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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 considering several criteria simultaneously. 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 allows 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 in Tarragona.

1. Introduction

Global CO_2 emissions increased by 3 % in 2011, reaching a total amount of 34 billion tones [1]. The CO_2 generated by anthropogenic sources plays a key role in global warming [2], so it is important to take actions in order to reduce them and prevent the dangerous effects of 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. In practice, however, the production of these materials might be energy intensive, which may result in an increment of the amount of energy embodied in the building. This issue was investigated by Sartori et al., who concluded that the environmental benefits of these materials tend to counterbalance the harmful effects associated with the energy embodied in them [8]. Thus, low-energy buildings are more energy efficient than conventional ones, even though their embodied energy is somewhat higher. The environmental impact of buildings can also be reduced by using better windows and 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 an existing building should be thus posed as a multi-criteria decision-making problem, in which the environmental impact and cost are properly assessed to finally identify the best solution to be implemented in practice.

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 low-emission and energy-efficient residential buildings design. 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 combined with IDA Indoor Climate and Energy (building performance simulation program) for reducing the CO_2 emissions and investment cost of a two-storey house and its 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 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 applied fairly simple environmental metrics. In fact, most of them attempt to reduce the environmental impact by minimizing only the amount of energy consumed by the building, in the form of either electricity or thermal energy. Because of this narrow environmental scope, they can lead to solutions where the energy consumption is reduced at the expense of worsening other environmental impacts. One possible manner to overcome this limitation consists of coupling this model with advanced environmental assessment tools like Life Cycle Assessment (LCA) methodology.

Particularly, in the recent past the combined use of LCA and multi-objective optimization has gained wider acceptance in the research community [15]. This strategy allows identifying in a systematic manner opportunities for environmental improvements that show good economic performance. This approach has been successfully applied to a wide variety of engineering systems. However, to the best of our knowledge, it has never been used in the context of buildings.

In this work we present a systematic framework for the retrofit of buildings according to several criteria that is based on the combined use of multi-objective optimization and LCA principles. To the best of our knowledge, this is the first time such an approach is applied in the context of retrofitting existing buildings. Numerical results show that it is possible to reduce significantly the environmental impact of a building by investing in retrofit alternatives.

The paper is organized as follows. We formally state the problem of interest in section two. The mathematical formulation is then described in section three, while the solution strategy is introduced in the next section before presenting some numerical results. The conclusions of the work are presented in the last section of the article.

2. Problem statement

The problem we aim to solve can be formally stated as follows. We are given a set of alternatives to retrofit a building, including different windows and wall types, roof insulations, and solar collectors. The space heating and hot water requirements are covered by burning natural gas, whereas space cooling consumes electricity. The associated economic and environmental data for a certain time horizon are given. The goal is to find the set of retrofit alternatives that optimize simultaneously the economic and environmental performance of the building.

3. Mathematical formulation

We present next an MILP model to solve the problem described above. This MILP is based on the one elaborated by Asadi et al. [13,14], which has been adequately modified in order to account for LCA principles. The model is a multi-period one, that is, it is defined over a set of time periods of equal length, in each of which the decision-maker has the option to implement any of the available retrofit alternatives.

Particularly, the MILP is composed of different sets of equations that allow determining the energy needs (for heating, cooling and hot water), as well as the economic and environmental performance of the system. The model is multi-period, and allows to account for a dynamic weather data profile. In each of the periods, the MILP can decide whether or not to install a given element (i.e., window type, isolation material or collector). If the element is installed, then it remains active during the entire time horizon. In the ensuing sections, we describe each block of equations in detail.

<u>Logic decisions</u>

The model contains two type of binary variables. Variables X denotes whether a design alternative is active or not in a given time period. In addition to this variable, we define the binary variable X^{INS}, that keeps track of the particular time period in which a design alternative is installed. Hence, we define the following binary variables

- $X^{INSWIN}(i,t)$ is equal to 1 if window type i is installed in period t and equals 0 otherwise.
- $X^{INSWALL}(j,t)$ is equal to 1 if wall insulation of type j is installed in period t and equals 0 otherwise.
- $X^{INSROOF}(k,t)$ is equal to 1 if roof material k is installed in period t and equals 0 otherwise.
- $X^{INSCOL}(l,t)$ is equal to 1 if solar collector l is installed in period t and equals 0 otherwise.

These binary variables are used in a set of logic constraints. The first set of logic constraints makes sure that we choose one single option for every design decision (i.e., windows, wall and roof isolation, and collectors type). These constraints ensure also that a design alternative is installed only once during the entire time horizon (note that this condition could be easily relaxed in order to account for another type of context):

$$\sum_i \sum_t X^{WIN}(i,t) = 1$$

$$\sum_j \sum_t X^{WALL}(j,t) = 1$$

$$\sum_k \sum_t X^{ROOF}(k,t) = 1$$

$$\sum_l \sum_t X^{COL}(l,t) = 1$$

The following logic equations establish the relationship between both sets of binary variables:

$$\sum_{1 \le t \le t+1} X^{INSWIN}(i,t) \le X^{WIN}(i,t) \le \sum_{1 \le t \le t+1} X^{INSWIN}(i,t) \qquad \forall t$$

$$\sum_{1 \le t \le t+1} X^{INSWALL}(j,t) \le X^{WALL}(j,t) \le \sum_{1 \le t \le t+1} X^{INSWALL}(j,t) \quad \forall t$$

$$\sum_{1 \le t \le t+1} X^{INSROOF}(k,t) \le X^{ROOF}(k,t) \le \sum_{1 \le t \le t+1} X^{INSROOF}(k,t) \quad \forall t$$

$$\sum_{1 \le t \le t+1} X^{INSCOL}(i,t) \le X^{WIN}(i,t) \le \sum_{1 \le t \le t+1} X^{INSCOL}(i,t) \qquad \forall t$$

That is, if a device is installed, then it remains active during the whole time horizon. This is because the summation terms in both sides of the inequality take a value of one, making the binary variable denoting the design alternative equal to one.

Overall energy balance

The overall energy balance of the building can be expressed as follows:

$$Q^{T}(t) = Q^{SHEAT}(t) + Q^{SCOOL}(t) + Q^{HW}(t)$$

That is, the total amount of energy required by the building in period t is obtained from the space heating and cooling needs along with the hot water requirements (all of them expressed in kWh/year). The next sections describe how we calculate each of the terms of this equation.

Space heating

Space heating is obtained from the combustion of natural gas. The amount of heat required, denoted by $Q^{SHEAT}(t)$, is obtained from the heat loss through the building envelope $Q^{LOSSE}(t)$, [kWh/year], the heat loss due to fresh air flow $Q^{LOSSFA}(t)$, kWh/year, and the useful heat gains (internal plus solar heat gains through glazing) $Q^{HGAINS}(t)$, kWh/year, as shown in the following equation:

$$Q^{SHEAT}(t) = Q^{LOSSE}(t) + Q^{LOSSFA}(t) - Q^{HGAINS}(t)$$

Internal heat gains are represented by sources inside the building. People and electrical equipment in buildings dissipate heat. The most common sources of internal heat gain are: appliances, electronic devices, and lighting.

The heat loss through the building envelope (Q^{LOSSE}) is calculated via the following equation:

$$Q^{LOSSE}(t) = Q^{LOSSO}(t) + Q^{LOSSNS}(t) - Q^{LOSSB}(t)$$

Where $Q^{LOSSO}(t)$ is the heat loss through zones in contact with outdoors (walls glazing roofs and pavements), $Q^{LOSSNS}(t)$ is the heat loss through zones in contact with outdoors glazing roofs and pavements, and $Q^{LOSSB}(t)$ is the heat loss through linear thermal bridges, all of them expressed in kWh/year. The second two terms are given parameters, while the first term is a variable calculated as follows [13]:

$$Q^{LOSSO}(t) = DD0.024\eta^{BL}(t)$$

Where DD is a temperature coefficient (in ^{o}C/days), and $\eta^{BL}(t)$ is the building load coefficient, which we obtain from the following equation:

$$\eta^{BL}(t) = \sum_{i} A^{WIN}\eta^{TTW}(i)X^{WIN}(i,t) + \sum_{j} X^{WALL}(j,t)A^{WALL}\frac{\lambda^{WALL}(j)}{d^{WALL}(j)} + \sum_{k} X^{ROOF}(k,t)A^{ROOF}\frac{\lambda^{ROOF}(k)}{d^{ROOF}(k)}$$

Where $\eta^{TTW}(i)$ is the thermal transmission coefficient of window type i, expressed in W/(K· m^2), $d^{WALL}(j)$ and $d^{ROOF}(k)$ denote the thickness of the external wall insulation and roof insulation, respectively, expressed in m, while $\lambda^{WALL}(j)$ and $\lambda^{ROOF}(k)$ are the thermal conductivity of the external wall insulation material and of the roof insulation material, respectively, expressed in

W/(m K). A^{WIN}, A^{WALL} and A^{ROOF} denote the areas of the windows, wall and roof, respectively. Finally, $X^{WIN}(i,t)$, $X^{WALL}(j,t)$, $X^{ROOF}(k,t)$ and $X^{COL}(l,t)$ are binary variables that take the value of one if the corresponding element (i.e., window, wall and roof type) is installed in a time period, and zero otherwise.

The value of $Q^{LOSSFA}(t)$ is given (it is a parameter). On the other hand, the useful heat gains, $Q^{HGAINS}(t)$, are obtained as follows:

$$Q^{HGAINS}(t) = \eta^{HG}\left(Q^{INT}\,0.720A^{NET}M\right) + \left(G^{SOUTH}M\sum_i \eta^{OR}(i)A^{GLA}(i)X^{WIN}(i,t)\right)$$

Where η^{HG} represents the heat gains utilization factor, which is the ratio between the utilized and total solar-heat gain in a building, Q^{INT} are the internal gains, A^{NET} is the net floor area, M is the heating season duration, G^{SOUTH} is the average monthly solar energy that reaches a south oriented vertical surface, expressed in kWh/(m^2·month), $\eta^{OR}(i)$ is an orientation coefficient, $A^{GLA}(i)$ is the effective glazing solar radiation collector area for the different windows orientations, and $X^{WIN}(i,t)$ is a binary variable that equals 1 if a window of type i is chosen, and it is zero otherwise.

<u>Space cooling</u>

The space cooling energy needs are obtained as follows:

$$Q^{SCOOL}(t) = \left(1-\eta^{HGAINS}\right)\left(Q1(t) + Q^{HGAINS}(t) + Q2 + Q3\right)$$

Where η^{HGAINS} denotes the heat gains utilization factor, Q1 is the heat gain through the envelope, $Q^{HGAINS}(t)$ are the useful heat gains, Q2 is the heat transferred due to infiltration, and Q3 are the internal heat gains, all of them expressed in kWh/year. Q2 and Q3 are given parameters, while Q1 is obtained using the following equation:

$$Q1(t) = 2.928\eta^{BL}(t)\left(T^{OUT} - 25\right) + \eta^{BL}\left(\frac{\eta^{EXT}I^{RAD}}{25}\right)$$

In this equation, I^{RAD} is the solar radiation intensity for each orientation, expressed in W/m2, while η^{EXT} is an exterior envelope solar radiation absorption coefficient

<u>Hot water needs</u>

The hot water energy needs, $Q^{HW}(t)$, are obtained as follows:

$$Q^{HW}(t) = \left(\frac{Q^{CONV}(t)}{\eta^{HG}} - E^{SOL}(t)\right)$$

where the energy contribution from the solar collectors, $E^{SOL}(t)$, is calculated as follows:

$$E^{SOL}(t) = \sum_l I^{SRAD}(t)\eta 1\cdot\eta 2\cdot\eta^{COL}(t)A^{COL}(l,t)$$

Where $\eta 1$ the share of the direct radiation in total solar radiation is, $\eta 2$ is the share of the solar radiation used in the collectors, η^{COL} is the collector efficiency, and $A^{COL}(l)$ is the collectors area. The area of the collectors in a time period is obtained from the previous area and the expansion in capacity $EXPA^{COL}(l,t)$ performed in a period as follows:

$$A^{COL}(l,t) = A^{COL}(l,t-1) + EXPA^{COL}(l,t)$$

In addition, the expansion in capacity must lie within lower and upper bounds provided they take place:

$$\underline{EXPA^{COL}(l,t)}X^{COL}(l,t) \leq EXPA^{COL}(l,t) \leq \overline{EXPA^{COL}(l)}X^{COL}(l,t)$$

The efficiency of the collector is calculated as follows:

$$E^{SOL}(t) = \sum_{l} I^{SRAD}(t)\eta 1\eta 2\eta^{COL}(l)A^{COL}(l,t)$$

$$\eta^{COL}(l) = (0.94b(l)) - \left(m(l)\frac{\left(T^{COL} - T^{AMB}\right)}{I^{SRAD}} \right)$$

where b(l) is the value of the earnings of the collectors provided by the test manufacturer, m(l) is the slope indicating the loss factor of the collectors, T^{COL} is the average temperature in the collector of type l, T^{AMB} is the average temperature during the daytime, ^{o}C, and I^{SRAD} is the average irradiance intensity in sunny hours, W/m^2.

The energy supplied with conventional systems for DHW (domestic hot water generation), Qa, kWh/year, is a given parameter.

The MILP seeks to optimize two objective functions simultaneously: total cost and environmental impact. We next explain in detail how to calculate these objectives.

4. *Objective functions*

We consider two indicators: the economic one, which is quantified by the cost (cost of operation and retrofit cost), and an environmental metric. Note that in the study of Asadi et al. (REF), energy savings were assumed to be the environmental objective function, while in this work we use more advanced environmental indicators based on LCA principles.

4.1.Economic performance. Total cost.

To decide whether it is worthy to retrofit the building, we perform an economic analysis that considers the cost of the natural gas and electricity consumed by the flat during its life-time along with the retrofit cost. Hence, the total cost, including the retrofit and operation cost (i.e., energy cost) is calculated as follows:

$$Cost = \sum_{t} (PRICE^{NG}(t)Qsh(t) + PRICE^{EL}(t)Qsc(t) + PRICE^{NG}(t)Qwh(t) + RC(t))\ \mathbf{;}$$

Where $PRICE^{NG}$ and $PRICE^{EL}$ are the prices of natural gas and electricity, expressed in Euro/kWh, respectively. In addition, the retrofit cost is obtained from the installation of solar panels, better isolation materials for walls and roof is calculated as follows:

$$RC(t) = A^{WIN}\sum_{i} COST^{WIN}(i)X^{WIN}(i) + A^{WALL}\sum_{j} COST^{WALL}(j)X^{WALL}(j,t) +$$

$$A^{ROOF}\sum_{k} COST^{ROOF}X^{ROOF} + \sum_{k} COST^{COL}A^{COL}$$

$$+ Aroof\sum_{k} Croof(k)\cdot Insroof(k,t) + \sum l, Ccol(l)\cdot Acol(t,l)$$

where A^{WIN} is the window surface in m^2, $COST^{WIN}$(i) is the cost of window type i expressed in €/m2, A^{WALL} is the exterior wall surface area in m^2, and $COST^{WALL}(j)$ is the cost for the external wall insulation material of type j in €/m2. *Aroof* is the surface area in m2, *Croof(k)* is the cost for roof insulation material type k in euro/m2, and *Ccol(l)* denotes the cost for solar collector type l, in euro/m^2.

4.2. Environmental performance. Environmental impact.

The environmental impact caused by the operation of the building is determined from the energy demand, which accounts for space heating, space cooling and hot water production. Hence, our study considers the impact associated with burning natural gas for heating the flat and for generating hot water, along with the electricity consumed for space cooling.

To quantify this environmental impact, we apply the life cycle assessment (LCA) methodology. LCA is a widely used methodology to evaluate the environmental load of a product or process over its entire life cycle [16]. It quantifies all the inputs and outputs of mass and energy through the entire life cycle of the process/product being assessed, that is, from the "cradle" to the "grave". Particularly, we apply here a "cradle-to-gate" analysis that comprises all the steps in the life cycle of the energy and electricity consumed. Our analysis neglects the impact caused during the construction phase, which includes the disposal and treatment of the waste generated after the useful life of the building. It is left out of the analysis due to the fact that it is proved to represent less than 10% of the total impact [17]

The LCA methodology as applied to our system comprises the following steps: (i) Definition of the purpose, goal, functional unit and system boundaries; (ii) inventory analysis; (iii) evaluation of the environmental effects; and (iv) interpretation of the results and identification of alternatives for environmental improvements. The goal of the study is to assess the environmental impact associated with the operation of the building considering all the stages in the life cycle of the energy consumed. Hence, the boundaries of the system encompass all the stages in the energy supply chain. The functional unit of the study is defined as a given amount of energy demanded in the form of heat, cooling needs and hot water.

Regarding the impact assessment, we use here the CML2001 methodology , which follows LCA principles. Following this approach, the total environmental impact associated with the amount of natural gas and electricity used for space heating, water heating and space cooling is obtained as follows:

$$CML(f) = \sum_t ((Qsh(t) + Qwh(t))CMLng(f) + Qsc(t)CMLel(f))$$

Where CMLng(f) and CMLel(f) represent the impact in category f associated with the generation of the necessary amount of natural gas and electricity, respectively. The data required for the calculation of the environmental impact are extracted from the Ecoinvent database (see Table 1).

Regarding the interpretation phase, this is carried out during the post optimal analysis of the solutions found by the optimization algorithm.

Table 1. Environmental impact of natural gas and electricity in different impact categories, per kWh.

Category (f)	*Units*	*CMLng*	*CMLel*
Climate change	kg $CO_{2\text{-Eq}}$/kWh	0.082095	0.49853
Human toxicity	kg 1,4-$DCB_{\text{-Eq}}$/kWh	0.0034744	0.058411
Aquatic toxicity	kg 1,4-$DCB_{\text{-Eq}}$/kWh	0.0070578	0.14644
Terrestrial toxicity	kg 1,4-$DCB_{\text{-Eq}}$/kWh	2.77E-06	9.48E-05
Eutrophication	kg $NOx_{\text{-Eq}}$ /kWh	6.65E-05	0.0020399
Acidification	kg $SO_{2\text{-Eq}}$ /kWh	7.65E-05	0.0047232

5. *Model and solution strategy*

The overall MILP can be expressed in compact form as follows:

$$
\begin{aligned}
(M) \quad & \min \quad && \{f_1, \ldots, f_O\} \\
& s.t. && h(x,y) = 0 \\
& && g(x,y) \le 0 \\
& && x \in \Re \quad y \in \{0,1\}
\end{aligned}
$$

The model seeks to optimize two objective functions subject to a set of equality and inequality constraints that describe the system's performance and operation. Two types of variables are considered: continuous (for example: energy needs for space heating, cooling and hot water generation) and discrete (wall and roof insulation materials, types of windows and solar collectors). Particularly, in our model we have the following parameters and variables:

- parameters (input data): prices of natural gas & electricity, heat loss reduction coefficient, linear heat flux transmission coefficient, exterior wall surface area, thickness of the roof/wall insulation, window surface, floor surface area etc;
- variables (those whose values are optimized by the optimization algorithm): windows types, external wall insulation, roof insulation materials, solar collector types and area

The solution of the multi-objective MILP described above is given by a set of points called Pareto optimal alternatives. They feature the property that they cannot be improved simultaneously in one objective without necessarily worsening at least any of the others.

There are different methods to solve multi-objective problems. Without loss of generality, we propose here to obtain the Pareto solutions of the model using the ε-constraint method, which is based on calculating a set of single-objective problems in which one objective is kept in the objective function while the others are transferred to auxiliary constraints that bound them within some allowable limits. This method allows dealing with non-convex solution boundary.

Therefore, after the MOO is performed, we obtain a set of Pareto optimal solutions. An example of a Pareto set is given on Fig. 1. These solutions feature the property that an improvement in one objective can only be attained by worsening at least another criterion. From one side of the curve lies the region of feasible (possible) solutions. They are possible, but sub-optimal. If we pick up one of the solutions from that region, we see that with the same performance in terms of f1 we can find a better performance in f2, or equivalently, with the same f2, we can find better performance of f1 [18].

6. Results

We applied our approach to a standard flat taken from Asadi et al. [13]. The main data of the study, including the set of retrofit strategies available, can be found in the original publication.

The MILP contains 2,800 binary variables, 1,110 continuous variables and ,3513 constraints. The CPU time is in the order of seconds depending on the instance being solved on a computer AMD Athlon(tm) II X2 B24 with a processor 2.99 GHz, 3.49 GB of RAM.

We solved 6 bi-criteria problems that trade-off each single impact category against the cost. Fig 2 depicts the Pareto curves corresponding to each impact category, in which each point represents a different solution entailing a specific retrofit design. The impact values have been normalized by dividing each of them by the maximum impact attained over all of the solutions of the curve. The extreme solutions correspond to the minimum cost and minimum environmental impact designs.

As observed, the maximum percentage of impact reduction depends on the category chosen. For instance maximum environmental impact reduction we can achieve in climate change category, where the reduction reaches 10.7% while in acidification we can decrease the impact only by less than 5%, human toxicity 6.5%, aquatoxicity by 6%.

Table 1 shows the design configurations for the minimum environmental impact and minimum cost designs. The extreme solutions differ in the installation of solar collectors (total surface area of 75 m^2 in the minimum environmental impact design and cero in the minimum cost one), and the type of windows chosen (with thicker layer of air between 2 sheets of glass in the minimum cost design).

We now turn our attention to the GWP case. Fig. 3 shows a breakdown of the main sources of this impact for the extreme solutions. Particularly, there are two sources of impact: natural gas combustion and electricity generation.

In the minimum environmental impact solution, the retrofit measures help to reduce the total impact by 10.7%, which consists of reduced impact from electricity by 4% and impact from natural gas by 68%.

Finally, we analyze the relationship between environmental indicators. More precisely, we investigate how the impacts change when we minimize the contribution to global warming, which is one of the main impact categories of concern for decision-makers. With this analysis we aim to get insight into the effects of implementing regulations that focus on decreasing only this impact category.

Figure 4 provides the normalized values of all the environmental impacts in the solutions obtained when climate change is being minimized. The normalization has been performed by dividing the values by the maximum ones obtained over all the solutions. Note that all the points lying in the same vertical coordinate represent the same Pareto solution, but show its environmental performance in different categories. Note also that figures 2 and 4 are not the same, since in the former we optimize every impact category separately, while in the latter we minimize only one impact (i.e., climate change) and show the normalized values of the rest. As observed, the minimization of climate change reduces in turn the remaining impacts, which suggests that buildings regulations aiming at climate change mitigation might also contribute to the decrease of other environmental impacts.

Figure 5 is a parallel coordinates plot that depicts all the Pareto solutions obtained by solving the 6 bi-criteria problems (i.e., cost vs each single impact category separately). In the parallel coordinates plot, the horizontal axis represents the different objectives, while the vertical axis shows the normalized value attained by every solution in each objective. Hence, each line in the plot represents a different Pareto solution and connects the performance of this retrofit alternative in every environmental impact category. As seen, all the environmental categories are highly correlated, since reductions in any of them entail reductions as well in the remaining ones. Hence, there are indeed only two independent objectives: Total cost and (any) environmental impact. This can be observed by looking at the lines denoting the Pareto points, which cross in one single point and are parallel in the other part of the graph. Hence, the environmental impact objectives used in the study are highly correlated, so we can simplify the analysis by just looking to one of them when devising new regulations.

Note that the results obtained in this analysis depend strongly on the environmental data retrieved from the database.

Table.1 Retrofit alternatives for the extreme designs.

	Min cost solution:	Min impact solution:
➢ Windows	• 2bl glazing, Without thermal break Uncoated air-filled metallic frame 4-12-4	• 2bl glazing, Without thermal break Uncoated air-filled metallic frame 4-16-4
➢ External wall insulation materials	• Cork	• Cork
➢ Roof insulation materials	• Spray polyurethane	• Spray polyurethane

➢ Solar collector type and area	• NO COLLECTORS	• DANOSA SOLAR (75 m2)

7. Conclusions

In this work we have presented a systematic tool for reducing the environmental impact in buildings taking also into account economic aspects. Our approach is based on an MILP formulation that identifies in a systematic manner the best alternatives for improving the environmental and economic performance of buildings simultaneously. This MILP accounts for a set of retrofit alternatives for space heating and cooling and hot water generation. It contains both continuous and binary variables that encode the different design options.

Numerical results show that it is possible to reduce the impact by improving the isolation of the buildings and by installing solar collectors. In the minimum environmental impact solution, the retrofit measures help to reduce the total impact by 10.7%, which consists of reduced impact from electricity by 4% and impact from natural gas by 68%. We found also that the different environmental impacts are highly correlated, so the minimization of one of them results in the minimization of the others. We hope these findings will help design more effective regulations for improving the environmental performance of buildings.

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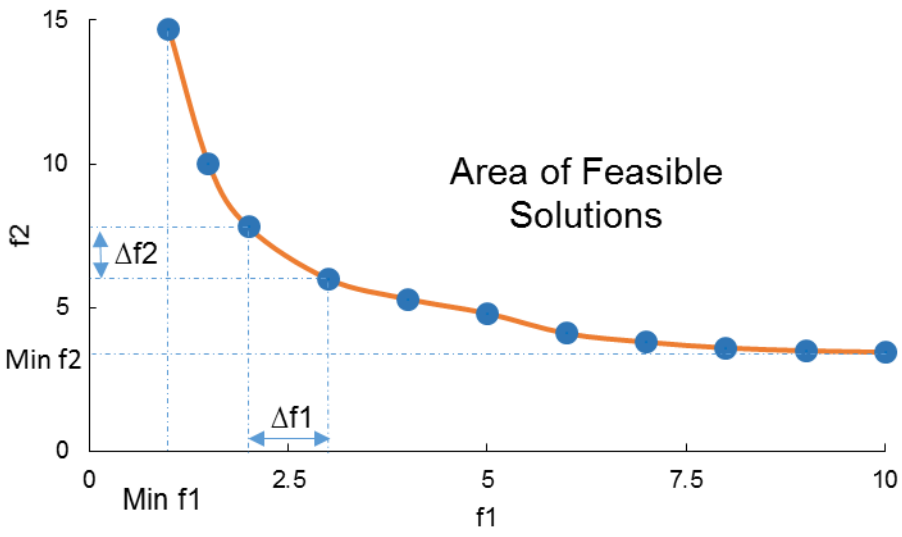

Figure 1. Pareto set of optimal solutions

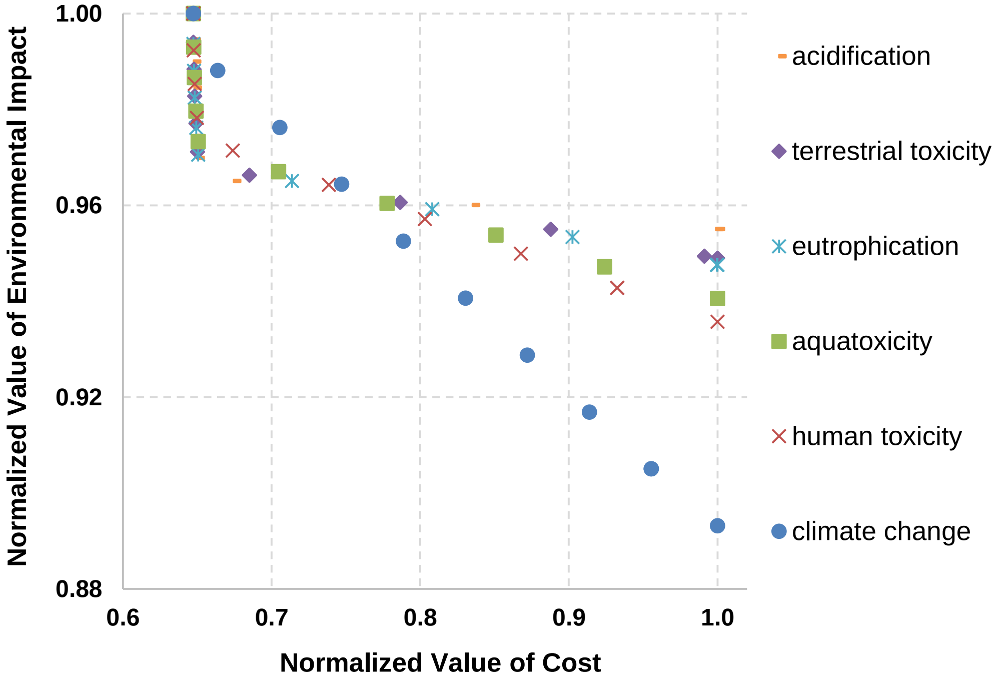

Figure 2. Pareto sets corresponding to each environmental impact category being optimized.

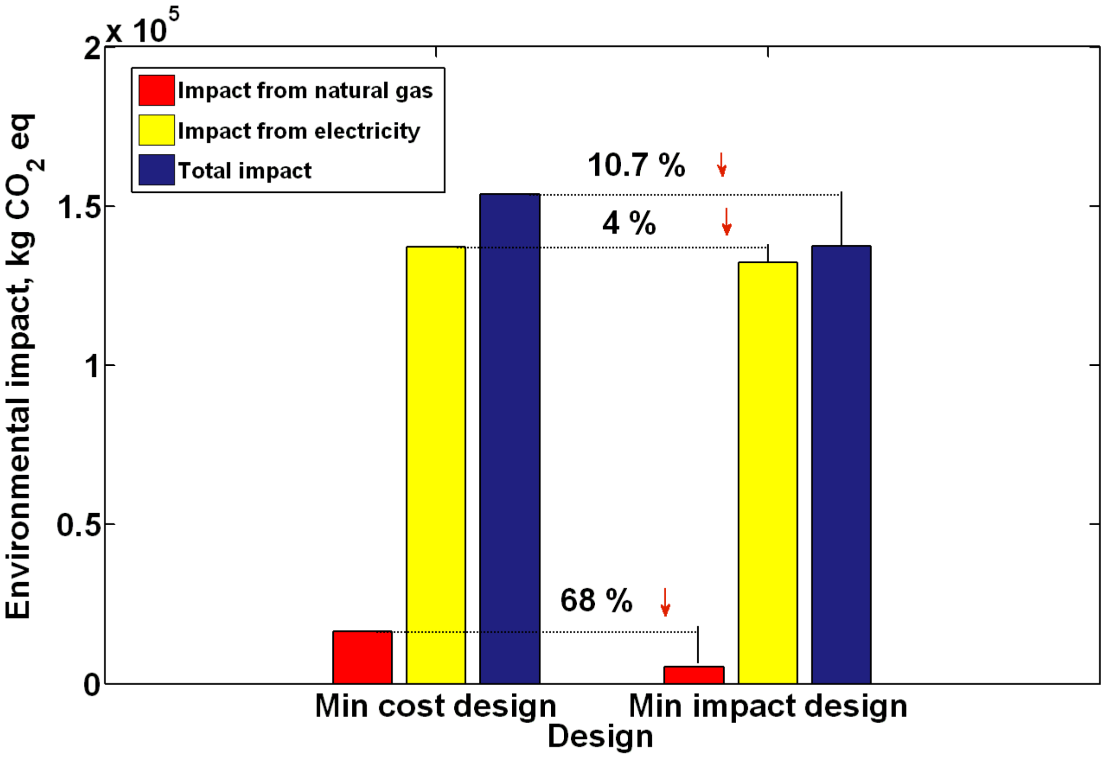

Figure 3. Environmental impact for the extreme designs.

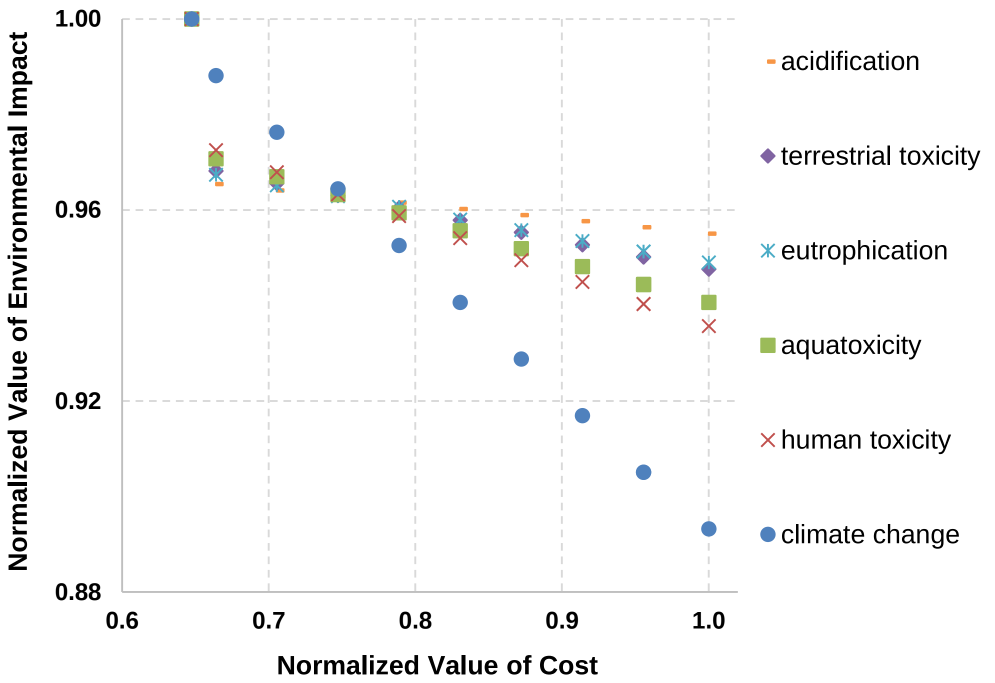

Figure 4. Interrelation between environmental impacts in different categories while one impact category (climate change) is optimized.

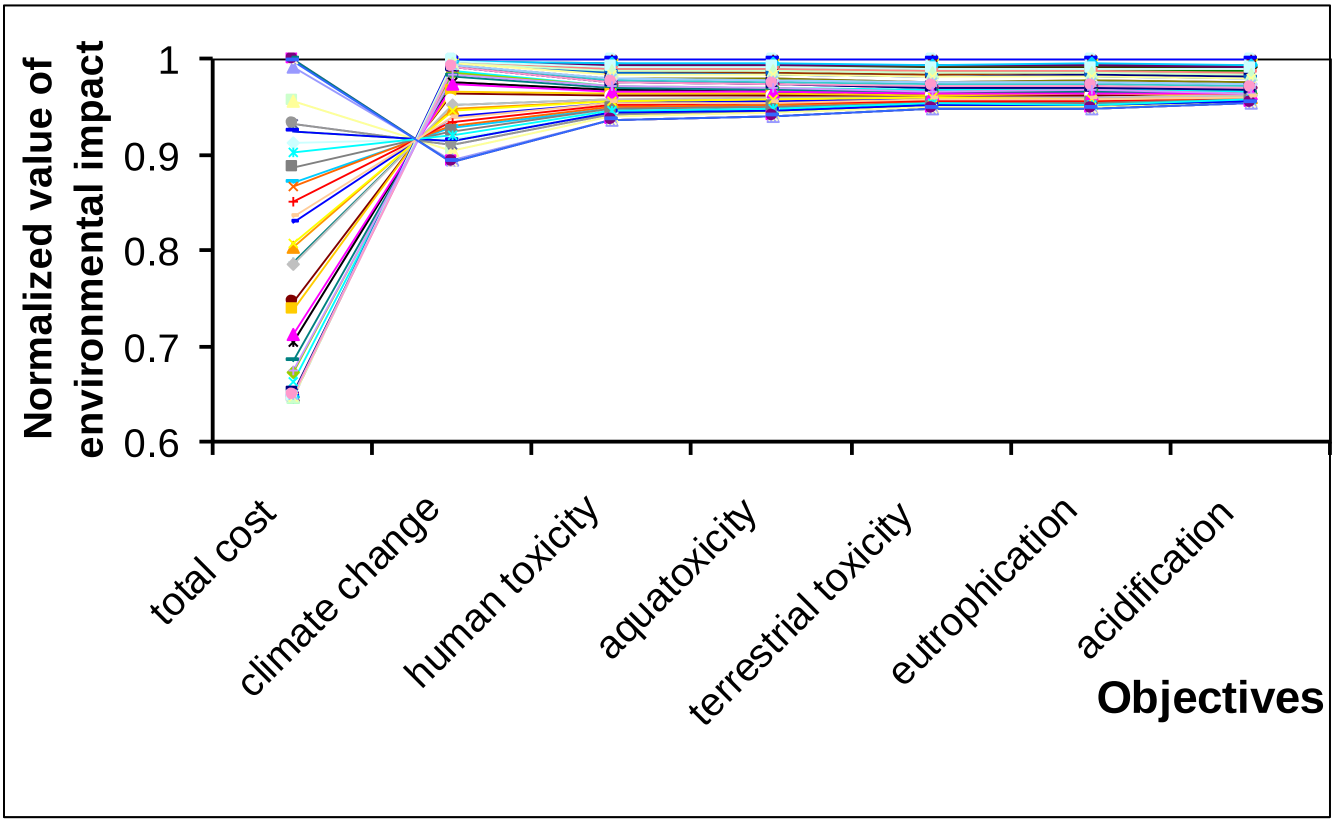

Figure 5. Parallel coordinate plot.

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-m2] for window type i, euro/m^2
Cinswall(j) cost in [D-m2] for external wall insulation material type j, euro/m^2
Croof(k) cost in [D-m2] 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 ^0C/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·ºC)
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 ^0C)
m1 (l) the slope and indicates the loss factor of the collector, W/m^2 ºC

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
Ta average temperature during the daytime (during the sunny hours), ^oC
Tav average outdoor temperature in the cooling season
Tm the average temperature in the collector, ^oC
U(i) window type i thermal transmission coefficient W/($^oC \cdot m^2$)
U1 building exterior envelope thermal transmission coefficient W/($^oC \cdot m^2$)
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
EAcol(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