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

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ABSTRACT

Energy efficiency strategies, such as building insulation, improve the building performance without compromising comfort. This study presents a methodology for determining the optimal insulation thickness for external building surfaces. Our approach is based on a multi-objective optimization model that minimizes simultaneously the cost and environmental impact associated with both the energy consumption over the operational phase and the generation of the construction materials (including the waste produced during the disposal phase). The thermal loads of the cubicles were calculated with EnergyPlus, a widely used simulation program for buildings. The environmental impact was quantified following the life cycle assessment (LCA) methodology. Our approach was applied to a case study of a house-like cubicle located in Lleida (northeast Spain). Taking as a basis a standard cubicle without insulation, our approach identifies solutions that reduce around 40% both, the cost and environmental impact. Optimal solutions show also important economic and environmental improvements compared to cubicles constructed with the Spanish legislation requirements. Our method is intended to assist decision-makers in the design of buildings.

1. Introduction

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

Many countries in OECD Europe have enacted measures to improve energy efficiency in the building sector. For example, the European Union (EU) approved a binding legislation, which aims to meet its ambitious climate and energy targets for 2020. The plan was launched in March 2007, and after months of tough negotiations it was adopted by the European Parliament [4].

Multiple energy efficiency strategies can be applied to achieve the reduction goals presented above. Among them, building insulation is particularly appealing, since it decreases the demand of both heating and cooling, thereby leading to significant environmental savings. For both new and existing buildings, there is a huge potential for improvements in this direction. According to the National Statistics Institute of Spain, 26% of the total houses in Spain were constructed before 1980 [5]. The first Spanish law requiring insulation in buildings dates back from 1979 [6]. Because of this, a high percentage of the buildings in Spain are not insulated, unless they were recently rehabilitated. From that moment on, it was required to include insulation in the constructions, but it was not until 2006 that a more restrictive law imposed higher levels of insulation in the buildings [7].

Abbreviations: IEO, International Energy Outlook; MOO, multi-objective optimization; LCA, life cycle assessment; PU, polyurethane; MW, mineral wool; EPS, polystyrene; NSGA-II, non-dominated sorting genetic algorithm-II; EA, evolutionary algorithms; EI99, Eco-indicator 99; IO, input-output; GLO, average global impact; ACH, air changes per hour.

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Nomenclature

List of symbols

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

Insulation materials can be implemented in all types of constructions. In the European market, inorganic fibrous materials, glass wool and stone wool account for 60% of the insulation materials, while organic foamy materials, expanded and extruded polystyrene and to a lesser extent polyurethane accounts for about 27%. The three most common insulation materials used in Spanish buildings are polyurethane (PU), mineral wool (MW) and polystyrene (EPS) [8].

The current trend is to promote thicker insulation because it reduces thermal energy consumption within the building. However, the extent to which this strategy reduces the environmental impact is still poorly understood. Thicker insulation does not necessarily involve less impact. This is because the impact generated during the construction and disposal phases might be significant. Neglecting this impact embodied in the insulation materials may lead to solutions where energy savings might be attained at the expense of increasing the environmental burdens elsewhere. Blengini et al. [9] conducted a detailed study on the impact caused in all the stages of the life of a low energy family house and concluded that the shell-embedded materials represented the highest relative environmental impact. Along the same lines, Stephan et al. [10] showed that the energy embodied in passive houses can represent up to 77% of the total (embodied and operational) energy over 100 years. Therefore assessing the whole life cycle impact is critical.

Many tools and indicators are available for assessing and benchmarking environmental impacts of different systems, including Life Cycle Assessment, Strategic Environmental Assessment, Environmental Impact Assessment, Environmental Risk Assessment, Cost-Benefit Analysis, Material Flow Analysis, and Ecological Footprint [11]. Among them, life cycle assessment (LCA) [12], has recently emerged as the prevalent approach. This methodology accounts for the impact caused in all the stages in the life cycle of the product being assessed. LCA quantifies the life cycle impact through a set of indicators that can be either midpoint or endpoint. The former refers to emissions, while the latter refers to impact in the human health, ecosystem quality and natural resources. Discussion amongst LCA experts showed that because of the mutually exclusive aspects of uncertainty and relevance, the midpoint/endpoint debate is controversial and difficult to reconcile. Lenzen [13] argued that if endpoint information is too uncertain to allow a decision to be made with reasonable confidence, then the assessment can be carried out in midpoint terms or even can be based on the stakeholders' subjective judgments about the more certain midpoint levels. In the present study we will work with endpoint levels. In general, a considerable research gap emerges in the field of environmental impact of buildings, as even the impact of new constructions has barely been evaluated in a systematic way [9,14–17].

Previous approaches for optimizing the insulation thickness considered only cooling loads [18–20], heating loads [21–25] or both cooling and heating loads [26–30], but neglected the impact of the construction materials. In addition, to find the energy loads, most of these studies applied the degree-days methodology [18,23,31–33], a heuristic approach that due to its narrow scope might lead to suboptimal alternatives. Recent developments in numerical methods and software applications have led to more precise tools, but their application in this field has been quite scarce. The degree-days method consider static conditions, while other studies take into account dynamic transient conditions [34–38]. Ozel [39] analyzed the effect of insulation location in the wall, finding that this has a significant effect on the yearly averaged time lag and decrement factor, but little impact on the yearly transmission loads and optimum insulation thickness. Al-Sanea et al. [35] analyzed the optimum insulation thickness depending on the electricity tariff as well as the cost of insulation material, lifetime of the building, inflation and discount rates, and coefficient of performance of the air-conditioning equipment. They found that the optimal thicknesses vary from 4.8 to 16 cm depending on the case study.

The aim of this study is to analyze how the selection of an insulation material and its thickness affects the energy consumption, the total cost and the environmental impact of the building. The final goal is to determine the thickness of the insulation that minimizes simultaneously the cost and environmental impact. Note that the minimum cost solution will differ, in general, from the minimum impact one. Hence, there will be a natural trade-off between both of them, and the solution of the problem will be given by a set of Pareto optimal points, each achieving a unique combination of cost and impact, rather than a single optimal solution. Polyurethane (PU), polystyrene (EPS) and mineral wool (MW) are considered as insulation materials. Our multi-objective optimization (MOO) approach offers decision makers a suitable framework to identify solutions to improve simultaneously different economic and environmental targets [40]. Our systematic methodology can work with different types of decision variables and objective functions.

The article is structured as follows. Section 2 provides the problem statement. Section 3 describes our methodology and the multi-objective optimization tool. The case study is explained in detail in Section 4. In Section 5 the results are presented and discussed, while the conclusions of the study are finally drawn in Section 6.

2. Problem statement

To derive our approach, we consider, without loss of generality, a general cubicle type building in which the space heating and cooling requirements are covered by a reversible heat pump. A construction profile is depicted in Fig. 1. Details about the cubicle configuration are provided in Sections 4.1 and 4.2.

The goal of the analysis is to find the type of insulation material and the thicknesses of the insulation wall that simultaneously minimize the total cost and the environmental impact of the building. The latter considers the impact associated with the generation of