temperature (°C)
θ_e	outside temperature (°C)
θ_i	inside temperature (°C)
$\theta_{si,min}$	minimum interstitial temperature (°C)
P_{sat}	saturation pressure (Pa)
Pi	vapour pressure (Pa)
θ	temperature (°C)
ϕ_i	internal relative humidity (%)
EMPD	Effective Moisture Penetration Depth
DB-HE	Basic document of Energy Efficiency

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·m^{-1}·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