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# Assessment of energy efficiency measures using multi-objective optimization in Portuguese households

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ABSTRACT

This paper presents an optimization model to identity the best set of retrofitting measures applied to four different regions of Portugal; Lisbon, Porto, Bragança and Évora. The main objective is to maximize the annual energy savings, expressed in Euros, while minimizing the initial investment expressed also in Euros, considering the retrofit strategies as decisions variables and evaluating their effect in the usage of space heating and cooling and costs, depending on the chosen technology. A multi-objective genetic algorithm coded in MATLAB© to solve the optimization problem. Different energy efficiency measures are considered, such as the improvement of U-values in external walls and windows through the application of insulation materials, the change of lighting fixtures and refrigerator model to reduce the electricity consumption, and the usage of PV panels for self-consumption, and the use of Heat Pumps for space heating and cooling. The fitness function is subjected to different constraints related with the fulfillment of the demand, the physical limitation of household space, the capacity to comply with the heating and cooling needs, and the non-negativity nature of the variables. The best set of retrofitting options are presented, the budget to implement them and the amount of achieved energy savings.

## 1. Introduction and background

In Portugal, like in the rest of Europe, the consumption of final energy at the residential sector represents the third largest share, respectively 17% and 25%, just after transport and industry (European Commission - EuroStat, 2014).

However, in Portugal and unlike the rest of Europe, space heating is only the third largest share of energy consumption in residential sector with 22%, after the kitchen uses 39% – which include the electricity consumption of white appliances such as refrigerator, and the energy for cooking – and hot water 23% (Direcção-Geral de Energia e Geologia, 2010).

Residential building owners need tangible information to decide on the implementation of different retrofit measures in order to maximize the savings in energy, and at the same time, minimize the investment cost (Ma, Cooper, Daly, & Ledo, 2012). However, building owners in general lack the technical knowledge to do it.

There are a lot of examples of how multi-objective optimization strategies can be applied to help decision makers to identify the best set of retrofit measures for several types of buildings.

Kolokotsa, Diakaki, Grigoroudis, Stavrakakis, and Kalaitzakis (2009) analyzed various decision support methods for energy management in buildings; they highlighted the advantage of combining different methods to get a better approach. Specifically, they mentioned the usage of specialized software as simulation tool in combination with multi-objective programming optimization techniques to aim on the assessment of different energy efficiency measures.

Pornkrisadanuphan and Chaiwiwatworakul (2011) used the genetic algorithm (GA) to minimize the life cycle cost (LCC) – which includes initial investment and operation costs of different buildings in Thailand. The main objective was to find the most suitable material and equipment in each case, giving as a result that for schools, hotels and hospitals, the minimum life-cycle cost is reached by improving the envelope system, due to the high wall-to-floor ratio in those buildings; on the other hand, for large retail stores, improving lighting systems provides the lowest life-cycle cost.

Hamelin and Zmeureanu (2012) used Particle Swarm Optimization algorithm available in GenOpt software to minimize both the life cycle energy use (LCE) and life cycle cost (LCC) of a single-family house envelope located in Montreal, Canada. The results demonstrated that higher levels of insulation were desirable.

Also, Asadi et al. (2012) conducted an optimization for retrofitting

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cost and energy savings of a semi-detached house built in 1945, located in the central region of Portugal. The simulation was based in the multi-objective optimization using TRNSYS, GenOpt and MATLAB. The decision variables included a wide selection of alternative materials for the external walls insulation, roof insulation, different window types, and installation of solar thermal collectors. Asadi et al. (2014) also proposed a multi-objective optimization model with genetic algorithm (GA) and artificial neural network (ANN) using a school building located in Coimbra, Portugal as case study.

Üçtuğ and Yükseltan (2012) used linear programming for the efficient allocation of budget to maximize the energy savings of a hypothetical household in Turkey, by implementing improvements in appliances, lighting, windows and PV usage. However, the authors avoided the inclusion of new heating and cooling systems due to the installation and operation expenses. The results presented some guidelines for investment, depending on the budget available: for low budgets, installing double-glazed windows and purchasing compact fluorescent light bulbs were the proper choices; otherwise, the installation of PV panels emerged as feasible choice only when the budget increased.

Malatji, Zhang, and Xia (2013) applied a model for energy efficiency investment decision in 25 different buildings in South Africa. The model was formulated as a multi-objective genetic algorithm to maximize the energy savings and minimize the payback period for six different budgets of initial investment; the constraints were related with the Net Present Value, available budget for Initial Cost, energy target and payback period. The results showed that the budget available for the initial cost directly affects the energy saved and the payback period of the project.

As part of a doctoral dissertation, Shao (2015)\ implemented the methodologies of requirement analysis and multi criteria decision analysis for the assessment of energy efficiency solutions in office building retrofitting. Shao (2015) also presented a new decision support methodology to help designers make informed decisions on choosing the most appropriate design options for retrofitting office buildings with a compromise between stakeholders' diverse and often conflicting requirements in the annual design phase.

Yu, Li, Jia, Zhang, and Wang (2015) presented a model using multi-objective genetic algorithm to obtain a set of optimal solutions for building design optimization using the Pareto front. This method helped to improve the back-propagation (BP) network to characterize the behavior of the typical building design in China.

Wu, Xia, and Wang (2015) developed a multi-objective energy efficiency retrofit model to optimize the retrofit cost, energy saving and net present value (NPV) while reducing the energy consumption of buildings with small amount of investment. In addition to the retrofit strategies, the maintenance strategies are also considered. This model showed a good ability to find the optimal solutions using Pareto front which helped to improve the overall performance of the building.

Karmellos, Kiprakis, and Mavrotas (2015) used a multi-objective mixed-integer non-linear programming to optimize the primary energy consumption and the initial investment cost for two case studies, a new building and retrofitting an existing one in two different cities with different climate characteristics. This model is considered as a decision maker to assess the energy efficiency measures for different building which show an inverse proportion between the energy consumption and the initial investment cost.

Almeida and De Freitas (2016) proposed a methodology to optimize the insulation of school buildings. The two clashing objectives were to minimize both the annual heat load and the discomfort in the classrooms due to overheating. This methodology was applied to two typical Portuguese school buildings, using DesignBuilder© and EnergyPLUS© and the results were analyzed in three locations representing the different climatic conditions in Portugal with four possible orientations. The decision variables were the U-values of wall, roof and windows, the air change rate and the solar energy transmittance of windows. The optimization procedure is based on evolutionary algorithms, but it required a large number of computer simulations. Therefore, Artificial Neural Networks were employed as an approximation method. While interpreting the Pareto fronts, the authors realized that the selection of a single solution is very complicated and therefore had to introduce the Life Cycle Cost as a decision criterion, but outside the optimization method and only for one of the locations.

Ascione et al. (2016) developed a model coupling EnergyPLUS© and MATLAB using multi-objective genetic algorithm to improve and optimize the integration of renewable energy systems into a building, minimizing the primary energy demand and the investment cost for a typical new Italian residential building located in Mediterranean area. Thermal solar systems, photovoltaic panels and efficient heat pumps are the renewable energy sources (RES) systems investigated during the simulation.

The objective of this paper is to focus on the residential sector to improve the model of Üçtuğ and Yükseltan (2012) by including the usage of Heat Pump technology as a decision variable, and including the thermal needs into the evaluation of the main fitness function; therefore, it is possible to calculate the energy savings due to the upgrade of insulations and usage of heat pump at the same time. The study is applied to the standard Portuguese households in four different climate zones.

Two conflicting objectives are analyzed and a Multi-Objective with Genetic Algorithms method is used to solve it. The first objective is to maximize the Energy Savings (ES) due to the implementation of energy efficiency measures, and the second is to minimize the initial installation cost which will define the required budget to start the retrofit project. The constraints are related with the compliance of heat and cooling demand, limitation of physical space at the house, the capacity of the technologies to comply with the heating and cooling needs, and the non- negativity nature of the variables. As expected, the energy savings are co-related with the budget available, but not linearly, because of the impact in the thermal needs, heating and/or cooling, is not directly related to the cost of the energy efficiency measure. Further, the impact of the application of two or more measures that contribute for the same objective (e.g. heating) is not additive in many cases.

Six different energy efficiency measures are proposed to reduce the energy consumption compared with the current situation. To reduce heating and cooling needs, the improvement of U-values in external walls and windows and the installation of Heat Pump for the space heating and cooling are considered. To reduce the electricity bill in general, the change from compact fluorescent light (CFL) to light-emitting diode (LED) represents a decrease of 12% in lighting consumption and changing refrigerators with EU efficiency label 'C' by equivalent appliances of efficiency 'A + ' also represent a reduction in electricity consumption of 80%. Finally, the installation of PV panels on roofs is included to generate electricity for self-consumption and reducing therefore the electricity bill.

In this paper, we also take into account the well-known "rebound effect" of energy efficiency measures, which is not taken into account in most of the studies (Buluş and Topalli, 2011; Sorrell and Dimitropoulos, 2008; Volland, 2016). The rebound effect describes the range of mechanisms that reduce or offset the expected savings after a new technology improvement that is supposed to increase efficiency. It can be measured as the ratio of the lost benefit to the expected benefit. For example, if the improvements for thermal efficiency is 25% in the heating system it will lead to a 25% reduction in aggregate energy consumption. According to economic theory, this may not happen, because these energy savings can be offset by various mechanisms, like the user uses much more the heating system than before because it works better or is more efficient.

This paper is organized as follows: Section 2; gives a detailed description of the case study selection and its data, assumptions of the model and analysis of the cost and energy savings for each EEMs chosen in the proposed model, Section 3 describes the methods followed to