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DEVELOPMENT OF AN OPTIMIZATION MODEL FOR DECISION MAKING IN BUILDING RETROFIT PROJECTS

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Abstract. Retrofitting of existing buildings offers significant opportunities for improving occupants' comfort and well-being, reducing global energy consumption and greenhouse gas emissions. This is being considered as one of the main approaches to achieve sustainability in the built environment at relatively low cost and high uptake rates. Although a wide range of retrofit technologies is readily available, methods to identify the most suitable set of retrofit actions for particular projects are still a major technical and methodological challenge. This study presents a simulation-based multi-objective optimization model to quantitatively assess technology choices in a building retrofit project (a combination of TRNSYS, and MOBO optimization freeware). This model is employed to assess a school building retrofit project as a case study to illustrate the practicability of the proposed approach, and therefore, the final decision (set of non-dominated solutions) for optimum building retrofit. The study starts with the individual optimization of objective functions focusing on building's characteristics and performance: primary energy consumption, global costs, and thermal discomfort hours. Then the proposed multi-objective optimization model is used to study the interaction between these conflicting objectives and assess their trade-offs.

Keywords. Energy, Indoor Environmental Quality for well-being in energy-efficient & retrofitted buildings.
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1. Introduction

Buildings are among one of the major consumers of energy and therefore have a significant adverse impact on the environment. Although construction activities consume large amounts of energy, more than 80% of the energy consumed by a building during its life-cycle occurs when the building is in actual occupancy and use [1]. A building retrofit is the physical or operational change in a building, its energy consuming equipment, or its occupant's behavior to reduce the amount of energy to convert the building to a lower energy consuming facility [2]. Retrofitting of a building offers great opportunities for improving energy efficiency by reducing maintenance costs, reducing air emissions, creating job opportunities, enhancing human health, and improving thermal comfort [3, 4].

There are a number of models and methods developed to assess conditions and support decisions pertaining to building retrofit. These methodologies can be broadly categorized into two main approaches: the models in which alternative retrofit solutions are explicitly known a priori (see e.g. [6], [7], [8], [9]) and the models in which alternative retrofit solutions are implicitly defined in the setting of an optimization model (see e.g. [10], [5], [11], [12]).

The current study proposes an integrated MOO approach to develop a decision support model for building retrofit projects, based on the combination of TRNSYS, MATLAB and MOBO. The proposed methodology is used for the optimization of primary energy consumption, global costs, and thermal discomfort hours in a school building retrofit project. A wide decision space is considered, including alternative materials for the external walls insulation, roof insulation, different window types, installation of a solar collector to the existing building, and a wide range of HVAC system types to meet heating and cooling requirements.

2. Methodology

The optimization framework is summarized in Figure 1. The scheme is a combination of TRNSYS 16, MOBO 0.3a and objective function calculator under MATLAB environment. TRNSYS [13] is a transient system simulation program with a modular structure that was designed to solve complex energy systems problems. MOBO is an optimization tool able to handle single and multi-objective optimization problems with continuous and discrete variables and constraint functions [14].

In this scheme first a model of the building before retrofit is created in TRNSYS. Then, using this model and MATLAB [15] as a post-processor of the objective functions, the combination is used within MOBO to evaluate the potential solutions.

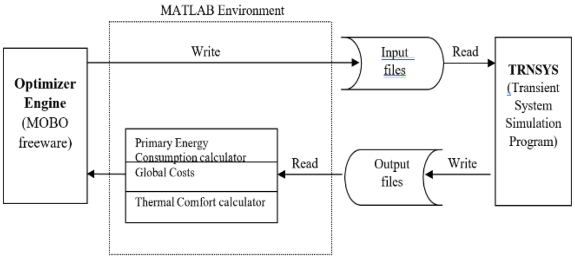

Figure 1 Optimization framework

2.1 Formulation of the optimization problem

This paper considers the multi-objective optimization (MOO) of buildings retrofit strategies. Therefore it requires the definition of appropriate decision variables, objective functions and constraints, and finally the selection of appropriate solution computation techniques.

2.1.1 Decision variables

The decision variables reflect the total set of alternative measures that are available for building retrofitting (e.g. windows, insulation materials, etc.). The set of retrofit actions concerns combinations of choices regarding external wall insulation material, roof insulation material, windows, installation of solar collector and different HVAC systems to the existing building. Five types of decision variables are defined concerning the alternative choices regarding:

- the external wall insulation materials;
- the roof insulation materials;
- the windows type;
- the solar collectors type;
- the HVAC systems.

For simplicity, it is assumed that only one retrofit action, from each one of the five sets of actions, may be selected for the building retrofit.

Assuming the availability of I alternative types of external wall insulation material, J alternative types of roof insulation material, K alternative types of windows, L alternative types of solar collector, and M alternative types of HVAC system, integer decision variables x^{EWAL}, x^{ROF}, x^{WIN}, x^{SC}, and x^{HVAC} are defined as follows:

x^{EWAL}: external wall insulation material type ident 1

x^{ROF}: roof insulation material type identifier 2

x^{WIN}: window type identifier 3

x^{SC}: solar collector type identifier 4

x^{HVAC}: HVAC system type identifier 5

A list of alternative retrofit actions applied in this study is based on a CYPE rehabilitation price generator database (CYPEingenieros 2010 [16]) and presented in Appendix A. This list includes 24 different external wall insulation materials, 18 roof insulation materials, 3 windows types, 4 solar collectors and 4 HVAC systems.

2.1.2 Objective functions

2.1.2.1 Primary Energy Consumption (PEC)

The primary energy consumption of the building is directly assessed by TRNSYS. The total primary energy consumption, PEC, consists in the sum of primary energy demands for space heating (QHEAT), space cooling (QCOOL) and sanitary hot water (QSHW) systems. SHW production by solar collector (QSC) is subtracted from the total primary energy consumption. Moreover, energy consumption for lighting is not included because this is not expected to significantly change as a result of the implementation of the considered retrofit actions.

2.1.2.2 Global Costs (GC)

The global costs for the building retrofit is defined as the NPV of all costs during the defined economic life cycle of the building, including investment costs (ReCost) and costs related to the use of the building. Investment costs include the initial costs for implementing the retrofit actions and also the NPV of the costs related to the replacement of building elements with a lifetime smaller than the defined economic life cycle of the building after the retrofit. Residual values for building elements with lifetimes longer than the economic life cycle are also taken into account. Energy costs refer to the NPV of the energy bills for each year of the economic life cycle and maintenance costs refer to the NPV of annual costs with the maintenance of each building element and system.

ReCost(X), where (X denotes the vector of all decision variables) is calculated by adding individual retrofit action costs as follows:

$$\begin{aligned} ReCost(X) = \ & A_{EWAL}.C^{EWAL}(X) \\ & + A_{ROF}.C^{ROF}(X) \\ & + A_{WIN}.C^{WIN}(X) + C^{SC}(X) \\ & + C^{HVAC}(X) \end{aligned} \qquad (6)$$

Where:

A_{EWAL} – exterior wall surface area [m^2];

C^{EWAL} - cost in [€/m^2] for selected external wall insulation material;

A_{ROF} - roof surface area [m^2];

C^{ROF}- cost in [€/m^2] for selected roof insulation material;

A_{WIN} - windows surface area [m^2];

C^{WIN}– cost in [€/m^2] for selected window;

C^{SC}- cost for selected solar collector [€];

C^{HVAC}- cost for selected HVAC system [€].

NPV of the costs are also calculated using the following formula:

$$NPV = -C_0 + \sum_{i=1}^{T} \frac{C_i}{(1+r)^i} \qquad (7)$$

Where

$-C_0$: Initial Investment

C_i: Cash flow

r: Discount rate

T: Time

The retrofit actions (RAs) corresponding costs ($C^{EWAL}, C^{ROF}, C^{WIN}, C^{SC}, C^{HVAC}$) and the related maintenance costs are extracted from RAs characteristics that is estimated using CYPE software.

2.1.2.3 Total percentage of discomfort hours (TPMVD)

The metric used to assess thermal comfort is the predicted mean vote (PMV), based on Fanger's model [17]. PMV is representative of what, in average, a large population would think about a thermal environment, and is used to assess thermal comfort in standards such as ISO 7730 [18] and ASHRAE 55 [19]. It ranges from -3 (too cold) to +3 (too warm), and a PMV value of zero is expected to provide the lowest predicted percentage of dissatisfied people (PPD) among a population. In this study, an absolute value of 0.7 for PMV, the upper limit of category C, the less exigent comfort category in ISO 7730, is considered as the borderline of the comfort zone. Therefore, in order to maximize the thermal comfort, the total percentage of cumulative time with discomfort ($|PMV| > 0.7$) over the whole year during the occupancy period, TPMVD(X), should be minimized. The total percentage of discomfort hours is also predicted by TRNSYS. After processing this function in MATLAB, the MOBO uses the result to estimate TPMVD.

2.2 Multi-objective optimization

MOO models aim at capturing the multiple, conflicting and incommensurate aspects of evaluation of the merits of potential solutions, in order to identify their trade-offs and provide a sound technical basis to decision support. In general, due to the conflicting objective functions there is no unique solution to MOO but a set of non-dominated (Pareto optimal) solutions. In our model the simultaneous optimization of primary energy consumption, global costs and thermal discomfort hours is sought. This MOO model is of combinatorial nature because of its structure and decisions to be made, and it is nonlinear due to the building performance calculations. Therefore, an MOGA has been selected from MOBO library to characterize the non-dominated front.

In this work NSGA-II [20] is used from the library of MOBO optimization algorithms to tackle the multi-objective problem. Like any other GA, NSGA-II is based on the evolution of a population of individuals, each of which is a solution to the optimization problem. In this study, an individual represents a retrofit option (embodying different technologies and types of intervention) to be carried out in a building. To use a genetic analogy, each individual is represented by a chromosome whose genes correspond to a number of the individual's characteristics, as in Figure 2.

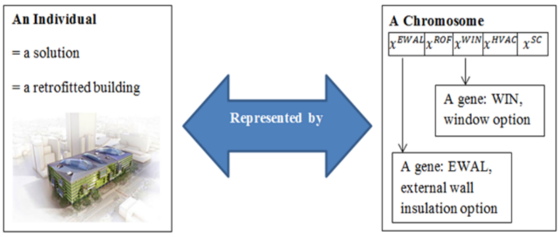

Figure 2 A solution to the retrofit optimization

problem, as presented by a chromosome

3. Model application on a school building

The school building is located in Coimbra, Portugal and serves some 800 students and 117 staff. The building consists of 6 blocks, the main block designed for administration purposes. 4 blocks (A, B, C and D), include classrooms and laboratories. These four blocks have similar architecture, with different number of stories. Blocks A and D have three stories and blocks B and C have 2 stories. The last block is the sport pavilion. Total occupied space floor area is 9,850 m2 and is divided between the 6 mentioned blocks.

In this project block A, one of the four identical blocks (Class rooms) is selected as a case study. The central zone in this block is a big atrium with visibility to all other sections in the building. This central zone uses natural lighting.

3.1 Building simulation

Table 2 presents summary of the set-up for the building. Based on this table, a building model is developed in TRNSYS. The type-56 multi-zone building is a reproduction of the reference building. The building model is divided into 5 zones: North zone, East zone, South zone, West zone, and Atrium zone. Heating is supplied locally in each room by electric resistance radiators; the buildings have no cooling system. However, as some of the considered HVAC retrofit actions include cooling systems, therefore, then an estimation of cooling needs was required. This has been taken into account by considering the recommended set point for cooling according to Portuguese national regulation RSECE [21] which is equal to 25°C.The atrium is neither heated nor cooled. The TRNSYS model has been run using the existing building parameters described earlier, with one hour time step, using DOE typical meteorological year version 2 (TMY2) weather data.

To ensure accurate predictions of simulation, the base-case results were compared with monthly utility billing data. ASHRAE Guideline 14 [22] defines the standard for simulated data calibration. According to this guideline, simulation's degree of accuracy can be found by comparing the whole-building simulation data with actual building data using the two indicators that define error margins in comparison: CV_RMSE (Coefficient of variation of the root mean square error), and NMBE (Normalized mean bias error). For this case, CV_RMSE should be less than 15% per ASHRAE Guideline 14 while NMBE is suggested to be less than 5%. CV_RMSE and NMBE were found to be 12.81% and 3.26% respectively. Therefore, the base case model developed was considered acceptable for this case building.

Table 1 Brief description of the base building parameters for simulation

Location		*Coimbra, Portugal*
Building type		*School building*
Floor areas	*utility floor area*	*1,886 [m^2]*
	conditioned floor area	*1,622 [m^2]*
Dimension and Heights	*Average floor height*	*3.02 [m]*
	Window height	*2.7 [m]*
	Window-to-wall ratio	*65% , except South façade 59%*
Construction of building envelope	*External walls*	*2cm plaster + 11 cm Brick + 4cm air space + 11 cm brick + 2 cm plaster (U-value = 1.737 W/m^2K)*
	Roof	*2cm plaster + 22cm concrete + 1cm bitumen + 4 cm cement (U-value = 2.654 W/m^2K)*
	Windows	*Single-pane simple glass (U-value = 5.68 W/m^2K, g-value = 0.855)*
Operating hours	*Monday to Friday*	*8:00 – 20:00*
	Weekend	*Closed*
HVAC parameters	*Total number of persons*	*200*
	Lighting + Equipment	*Lighting 10 W/m^2, Equipment 12 W/m^2*
	Infiltration rate	*0.9 ACH*
	Cooling system	*None*
	Heating System	*electric resistance radiators*

	Thermal set points	*20°C – No max.*

3.2 Multi-objective optimization

The final goal of the optimization problem in this phase is the simultaneous optimization of primary energy consumption, global costs, and total percentage of discomfort hours. The NSGA-II in MOBO is used to tackle this MOO problem and identify the set of non-dominated solutions. The MOO problem can be summarized as follows, using integer decision variables stated in (1) – (5):

$$Min\ Z_1(X) = PEC(X)$$

$$Min\ Z_2(X) = GC(X)$$

$$Min\ Z_3(X) = TPMVD(X)$$

$$S.t.$$

$$1 \leq x^{EWAL} \leq I, (I = 24) \tag{8}$$

$$1 \leq x^{ROF} \leq J, (J = 18)$$

$$1 \leq x^{WIN} \leq K, (K = 3)$$

$$1 \leq x^{SC} \leq L, (L = 4)$$

$$1 \leq x^{HVAC} \leq M, (M = 4)$$

3.2.1 First set of optimization (single-objective)

In this first optimization set, the three objective functions (primary energy consumption, global costs, and total percentage of discomfort hours) have been individually minimized.

3.2.1.1 Single-objective minimization of primary Energy Consumption

The goal is to minimize primary energy consumption for heating, cooling and SHW purposes. The results are given in Table 3.

In the PEC optimized building, the insulation level is high with thick layers of insulating material with low U-values for external wall and roof. In addition, window type 3, which has the lowest thermal transmittance, is selected. Regarding the HVAC system, a natural gas boiler is recommended. Furthermore, the flat solar collector with highest area among all the systems considered is recommended. However, this set of retrofit actions resulted in a significant increase of the global costs with respect to the GC optimized building.

Table 2 Results of single-objective optimization (Refer to Appendix A for RAs characteristics)

Type of solution	*PEC [kWh/m^{2}year]*	*GC [k€/ m^2]*	*TPMVD [%]*	*EWAL*
[min] PEC	***4.69***	*147.36*	*16.85*	*15*
[min] GC	*44.40*	***21.19***	*36.46*	*1*
[min] TPMVD	*18.40*	*101.13*	***16.7***	*16*

3.2.1.2 Single-objective minimization of global costs

The results of this optimization are given in Table 3. Minimizing global cost results in low insulation level of external wall insulation and single glazed window. In addition, the cheapest HVAC system (oil-based boiler without cooling system) and the cheapest solar collector are recommended. However, this results in a significant increase of the energy consumption and thermal discomfort hours compared to the EC and TPMVD optimized buildings.

3.2.1.3 Single-objective minimization of total percentage of discomfort hours

The aim is to minimize the total percentage of thermal discomfort hours in the building. There is no cooling system in the existing building, either active or passive. The results are given in Table 3.

Minimizing TPMVD results in high insulation level and double glazed windows, similarly to minimization of energy consumption. Regarding HVAC system, HVAC type 2 with natural gas boiler for heating and chiller for cooling is selected that leads to significantly better indoor comfort compared to the existing building.

As can be seen from Table 3, the results for minimization of global costs diverged significantly from the others. The solutions that minimizes primary energy consumption and thermal discomfort are comparable, which is due to the nature of retrofit actions considered and objective functions. This table can be used to shape the expectation of the DMs and help them to elicit appropriate bounds to objective function values to focus the search for new solutions in restricted regions of the search space.

3.2.2 Second set of optimization (two-objective)

In each of these multi-objective optimizations, two objectives were chosen from among primary energy consumption, global costs, and total percentage of discomfort hours.

3.2.2.1 Multi-objective optimization of primary energy consumption and global costs

The single-objective optimization suggests that these objectives are strongly opposed. The results are given in Figure 6. Each point on the Pareto front is a solution associated with a set of decision variables representing retrofit actions.

Wall and roof insulation material as well as windows and HVAC and solar collector systems vary in different non-dominated solutions. Also, it is worthwhile to mention that the solutions on the Pareto front are grouped according to the window types. This reveals that the window type has a stronger influence on the low PEC cost-effective solutions than the other decision variables.

To obtain the best solutions of GC, single glazed window (WIN=1), the lowest price window is found to be optimal with incrementally additional insulation. As the thickest insulation with lowest U-values for external wall and roof (EWAL= 24, ROF = 6) as well as the largest solar collector (SC=2) are selected, the optimization leads to double-glazed window (WIN=2). This leads to a significant reduction in the PEC, explaining the discontinuity in the Pareto front at 39 kWh/m^{2}year of PEC as illustrated in Figure 6. A similar gap happens at PEC = 27.8, where the optimization leads to window type 3 with lowest U-value resulting to a significant reduction in the PEC.

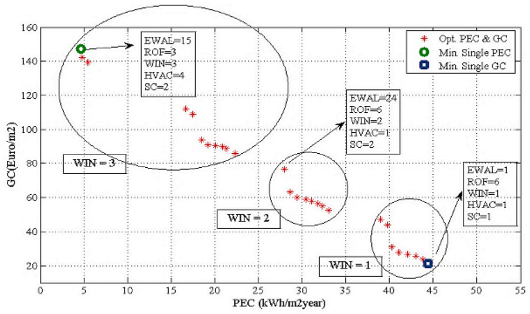

Figure 3 Multi-objective solutions for the building retrofit strategies (PEC - GC) (Refer to Appendix A for RAs characteristics

3.2.2.2 Multi-objective optimization of total percentage of discomfort hours and global costs

The results of this optimization are given in Figure 7. The different non-dominated solution all fall between two single-objective optima.

Regarding the solar collector, all the recommended solutions are equal: the cheapest solar collector is recommended. All the other retrofit actions vary in different non-dominated solutions. The optimization of TPMVD leads to using optimal combinations between the building envelope parameters (including external wall and roof insulation materials, and window type) and the HVAC system type. As in previous case, the solutions obtained on the Pareto front are grouped according to the window types. This again indicates that the window type has a stronger influence on the solutions than the other decision variables.

Double glazed window with lowest thermal transmittance, thick layer of insulation with low U-values for external wall insulation and roof, and the HVAC system type 2 with cooling option are selected giving the lowest TPMVD value. For a higher reduction in GC, HVAC system type 1 is used. Moreover, window type 2 and then type 1 is selected to reduce the GC. There is a large discontinuity in the Pareto front at 34.41% of TPMVD. This can be explained by changing the HVAC type 1 to 2 with cooling option.

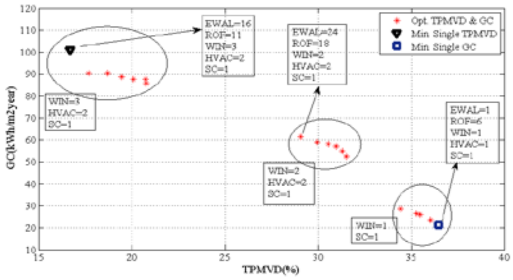

Figure 4 Multi-objective solutions for the building retrofit strategies (TPMVD - GC) (Refer to Appendix A for RAs characteristics)

3.2.2.3 Multi-objective optimization of primary energy consumption and total percentage of discomfort hours

The aim is to simultaneously minimize PEC and TMPVD. The optimization process generates just three solutions, which form the Pareto front. The single-objective optimization results for PEC and TPMVD are similar, with one major difference regarding the HVAC system. It is worthwhile also to mention that the small number of non-dominated solutions is due to the fact that the lower PEC values are mainly achieved with the HVAC system type 1 without cooling option (HVAC = 1) that leads to high TPMVD values. Therefore, a large number of potential solutions are dominated by the PEC optimal solution.

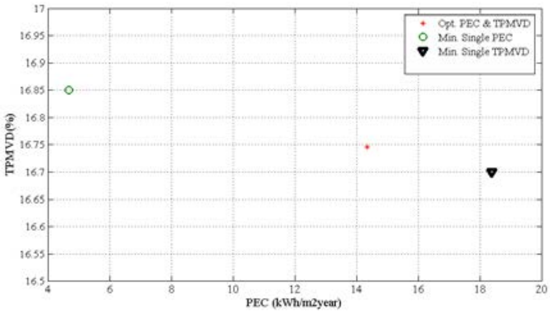

Figure 5 Multi-objective solutions for the building retrofit strategies (PEC – TPMVD) (Refer to Appendix A for RAs characteristics)

The three sets of optimization presented above results in the following conclusions:

- The number of non-dominated solutions for objectives with not much in conflict characteristics is lower than for those with dissimilar characteristics.
- The analysis of the results shows the physical characteristics of solutions and helps to understand the simultaneous influence of the decision variables on the PEC, GC, and TPMVD.
- Without considering a constraint on summer overheating, the influence of the window type on the results is more significant than the influence of the other decision variables.
- There are often discontinuities in the Pareto front where it is possible to gain a lot in one objective by sacrificing only a little in the other objective, so the trade-off analysis is essential for reaching a compromise solution.

4. Conclusions

This project proposed a multi-objective optimization model based on a combination of TRNSYS, MATLAB and MOBO. The proposed approach was applied to a school building case study, and the results demonstrate its practicability to provide decision support in an actual setting. In case an exhaustive-computation search method is implemented, then 20,736 simulation runs are needed to obtain all possible candidate solutions. The execution time of one simulation run is about 5.19 min. This means that 75 days would be required to get the result of an exhaustive search for this problem, which means the computation and analysis is only practical using an approach as the one herein proposed.

The single-objective optimization runs offered an overview of the impact of more “extreme” sets of retrofit actions, i.e. the ones individually optimizing each objective function, on the building’s overall performance after retrofit. Then, the proposed multi-objective approach produced a wide range of non-dominated solutions embodying distinct trade-offs between the competing objectives. The model assessed the solution overall performance, while at the same time quantifying the impact of individual components. Furthermore, 2D graphical representation of non-dominated frontier unveils the trade-offs between the objectives.

Moreover, using the graphs, one can ascertain the impact on thermal comfort and global costs of any reduction or increase in the energy consumption. The final decision can therefore be based on a thorough understanding of the trade-offs, and the impact of primary energy consumption on thermal comfort and global costs. The search space, and therefore the set of non-dominated solutions, depends on the alternative retrofit actions considered and the constraints that may be imposed to their combination.

The proposed approach shows a great potential for the solution of multi-objective building retrofit problems, and can be used as an aid to decision-making in the context of a retrofit project. Knowing what can be feasibly achieved and what trade-offs are at stake, the DMs can progress towards the choice of the best compromise solutions by inserting additional bounds on the objective function values or look for solutions closer to their aspiration levels.

5. Acknowledgement

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