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Optimization of government subsidization strategies for building stock energy refurbishment

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ABSTRACT

The high initial investment required in existing building refurbishment can limit the initiative of the building owners and prevent the full exploitation of a huge energy saving potential. Public incentives can play an essential role in fostering the energy retrofitting of the existing buildings and in increasing the renovation rate of the building stock, effectively reducing the energy final uses, the dependence on the fossil fuels, and helping meet the national efficiency targets. Public subsidization are intended to enhance the economic performance in terms of global cost of the energy efficiency measures for the owner, in order to induce positive actions and move optimality from low to high energy efficient solution. In contrast, the overall economic efficiency is obtained with combinations of interventions, able to achieve a certain energy saving target for the entire building stock at the minimum initial Investment Costs (IC).

This paper tries to identify the overall economic efficiency in reducing the energy consumption of the existing stock and compares it with the efficiency of solutions optimal from the owner's perspective, in order to support more efficient subsidization strategies. Different mixes of three reference building archetypes, representative of the existing buildings, are considered to define different possible stocks, in order to analyse their impact on the efficiency of energy renovation solutions. Four groups of energy efficiency measures (EEMs) dealing with respectively the opaque envelope insulation, the windows substitution, the heat generating system replacement, and the mechanical ventilation introduction are defined and their combinations considered.

KEYWORDS

Government subsidies optimization
Stock Retrofit
Multi-objective optimization

INTRODUCTION

Buildings, including households and services, are responsible for more than 30 % of world Total Final Consumption (TFC) (IEA, 2017), and an even larger share of 41 % (Eurostat, 2016) in the European Union (EU). Conversely, a largest share of the existing buildings is considered to be energy inefficient. In EU, 75 % of the buildings have been built before 1990 (i.e. before any EU building regulation) and over 97 % are in class B or worse (BPIE, 2017), so not ready to meet the challenging 2050 decarbonisation target, i.e. a reduction of greenhouse gas by 90 % with respect to 1990 (EU Commission, 2011). This can be obtained only through energy efficiency measures, aimed at a direct reduction in the use of fossil fuels, and at a deeper penetration of renewable energy sources. For these reasons, EU aims at increasing the current rate of renovation, close to 1% (BPIE, 2011), through new policies and

market tools. Government financial incentives play a crucial role to promote the energy retrofitting of existing buildings since they should remove the barriers due to the high up-front initial Investment Costs IC (Amstalden et al. 2007; Gamtessa 2013; Higgins et al. 2014). Incentives able to change the consumer's behaviour and investment convenience, such as financial (penalizing or rewarding) or non financial (as for instance on-site advice by experts) are required, together with stricter performance targets for new and renovated buildings. In Europe, a wide variety of financial incentives is applied to support the enhancement of buildings energy performance such as grants, subsidies, preferential loans, tax reduction and tax credit (BPIE, 2012). Besides their effectiveness in driving the decision maker toward the best solution, which can be affected by different factors that make it uncertain, their efficiency should be accounted for, in order to maximize their impact and limit their societal cost. For instance, Di Pilla et al (2016) analysed the incentives in the Italian context, investigating the optimal regional distribution of subsidies through linear programming.

In this work, the economic efficiency of possible incentives policies is analysed through a multi-objective optimization approach. For a given percentage energy saving target, the public authority perspective, aiming at minimizing the overall initial IC is compared with the owner's one, which aims at minimizing the global cost of each single building over its lifespan. Several stock compositions are defined as a mix of three archetypical residential building modules. Four groups of energy efficiency measures (EEMs) dealing with respectively the opaque envelope insulation, the windows substitution, the heat generating system replacement, and the mechanical ventilation introduction are defined and their combinations considered. No cooling system is considered, since the existing stock is assumed not to be conditioned, as is usually the case in Italy (STRATEGO, 2016), and the EEMs with an appropriate operation strategy of natural ventilation and shading systems have been recognized to be effective in limiting overheating occurrences below the initial conditions. The initial IC in the two optimization approaches is then compared as representative of the social cost for achieving the same savings target, and of the possible financial incentive required, which is generally defined as a percentage of the IC.

METHODS
Building Archetypes
The analysis focuses on the economic efficiency of the renovation of a residential building stock as a function of its characteristics. For this reason, different building stocks have been defined starting from three archetypical buildings described in Penna et al (2015). These represent a semi-detached house with a compactness ratio of 0.97, a penthouse with a compactness ratio of 0.63 and an intermediate flat in an apartment building, with a compactness ratio of 0.30. Concerning the building envelope and heating system components they represent a typical configuration of Italian households built prior to the first energy legislation. Hence, a non-insulated envelope, with single pane glazing system and a hydronic system with a standard gas boiler coupled with radiators and on-off control system define the initial configuration for all the archetypes. Before renovation, the semi-detached house has an energy demand for heating of 269.17 kWh m^{-2} yr^{-1}, the penthouse needs about 190.30 kWh m^{-2} yr^{-1} and the intermediate flat about 113.81 kWh m^{-2} yr^{-1}.

Three different energy saving targets are considered for the stock, that are the reduction of 50%, 60% and 70% compared to the original primary energy demand.

Six off the shelf energy efficiency measures (EEMs) categories are considered:

- external insulation of the external opaque envelope with an expanded polystyrene layer. The insulation thickness is optimized independently for vertical walls, roof and floor in the range 0 to 20 cm and in steps of 1 cm;

- windows replacement with double or triple pane with either high or low solar heat gain coefficient;
- boiler replacement with either a modulating or condensing boiler with an outside temperature reset control;
- mechanical ventilation system installation with a heat recovery system.

The IC is derived from regional price list (Penna et al. 2015) for all the EEMs, and contributes to the global cost expressed by the Net Present Value (NPV), together with the annual energy cost, the maintenance cost, the replacement cost and the residual value for the pieces of equipment with longer lifespan. The simulations of the energy performance of the building stock are carried out in Trnsys considering the weather conditions of Milan (Latitude 45°27'51'' N, Longitude 9°11'22'' E), a city with a 4A climate according to Ashrae 90.1 classification (Ashrae, 2007). Sixty-six building stock configurations were considered by varying the share of each archetype in the range from 0 to 100% in steps of 10 %.

Optimization Algorithm

A large number of optimization algorithms have been developed for solving multi-objective optimization problems however, according to Wetter and Wright (2004) the gradient-based optimization and the linear programming methods are not suitable to Building Performance Optimization (BPO). Evolutionary algorithms are the most popular optimization methods, and non-dominated sorting genetic algorithm (NSGA-II) is one of the most implemented in BPO (Nguyen et al., 2014). The NSGA-II, firstly developed by Deb et al, (2002), uses elitism by maintaining the current and the previous population. Then, after the population mating, the populations are sorted according to the non-domination concept and the best ranking solutions are selected as the next parent population.

In this research, we implemented the NSGA-II with some customizations such as sampling, external data-set and convergence criterion. Firstly, the code included a Sobol sequence sampling to overcome the clustering that can occur with other sampling techniques. Besides, an external data-set of the simulation runs is saved in order to avoid repeating expensive simulation runs during the BPO. Finally, the hypervolume measure (Zitzler and Thiele, 1999) was used as a stopping criterion.

Optimization with the authority's or with the owner's perspective

In the Italian scenario, incentives are provided for energy refurbishment investment in the form of tax credit calculated as a percentage of the IC. This is independent of the energy saving actually achieved, provided the law minimum requisites are fulfilled, so that the economic efficiency of the intervention and most importantly of the action on the entire building stock is left to the owners' decision. However, the optimum of the building stock does not necessarily coincide with the individual optima of all the buildings. First, the building owner convenience is typically expressed by the global cost in the lifespan, while the social cost, in presence of incentives, is better represented by the IC. Second, when optimizing the interventions over the entire stock, the marginal return of an investment on a building can be very different from that on another, making it possible to prioritize the interventions on the different buildings according to criteria of overall efficiency.

For the above reasons, a first optimization considers the minimization of primary energy for heating (EP_H) and, simultaneously, the initial IC for the entire building stock. These two indices are calculated by summing the energy performance and the IC of all the buildings renovation in the stock, and then dividing them by the total floor area of the building stock, in order to normalize the indicators independently of the stock size.

Each owner aims at achieving a given energy saving target in such a way to maximize the economic benefit during the building lifespan. Either energy efficiency requisites or public

incentives recognized to interventions able to overcome a minimum law target, will therefore foster the individual optimization of the EEMs for each building. This perspective does not necessarily lead to the most effective solutions from the point of view of the public authority. A second optimization run has then been conducted, with the optimal refurbishment of each building is evaluated by optimizing the energy and cost savings following the cost-optimal approach. The first objective is the reduction of the primary energy for heating (EP_H) in order to reach the requested target. Moreover, the minimization of the global cost of the building, the total cost of the building over a 30-year lifespan, quantified through the NPV, is pursued. The energy savings and the total IC for the building stock is subsequently quantified as the sum of the values obtained for the optimal solutions of each individual building, and compared with those of the first optimization in order to understand the extent to which the individual point of view produces suboptimal results for the community.

RESULTS AND DISCUSSION
Figure 1 (left) show on three-coordinate diagrams the absolute difference between the IC needed for the optimal solution of the two optimizations, ΔIC, considering three specified targets for energy saving (e.g., 50%, 60% and 70%). Each side of the triangular plots reports the percentage of buildings with the same compactness ratio, S/V (e.g. 0.30, 0.63, 0.97), so the position of each point represents a different percentage composition of the building stock. The colour of the points follows from blue (no difference) to red (highest difference) highlights the difference in the IC (ΔIC) between the owner's and authority point of views. It should be noticed that the larger the difference, the more the retrofit measures in the optimal solution and the performance itself of each single type of buildings will differ in the two perspectives. For instance, for the target 50% the high values of ΔIC (up to 1322 EUR/ 100 m^2) imply that it is possible to reach the target energy saving applying retrofit actions very different from the ones that optimize the NPV for the single building. Thus the target is reached by saving more energy in some types of buildings and less in others. Comparing the results of the three targets it is evident that the suggested approach is more convenient for the target of 50% and 70%, than for 60%. In the first case, it is possible to obtain a saving of more than 670 EUR/100 m^2 in 75 % of the reference stocks, and more than 922 EUR in 50 %. The largest benefits are when the building stock tends to have a smaller share of buildings with S/V=0.3 and medium to high with S/V=0.63. In the last case, the NPV optimization or the IC optimization give similar results and savings are higher than 100 EUR/100 m^2 in 75 % of the reference stocks, and more than 159 EUR/100 m^2 in 50 %, with maximum savings lower than 400 EUR. The best performance of the whole stock optimization (authority point of view) is for 10 % of S/V=0.3 buildings, 20 % of 0.63 and 70 % of 0.97. The best performance when target is 70 %, is for 10 % of S/V=0.3 buildings, 30 % of 0.63 and 60 % of 0.97.
As regards percentage savings, (Figure 1, right), it can be seen that the impact of a whole stock optimization is quite high when the smallest target is considered. Savings are up to 22 %, with 75 % of the building stocks saving more than 14.8 %, and 50 % more than 18.7 %. Very low in percentage terms is the advantage for 60 and 70 % EP_H saving targets, reaching at most 4 %. With 50 % savings target it is also clear a trend, showing the maximum percentage saving at a similar value for many stock configurations up to a maximum share of S/V=0.3 buildings of 40 %. Larger shares of compact buildings (S/V=03) reduces the maximum advantage of the authority perspective approach. Trends get less clear when larger saving targets are considered.

CONCLUSIONS
In this work the overall economic efficiency, in terms of IC, in reducing the energy consumption of the existing stock (authority point of view) has been assessed and
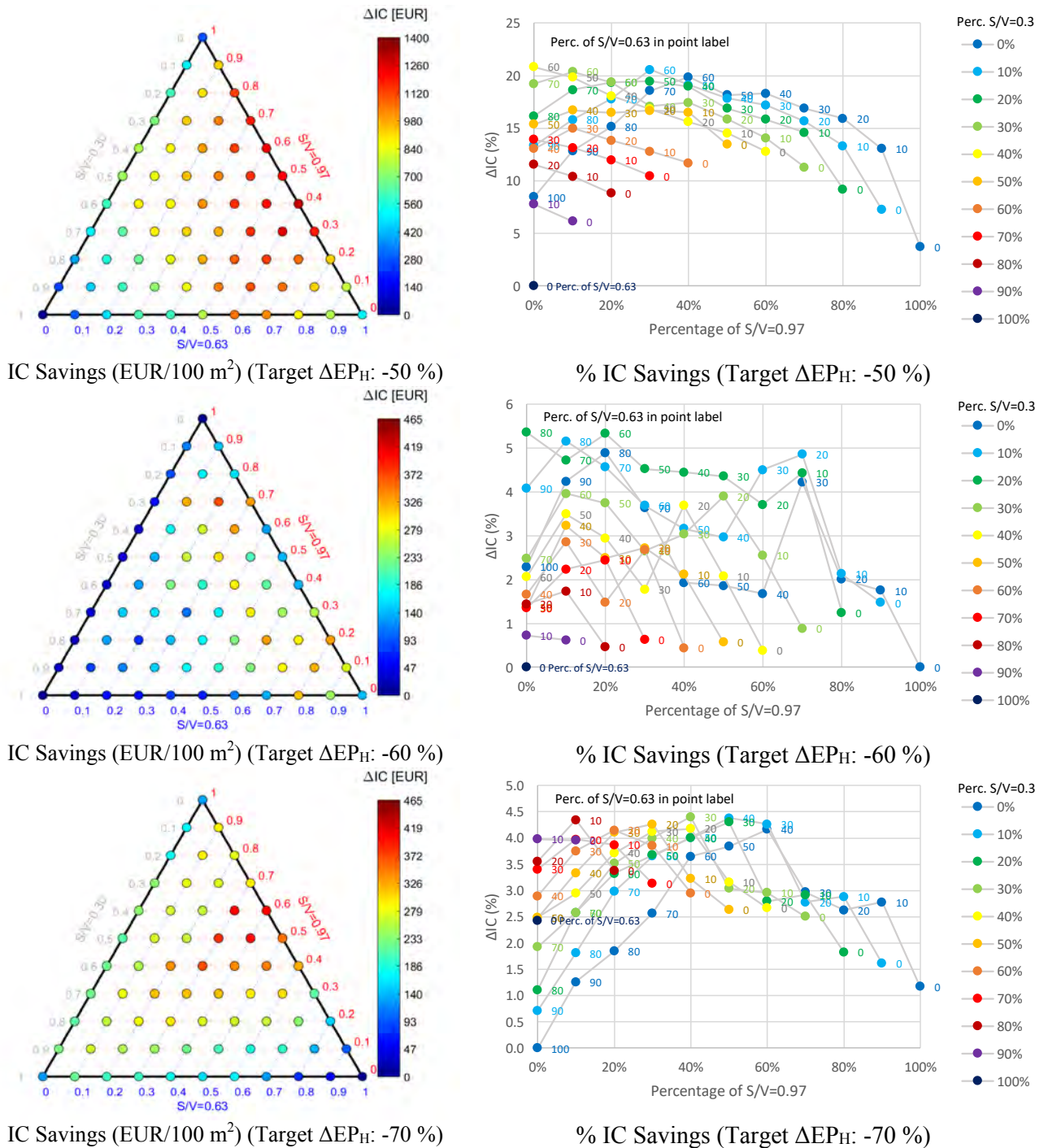
IC Savings (EUR/100 m^2) (Target ΔEP$_H$: -50 %)

% IC Savings (Target ΔEP$_H$: -50 %)

IC Savings (EUR/100 m^2) (Target ΔEP$_H$: -60 %)

% IC Savings (Target ΔEP$_H$: -60 %)

IC Savings (EUR/100 m^2) (Target ΔEP$_H$: -70 %)

% IC Savings (Target ΔEP$_H$: -70 %)

Figure 1: Absolute and percentage IC savings of the authority vs owner optimization perspective with the three EP$_H$ savings (50, 60, and 70 %).

compared with that of solutions optimal from the owner's perspective. Different mixes of three reference building archetypes have been considered to define different possible stocks, in order to analyse their impact on the efficiency of energy renovation solutions. Four groups of energy efficiency measures (EEMs) have been defined and their combinations considered. Three target energy savings have been considered, namely 50, 60 and 70 % with respect to the initial building stock performance.

The main findings show that in some cases the optimal solutions at a stock level do not coincide with those at an individual level. Depending on the target, the stock optimization (authority point of view) is always preferable to individual optimization (owner's point of view). Very large savings on the IC are obtained when optimizing the intervention on the entire stock for the lower target performance (50 %).

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