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Eco-costs evaluation for the optimal design of buildings with lower environmental impact

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ABSTRACT

At present, most products and processes are optimised according only to their economic performance and disregarding environmental aspects. To promote a more sustainable economy, however, the environmental performance should be accounted for in the analysis. The prevalent method to include the environmental impact as a key aspect in decision-making relies on the use of multi-objective optimisation. Following this approach, the environmental and the economic performance are quantified separately as two different objectives, and the final result is given by a set of Pareto optimal solutions. In this study, we resort to eco-costs, a method that translates the environmental impact of a product or activity into monetary units, which can then be incorporated explicitly into the economic performance assessment. Hence, a unique optimal solution is attained, thereby avoiding the task of deciding among different optimal alternatives. The approach presented is illustrated through a case study where we test the eco-costs capabilities in the building sector. The objective is to optimise the thermal insulation of a building envelope in different climate zones. Our approach identifies building solutions that improve significantly the environmental performance at a marginal increase in cost.

1. Introduction

Environmental issues are gaining wider interest in the engineering domain, which is at present striving to develop more sustainable products and processes. Specifically, the building and construction sector offers many opportunities for environmental improvements. This sector represents 40% of the total annual energy consumption worldwide [1] and, because of this, improving its energy efficiency, particularly in new and existing buildings, is becoming a priority objective in the EU and US [2,3]. One of the most promising energy efficiency strategies, among the options available, is the application of a proper thermal insulation in the building envelope [4,5].

At present, the trend in the construction sector is to promote high insulation thicknesses in order to reduce energy consumption for heating and cooling. This strategy may lead to sub-optimal solutions when one seeks to optimise the economic and environmental performance of the building simultaneously. This is because the environmental impact embodied in the insulation material can be significant, to the extent that it might not eventually compensate for the associated energy savings. In the European and North American market, the most widely used insulation materials are inorganic fibrous materials, glass wool and stone wool, followed by organic foamy materials, and expanded and extruded polystyrene [6,7]. Some studies have shown that the impact embodied in these construction materials contribute very significantly to the total environmental impact of a building [8,9]. To assess in a rigorous manner the environmental impact of buildings, it is therefore required to adopt a life cycle approach. Life cycle assessment (LCA) is an objective methodology to quantify the environmental burdens of a product considering all the stages in its life cycle [10,11]. Environmental indicators based on LCA enable us to quantify a wide variety of environmental problems related to human health, ecosystem quality and resources depletion.

Economic and environmental objectives tend to be conflicting targets. Hence, to optimise both criteria simultaneously, we need to resort to multi-objective optimisation (MOO) techniques [12–16]. The final result of a MOO typically consists of a set of Pareto optimal

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Nomenclature

Abbreviations

LCA	Life cycle assessment
MOO	Multi-objective optimisation
SOO	Single-objective optimisation
LCIA	Life cycle impact assessment
EVR	Eco-costs/value ratio
NSGA-II	Non-dominated sorting genetic algorithm-II
LCI	Life cycle inventory
ECN	Energy research centre of the Netherlands
ILCD	Life cycle data system
JRC	European Commission Joint Research Centre
TCE	Total conventional cost and eco-costs
PU	Polyurethane
MW	Mineral wool
ITeC	Instituto de Tecnología de la Construcción (Institute of Construction Technology)
GLO	Average global impact
EI99	Eco-indicator 99
ACH	Air changes per hour
COP	Coefficient of performance

Variables

$COST$	Cost [€]
$UCOST$	Unitary cost [€ /kg]
M	Quantity [kg]
$CONS$	Consumption [kWh]
ECO_COSTS	Eco_costs [€]
$UECO\_COSTS$	Unitary eco_costs [€/kg]

Indices

TOT	Total
MAT	Materials
EN	Energy
k	Construction materials
n	Years

Symbols

ir	Electricity inflation rate (%)
z	Objective functions
x	Decision variables
X	Space of feasible solutions

solutions, each achieving a unique combination of objective function values. When several players take part in the decision-making process and/or many conflicting criteria need to be analysed, it might be difficult to generate the Pareto points and identify from them a final alternative to be implemented in practice. As an example, some decision-makers might prefer the solution showing the maximum economic performance, whereas others may chose an intermediate trade-off solution (or even the minimum impact one). Similarly, some may prefer the solution with minimum global warming impact, while others might go for the one with minimum eco-toxicity, and so on.

To overcome this limitation, this work explores the use of monetization techniques as an effective manner to incorporate environmental aspects in the design of buildings. The advantage of this approach is that it avoids the use of multi-objective optimisation models, which might be difficult to handle when several environmental impacts need to be assessed in the study. In essence, we aim to develop an approach for designing buildings based on on a single-objective optimisation (SOO) formulation in which all of the environmental objectives are expressed in monetary terms. By doing so, the trade-offs between economic and environmental objectives will be explicitly considered via economic penalties, thereby enabling the formulation of a SOO with a unique optimal solution.

Different approaches exist to convert environmental impacts into cost. They can be classified into two main groups [17–19]. The first is the damage-based approach, in which the monetary cost is assigned at the end of the life cycle impact assessment stage (LCIA). This cost expresses in monetary terms the amount of wellness losses due to the impacts of a product or activity. The economic quantification is based on the people's willingness to pay a given amount of money in order to avoid an impact, which reflects individual preferences [20,21]. The second is the prevention based approach (also known as Marginal Abatement Cost). In this latter case, the damage cost depends on the policy targets fixed by each government regarding each specific environmental problem. In this context, society fixes indirectly the environmental policies through their vote to one or another political proposal. These costs are therefore based on the cost of additional impacts reduction measures that will keep the environmental damages within some allowable limits. These political targets, theoretically, reflect the collective preferences of society [22,23].

The Eco-costs approach, which is the one followed in this work, is a prevention based that differs from other prevention methods in that the goal is not based on policy targets, but rather established by "the earth's estimated carrying capacity". This capacity is estimated according to the definition of eco-efficiency made by the World Business Council for Sustainable Development [24]. The eco-costs methodology translates the environmental impact into economic cost by measuring the cost of preventing a given amount of environmental burden [23]. The eco-costs indicator has found several applications in the assessment of products. Vogtländer et al. [25] used eco-costs to compare the environmental impact of bamboo materials shipped to Western Europe with that associated with commonly used materials such as timber. Morales-Mora et al. [26] evaluated the marginal prevention cost associated with the capacity expansion of an acrylonitrile plant in Mexico. Baeza-Brotons et al. [27] used eco-costs to compare the environmental impact of concrete with and without addition of waste. Kravanja and Čuček [28] presented a novel indicator called eco-profit which is based on the concept of eco-costs. Eco-profit considers the environmental burden of a product or activity along with its environmental credits (i.e. unburden on the environment). These credits assume that some products or activities may have a positive impact (i.e. environmental benefit) on the environment (e.g., when waste is used). Vogtländer et al. [23] introduced also a new indicator based on the eco-costs concept called eco-costs/value ratio (EVR). As stated by the authors, the design with the lowest eco-costs might not be always the best choice, mainly because product quality plays as well a key role in the assessment procedure. The EVR overcomes this problem by adding the "value" to the eco-costs indicator. This is defined as the perception of the consumer towards the product and it is related with its overall quality, service quality and image.

Here we explore the capabilities of the eco-costs methodology in the context of finding the optimal thermal insulation for building envelopes. We find that the use of eco-costs identifies solutions attaining significant environmental improvements at a marginal increase in cost.

The article is organized as follows. Section 2 formally states the problem of interest. Section 3 defines the methodology and the eco-costs approach. In Section 4, the case study is introduced. In Section 5, the results are presented and discussed. The conclusions of the study are finally drawn in Section 6.