MULTI-OBJECTIVE OPTIMIZATION MODEL FOR BUILDING RETROFIT STRATEGIES

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ABSTRACT

In face of the multiple choices for retrofitting a building, the main issue is to identify those that prove to be the most effective in the long term. In this work, a simulation-based multi-objective optimization scheme (a combination of TRNSYS, GenOpt and a Tchebycheff optimization technique developed in MATLAB) is employed to minimize energy use in the building in a cost effective manner, while considering the occupant's requirements. In order to achieve the best compromise solutions a wide decision space is considered, including alternative materials for external wall insulation, roof insulation, different window types, and installation of solar collector in the existing building. An existing house needing retrofit is taken as a case study and the effectiveness of the approach is demonstrated for identifying a number of Pareto optimal solutions for building retrofit. The results verify the practicability of the approach and highlight potential problems that may arise.

INTRODUCTION

The building sector has an important role in energy consumption. In Europe it represents 40% of the final consumption (Parliament 2002) and in Portugal it represents 30%. Thus, the European Union has approved several energy policies, such as the Energy Performance of Building Directive (EPBD) 2002/91/EC and its recast.

The EPBD's main objective is to promote the cost-effective improvement of the overall energy performance of buildings. One of the best opportunities to do so would be during building retrofit (Asadi, da Silva et al. 2012). However, a thorough building's retrofit evaluation is quite difficult to undertake, because a building and its environment are complex systems, in which all sub-systems influence the overall efficiency performance and the interdependence between sub-systems plays a significant role (Kaklauskas, Zavadskas et al. 2005).

Moreover, as innovative technologies and energy efficiency measures for buildings are well known, the main issue is to identify those that will prove to be the more effective in the long term. In practice, seeking such a solution is mainly attempted via two main approaches (Diakaki, Grigoroudis et al. 2008).

In the first approach, an energy analysis of the building is carried out and several alternative scenarios predefined by a building expert are developed and evaluated mainly through simulation.

The second approach includes decision aid techniques, such as multi-criteria analysis (e.g. (Alanne 2004)), multi-objective optimization (e.g. (Asadi, da Silva et al. 2012)), energy rating systems (e.g. Zmeureanu et al, 1999), etc.), which are ususally combined with simulation to assist the reaching of a final decision among a set of alternative actions predefined by the building expert.

In both these approaches, the whole processes as well as the final decisions are significantly affected by the experience and the knowledge of the Decision Maker (DM). Although this experience and knowledge are important elements to the whole process, it is necessary to develop practical tools that will assist DMs taking into account sets of objectives and sets of alternatives as large as required for adequately modelling the actual decision situation. Such tools may be developed based upon multi-objective optimization techniques.

In the current study a multi-objective optimization approach is used and combined with TRNSYS (a building performance simulation program) and GenOpt (an optimization program). The combination of these tools is used for the optimization of retrofit cost and energy savings of a residential building, in the framework of a multi-objective model. Decision variables represent a wide selection of alternative materials for the external walls insulation, roof insulation, different window types, and installation of a solar collector to the existing building. A case study is used to demonstrate the functionality of the proposed approach in a real-world setting.

MULTI-OBJECTIVE MODEL AND METHODOLOGY

Optimization approach

In the current study, a simulation-based optimization scheme (Figure 1) has been developed to optimize multiple objective functions. This scheme is a combination of TRNSYS 16, GenOpt 3.0.3 and Optimizer under MATLAB environment. TRNSYS (TRNSYS16 2009) is a transient system simulation program with a modular program structure that was designed to solve complex energy systems problems. GenOpt is an optimization program for the minimisation of a cost function that is evaluated by an external simulation program (Wetter 2009).

In this scheme first a model of the building before retrofit is created in TRNSYS. Then, using this model and GenOpt results are obtained for the implementation of each retrofit action, regardless of other actions. However, GenOpt is not capable of handling multi-objective optimization. Therefore, in this work the capability of GenOpt for parametric runs is used only to launch automatic simulations of the building.

Finally, an optimizer developed in MATLAB (Mathworks 2010) was run to evaluate potential solutions.

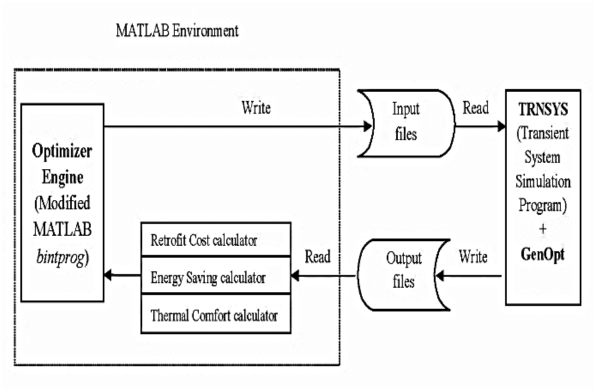

Figure 1. Optimization framework

Formulation of the optimization problem

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

Decision variables

The set of retrofit actions in this study concerns combinations of choices regarding windows, external wall insulation material, roof insulation material and installation of solar collector to the existing building. Therefore, four types of binary decision variables $x_i^{WIN}, x_j^{EWAL}, x_k^{ROF}, x_l^{SC}$ for different window types, external wall insulation material, roof insulation material and alternative solar collectors are defined, respectively.

Objective functions

Retrofit Cost (ReCost)

The overall investment cost for the building retrofit ReCost(X) (X denotes a solution consisting in a vector of all decision variables stated above) is calculated by adding retrofit action costs as follows:

$$ReCost(X) = A_{EWAL} \sum_{i=1}^{I} C_i^{EWAL} x_i^{EWAL} + A_{ROF} \sum_{j=1}^{J} C_j^{ROF} x_j^{ROF} + A_{WIN} \sum_{k=1}^{K} C_k^{WIN} x_k^{WIN} + \sum_{l=1}^{L} C_l^{SC} x_l^{SC}$$

Where:

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

C_i^{EWAL} - cost in [€/m^2] for external wall insulation material type i;

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

C_j^{ROF} - cost in [€/m^2] for roof insulation material type j;

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

C_k^{WIN} – cost in [€/m^2] for window type k;

C_l^{SC} - cost for solar collector type l.

Energy Savings (ES)

The general procedure for estimating the energy savings, ES, from a retrofit project is based on the calculation of the difference between the pre-retrofit energy demand predicted from a model and the post-retrofit energy demand:

$$ES(X) = E_{pre} - E_{post}(X) \qquad (2)$$

where

E_{pre} - the energy demand derived from a pre-retrofit simulation of the building.

E_{post} - the building energy demand after implementing the retrofit actions, predicted by simulation.

The annual energy demand of the building, calculated by TRNSYS, consists in energy demand for space heating, cooling and domestic hot water (DHW) systems. Energy demand for lighting is not included because it is not expected to significantly change a result of the implementation of retrofit actions.

Multi-objective optimization approach

The decision variables, objective functions and constraints developed above, lead to the formulation of multi-objective programming problem (3):

$$Min\ Z_1(X) = ReCost(X)$$
$$Max\ Z_2(X) = ES(X)$$
s.t.
$$x_i^{EWAL} \in \{0,1\}\ \forall\ i \in \{1,2,\dots,I\}$$
$$x_j^{ROF} \in \{0,1\}\ \forall\ j \in \{1,2,\dots,J\}$$
$$x_k^{WIN} \in \{0,1\}\ \forall\ k \in \{1,2,\dots,K\}$$
$$x_l^{SC} \in \{0,1\}\ \forall\ l \in \{1,2,\dots,L\}$$
$$\sum_{i=1}^{I} x_i^{EWAL} = 1 \qquad (3)$$
$$\sum_{j=1}^{J} x_j^{ROF} = 1$$
$$\sum_{k=1}^{K} x_k^{WIN} = 1$$
$$\sum_{l=1}^{L} x_l^{SC} = 1$$

Problem (3) is a combinatorial multi-objective problem, in which the objectives of minimizing retrofit costs and maximizing energy savings are conflicting.

The model has been implemented in MATLAB and a Tchebycheff programming procedure has been developed to tackle the multi-objective optimization.

To apply Tchebycheff programming, the decision model is rearranged to aggregate the two objective functions. In this method weighting vectors p are used to define different weighted Tchebycheff metrics (Steuer 1986). Considering this, the decision problem is formulated as follows:

$$Min\ \{\alpha\}$$
$$s.t.$$
$$\alpha \geq (Z_1(x) - Z_1^*)\left(\frac{p_1}{Z_1^*}\right)$$
$$\alpha \geq \left(Z_2^* - Z_2(x)\right)\left(\frac{p_2}{Z_2^*}\right) \qquad (4)$$
$$\alpha \geq 0$$
$$x\ \hat{I}\ S$$

where:
S denotes all the vectors that satisfy all the feasible region of multi-objective problem (3);
Z_1^* denotes the cost of the solution that minimizes the first objective;
Z_2^* denotes the energy savings of the solution that minimizes the second objective.

In the above formulation, $(p_1, p_2) \in \bar{\Lambda}$ are constants representing the weight of each objective, where:

$$\bar{\Lambda} = \left\{(p_1, p_2) \in R^2 \mid p_i \geq 0, \sum_{i=1}^{2} p_i = 1\right\}$$

For strictly positive weight values this formulation yields solutions that are non-dominated (efficient, Pareto optimal): for each of these solutions there is no other feasible solution able to improve one of the objectives without worsening, at least, one of the other objectives. These weights can be changed to obtain different compromise solutions. In this work weights have been used to sample the entire decision space and provide the DM a sub-set of non-dominated solutions that is representative of different trade-offs at stake in different regions of the decision space, thus avoiding an exhaustive computation. For this purpose, weights have been changed with a given step, while respecting $p_i \in \bar{\Lambda}$. The aim is to offer the DM usable information for actual decision purposes; for instance, grasping that in a certain region of the decision space it is necessary to sacrifice cost a significant amount to gain just a small amount in the energy savings objective function.

AN ILLUSTRATIVE EXAMPLE

The building under study is a semi-detached house (one family) constructed in 1945, situated in central region of Portugal (Figure 1). The gross floor area of the house is 97 m^2 and its average height is 2.47 m. The glazing area represents 10% of the floor area.

The building has a concrete structure. The walls are built in concrete with no thermal insulation (U = 2.37 W/ m^2K). The house has standard single glazing (U = 3.4 W/m^2K) and window frames are in wood. Its main facade is toward south-east. The house is heated with electrical heaters, using a natural gas standard boiler for sanitary hot water production.

To reduce the execution time of simulation, a simplified model is used to represent the house as a single zone. The summary of results from the energy analysis of the building before retrofit is reported in Table 1.

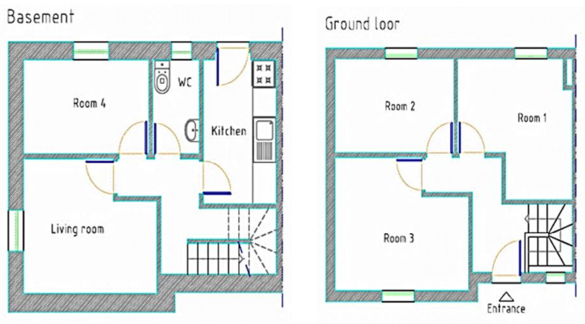

Figure2. Schematic plan of basement and ground floor of case study.

Table 1. Building performance before retrofit

Building performance indicators	
Total annual heating demand	216.35[kWh/m^{2}yr]
Total annual cooling demand	4.95[kWh/m^{2}yr]
Total annual DHW demand	52.33[kWh/m^{2}yr]
Total annual energy demand	273.63[kWh/m^{2}yr]

A list of alternative retrofit actions applied in this study is based on a CYPE rehabilitation price generator database (CYPEingenieros 2010). Typical retrofit actions including different external wall insulation materials, roof insulation materials, window types and solar collectors have been introduced in the list aiming at improving the building energy savings and thermal comfort in a cost effective manner. Tables 2-5 present lists of the retrofit actions.

After energy analysis of the building, the non-dominated solutions to the MOO problem that individually optimize each objective function are computed (solutions S1, and S2 in Table 6). The components of the ideal solution (the individual optima to each objective function), which is the initial reference point, are displayed in bold italic. That is, the reference point in the objective function space consists in the individual optimal value to each objective functions, which cannot be attained simultaneously since the functions are conflicting. Table 6 also indicates the solution configuration, that is the identification of the corresponding retrofit actions leading to each solution.

It is seen from this table that when retrofit cost (ReCost) is optimized, the external wall and roof insulation material, window and solar collector with minimum cost are selected, resulting, however, in minimum energy savings.

On the other hand, when the energy savings objective is optimized, the external wall and roof insulation material and window with the minimum thermal transmittance are selected. Furthermore, a solar collector with the highest area and energy efficiency is selected. However, the retrofit actions combination results in a significant increase of the retrofit cost.

As stated earlier, a Tchebycheff programming approach has been used to compute non-dominated solutions displaying different trade-offs between the objective functions. The non-dominated solution that minimizes the Tchebycheff distance to the ideal solution is then computed for different combinations of objective function weight coefficients, which makes possible to obtain a representative sample of the non-dominated frontier.

Figure 3 displays the non-dominated solutions for the biobjective model (3). Figure 4 shows how the objective values change in relation with the specific value of the weights (each point depicts the compromise obtained for a different combination of weight values). This figure clearly shows the competitive nature of objective functions energy savings and retrofit costs. As the weight on energy saving (*p2*) increases, the set of actions leading to higher energy savings and at the same time higher cost have been selected.

For intermediary values of the weight coefficients, several solutions are obtained that favour each objective function at a higher or lower level depending on the specific values that have been selected.

For this particular case, most of the potential savings can be achied with a relatively low cost. Savings increase steeply with costs until a “sweet spot” of spending 3800€ to achive savings of 1.21E04 kWh/year. After that, more spending leads to diminishing returns as far as energy savings concerned.

The results of the proposed approach demonstrate the practicability as well as the strength of applying it to provide decision support in the problem of building retrofit, namely for exploiting the trade-offs between the competing objectives in different regions of the non-dominated frontier. This approach allows for simultaneous consideration of all available combination of retrofit actions, as well as consideration of any logical, physical, and technical constraints. Furthermore, the multi-objective model provides the possibility of considering multiple objective functions without confining the user to single objective function.

Finally, the result of the application of a Tchebycheff programming technique to compute solutions to the case study shows the feasibility of this methodology to find well balanced strategies for retrofitting of buildings to be presented to a DM in the framework of a decision support system.

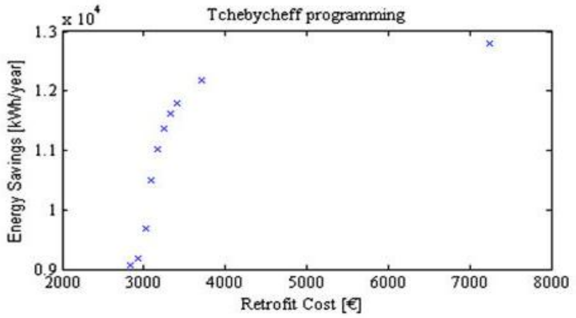

Figure 3. Multi-objective solutions for the building retrofit strategies (two objective functions)

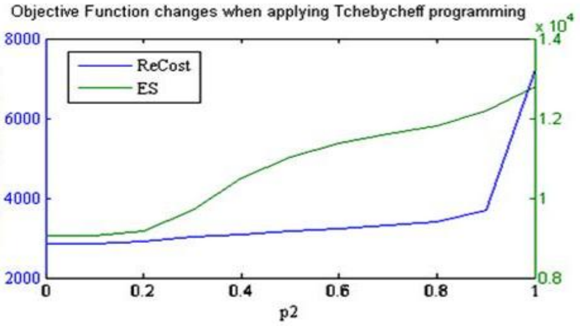

Figure 4. Objective functions changes with respect to weights in the Tchebycheff formulation.

CONCLUSION

One of the key steps in building retrofit is the selection of retrofit actions among a large number of possibilities. This problem, is in fact a multi-objective optimization problem, characterized by the existence of multiple and competing objectives, a set of feasible solutions that are not predefined but are implicitly defined by a set of parameters and constraints that should be taken into account to reach the best possible solution.

This paper described an optimization methodology based on a combination of TRNSYS, GenOpt and a multi-objective optimization algorithm developed in MATLAB. The proposed approach was applied to a real world case study, and the results demonstrate the practicability of the approach.

Considering all the possibilities that the DM has available for building retrofit (e.g. HVAC systems and renewable energy sources), as well as all the objective that he/she may wish to optimize (CO_2 emission, social objective, etc.) may lead to combinatorial explosion of the decision problem, thus making the solving procedure extremely difficult and time-consuming. In such case, other optimization techniques, namely evolutionary multi-objective algorithms may become necessary for tackling the problem. Besides, using approximation methodologies like regression modelling of the building in the optimization part would be of interest.

ACKNOWLEDGMENTS

The presented work is framed under the Energy for Sustainability Initiative of the University of Coimbra and was supported by the Foundation for Science and Technology (FCT) under grant SFRH / BD / 68937 / 2010, through the MIT-Portugal Program. C. H. Antunes and L. Dias also acknowledge the support of projects PEst-C/EEI/UI0308/2011 and MIT/SET/0018/2009 and M. Gameiro da Silva of project SB-Sustainable Buildings QREN 11508.

REFERENCES

Alanne, K. (2004). "Selection of renovation actions using multi-criteria "knapsack" model." Automation in Construction **13**(3): 377-391.

Asadi, E., M. G. da Silva, et al. (2012). "Multi-objective optimization for building retrofit strategies: A model and an application." Energy and Buildings **44**: 81-87.

Asadi, E., M. G. da Silva, et al. (2012). "A multi-objective optimization model for building retrofit strategies using TRNSYS simulations, GenOpt and MATLAB." Building and Environment **56**: 370-378.

CYPEingenieros (2010). Software for Architecture, Engineering & Construction.

Diakaki, C., E. Grigoroudis, et al. (2008). "Towards a multi-objective optimization approach for improving energy efficiency in buildings." Energy and Buildings **40**(9): 1747-1754.

Kaklauskas, A., E. Zavadskas, et al. (2005). "Multivariant design and multiple criteria analysis of building refurbishments." Energy and Buildings **37**(4): 361-372.

Mathworks, T. (2010). The Mathworks, MatLab Natick. MA.

Parliament, E. (2002). 2002/91/EC Directive. Official EU Journal. E. Parliament. Brussels, Belgium.

Steuer, R. E. (1986). Multiple criteria optimization: Theory, Computation, and Application, John Wiley & Sons.

TRNSYS16 (2009). TRNSYS, . A TRaNsient SYstems Simulation Program.

Wetter (2009). GenOpt: Generic Optimization Program, User Manual version 3.0.0, Lawrence Berkeley National Laboratory.

Table 2. Characteristics of alternative external wall insulation materials

N	Insulation types	Name	Thickness (m)	U (W/m^{2}K)	Cost (€/m^2)
1	Cork	OUTWALL_CORKHIGH3	0.03	1.408	5.55
2		OUTWALL_CORKHIGH4	0.04	1.124	7.18
3		OUTWALL_CORKHIGH5	0.05	0.935	8.98
4		OUTWALL_CORKHIGH6	0.06	0.800	10.77
5		OUTWALL_CORKHIGH7	0.07	0.699	12.23
6		OUTWALL_CORKHIGH8	0.08	0.621	14.36
7		OUTWALL_CORKHIGH9	0.09	0.559	16.78
8		OUTWALL_CORKHIGH10	0.1	0.508	17.95
9	EPS	OUTWALL_EPSLOW3	0.03	0.800	7.64
10		OUTWALL_EPSLOW4	0.04	0.621	8.34
11		OUTWALL_EPSLOW5	0.05	0.508	9.03
12		OUTWALL_EPSLOW6	0.06	0.429	9.74
13		OUTWALL_EPSLOW7	0.07	0.372	10.44
14		OUTWALL_EPSLOW8	0.08	0.328	11.15
15		OUTWALL_EPSLOW9	0.09	0.293	12.35
16		OUTWALL_EPSLOW10	0.1	0.265	13.68
17	XPS	OUTWALL_XPSLOW3	0.03	0.800	9.65
18		OUTWALL_XPSLOW4	0.04	0.621	11.64
19		OUTWALL_XPSLOW5	0.05	0.508	14.43
20		OUTWALL_XPSLOW6	0.06	0.429	17.22
21		OUTWALL_XPSLOW7	0.07	0.372	19.34
22		OUTWALL_XPSLOW8	0.08	0.328	22.78
23		OUTWALL_XPSLOW9	0.09	0.293	24.43
24		OUTWALL_XPSLOW10	0.1	0.265	26.78

Table 3. Characteristics of alternative roof insulation materials

N	Insulation types	Name	Thickness (m)	U (W/m^2K)	Cost (€/m^2)
1	XPS (extruded polystyrene stone wool)	ROOF_XPS3	0.03	0.800	9.65
2		ROOF_XPS4	0.04	0.621	11.64
3		ROOF_XPS5	0.05	0.508	14.43
4		ROOF_XPS6	0.06	0.429	17.22
5		ROOF_XPS7	0.07	0.372	19.34
6		ROOF_XPS8	0.08	0.328	22.78
7	EPS (expanded polystyrene)	ROOF_EPS3	0.03	0.800	4.32
8		ROOF_EPS4	0.04	0.621	5.60
9		ROOF_EPS5	0.05	0.508	6.87
10		ROOF_EPS6	0.06	0.429	8.14
11		ROOF_EPS7	0.07	0.372	9.43
12		ROOF_EPS8	0.08	0.328	10.70
13	Polyurethane	ROOF_PU3	0.03	0.658	8.34
14		ROOF_PU4	0.04	0.508	10.98
15		ROOF_PU5	0.05	0.413	13.40
16		ROOF_PU6	0.06	0.348	15.30
17		ROOF_PU7	0.07	0.301	17.86
18		ROOF_PU8	0.08	0.265	20.18

Table 4. Characteristics of alternative windows

N	Name	Thermal transmittance (W/m$^{2°}$C)	Effective solar energy transmittance (%)	Cost (€/m^2)
1	SGSILVER	1.05	28.80	58.70
2	SGPLANISOLGREEN	1.16	26.50	67.82
3	SGCLIMATOP	0.52	58.50	102.25

Table 5. Characteristics of alternative solar collector systems

N	Type	Name	Generation efficiency (%)	Collector area (m^2)	Cost(€/m^2)
1	Flat collector	FC702	70	2	700
2		FC802	80	2	800
3		FC704	70	4	1250
4		FC804	80	4	1600

Table 6. Non-dominated solutions that optimize each objective.

Solution	Type of solution	ReCost(€)	ES (kWh/year)	EWAL	ROF	WIN	SC
S1	[min] ReCost	***2843.15***	9065.06	1	7	1	1
S2	[max] ES	7245.52	***12792.15***	24	18	3	4