

Multi-Objective Building Envelope Optimization through a Life Cycle Assessment Approach

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Abstract—This work describes a methodology for the identification of the optimal features for the envelope of a residential building. The optimization process allows minimizing operating energy consumption, investment costs and life cycle energy and environmental embodied impacts. A dynamic model for the estimation of building energy consumption during its use phase has been employed, while literature data were adopted for embodied energy and global warming potential impacts. The considered variables refer to the envelope of the building, i.e. external walls and roof insulation and external walls thermal mass. The model was obtained combining *EnergyPlus* building energy simulator and *MOBO*, a versatile freeware that allows running the optimization of building features. The optimization was solved using NSGA II, a widespread adopted multi-objective genetic algorithm available in *MOBO*. The same building was simulated in two different climatic zones, namely Palermo (Italy) and Copenhagen (Denmark), in order to compare differences attained in the optimal solutions. The case study shows that the adoption of glass wool for the roof insulation and small concrete layers for external walls are to be preferred, providing optimal results in both climates. The present work was developed within the framework of IEA EBC Annex 72.

Keywords—air conditioning, buildings, genetic algorithms, life cycle, multi-objective programming

I. INTRODUCTION

The building sector is one of the most impacting on energy consumption in Europe, where it causes about 40% of energy consumption and 36% of CO₂ emissions [1]. Focusing the attention on final uses, the residential sector accounts for 25.4% of European energy demand. For this reason, EU promoted different policies for the reduction of energy demand, as the Energy Performance of Buildings Directive (EPBD) Recast, where the concept of Nearly Zero Energy Building (NZEB) is defined as a building producing almost as much energy as it consumes [2]. According to the definition, the design of NZEBs is mainly based on the reduction of energy consumption for air conditioning, through the rise of thermal resistance of the envelope and the adoption of passive strategies. The residual energy requirement has to be fulfilled in a great percentage through renewable energy sources. The diffusion of low-energy buildings should improve the energy and carbon footprint of the building sector, mainly regarding the residential districts.

Low-energy buildings designers often have to compare different alternatives and perform many energy simulations to find the building showing the lowest energy consumption and to design the renewable energy systems and other equipment covering these consumptions. This is due to the great number of energy efficiency solutions available and to the existence of conflicting measures (solutions that have both positive and negative impacts on the building). For the above reasons, researchers and designers often combine Building Performance Simulation (BPS) software with parametric analyses or mathematical optimization tools, in order to easily compare different alternatives. The optimization can be a constrained problem if legal obligations or cost-effectivity are also taken into account.

When a simulator and an optimization tool are combined, the function evaluated by the simulation cannot be subjected to mathematical derivation. In these cases, heuristic algorithms are the best option. Furthermore, the design may be oriented to fulfill different goals, as maximum energy saving, minimum cost or maximum internal comfort. These goals can be conflicting, as a very efficient solution usually is

also expensive. When more than one objective function has to be optimized, a multi-objective approach has to be adopted, making the analysis more complex and requiring a multidisciplinary background.

A recent literature review study highlighted that, in the field of low-energy buildings design optimization, life cycle impacts related to buildings are often neglected. As the main reason of the low-energy buildings is to reduce the global energy demand, a Life Cycle Assessment (LCA) of energy and environmental impacts should be the main approach to be adopted, in order to avoid that the use phase energy saving is shifted to other life cycle phases [3].

This paper is one of the first attempts to fill this research gap in the topic of low-energy buildings, providing a framework to integrate the holistic approach of the LCA methodology, the accuracy of building performance simulation and the extensive scenarios comparison allowed by multi-objective optimization. The aim of the work is to identify the optimal set of envelope layers allowing to minimize the Life Cycle energy and greenhouse impacts of a building and at the same time reducing the related investment costs. The methodology can be applied both to the preliminary design of a new building and to the retrofit of an existing building. Furthermore, this study has been developed in the framework of IEA EBC Annex 72 “Assessing Life Cycle Related Environmental Impacts Caused by Buildings”.

The case study is related to the retrofit of a very simplified building, in order to avoid that shape-related features may affect the generality of results. The analysis was thus repeated optimizing the building’s performance into two very different climatic contexts: Mediterranean climate (Palermo, Italy) and Continental climate (Copenhagen, Denmark). The case study was analyzed using two freely available software, namely *EnergyPlus* as building energy performance simulator and *MOBO* as optimization tool, representing one of the first scientific paper showing the interaction between these tools.

II. METHODOLOGY AND CASE STUDY DESCRIPTION

A. Methodology

The present study combines different techniques and areas of knowledge with the aim of obtaining the optimal set of retrofit options for the envelope of an existing building or for the envelope of a preliminary design of a new building. As the aim of low-energy buildings is to reduce the energy demand and the environmental impact of building sector, a life cycle approach, i.e. an evaluation of the impacts related to the building “from cradle to grave”, should be always followed. Furthermore, the building thermal analysis through BPS ensures the detailed evaluation of energy performance during the use phase of the building, and the adoption of a multi-objective optimization allows comparing multiple scenarios through a search algorithm (instead of a random comparison) and obtaining optimal combination of available retrofit options, also according to multiple aspects (economic, energy and environmental).

In order to show the advantages deriving from this approach, reader is provided with a brief background on adopted techniques and with a case study on an ideal building. Furthermore, to show how boundary conditions affect the optimal set of retrofit interventions, the building performance optimization was repeated in two different climatic conditions.

Simulation software employed for the study are *SketchUp* [4] for the building shape modelling, *EnergyPlus* [5] for the building thermal modelling and simulation and *MOBO* [6] for the optimization of the building envelope. These tools were selected according to following criteria:

- research-oriented
- interoperability
- freeware

Indeed, although these tools are not as user-friendly as other commercial software, they are free and versatile, and the availability of their source code allows researchers to customize these tools to each specific need [7], [8]. Furthermore, after an accurate check on *MOBO* existing international literature, Authors realized that this work is one of the first research studies illustrating the combination between *MOBO* and *EnergyPlus*.

B. Building physical model

Building physics is the application of the principles of thermal sciences to the built environment with the aim of rising energy efficiency in the building sector and reducing its fossil fuel dependence. The study of buildings thermal behavior can be assessed through many mathematical models available in literature, having different accuracy, with the most complex ones requiring necessarily specific advanced tools as BPS [9]. For example, *TRNSYS* and *EnergyPlus*, two of the most employed BPS, are based on the *Conduction Transfer Function* method [10], [11].

This study involved a preliminary building modelling phase. As the aim of this paper is to show the methodology and how the algorithm works, a simplified cuboid-shaped building was modelled in *SketchUp*. Furthermore, this shape avoids results being affected by geometric-specific features. The model is illustrated in Fig. 1.

The building's dynamic thermal performance was assessed through *EnergyPlus* simulator, analyzing a standard year with a time detail equal to one hour. Default *EnergyPlus* stratigraphic layouts and properties of the external walls, roof, floor, door and windows were adopted for the base case scenario. Internal gains (i.e. occupants, lighting and electric equipment) were neglected, as the scope of this work is to focus on the building's envelope. Physical analysis was evaluated for two different climatic conditions: Mediterranean climate (city of Palermo, Italy) as warm region, and continental climate (city of Copenhagen, Denmark). In the model, *Conduction Transfer Function* algorithm was applied to the *Heat Balance Method* [10], [11], with a third order backward difference algorithm for the air node. *DOE-2* and *TARP* algorithms were selected for the convective heat transfer simulation between the building and the outside environment and between the building and the indoor environment, respectively [12].

Building operating final energy demand was obtained by fixing indoor required temperatures equal to 20 °C for heating season and 26 °C for cooling season, and simulating an ideal HVAC plant with infinite rated power and unitary efficiency. In this way, technology's performance do not affect the results.

C. Life Cycle Assessment

Life Cycle Assessment (LCA) is a widely used methodology that allows assessing the potential environmental impacts of products and process throughout their life cycle. The life cycle is composed by the following phases: raw material extraction/acquisition, production, use, end-of-life [13].

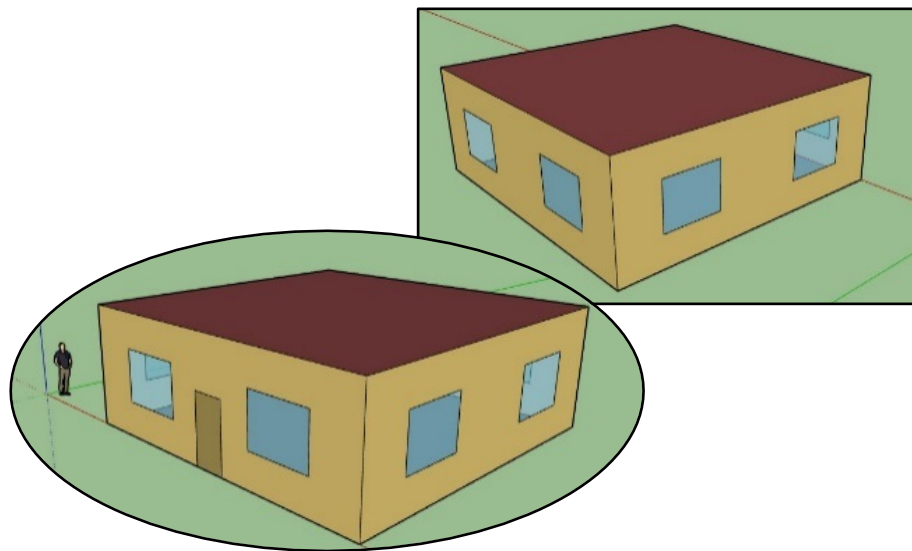


Fig. 1. Front and back views of building model used for simulations

According to international standards, a LCA study is composed by four stages, each one interacting with others: goal and scope definition, inventory analysis, impact assessment, and interpretation [14],

[15]. Focusing on buildings and building materials, a specific LCA methodology framework exists for the evaluation of energy and environmental performance, further specifying life cycle stages and boundaries of the study [16].

In LCA literature studies, many indicators are employed to assess the energy and environmental performance of buildings. As most of world's countries are currently making arrangements on climate and energy saving, as COP 21 Paris Agreement and EU Revised EPBD [17], the objective functions considered in this study have also taken into account obligations deriving from these regulations. For this reason, the environmental performance of building was assessed through the Global Warming Potential (GWP), indicating the emission of greenhouse gases during the life cycle of the building, i.e. its carbon footprint, and expressed as tons of CO₂ equivalent. Regarding the energy impact, as the operating energy consumption was already assessed by the BPS tool (although not in life cycle terms), the Embodied Energy (EE) related to building was selected. The embodied energy is the sum of energy used for raw materials' extraction, transportation, final component production, building construction and end-of-life [18], [19]. Although the embodied energy term is often neglected in ordinary buildings, the development of low-energy buildings or net zero energy buildings gave rise to the investigation of this term, that becomes obviously predominant compared to the operational term, that is very low or null [20].

D. Optimization model

Optimization problems can be categorized as single or multi-objective, depending on the number of objective functions to be considered. While single-objective optimization problems typically have only one global maximum or minimum and only one best solution exists (or none, eventually), multi-objective optimization problems aim at identifying a vector of decision variables that optimizes all objective function [21], [22]. As the objective functions usually conflict with each other, optimizing each function separately gives a different solution. For this reason, the solution of a multi-objective optimization problem is a set of trade-off solutions that are considered equally optimal if no preference is expressed. In detail, the set of optimal solutions is known as Pareto front [23].

According to the solutions space exploration technique, single or multi-objective optimization algorithms can be classified as deterministic or heuristic methods, where the first group is based on derivatives of objective functions, while the second is based on criteria derived from the experience of the analyst or from similarities with natural phenomena. The great advantage of heuristic algorithms is that they usually do not require continuity and differentiability of the objective function, but are based on the evaluation of a fitness function [24]. A widely-used category of heuristic methods is known as genetic algorithms, because they mime biological evolution mechanisms as reproduction, recombination, mutation, and selection for the exploration of the feasible space during the research of the optimum [25].

The *EnergyPlus* model described in the previous paragraph was used as input for *MOBO*, an optimization tool developed in Aalto University for the optimization of building thermal models [6]. *MOBO* allows interacting with any external simulation tool with a text file-based output. In detail, the input file has to be marked with delimiters, indicating the variables for the optimization model, while details on the variable as range of variation were specified into *MOBO* itself.

As the main target of a low-energy building and of NZEBs is to reduce the operating final energy demand, one of the objective functions of this optimization work is the sum of yearly heating and cooling requirements of the building, as in Eq. (1). Electricity demand was not evaluated as no equipment or lighting is simulated. To scale the building final energy demand to its useful life, set equal to 60 years, the present study assumes that the building energy performance is the same every year. Although it is evaluated along the useful operating life of the building, this function cannot be considered a life cycle indicator, as the building HVAC system was not specified and the operating energy consumption was evaluated in final energy terms by *EnergyPlus*.

$$OF_1 = \text{Oper. Ene. Cons.} = UL \cdot \sum_{t=1}^{8760} (H_t + C_t) \quad (1)$$

where H and C are the heating and cooling demand of the building at the t -th hour of the year and UL is the building useful life.

In order to consider the life cycle impact of the building, GWP and EE indicators were selected as objective functions to describe the environmental and energy performance of building, respectively. As embodied impact related to the retrofit interventions was expressed in primary energy and OE obtained in this study is evaluated in final energy terms, these two quantities cannot be summed or compared. In detail, these indicators were calculated as differential values, considering only the embodied impacts related to retrofit materials and neglecting the amount related to the existing building. LCA specific impacts were derived from Environmental Product Declarations (EPD) of insulation and construction building materials [26]. As the building shape is fixed in the optimization, the unique problem variables are the thicknesses of materials. For this reason, impact factors derived from EPDs were scaled and referred to the entire external walls surface or roof surface, obtaining specific impacts values expressed in impact per unit thickness of material. Thus, GWP and EE were evaluated according to Eqs. (2) and (3), respectively:

$$OF_2 = GWP = \sum_{r=1}^n Thick_r \cdot ECF_r \quad (2)$$

$$OF_3 = EE = \sum_{r=1}^n Thick_r \cdot EEF_r \quad (3)$$

where $Thick$ is the thickness of the r -th layer, ECF is its embodied carbon factor and EEF is its embodied energy factor.

As EPBD states that NZEBs, as well as reduce their operational energy demand, should be cost-optimal, the minimization of retrofit cost was also considered as objective function. Retrofit cost was assessed through unit price of materials, derived from a market analysis in European context. These values were scaled to the thicknesses of materials, as already explained for LCA impacts. Investment Cost objective function was evaluated according to Eq. (4):

$$OF_4 = Investment\ Cost = \sum_{r=1}^n Thick_r \cdot UP_r \quad (4)$$

where $Thick$ is the thickness of the r -th layer and UP is its unit price.

The variables selected for this optimization problem are the thicknesses of six insulation materials and the thicknesses of two construction materials. In detail, the installation of EPS, rock wool and glass wool insulation boards were considered for both external walls and roof, while further layers of concrete and hollow bricks were considered for walls only. Excluding concrete layer thickness, modelled as a continuous variable, each variable can assume six or seven values, selected from commercial sizes. The search space is thus composed by 259,308,000 building configurations.

MOBO allows to perform single or multi-objective optimizations through seven different algorithms. For this study, the multi-objective genetic NSGA II algorithm was selected [27], as it is one of the most employed and performing one [3], [28]. The optimization algorithm parameters were set equal to values suggested by the optimization tool, as they are customized for the specific problem, being evaluated through relations as a function of number of continuous and integer variable. Through the appropriate selection of algorithm parameters, reported in TABLE I., the entire search space was investigated through only $16 \times 126 = 2,016$ building configurations over 259 million, with an enormous time saving.

TABLE I. NSGA II PARAMETERS ADOPTED FOR THE OPTIMIZATION

Parameter	Value
Population size	16
Generations	126
Mutation Probability	0.1
Crossover Probability	0.9

III. OPTIMIZATION RESULTS

The optimization of the building according to the methodology illustrated in previous paragraphs allowed to obtain the set of optimal retrofit interventions constituting the four-dimensional pseudo-Pareto Front, i.e. sub-optimal compromise solutions identified by the genetic optimization algorithm [25]. Optimal and dominated solutions in two climate scenarios are reported through two-dimensional graphs in Figs. 2 - 7. As in this study GWP, EE and Investment Cost objective functions were evaluated with analogous formulas, they result as non-conflicting objectives, as shown in Figs. 4 and 6. On the opposite, the Operating Energy Consumption is a conflicting objective with respect of the three other functions, thus a Pareto-like distribution is identifiable in Figs. 2, 3, 5 and 6. Furthermore, TABLE II. and **Errore. L'origine riferimento non è stata trovata.** illustrate the values assumed by the objective functions at extreme solutions, the solutions obtained by the multi-objective optimization algorithm attaining the best value of a single objective function at a time. As GWP, EE and Investment Cost are non-conflicting objectives, their extreme solutions overlap.

A. Mediterranean scenario

In Mediterranean climate, the optimization converged to 10 retrofit solutions that always exclude external walls insulation, while only glass wool was selected as optimal material for roof insulation, adopting the lowest available thickness (0.025 m). Regarding external walls massive layers, brick layer was never adopted, preferring small amounts of concrete (between 0 and 0.012 m).

B. Continental scenario

The optimization in Continental climate identified 28 retrofit solutions. Similarly to previous scenario, the optimization preferred glass wool as optimal material for roof insulation and concrete layers for external walls, setting all other variables to zero. In detail, up to 3 insulation layers were considered as optimal, with optimal thickness values ranging between 0 and 0.075 m (single layer thickness is 0.025 m), while the highest additional concrete thickness is equal to 0.018 m.

TABLE II. OBJECTIVE FUNCTIONS AT EXTREME SOLUTIONS AND VARIABILITY RANGE IN MEDITERRANEAN CLIMATE

	Oper. Energy Cons. [GJ]	GWP [kg CO _{2,eq}]	EE [MJ]	Inv. Cost [€]
Oper. Ene. Cons. extreme solution	1,160	329	6,115	253
GWP, EE, Inv. Cost extreme solution	1,518	0	0	0
Range	724 – 1,518	0 – 80,205	0 – 1.5 * 10 ⁶	0 – 19,200

TABLE III. OBJECTIVE FUNCTIONS AT EXTREME SOLUTIONS AND VARIABILITY RANGE IN CONTINENTAL CLIMATE

	Oper. Energy Cons. [GJ]	GWP [kg CO _{2,eq}]	EE [MJ]	Inv. Cost [€]
Oper. Ene. Cons. extreme solution	1,768	900	17,350	746
GWP, EE, Inv. Cost extreme solution	3,024	0	0	0
Range	857 – 3,024	0 – 78,315	0 – 1.4 * 10 ⁶	0 – 19,903

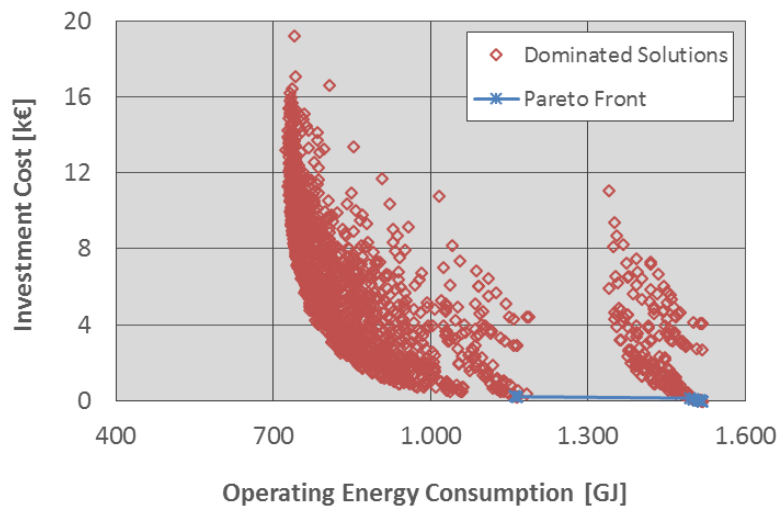


Fig. 2. Investment Cost against Operating Energy Consumption for Mediterranean scenario

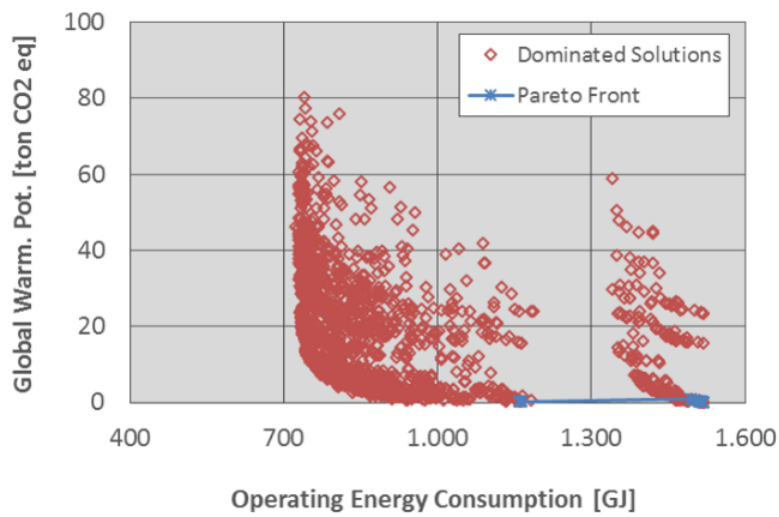


Fig. 3. Global Warming Potential against Operating Energy Consumption for Mediterranean scenario

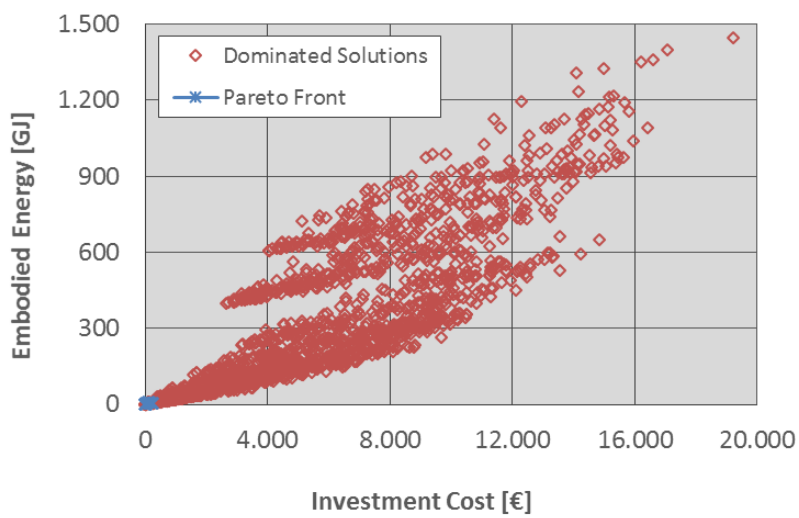


Fig. 4. Embodied Energy against Investment Cost for Mediterranean scenario

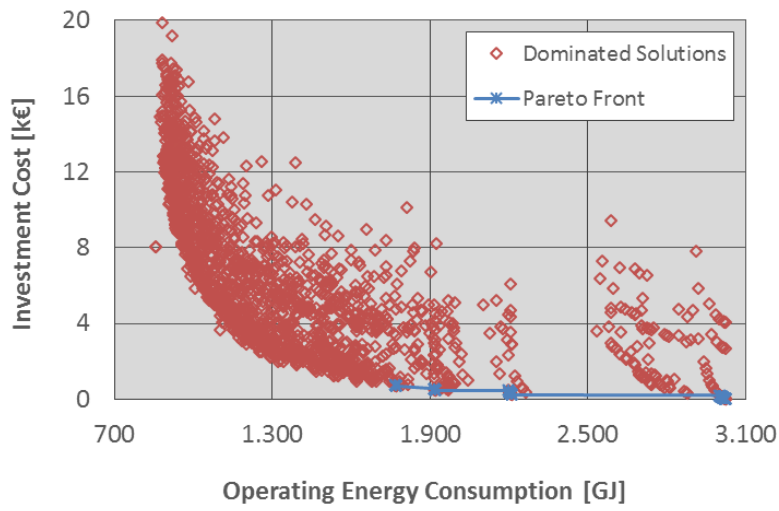


Fig. 5. Investment Cost against Operating Energy Consumption for Continental scenario

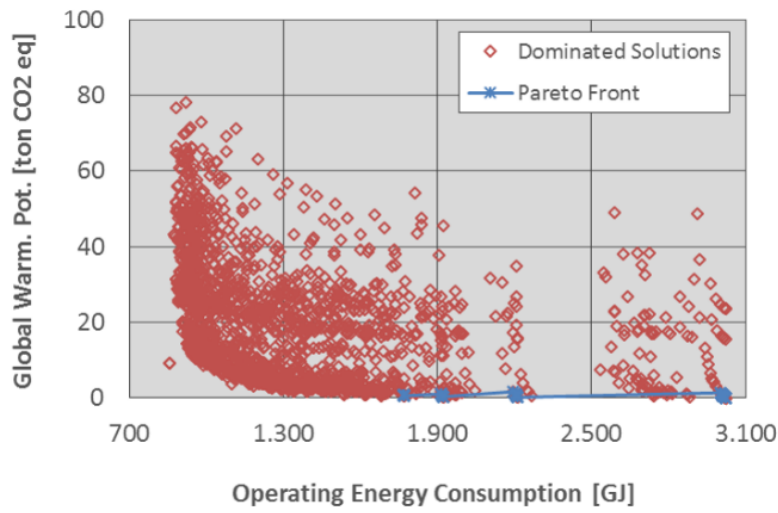


Fig. 6. Global Warming Potential against Operating Energy Consumption for Continental scenario

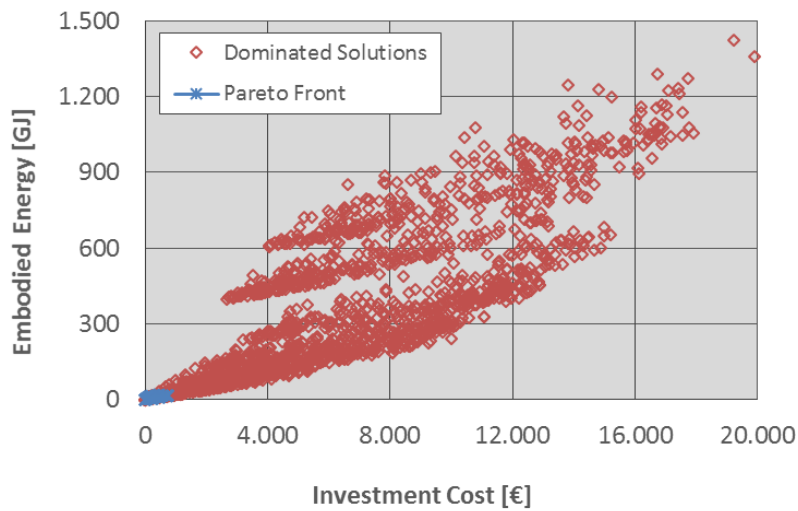


Fig. 7. Embodied Energy against Investment Cost for Continental scenario

IV. CONCLUSIONS AND FUTURE DEVELOPMENTS

In this work, a new methodology for the integration of building performance simulation, life cycle assessment and multi-objective optimization combining freeware tools was shown. In detail, the study is focused on the identification of optimal retrofit solutions for the envelope of a building allowing to minimize investment costs, operating energy consumption for air conditioning and embodied energy and greenhouse impacts. The widespread adoption of the proposed method by building designers may also help at fulfilling international target of energy saving and carbon emissions reduction. In order to show the potential saving deriving from the combination of these three areas of knowledge, a simple case study was evaluated, showing also that some difference exists if the building is studied in different climates.

As the initial building configuration already had high thermal performance, the optimization selected limited interventions in both climates, preferring to increase the insulation of roof and the thermal mass in external walls. In detail, the preferred insulation was the glass wool while the preferred massive material was the concrete. This result suggests that these materials should be preferred according to economic, energy and environmental criteria, while the higher thickness values obtained in Continental climate are due to lower average external temperatures.

In both climatic contexts, notwithstanding the optimization identified a certain amount of compromise solutions, the values of thicknesses of the materials are quite concentrated in a limited portion of the feasibility space, allowing the designer or the customer, that are usually more interested into economic aspects, to select the cheapest solution without impacting significantly on final energy consumption. On the opposite, minimizing only the operating energy consumption for air conditioning shows that, with an economic expenditure lower than 1,000 €, the energy demand can be reduced from 1,518 GJ to 1,160 GJ (- 24%) and from 3,024 to 1,768 (- 42%), for Mediterranean and Continental climates, respectively. It is worth to underline that, as the HVAC was not specified, running costs for air conditioning were not assessed in this study. In both climatic contexts, GWP related to the embodied impact of optimal retrofitting interventions is always lower than 1 ton of CO_{2,eq}.

From the comparison between the extreme solution minimizing operating energy consumptions and the variability range of the other objective functions, it is possible to state that this one represents a very good retrofit solution of the problem for both climate scenarios, although three objectives over four are not near to their minimum values.

The main target for further developments of this study is to improve the methodology, extending the analysis to fixtures, in order to evaluate all the envelope components, and also to equipment design (HVAC, RES, storages), in order to identify a unique framework for the evaluation of building performance. The complete analysis of building component will allow to compare the embodied life cycle impacts of retrofits with deriving operating savings, also including electricity demand. Furthermore, evaluating running costs of the building and primary energy demand in use phase, economic, energy and greenhouse objective functions will be all contrasting with each other, providing more useful and interesting results. Moreover, the method will be applied to existing buildings in different climatic and socio-economic contexts, in order to identify the optimal retrofit or design actions also for real buildings and for developing countries.

ACKNOWLEDGMENT

The authors wish to thank the Italian Ministry of Foreign Affairs and International Cooperation and the General Directorate for the promotion of the Italian economic System for their support to the research activity within the frame of the scientific cooperation Italy-Vietnam 2017-2019 project: “*Greening the power systems with solar power for GreenHouse Gas emission reduction in Vietnam*”.

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