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Genetic Optimization for economic feasibility of refurbishment in buildings

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Abstract

This paper investigates the possibility to enhance the thermal characteristics of a building fabric taking into account the economic feasibility in order to avoid useless expensive interventions. The problem consists in realizing an internal insulation system for a single apartment located in Trieste.

A genetic optimization has been implemented in order to search a large number of solutions with multiple objects and constraints. EnergyPlus has been used for dynamic building and plant simulation and modeFRONTIER for optimization loop setup. The objectives are the used heating energy consumption and the life cycle refurbishment cost, using a net present value approach. An additional objective has been added in order to guarantee the maximization of the interior useful floor area, which is directly influenced by the internal insulation thickness. Different approaches have been compared, considering actions dealing with opaque surfaces only or considering the replacement of existing windows. The paper demonstrates that an automatic optimization approach can help designers to identify the best suited intervention for building refurbishment.

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Keywords: Energy performance; Optimization; Genetic algorithms; Energy simulation

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1. Introduction

Energy consumption in the residential sector has been constantly increasing at global level; from 1973 to 2012 the consumption has doubled. In Italy, the share of consumption for civil use has reached the value of 36 % higher than that of other important sectors, such as the transport 32 % and industrial 23 %. In order to tackle the problem European Union has put a great effort in developing standards and regulations to reduce the amount of energy required for building climatization. In this framework, European members are required to introduce strict energy requirements for new and refurbished buildings, encouraging the policies that can lead to an improvement of the thermal characteristics of existing buildings. In order to achieve the energy savings goals different problems should be addressed. The solution requires an accurate design, not only for new buildings, but also for planning the interventions in existing ones, with an accurate control of costs, avoiding expensive solutions causing a loss of interest by building owners.

Among the different possible strategies, the intervention on building fabric is, in our opinion, the first one to be addressed. It affects directly both the building consumption and allows the adoption of different heating plant systems, especially the ones working with low fluid temperature.

Some works, which consider the thermal and economic problems, are present in literature. A lot of works use a semi-stationary approach for computing the energy requirement, the degree-day method [1] and degree-hour [2] are examples, however dynamic approaches are widespread using different methods such as the Complex Finite Fourier Transform (CFFT) [3] or finite differences [4,5] and software for dynamic simulation [6]. In order to explore different solutions optimization methods, such as genetic algorithms [6] and neural nets [7], have been explored by authors.

The main objective of the studies is to reduce the overall cost taking into account the initial investment and the annual cost. Some Authors [8, 9] coupled the analysis with an environmental analysis minimizing emissions due to fuel combustion and low insulation environmental impact.

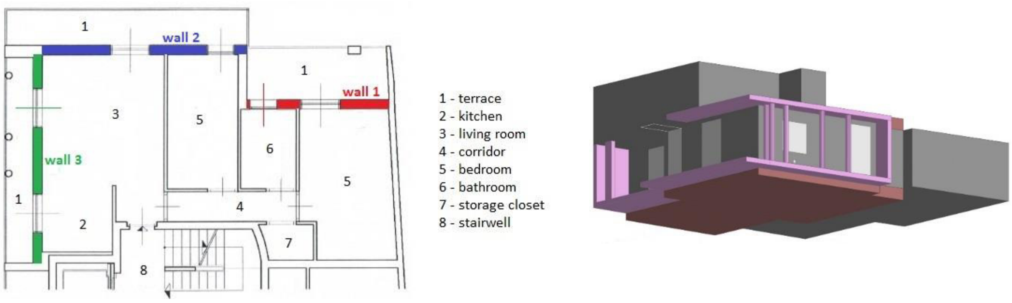
The optimal insulation thickness is the main object of this approach, while additional researches [2, 6, 8] investigated the impact of transparent surfaces and the impact of single and double glazing layers.

In [2] three different refurbishing activities for a residential flat have been compared by evaluating the effect at an economical and environmental level of internal insulation and window substitution.

In this paper, the problem of the refurbishment of a single residential flat is carried on by using different software. DesignBuilder has been used for problem definition and initial optimization, Energy Plus for energy computation and modeFrontier for driving the optimization loop and performing the genetic optimization. Different objectives have been used, considering energy and environmental issues, economical feasibility and evaluating different strategies of intervention.

2. Problem description

The object of this work is an apartment positioned at the top of a multistory building located in Trieste, it features a net surface of 64.57 m^2 and a heated volume of 161.4 m^3, Figure 1 a) reports a map highlighting the external insulated walls. The construction, realized in year 2006, is relatively recent and features external surfaces insulated according to the levels required at the time. External wall have transmittance U_w = 0.62 W/(m^2 K) and windows feature a double glass with glass transmittance U_g = 1.76 W/(m^2 K) with plastic frame having transmittance U_f= 2 W/(m^2 K); the specific heating primary energy consumption is EP= 143.8 kWh/m^2. Thermal insulation of external walls is not aligned with the more advanced regulations introduced afterwards, but are fairly better than the ones of older buildings. However, in this paper it is explored if it is still economically feasible to enhance the thermal characteristics of building fabric, reducing energy consumption. The building has been first modeled using software DesignBuilder and the model is reported in Figure 1 b). Heating system features a standard boiler with radiators, the same system provides instantaneously domestic hot water. No cooling system is considered in this work.



a) b)

Fig. 1. a) Map of the building with external insulated walls b) developed model

2.1. Refurbishment activities

External walls feature 4 cm thick external insulation, an internal insulation system has been considered as a possible intervention. To complete the analysis a possible substitution of existing windows has been inspected as well. Therefore, three different approaches have been considered as described in the following: Case 1 considers the addition of a uniform layer of insulation on external walls, Case 2 applies different insulation layer thickness for different exposition, while Case 3 adds window substitution to the application of uniform thickness layers on exposed walls. An additional case could have been considered, such as the replacement of windows and non-uniform thickness insulating layers; however, this solution has not been considered due to the analysis of results of Case 3.

2.2. Numerical method

Dynamic simulation of the building has been performed using the EnergyPlus v 8.1, preliminary results were obtained using DesignBuilder v 4.2 used for the model definition. For instance, using this version of DesignBuilder it is possible to perform some optimization loops, but in order to analyze the refurbishment effects with different objectives, not programmable directly with DesignBuilder software, the model has been exported and used directly with EnergyPlus as a computational backend. Simulation have been performed for the entire heating season, from 15th October to 15th April. For each solution the consumed primary energy is computed, considering the amount of consumed natural gas only, since the electricity absorbed by auxiliaries does not change between designs. The consumed natural gas defines the operating costs. Climatic data is obtained from the IGDB database for Trieste. The model comprises seven heated zones corresponding to the ones reported in Figure 1 a) plus a non-heated zone corresponding to the stair zone and a heated zone corresponding to a heated nearby similar flat. For each zone thermal loads due to persons and internal loads are defined following daily schedules. As an example Figure 2 presents the distribution of internal load and persons for the kitchen. Ventilation is considered by adding windows opening schedules, during heating seasons one hour of open windows is considered from 8:00 to 9:00. During summer period, the windows are opened when internal temperature is greater than the external one and higher than 24°C .

3. Optimization

Optimization can be defined as the task of obtaining the best configuration for a system with a defined number of input variables, subjected to constraints and objectives.

If there is a single objective to be searched, the problem is called single-objective optimization, otherwise multi-objective optimization, in this case the objectives usually represent contrasting choices and the best solution is left to the designer.

Several algorithms can be used to solve optimization problems. Classical or deterministic techniques, such as gradient-based methods, present some limitations, such as the restriction to continuous variables, as highlighted by Wetter and Wright (2004) [10] and restriction to single-objective optimization problems. On the other hand, the most robust algorithms can be considered as the ones belonging to the category of evolutionary, or stochastic, algorithms, and in particular, the ones based on genetic algorithms. In the present work, a classical Multi Objective Genetic Algorithm (MOGA II) available in modeFRONTIER has been used.

3.1. Parameters and objectives

The three Cases differ mainly by the number of free parameters while share the same objectives of optimization. In Case 1 the external walls highlighted in Figure 1 a) are improved by adding an internal insulation structure. The structure is composed by a layer of insulating material having conductivity λ = 0,042 W/(m K) and an internal plasterboard.

Case 2 differs from Case 1 because different insulation thicknesses are considered for the three external walls of Figure 1 a). Case 3 considers only a single insulation thickness, such as Case 1, but in addition, the replacement of existing windows with high performance triple glazing systems is considered. For all cases the insulation layers tested increase from 3 cm to 20 cm with steps of 1 cm.

The three cases share the same optimization objectives, the first one is the reduction of specific primary energy *EP,* defined in Eqn. 1

$$EP = \frac{Q}{A_f} \tag{1}$$

Where A_f is the net floor area of the original flat and Q is the primary energy consumption. The second objective takes into account the expenses for the installation of insulation material, window replacement and the actualized savings in operational costs due to natural gas during the lifespan of the apartment. The third objective takes into account the effect of internal insulation on the net floor surface; solutions with too intrusive insulation thickness can be unacceptable because of the reduction of internal live space. Table 1 reports a summary of the optimization carried on.

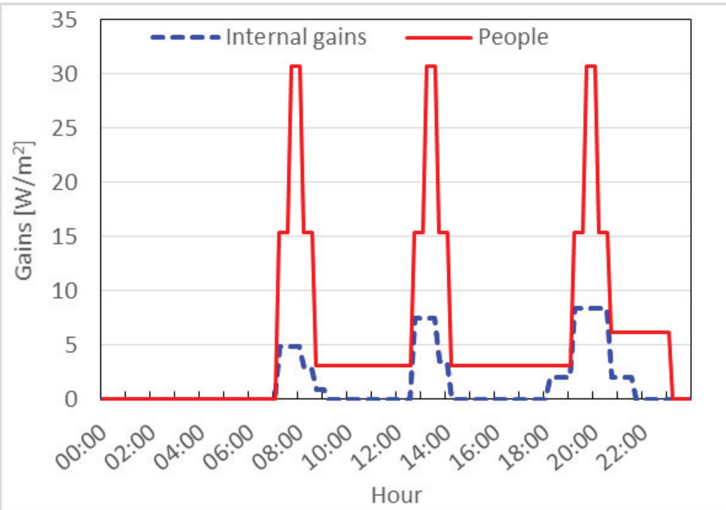


Fig. 2. Gain distribution for kitchen

3.2. Economic analysis

In order to take into account the life cycle cost (LCC) considered as the sum of the internal insulation construction cost and annual heating operating cost, the net present value (*NPV*) has been computed.

$$NPV = -I_0 + \sum_{k=1}^{N} C_k \cdot \left(\frac{1+g}{1+d}\right)^k \tag{2}$$

Where I_0 is the initial investment, C_k the cash flow during year k, g inflation rate, d the discount rate, N is the number of years considered, in this case $N = 30$. In Equation 2 no maintenance costs have been considered, due to the type of intervention considered. The cash flow is computed as

$$C_k = \Delta Q \cdot c_{fuel} \tag{3}$$

Where ΔQ represent the difference between the seasonal energy consumed by fuel with refurbishment intervention and the base case, while c_{fuel} is the unitary cost of natural gas. The cash flow represents the amount of money saved from the energetic bill each year thanks to the refurbishment activity on the building. In computing Equation 2 the economic values have been taken as $g = 0.19$ %, $d = 1.17$ % and $c_{fuel} = 0.63$ €/stdm^3. The prices for fuel are obtained from national values published by the energy authority; initial costs are obtained from a regional database. [11]

Economic analysis is strongly dependent on the energy cost, the variable prices, the prices of the material used, but especially by the policies that each country introduces in order to support and encourage energy aware initiatives. The typical support available in Italy for insulation enhancement and window replacement is in form of tax reduction, distributed in a ten years frame time, of the 65% of the initial costs. This form of subsidy has a strong effect on *NPV* since it increases the cash flow for the time in which the reimbursement is active.

Table 1: Optimization, parameters and objectives for different cases

	Parameters	Objectives		
Case 1	$L_1 = L_2 = L_3 = L_{ins}$ [mm]	*NPV* [€]	*EP* [kWh/m^2]	A_f [m^2]
Case 2	$L_1 \neq L_2 \neq L_3$ [mm]			
Case 3	$L_1 = L_2 = L_3 = L_{ins}$ [mm] Triple glazed windows type			

4. Optimization Results

Described cases have been simulated varying the relative parameters. Results are presented using the Pareto front, the set of solutions with an objective that cannot be improved without affecting the other ones.

4.1. Case 1

All the external walls of Figure 1 share the same insulation thickness, the variable L_{ins} varies between 3 cm to 20 cm with intervals of 1 cm. Due to the single parameter, a simple Designs of Experiments (DOE) has been performed. Figure 3 reports the results of the simulations using bubbles to represent the three objectives, the axis report in abscissa the *NPV* of the investment, while in ordinate appears the specific primary energy *EP*. The third objective, the net floor area A_f ranging from 62.2 m^2 to 64.2 m^2, is directly related to the size of the circles, a larger circle means a less intrusive internal insulation. As expected, national subsidy influences remarkably the *NPV* objective. In Figure 3 the solutions without subsidy fall at the left side of the plot. On the contrary, the results which considered subsidy appear at the right hand with higher values of *NPV*. The results with less consumption are the ones with larger insulation thickness, that are also characterized by lower values of free floor surface A_f. Subsidy has a strong effect also on the solutions from an economical point of view. Solutions with large insulation thickness are not economically efficient. The cash flow increase during the life of the structure doesn't cover the increase of initial costs. Scenario changes completely with subsidy: in this case large insulation layers are the preferred ones, such solutions are the ones with better *NPV*. However, a designer must take into account also the strongly reduced free floor area A_f of about 2 m^2, covered by a too intrusive internal insulation.

4.2. Case 2

In this analysis, the three external walls *Wall 1, Wall 2* and *Wall 3* of Figure 1 are insulated with different insulation thicknesses: *L1, L2* and *L3* respectively. The possible solutions increase dramatically and a simple DOE is not feasible. To search optimal solutions the MOGA II optimization algorithm is selected using 20 generations with 40 individuals each. Figure 4 presents the optimization results, using a bubble chart. Subsidy affect the solutions as noted in paragraph 4.1. The results without subsidy appear at the left side of Figure 4, while the ones with subsidy at the right of the plot. The solutions pertaining to the Pareto front for both cases are reported as a red circle. The solutions behave in a similar manner as in Case 1. Moderate insulation thickness are the preferred without subsidy, while with subsidy higher *NPV* are obtained using large insulation thicknesses, again at the cost of less usable floor area.

4.3. Case 3

An additional approach for improving the thermal characteristics of the apartment is to replace existing windows using high performance glasses. A series of triple glazed windows has been tested as replacement of the existing ones. The choice of a triple glazing is due to the requirement of improving the already good thermal characteristics of present double glazed windows. The windows considered have U_g ranging from 0.78 to 1.57 W/(m^2 K) with solar factor *SHGC* ranging from 0.154 to 0.579. As can be seen in Figure 5, no positive *NPV* can be obtained without subsidy, the cash flow is not capable of paying the large initial investment, however with subsidy the *NPV* increases reaching positive values assuring the profitability of the investment, though the values obtained are lower if compared with previous cases. However, considering the solution from environmental point of view, these solutions are the ones that present the lower energy consumption.

Table 2. Results from the optimization for Case 2 and Case 3.

Case 2										
ID	L_1	L_2	L_3	U_g	*SHGC*	Subsidy	*NPV*	*EP*	A_f	Target
-	mm	mm	mm	W/(m^2 K)	-	-	€	kWh/m^2	m^2	-
120	100	30	30	1.76	0.68	No	3428	83.01	64.02	*NPV max*
750	180	200	200	1.76	0.68	No	2961	76.71	62.25	*EP min*
714	150	190	190	1.76	0.68	Yes	5274	77.05	62.43	*NPV max*
81	200	200	200	1.76	0.68	Yes	5262	76.51	62,19	*EP min*
Case 3										
360	130	130	130	0.78	0.474	Yes	4029	72.04	63.07	*NPV max*
350	200	200	200	0.78	0.474	Yes	3863	70.02	62,18	*EP min*

5. Discussion

Table 2 presents some results pertaining to the Pareto front for the analysed solution and identified in Figures 4 and 5. The presented individuals are those, which have the highest *NPV* and lowest *EP*, for Case 3 only results with positive *NPV* are presented. It is interesting to note that the solutions with low *EP* are characterized by low values of free floor surface A_f, the solution can become unacceptable since reduce too much the internal available surface.

Without subsidy the individual with best economic value and energy don't correspond as happens with subsidy, since the higher initial investment is not paid back with the additional reduction in consumed natural gas. This is a point to take into account in order to select among a profitable or energy aware intervention.

6. Conclusions

Three refurbishment scenarios have been applied to a relatively recent apartment located in Trieste. The scenarios consist in the addition of an internal insulation with uniform or different insulation thicknesses and the replacement of existing window. To identify possible approaches, a genetic optimization has been performed in order to select the best solutions. The building model has been developed using DesignBuilder, while the energy computation have been performed with EnergyPlus, while modeFRONTIER code has been used for carrying on the optimization. Although the considered flat shows already good thermal characteristics, an additional refurbishing presents positive *NPV*, especially in presence of subsidy actions, which can represent the motivation for the owners to perform refurbishing activities. Others forms of subsidy can be considered at regional level and considered in a thermal-economic analysis. The results show that an accurate analysis is required in order to decide if particular actions, on existing buildings, could be implemented with the aim of improving the thermal characteristics of existing buildings and, hopefully, to increase the number of highly efficient and even NZEB buildings.

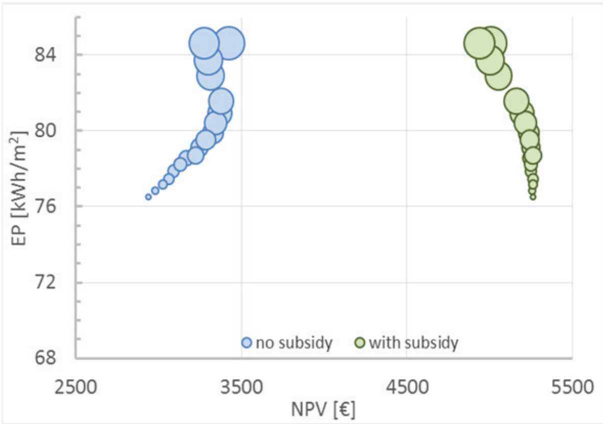


Fig. 3. Solutions for Case 1, without subsidy at left and with subsidy at right

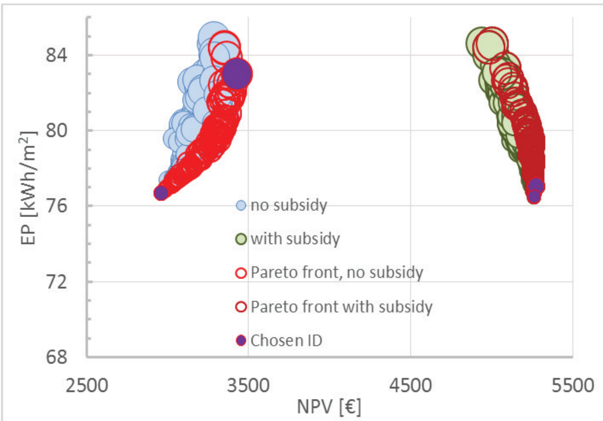


Fig. 4. Solutions for Case 2, without subsidy at left and with subsidy at right

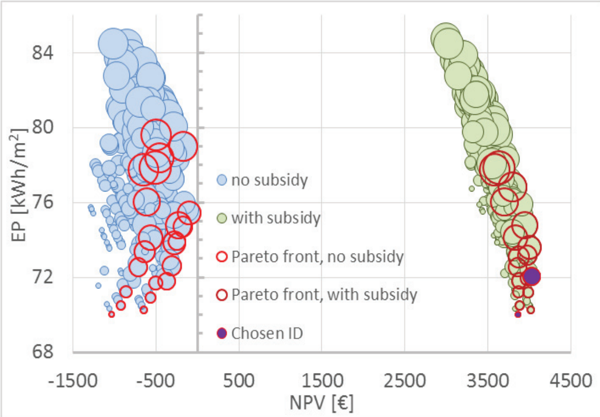


Figure 5. Solutions for Case 3, without subsidy at left and with subsidy at right

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