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UNCERTAINTY BASED OPTIMAL PLANNING OF RESIDENTIAL BUILDING STOCKS RETROFITS

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ABSTRACT

In this work the uncertainties related to the optimal planning/allocation of government subsidies for residential building stocks retrofits are considered and the uncertainty based planning problem is formulated and solved as a multi-objective, constrained problem. Different multi-objective algorithms are considered with the idea to determine the most effective and efficient approach that can be customized as planning tool to be used by the public administration personnel. The preliminary comparison between 2 multi-objective evolutionary algorithms and a deterministic one is presented and optimal/pareto results are analysed.

Keywords: Uncertainty based Optimal Planning, Subsidies Planning, Residential Building Retrofit, Multi-Objective Optimization.

1 INTRODUCTION

A series of emergencies related to the current model of global development, (frequent energy crisis, climate change, heat island, etc.) have led central governments of the industrialized countries to take actions to optimize the use of natural resources. From the second industrial revolution, in the second half of 18th Century, it started the gradual abandonment of agricultural land on favor of the cities.

This change of lifestyle was allowed by the possibility of concentrating the energy needed in small spaces. However concentrate and then consume these sources strongly pollute the areas where they are used. Second the natural resources are not infinite, so a reduction in their utilization is necessary to preserve them for the future generation.

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Second the natural resources are not infinite, so a reduction in their utilization is necessary to preserve them for the future generation. Based on this, the national planning activities in terms of energy exploitation include a more efficient use of them, and the utilization of renewable energy sources. Particularly for buildings, sustainable development, energy-retrofitting the existing buildings stock, changing the users' behaviors sustainable approach, have to be cleverly planned. In Italy, the Energy Performance of Buildings Directive (Directive 2002/91/EC, EPBD) was also adopted by the government subsidy for the renovation of private dwellings. For ten years there has been a political scheme introduced to incentive energy efficiency works: the so-called "Piano Casa" and a 55% tax reduction scheme. But none of them has carefully been planned. Both are completely governed by householders' and private investors' decisions, and to have energy saving measures closer to the target, any consideration to: the building features (age, dimensions, construction technologies, HVAC systems and use); the local climatic conditions; the market costs of energy saving measures are taken into account. Instead the second main policy, which consists in 55% tax-reducing, is managed by ENEA (National Agency for New Technologies, Energy and Sustainable Economic Development), that every year, since 2007, has produced the database with the analysis of the requested public subsidies for the energy efficiency work on dwellings; named: “Energy and Environmental ENEA Report” http://www.acs.enea.it/rapporti/ . They are given for the entire country but also divided into five different geographical macro-areas: North-West, North-East, Central, South, Islands. The data examined are: the number of works, the annual average values of energy saving [MWh], the average costs for works [e] by macro-geographical area, carried out according to this categorization of intervention: partial or complete renovation of HVAC system, horizontal structures (roofs included) insulation, external wall insulation, external windows or doors replacement, thermal or PV solar panels installation.

In Desogus et al [1] and Di Pilla et al [2,3] the application of the simplex method to obtain a deterministic solution that minimizes the resources invested by the Italian government and maximizes the energy savings achieved, starting from the above cited values published by ENEA, is proposed. However data from ENEA are affected by uncertainty and consequently a deterministic solution is not trustworthy, furthermore to maker harder the problem, the distribution is not known a priori due to the nature of the variables.

In this paper, a suitable approach for the uncertainty based optimal planning of energy efficiency retrofits is shown. The values of the standard deviation and probability distribution of the variables are assumed starting from practical considerations related to the certifications of performance of industrial type (i.e.: external windows or doors replacement) and to practices of building site (i.e.: external wall insulation). In particular, in this first presented case, we impose two values of uncertainty: _20% and _2%. The first value is used for the all types of insulation works, because these are performed mainly in construction site and the uncertainty is considerably higher (one order of magnitude) than the other works. In all cases, the type of the probability distribution is considered uniform to maximize the uncertainty.

2 GENERAL PROBLEM

In a previous work [1] the problem was formulated in a deterministic way, with the objective to find the numbers of interventions for each single category that could maximize the energy efficiency, subject to a constraint on the available budget:

$$\begin{array}{ll} \max & {E_S}^T x \\ subject\ to & {C_S}^T x \le C_{max} \end{array} \quad (1)$$

where $\boldsymbol{x}$ is the n_d-dimensional vector of interventions, $\boldsymbol{E_s}$ is the n_d-dimensional vector containing the energy saving for each intervention type, $\boldsymbol{C_s}$ is the n_d-dimensional vector containing the cost for each intervention type, and $\boldsymbol{C_{max}}$ is available budget.

2.1 UNCERTAINTY BASED OPTIMIZATION

As it is formulated, the planning problem is very similar to a financial portfolio optimization problem, and as this latter, it is also heavily affected by uncertainties. The uncertainties on the costs and energy saving values for each intervention are both aleatory and epistemic, and are related to a) how the data have been collected and processed, b) the kind of operations, etc.

As for the finance optimization problems, also in this case, the obtained solution should be robust and resilient against the considered uncertainties. This means that the problem to be solved is a bi-objective one, aimed at maximizing the mean value of the saved energy and minimizing its standard deviation. If a general multi-objective optimization can be formulated as

$$\begin{array}{ll} \min & f(x) = [f_1(x), f_2(x), \dots, f_k(x)]^T \\ \text{subject to} & g_i(x) \le 0 \ i = 1,2, \dots, m \end{array} \quad (2)$$

this test case problem can be formulated as:

$$\begin{array}{ll} \min & \left[-{E_S}^T x, \left({\sigma_{E_S}}^T x^2\right)^{1/2}\right] \\ subject\ to & {C_S}^T x \le C_{max} \end{array} \quad (3)$$

3 TEST CASE

Data on costs and energy saving are available for five macro-areas in Italy (North-West, NW, North-East, NE, Center, CE, South, SO, Islands, IS), and relative to five kind of operations: installation of Opaque Horizontal (OH) surfaces, installation of Opaque Vertical (OV) surfaces, Windows Replacement (WR), Solar Panel (SP) installation, and Heating Plant (HP) replacement.

3.1 Objective and constraints

The objective of the considered test case is to maximize the expected value of the total energy that can be saved in Italy, while keeping its standard deviation as low as possible, subject to a constraint on the total budget, C_{max} = 840241834 [€]

3.2 Optimisation methods

As it is formulated in the Eq. 3, the problem is a classic bi-objective problem, which, in theory should be easily and quite efficiently solved by using one of the many available Multi-Objective Evolutionary Algorithms (MOEAs), such as the well-known Non-dominated Sorting Genetic Algorithm - 2 (NSGA2)[4] or the Multi-Objective Parzen Based Estimation of Distribution (MOPED) [5]. Preliminary results, shown later on in this paper actually demonstrate that for this kind of problem the e-constrained approach is both more effective and efficient. Together with the weighted-sum, the ε-constrained (*ε-con*) approach is another well-known technique to solve multi-objective problems via a priori articulation of preference. In this case there is no aggregation of criteria, instead only one of the original objectives is minimized, while the others are transformed into (additional) constraints.

The general multi-objective optimization problem as presented in Eq. 2 becomes:

$$\begin{array}{ll} \text{minimize} & f_q(x) \\ \text{subject to} & f_i(x) \leq \varepsilon_i \; i = 1,2,\ldots,k \quad i \neq q \\ & g_i(x) \leq 0 \; i = 1,2,\ldots,m \end{array} \qquad (4)$$

where $\varepsilon \in \mathbb{R}^{k-1}$.

For this particular test case, the problem

$$\begin{array}{ll} \min & \left[-\boldsymbol{E_S}^T \boldsymbol{x}\right] \\ \textit{subject to} & \boldsymbol{C_S}^T \boldsymbol{x} \leq \boldsymbol{C}_{max} \\ & \left(\boldsymbol{\sigma}_{\boldsymbol{E_S}}{}^T \boldsymbol{x}^2\right)^{1/2} \leq \sigma_{Budget,max} \end{array} \qquad (5)$$

is solved iteratively to approximate the Pareto front: $\sigma_{Budget,max}$ is initially set to the value of $\left(\boldsymbol{\sigma}_{\boldsymbol{E_S}}{}^T \boldsymbol{x}^2\right)^{1/2}$ obtained for the deterministic solution and then the problem in eq. (5) is solved for a value of $\sigma_{Budget,max}$ progressively decreasing. Used data are listed in Tables I and II.

Table I - Costs and energy savings for each intervention (Italy 2007)

Intervention	C_s [€]	Es [MWh]
OH-NW	35721.69	855.45
OV-NW	21573.11	399.85
VR-NW	10517.35	113.07
SP-NW	9968.49	128.95
HP-NW	12848.64	359.19
OH-NE	28466.74	812.61
OV-NE	20577.44	465.67
VR-NE	10377.48	113.5
SP-NE	7101.84	103.25
HP-NE	10218.78	224.34
OH-CE	23881.13	544.29
OV-CE	15002.42	255.28
VR-CE	9422.62	83.29
SP-CE	6171.21	103.98
HP-CE	8083.54	173.4
OH-SO	18304.63	260.92
OV-SO	13578.09	193.35
VR-SO	11086.18	71.66
SP-SO	6492.09	174.54
HP-SO	5134.22	100.64
OH-IS	10435.85	200
OV-IS	13985.85	112.26
VR-IS	10339.83	60
SP-IS	4187.2	113.38
HP-IS	5508.54	75

Table II - Lower ($\boldsymbol{B_L}$) and upper ($\boldsymbol{B_U}$) bounds for the number of interventions (Italy 2007)

Intervention	$\boldsymbol{B_L}$	$\boldsymbol{B_U}$
OH-NW	0	7444761
OV-NW	0	7444761
VR-NW	0	7444761
SP-NW	0	7444761
HP-NW	0	7444761
OH-NE	0	5075838
OV-NE	0	5075838
VR-NE	0	5075838
SP-NE	0	5075838
HP-NE	0	5075838
OH-CE	0	5137694
OV-CE	0	5137694
VR-CE	0	5137694
SP-CE	0	5137694
HP-CE	0	5137694
OH-SO	0	6260594
OV-SO	0	6260594
VR-SO	0	6260594
SP-SO	0	6260594
HP-SO	0	6260594
OH-IS	0	3349993
OV-IS	0	3349993
VR-IS	0	3349993
SP-IS	0	3349993
HP-IS	0	3349993

4 RESULTS

The problem in Eq. (3) has been solved for two different uncertainty vectors and results in terms of Pareto front solutions are shown in Figg. (1) and (2). The NSGA2 algorithm has been setup with: population size, n_{pop} = 100, maximum number of generations, $n_{gne;max}$ = 2000, crossover parameter, $p_{cross;real}$ = 0:9, crossover parameter, $p_{mut;real}$ = $1/n_d$, η_c = 10, η_m = 10.

The MOPED algorithm has been setup with: population size, n_{pop} = 100, maximum number of generations, is solved iteratively to approximate the Pareto front: $n_{gne;max}$ = 600.

Fig. (1) is relative to the case (Case U1) where the uncertainties on the elements of $\boldsymbol{E}_s$ were set as uniform distributions, with lower and upper bound as follows:

- lower - 80% of the nominal value for elements relative to OH and OV operations, and 98% of the nominal value for elements relative to VR, SP, and HP operations;
- upper - 120% of the nominal value for elements relative to OH and OV operations, and 102% of the nominal value for elements relative to VR, SP, and HP operations.

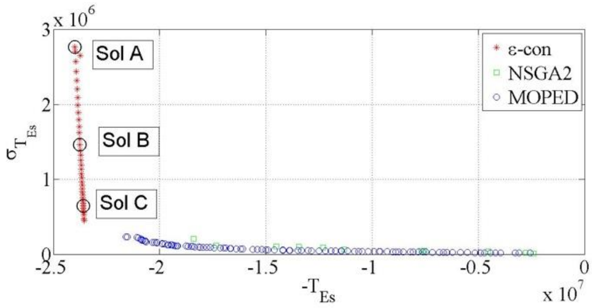

Figure 1: Pareto front approximations given by the three used optimization approaches for the Case U1 ($T_{Es} = |\boldsymbol{E}_S^T \boldsymbol{x}|$)

On the other hand, Fig. (2) is relative to the case (Case U2) where the uncertainties on the elements of $\boldsymbol{E}_s$ were set as uniform distributions, with lower and upper bound as follows:

- lower - 80% of the nominal value for all the elements;
- upper - 120% of the nominal value for all the elements.

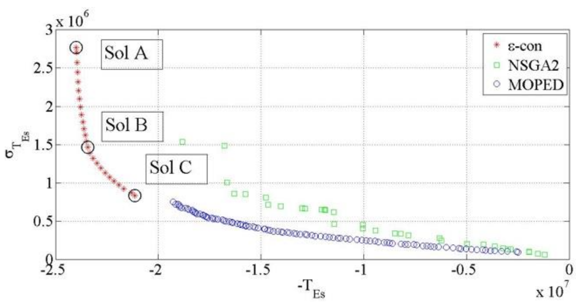

Figure 2: Pareto front approximations given by the three used optimization approaches for the Case U2

Both figures show only feasible solutions. It can be noted that in both cases NSGA2 after 200e^3 function evaluations can find only few (< n_{pop}) feasible solutions. Both EAs can only find an approximation of the lower-right part of the front, which is the less appealing one, due to the fact that very low deviations of the total saved energy are associated to very low values of its expected value. This aspect will be investigated better and new evidence will be integrated in the full paper.

The interesting part of the Pareto front is approximated very well by the *ε-con* iterative algorithm, by using less than 10e^3 function evaluations for Case U1 and near 34e^3 evaluations for Case U2. Solution A in both figures corresponds to the solution of the deterministic problem. It can be seen in Fig. (3) that, when uncertainties U1 are considered, it is possible to find robust solutions that have considerably small standard deviations with negligible losses in terms of the expected value of the energy saving (Solutions B and C).

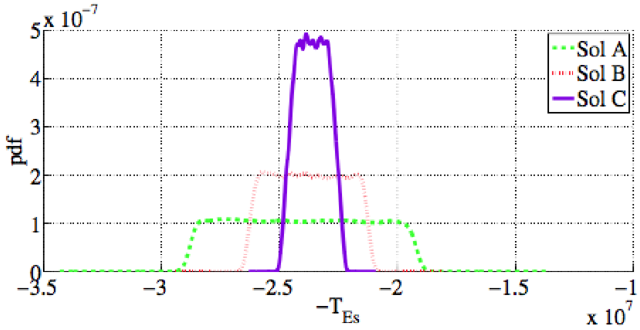

Figure 3: PDF of -T_{Es} for 3 solutions belonging to the Pareto approximation given by the iterative ε-con approach for Case U1

On the other hand, when uncertainties U2 are considered (Fig. 4), the Pareto solutions are such that greater robustness is associated to less negligible losses in terms of expected value. When uncertainties are the same (in percentage) for all the variables/interventions, a reduction of the standard deviation is achieved by progressively using more operations (see Table III).

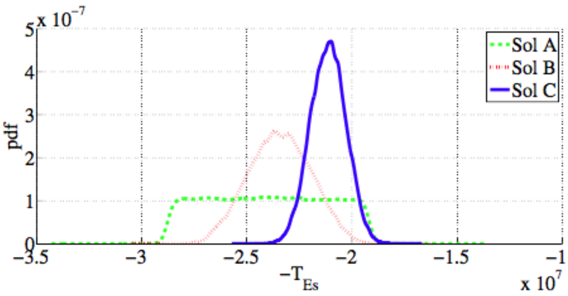

Figure 4: PDF of of -T_{Es} for 3 solutions belonging to the Pareto approximation given by the iterative *ε-con* approach for Case U2

5 CONCLUSION AND FUTURE WORK

In this work the optimal planning/allocation of government subsidies for residential building stocks retrofits are considered and implemented as optimisation under uncertainty problem, which is then solved by means of different approaches. The results clearly show that today numerical techniques can solve the problem, even if with different degrees of efficiency, and the real limitation for the practical implementation of the methods comes from the availability of data, including the characterisation of the involved uncertainties.

Future work, in part already started, includes: a) the application of the uncertainty based optimization approach to different scenarios to highlight pros and contras when different constraints on the budget, as well as the energy savings, are considered; b) the re-formulation of the planning problem as a reliability based optimization problem, where the constraints have to be satisfied with a probability Pc > 0.5; and c) full statistical analysis of the performance of the used optimization methods when applied to the uncertainty based optimization planning of interventions, with the idea to further clarify which could be the best tool to customize for public administration personnel.

The use of additional and more complete data will be considered as well.

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Table III - Sampled optimal solutions

Interv.	Sol A	Sol B1	Sol C1	Sol B2	Sol C2
OH-NW	0	0	0	0	2453
OV-NW	0	0	0	0	0
VR-NW	0	0	0	0	0
SP-NW	0	0	0	0	0
HP-NW	0	30984	51036	19782	8786
OH-NE	29517	15532	6481	11279	4053
OV-NE	0	0	0	0	3573
VR-NE	0	0	0	0	0
SP-NE	0	0	0	0	0
HP-NE	0	0	0	0	6337
OH-CE	0	0	0	0	3165
OV-CE	0	0	0	0	0
VR-CE	0	0	0	0	0
SP-CE	0	0	0	0	0
HP-CE	0	0	0	0	7197
OH-SO	0	0	0	0	0
OV-SO	0	0	0	0	0
VR-SO	0	0	0	0	0
SP-SO	0	0	0	17780	16662
HP-SO	0	0	0	0	4245
OH-IS	0	0	0	0	1282
OV-IS	0	0	0	0	0
VR-IS	0	0	0	0	0
SP-IS	0	0	0	35718	26017
HP-IS	0	0	0	0	0