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Multi-objective optimization coupled with life cycle assessment for retrofitting buildings

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ABSTRACT

In this work we present a systematic tool for the optimal retrofit of buildings that considers several economic and environmental criteria simultaneously at the design stage. Our approach is based on a rigorous mixed-integer linear program (MILP) that identifies in a systematic manner the best alternatives for reducing the environmental impact of buildings. These include the use of different insulation materials and windows as well as the installation of solar panels. Environmental concerns are explicitly accounted for in this MILP by means of Life Cycle Assessment (LCA) principles, which allow evaluating the impact of each alternative being assessed considering all the stages in its life cycle. We illustrate the capabilities of our approach using a case study that considers weather data for Central Portugal.

1. Introduction

Global CO_2 emissions increased by 3% in 2011, reaching a total amount of 34 billion tones [1]. Since CO_2 emissions generated by anthropogenic sources play a key role in global warming [2], it is important to take actions in order to reduce them and mitigate climate change [3]. Particularly, energy consumption in buildings represents 30% of the global energy-related CO_2 emissions [4], while approximately 6% of the total CO_2 emissions are due to fuel combustion in households. Hence, minimizing the environmental impact of buildings can lead to significant environmental benefits [5].

The operation of a building is responsible for a large percentage of its overall environmental impact [6,7]. This impact can be reduced by using better construction materials that increase energy efficiency. Despite being energy intensive, it has been shown that the environmental benefits of insulation materials tend to counterbalance the harmful effects associated with the energy embodied in them [8]. Thus, low-energy buildings that make use of insulation materials are more energy efficient than conventional ones, despite the fact that the amount of energy embodied in the thermal insulation is likely to be high. The environmental impact of buildings can also be reduced by using better windows and by installing solar panels, among other options. Unfortunately, these strategies tend to be expensive, so a proper balance between cost and environmental performance needs to be found. The retrofit of a building can thus be posed as a multi-criteria decision-making problem, in which the environmental impact and the cost are the objectives optimized.

Diakaki et al. explored the use of multi-objective optimization in the design of energy efficient buildings. They proposed a multi-objective model for optimizing buildings according to several criteria, including the annual primary energy consumption of the building, the annual carbon dioxide emissions and the initial investment cost [9,10]. A multi-objective optimization model coupled with a harmony search algorithm was presented by Fesnaghari et al. for the design of low-emission and energy-efficient residential buildings. This model minimizes the life cycle cost and carbon dioxide equivalent emissions of the building [11]. Hamdy et al. developed a modified multi-objective optimization approach based on genetic algorithms that was combined with the simulation software IDA Indoor Climate and Energy and that aimed to reduce the CO_2 emissions and investment cost of a two-storey house coupled with an HVAC system. They identified a solution with 32% less $CO_{2\text{-eq}}$ emissions and 26% lower investment cost compared to the base design [12]. Asadi et al. proposed a multi-objective model for the retrofit of an existing building that minimizes simultaneously the energy consumed and total cost. The model accounted

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Nomenclature

Indices

f	impact category
i	windows
j	wall insulation
k	roof insulation
l	collectors
t	time period

Parameters

a	exterior envelope solar radiation absorption coefficient
A1	building envelope in contact with non-heated spaces m^2
ACH	air change per hour h^{-1}
Acol(l)	area of the solar collectors of type l, m^2
Ae(i)	effective glazing solar radiation collector area for the different windows orientations
Ainswall	exterior wall surface area, m^2
Ap	net floor area, m^2
Aroof	roof surface area, m^2
Awin	window surface, m^2
$B(m)$	floor or wall interior linear perimeter for envelope in contact with the soil or thermal bridge interior length (m)
b1(l)	the value of earnings of the collector provided by the test manufacturer (dimensionless)
Cwin(i)	cost in [D-m^2] for window type i, euro/m^2
Cinswall(j)	cost in [D-m^2] for external wall insulation material type j, euro/m^2
Croof(k)	cost in [D-m^2] for roof insulation material type k, euro/m^2
Ccol(l)	cost for solar collector type l, euro/m^2
$d(j)$	thickness of the external wall insulation m
d1(k)	thickness of the roof insulation m
DD	degree days °C/days
eta	heat gains utilization factor
eta1	domestic hot water (DHW) system efficiency
$\eta 2$(l)	collector efficiency
eff1	share of the total radiation
eff2	share of the solar radiation used in the collectors
Esol(l)	total energy contribution from all collectors
$F(m)$	linear heat flux transmission coefficient, W/(m °C)
Gsouth	average monthly solar energy that reaches a south oriented vertical surface kWh/(m^2 month)
Iav	average irradiance intensity in sunny hours, W/m^2
Ir	solar radiation intensity for each orientation, W/m^2
lamda(j)	thermal conductivity of external wall insulation material W/(m °C)
lamda1(k)	thermal conductivity of the roof insulation material W/(m °C)
m1 (l)	the slope and indicates the loss factor of the collector, W/m^2 °C
ME	heating season duration months
MAQS	average daily reference consumption
nd	annual number of days with DHW consumption
Pd	floor to ceiling height, m
priceng(t,s)	price of natural gas, euro/kWh
priceel(t,s)	price of electricity, euro/kWh
q	internal gains, W/m^2
Qenu	heat loss through zones in contact with outdoors glazing roofs and pavements, kWh/year
Qpt	heat loss through linear thermal bridges, kWh/year
Qv	heat loss due to fresh air flow kWh/year
$Q2$	heat transfer due to infiltration, kWh/year
$Q3$	internal heat gains, kWh/year
Qa	energy supplied with conventional systems for DHW, kWh/year
T_a	average temperature during the daytime (during the sunny hours), °C
T_{av}	average outdoor temperature in the cooling season
T_m	the average temperature in the collector, °C
$U(i)$	window type i thermal transmission coefficient W/(°C m^2)
$U1$	building exterior envelope thermal transmission coefficient W/(°C m^2)
$X(i)$	orientation coefficient for different facade orientation
θ	losses to non-heated spaces reduction coefficient kWh-year (heat loss reduction coefficient)

Variables

Acoltot	total area of the collector, m^2
BLCext(t)	building load coefficient
Cost(s)	cost of retrofit plus energy used for the building operation
CML(j)	environmental impact related to use of natural gas and electricity (fossil fuels) in category j
EA	col(t,l)
Eren(t)	energy contribution from other renewable sources
Esolar(t)	energy contribution from solar collector type l
$E(1)$	minimum energy limit, kWh
$E(2)$	maximum energy limit, kWh
Recost(t)	overall investment cost for the refroit of the building
Q1(t)	heat gain through envelope [kWh-year]
Qext(t)	heat loss through zones in contact with outdoors (walls glazing roofs and pavements) kWh year
Qgu(t)	useful heat gains (internal plus solar heat gains through glazing) kWh year
Qsc(t)	energy needed for space cooling
Qsh(t)	energy needed for space heating
Qt(t)	conduction heat loss through building envelope kWh year
Qwh(t)	energy needed for water heating

Binary variables

Insroof(k,t)	is equal to 1 if k type of roof material is chosen otherwise 0
Inswall(j,t)	is equal to 1 if j type of wall insulation is chosen otherwise 0
Win(i,t)	is equal to 1 if i type of window is chosen otherwise 0
Col(l)	is equal to 1 if l type of collector is chosen otherwise 0

for different retrofit strategies, including the installation of several window types, wall and roof insulation materials, as well as solar collectors [13,14].

Most of the multi-objective models proposed so far for retrofitting buildings have attempted to minimize fairly simple environmental metrics, typically the amount of energy consumed by the building, in the form of either electricity or thermal energy. Because of this narrow environmental scope, this approach can lead to solutions where energy consumption is reduced at the