Sustainability **2015**, *7*, 10809-10836; doi:10.3390/su70810809

OPEN ACCESS

sustainability

ISSN 2071-1050

www.mdpi.com/journal/sustainability

Article

Design of the Building Envelope: A Novel Multi-Objective Approach for the Optimization of Energy Performance and Thermal Comfort

Fabrizio Ascione [1,*], Nicola Bianco [1], Rosa Francesca De Masi [2], Gerardo Maria Mauro [1] and Giuseppe Peter Vanoli [2]

[1] DII—Department of Industrial Engineering, University of Naples Federico II, Piazzale Tecchio, 80, 80125 Napoli, Italy; E-Mails: nicola.bianco@unina.it (N.B.); gerardomaria.mauro@unina.it (G.M.M.)

[2] DING—Department of Engineering, University of Sannio, Piazza Roma, 21, 82100 Benevento, Italy; E-Mails: rfdemasi@unisannio.it (R.F.D.); vanoli@unisannio.it (G.P.V.)

* Author to whom correspondence should be addressed; E-Mail: fabrizio.ascione@unina.it; Tel.: +39-81-7682292; Fax: +39-81-2390364.

Academic Editor: Francesco Asdrubali

Received: 11 June 2015 / Accepted: 4 August 2015 / Published: 7 August 2015

Abstract: According to the increasing worldwide attention to energy and the environmental performance of the building sector, building energy demand should be minimized by considering all energy uses. In this regard, the development of building components characterized by proper values of thermal transmittance, thermal capacity, and radiative properties is a key strategy to reduce the annual energy need for the microclimatic control. However, the design of the thermal characteristics of the building envelope is an arduous task, especially in temperate climates where the energy demands for space heating and cooling are balanced. This study presents a novel methodology for optimizing the thermo-physical properties of the building envelope and its coatings, in terms of thermal resistance, capacity, and radiative characteristics of exposed surfaces. A multi-objective approach is adopted in order to optimize energy performance and thermal comfort. The optimization problem is solved by means of a Genetic Algorithm implemented in MATLAB®, which is coupled with EnergyPlus for performing dynamic energy simulations. For demonstration, the methodology is applied to a residential building for two different Mediterranean climates: Naples and Istanbul. The results show that for Naples, because of the higher incidence of cooling demand, cool external coatings imply significant energy savings, whereas the insulation of walls should be high but not excessive (no more than 13–14 cm). The importance of high-reflective coating is clear also in colder Mediterranean climates, like Istanbul, although the optimal thicknesses of thermal insulation are higher (around 16–18 cm). In both climates, the thermal envelope should have a significant mass, obtainable by adopting dense and/or thick masonry layers. Globally, a careful design of the thermal envelope is always necessary in order to achieve high-efficiency buildings.

Keywords: energy efficiency; building envelope; building energy simulation; multi-objective optimization; genetic algorithm; Mediterranean climates; cool materials

---

1. Introduction

The recent European Directives—in matters of rational use of energy for a low carbon future and a sustainable development—aim at a building sector characterized, in the next years, by high-energy performance concerning both new and renovated constructions.

Starting from the first version of the EPBD 2002/91/EC (Energy Performance of Building Directive [1]), for the first time in history, all EU Member States tried to define a common journey for reducing the energy and environmental impact of the building sector. In particular, by means of the definition of common guidelines for obtaining a significant improvement in the sustainability of buildings and cities, the EPBD defined goals and prescriptions to be implemented by the Member States by 2006. In order to provide a comprehensive set of procedures and calculation methods, together with the emanation of the EPBD, the CEN (European Committee for Standardization) was called to provide a wide set of suitable standards, harmonized according to the prescriptions of the so-called umbrella document [2]. In more detail, according to several heat and energy transfer phenomena, calculation methodologies were developed for evaluating the efficiency of both new and renovated buildings, with references to thermal envelopes, active energy systems, and conversion from renewable energy sources. Some years later, during 2010, the targets have been moved forward. The recast version of the EPBD, Directive 2010/31/EU [3], has introduced the goal of nearly zero-energy buildings by underlining both the high required energy performance as well as the economic feasibility of the "building system" by means of the new concept of cost-optimality. Most notably, the EPBD Recast states that the minimum energy requirements of buildings should be defined "with a view to achieving cost-optimal levels", thereby pursuing the "energy performance level which leads to the lowest cost during the estimated economic lifecycle". The definition of cost-optimal levels has to be established at national levels, by taking into account all costs and, thus, investments, maintenance and replacement, operating costs, and cash flows due to the achieved energy savings. The operative methodology for identifying the cost-optimality, for reference buildings, is exhaustively described in the EU Commission Delegated Regulation n. 244/2012 [4], which provides a comparative method. This approach has been already proposed in sample studies, such as the one of the Building Performance Institute European (BPIE) for Germany, Poland, and Austria [5], but also in recent scientific papers concerning the design of new buildings [6,7] or the refurbishment of existing ones [8,9], even when characterized by historical value. Furthermore, with reference to the EPBD Recast, the optimized energy demand of a building should be mainly met by means of the use of *in-situ* renewable energy systems. In detail, the following time schedule has been established, according to article 9 of the Directive:

- all new buildings, starting from January 2021, have to fulfill the nearly zero-energy standard;
- all new buildings owned and/or occupied by public administration and authorities have to meet the nearly zero-energy standard starting from January 2019.

Of course, the EPBD Recast has introduced a significant breakthrough compared to the version from 2002. The Member States have a wide freedom in defining their key strategies, according to the particular conditions in terms of climate building techniques, materials, available energy sources, and costs, but, at the same time, they have the responsibility of fulfilling the final goal. This construction activity must be fully sustainable under economic and energetic points of view.

At the same time, the EU Guidelines establish that great attention should be given to the refurbishment of existing buildings. In particular, the EU Directive 2012/27/EU [10], in article 4, underlines the necessity for all Member States to promote "a long-term strategy for mobilizing investment in the renovation of the national stock of residential and commercial buildings, both public and private". Furthermore, this Directive promotes "cost-effective approaches to renovations, relevant to the building type and climatic zone" as well as "policies and measures to stimulate cost-effective deep renovations of buildings, including staged deep renovations". The same document underlines the effectiveness of plans proper for guiding the investments of private persons, the construction industry, and financial institutions. Moreover, it suggests "an evidence-based estimate of expected energy savings and wider benefits". In this frame, the public role should be exemplary, as stated by article 5 of the Directive 2012/27/EU. In more detail, "each Member State shall ensure that, as from 1 January 2014, 3% of the total floor area of heated and/or cooled buildings owned and occupied by its central government is renovated each year to meet at least the minimum energy performance requirements".

The proposed paper is framed just in this cornice. Presently, at least at the Italian level, the design activity is still related to old criteria for both the construction of new buildings and the refurbishment of existing ones, where the main attention is placed on the reduction of energy demand for space heating. This is an old approach, derived from trends of Central and Northern Europe, which should necessarily be changed because of the large use of systems and equipment for summer cooling in the Mediterranean countries. This paper overcomes this old approach by tackling the design of the thermal characteristics of the building envelope via a novel methodology that takes into account both heating and cooling needs.

2. Literature on the State of the Art and Motivations for a New Investigation

For both reasons of indoor comfort and limitations to the use of cooling systems, a new focus, mainly in Mediterranean climates, has to be pinpointed, since a too-high level of thermal insulation can cause a substantial increase of summer energy demands for cooling because of the phenomenon of indoor overheating. Finally, a proper choice of building envelope thermal resistance should be made in accordance with other parameters and overall evaluations such as the annual energy performance, the thermal capacity, and the radiative characteristics of external coatings. Moreover, one should carefully investigate the potential of indoor free cooling, mainly during nighttime, by means of various heat transfer phenomena, such as the emissions to the sky and the external environment and/or the nocturnal ventilation, which is better if it is natural in order to avoid the energy demands for fans and auxiliaries. All told, the combined effects of insulation, thermal capacity, radiative behavior, free cooling, climate, and building use have to be considered.

The phenomena concerning the matter of thermal comfort in civil buildings during the warm season are quite complex. A double approach can be considered, according to the most recent international standards and, thus, ANSI/ASHRAE 55/2004 of the American National Standards Institute and American Society of Heating, Refrigerating and Air-Conditioning Engineers [11], the EN 15251/2007 [12], and the revised version of the well-known standard UNI EN ISO 7730 [13]. In more detail, according to the adaptive approach of [12], the indoor comfort conditions are strictly related to the outside temperatures, which affect the admitted comfort ranges of the indoor operative temperatures. The exponentially weighted running mean of the daily external temperatures' series has to be calculated according to Appendix A of the standard (Equation (1)) and then, depending on these values, three comfort categories (I, II, and III) are calculated by means of the definition of top (Equation (2)) and bottom (Equation (3)) limits.

$$\theta_{rm} = (1-\alpha)\cdot\left\{\theta_{ed-1} + \alpha\cdot\theta_{ed-2} + \alpha^2\cdot\theta_{ed-3}.....\right\} \quad (1)$$

$$\textit{Comfort upper limit} \rightarrow \theta_{INDOOR\,MAX} = 0.33\cdot\theta_{rm} + 18.8 + x \quad (2)$$

$$\textit{Comfort lower limit} \rightarrow \theta_{INDOOR\,MIN} = 0.33\cdot\theta_{rm} + 18.8 - x \quad (3)$$

In the above-reported equations:

- Θ_{rm} is the running mean temperature for the investigated day;
- $\Theta_{ed-1,ed-2,....}$ are the daily mean external temperatures of the previous days;
- α is a constant term: the EN 15251/2007 proposes a value equal to 0.8;
- $\Theta_{INDOOR\ MIN}$ is the lower value of the indoor operative temperature for thermal comfort;
- $\Theta_{INDOOR\ MAX}$ is the upper value of the indoor operative temperature for thermal comfort;
- x is a scalar equal to: 2 for Category I (90% acceptation, 10% dissatisfied), 3 for Category II (80% acceptation, 20% dissatisfied), 4 for Category III (65% acceptation, 35% dissatisfied).

Similar methodologies—where the comfort is related to the ambient conditions of the location—can be found in [11,13]. However, if the indoor microclimate is conditioned by the use of cooling systems, it is very common, even today, to evaluate based on the old approach by means of the definition of fixed levels of operative temperatures. This is the method developed starting from the studies of O. Fanger, still widely used today, mainly in buildings provided with air conditioning systems aimed at space cooling during the warm season.

In Italy, the set-point temperature for comfort in summertime is usually 26 °C. With reference to non-air-conditioned buildings, the first aim is to guarantee, in the warm season, comfortable conditions as long as possible. Diversely, in air-conditioned ones, a priority is the reduction of the energy requests for space cooling, above all in Mediterranean climates. A primary role is played by the building envelope, which has to mitigate the heat transfer between the external environment and the internal one, due to high external temperatures during the central hours of the day and, above all, due to solar radiation. Solar radiation becomes a cooling load, starting as heat gain, because: (*a*) it is incident on the external surface, and thus raises the sol-air temperature ($T_{SOL\text{-}AIR}$); (*b*) it enters into the environment directly through the windows; (*c*) it is reflected into the building because of the reflection of the surrounding elements. By means of the selection of proper levels of thermal insulation, thermal mass, and, thus, thermal capacity, through proper coatings for optimizing $T_{SOL-AIR}$ (which affects the heat transfer through the opaque structures) as well as proper window shadings and controls, the design of the building envelope can exercise a huge influence on the improvement of building energy performance. Really, when the target is, beyond thermal comfort, the achievement of low energy buildings from a point of view of the global performance (heating, cooling, and lighting), the best compromise among the aforementioned characteristics should be selected. In this regard, some choices can have contrasting effects, for instance:

- too-high levels of thermal insulation, even if surely profitable during the heating season, can induce phenomena of indoor overheating in summertime. In particular, when solar gains and plugged powers are significant, low values of the thermal transmittance (U_{value}) of the building walls and structures can reduce the useful heat losses, also during nighttime, so that a common hyper-insulation phenomenon can occur;
- very high levels of thermal capacity can provide useful time lags and decrement of the heat wave transferred between the external and internal environments but, at the same time, can also imply a long inertia of the indoor environment for reaching the desired indoor temperatures when the Heating, Ventilating and Air Conditioning (HVAC) System is turned on (mainly if with radiant terminals);
- high-reflective (cool) coatings, even if suitable for keeping the outer building surfaces cool (by reducing the sol-air temperatures), conversely can cause too-cold surfaces in winter, especially if these are also characterized by high thermal emissivity, so that the building shell is also cooled by the nocturnal radiation with the sky and the surrounding environments;
- a very important role is played by windows that—characterized by different coatings (low emissive, reflective, selective, and so on) or by different shading systems (internal, external, managed by manual operation, or based on the incident solar irradiance)—greatly affect, in all seasons, the amount of favorable (in winter) or penalizing (during the cooling season) solar gains.

As is known, Southern Europe needs help in defining the best solution for optimizing the thermal behavior of the building envelope. This is the motivation of several recent studies on the matter of net and nearly zero-energy buildings, tailored for Mediterranean climates. Diversely from the consolidated approach of cold climates, where the first need is the reduction of energy demand for space heating, in warm climates, a design activity merely aimed at reducing the overall heat transfer coefficients of the envelope components cannot be effective. In cold regions characterized by cool summers, even in the central period of the cooling seasons, the significant excursion of the outdoor air temperatures in the day/night cycle allows a possible nocturnal free cooling by means of heat loss through the envelope and natural ventilation. The study of Kolokotroni *et al.* [14] on this topic is very interesting. These authors investigated indoor overheating in summer by means of research that looks also at the future, by taking into account climate projections for the next years. The authors concluded that, in the next decades, the heating needs will decrease, with a significant increment of cooling loads and overheating hours in naturally ventilated buildings. However, it should be noted that, even if the considered climate is heating dominated, the challenge for reducing the environmental impact is the reduction of cooling requirements.

Jenkins *et al.* [15], on the same track, developed a surrogate model by means of a novel integration of dynamic energy investigations and probabilistic climate forecasts. The regression model is very reliable and is able to predict the hourly internal temperatures with an error of about 5%, compared to the outcomes of a transient commercial simulation software (ESP-r), for different investigated climates in the United Kingdom. Recently, the large studies of Santamouris and Kolokotsa [16,17] and Santamouris *et al.* [18] discussed the impact of the progressive overheating of urbanized areas on energy demand and health conditions in civil European buildings. In [16], the authors explored the potentialities and limitations of passive cooling techniques for contrasting the urban climate change and the heat island effect. In greater detail, passive cooling solutions can reduce the cooling demand to 70% compared to a traditional air-conditioned building. Moreover, as stated in [17], energy efficiency and high thermal performance by means of mitigation and adaptation technologies should be a priority for contrasting the energy poverty, which causes a low life quality for a significant share of the European population, from the point of view of healthy life and general livability. Specific policies are necessary, by means of an integrated approach, in order to fight further marginalization, and this is an important part of sustainable development. Global warming and the urban heat island effect produce not only an obvious depletion of the city's comfort conditions, but also a significant increase in energy demand. In this regard, [18] evaluated that the additional electricity penalty due to urban overheating is around 21 (±10.4) W per degree of ambient temperature increase and per person, even if significant differences can be found around the world (*i.e.*, from Thailand to California, 10 locations are considered). In greater detail, the peak electricity demand rises between 0.45% and 4.6% per degree of increase of ambient temperature, and this is due to urban overheating and to the consequent larger use of cooling systems. The aforementioned range depends on climate, building topologies, and the rate of penetration of the use of air-conditioning systems. Porritt *et al.* [19] underlined how the progressive increasing frequency of extreme weather events could affect indoor comfort in residential buildings of the United Kingdom, and the attention has also been brought to the coming decades. The authors showed that measures for managing solar gains and external thermal insulation of the envelope can be effective. On the other hand, thermal insulation, placed internally, can increase indoor overheating during the warm season. Really, two kinds of buildings were investigated, an end house and a mid-terrace house, so further studies are necessary. Each technology (e.g., solar shadings, night ventilation, blinds, and curtains) has different impacts, depending on the installation conditions (for example, on varying the exposure of the rooms). The study is very interesting because it also takes into account different occupant behavior patterns based on the kind of families living in the investigated dwellings.

As shown by Ascione *et al.* [20] for various European climates, the right combination of insulation, thermal mass, and radiative peculiarities of the external coatings is related to both the climate and potential of the summer free cooling by means of ventilation. In this regard, beyond the thermal mass, even new technologies, based on the adoption of PCMs (*i.e.*, phase change materials), can be successfully adopted [21], although the costs have to be carefully evaluated. For instance, [20] emphasized that the power required by fans can limit the benefits of night ventilation, if mechanical, so that the building design should assure natural convective free cooling during nighttime in order to avoid or reduce the use of mechanical devices for ventilation. The potentialities of PCMs are strongly related to the composition of the wall, to the designed melting temperature, and to the climate [21]. For instance, with a melting temperature of 29 °C, there is a decrease in cooling energy demand of around 7% in Ankara and around

3% in hot Mediterranean climates, such as Seville and Naples. Beyond mere energy saving, PCMs imply a significant improvement of the thermal comfort in naturally ventilated buildings.

Several other authors, such as Mlakar and Štrancar [22] and Badescu *et al.* [23], showed the problem of indoor comfort conditions not always being favorable in low-energy buildings. In further detail, the authors of [22] focused on the possible overheating in dwellings in Slovenia and investigated a double approach that was both numerical and experimental. The outcomes revealed that a passive house can be much more comfortable during the warm season if there is a proper use of shadings during the day and a large night ventilation is applied. Finally, the concept of the passive house can be extended also to climates with both critical summers and winters, and proper occupant behavior, in managing the control of heat gains and achievable free cooling, is definitely necessary.

Analogously, for the climate of Bucharest, the study of [23] underlined that uncomfortable indoor microclimates are more frequent in high-insulated and energy-efficient houses compared to standard buildings. The authors applied two numerical procedures, namely a steady-state model and a transient simulation, and the outcomes underlined that a dynamic investigation, even if more complex, yields results characterized by a much higher quality because this approach is able to evaluate heat loads with the necessary level of reliability. Also, this study underlined the usefulness of passive techniques such as night ventilation by showing that this strategy can reduce the summer overheating rate by around 31%.

In buildings not equipped with air-conditioning systems, even if the effectiveness of each energy efficiency measure is strongly related to the building use and to the specific climate, two macro-strategies can be identified for improving comfort during the warm season:

(a) the reduction of the heat gains that, instantaneously or shifted, becomes cooling load;
(b) the use of techniques for discharging the building envelope and operating a passive cooling of indoor spaces.

With reference to point (*a*), the use of solar shadings and their effectiveness [24–28], the adoption of reflective coatings [20,29], also by taking into account the interrelation among buildings [30–32], has been largely studied in recent years by authoritative authors. In particular, Bellia *et al.* [24] investigated the suitability of various kinds of window screens for several climates in Italy. The reduction of annual energy demand for the microclimatic control, if proper shading devices are installed, can be around 20% in warm climates (Palermo, Sicily) and around 8% in colder contexts such as Milan (Northern Italy). With reference to solar screens, Katunský and Lopušniak [25] analyzed the performance of such systems in terms of the reduction of cooling demand and the variation of the indoor overheating effect in low-energy buildings. The authors pointed out that the possibility of variation and adaptation of the solar screens is necessary for achieving a suitable performance. In the same vein, Yao [26] showed that movable solar shading systems can reduce building energy consumption significantly, concerning hot summer zones of China. In particular, the author performed a detailed building simulation study, thereby showing that movable solar shades used for south-facing windows of a residential building in Ningbo (China) not only reduce energy demand by 30.9%, but also implied a substantial improvement of thermal and visual comfort. Given the high impact of solar shading on building energy performance and indoor thermal comfort, the operation of manually controlled solar shades, depending on occupant behavior, should be carefully modeled. In this regard, Yao *et al.* [27,28] developed a stochastic model for manually adjusted solar shades in the Building Controls Virtual Test Bed, which was coupled with EnergyPlus for co-simulation in order to detect the influence of control behavior on energy performance. Simulations showed that the adoption of an ideal assumption for solar shading control, as done by most studies concerning building simulations, can imply an overestimation of energy saving by about 16%–30%.

Concerning cool colors and cool paints, Ascione *et al.* [20] proposed an index for orienting the choice of proper solar reflectance and thermal emissivity by taking into consideration the heating degrees day and the solar irradiance in summer. Furthermore, Cotana *et al.* [29] estimated how much the albedo of the building envelopes, at an urban scale, can contribute at reducing global warming. The suitable management of the albedo can be profitable because it allows a better reflection of radiation, a lower use of mechanical cooling in buildings with reflective coatings, and a mitigation of the urban heat island effects. The case study, a factory located in Tunisia, showed that the installation of reflective coatings on the building opaque envelope can reduce, in 30 years, around 16,000 tons of $CO_{2\text{-eq}}$ emissions. Some of the same authors, in previous works [30,31], analyzed what happens because of the mutual reflection among buildings. In warm climates, the inter-building effect can cause inaccuracies of predictions up to 42%, whereas in cold climates, the error in the evaluation can be greater than 20%. Moreover, [31] demonstrated that, beyond the alteration of heating and cooling loads, the need of artificial lighting is also strongly influenced by the mutual energy exchange of radiation among buildings. Also, Salata *et al.* [32] studied the role of albedo and plants in mitigating the microclimate of parts of cities. The high reflection of sun-exposed building surfaces and materials, as well as the urban vegetation, greatly affect the environmental comfort because of changes in air temperature, relative humidity, the radiant temperature of surfaces, and wind speed. Finally, positive effects can be found both at the building level (reduction of cooling loads) and at the urban level (a better livability of the outdoor environment).

With reference to passive cooling techniques—point (*b*)—a wide review was proposed by Kamali [33], who discussed the potentiality of ventilation systems based on technologies using phase change materials. This investigation underlined that climates and melting temperatures of PCMs are key factors for successful design. In the same vein, Inard *et al.* [34] found huge energy savings for space cooling achievable by means of natural ventilation during the warm season. In particular, monitoring and numerical evaluations were applied for verifying the free cooling potential in low-energy offices in Germany. The investigations revealed that, for the 14 office rooms analyzed, the free cooling potential of suitable ventilation can be estimated on the basis of the difference between the free-running temperature and the comfort limit temperature. This topic has been central in the investigation on the matter of building energy efficiency for several years. Shaviv *et al.* [35] explored the effects of natural ventilation and building thermal inertia as a passive cooling strategy. The outcomes showed a reduction of up to 6 °C of indoor temperature for heavy-constructed buildings. Beyond mass and night ventilation, the temperature excursion in the night-day cycle also has a primary role. Furthermore, a very promising technology seems to be the adoption of breathing walls. Recent research from Ascione *et al.* [36] proposed a novel technique for nocturnal free cooling in summertime by means of the coupling between a ventilation system and a dynamic (*i.e.*, air-permeable) building envelope. The proposed numerical model, operating under transient conditions and developed in the MATLAB® environment, was compared with both a steady state methodology and a finite element model (built in COMSOL®). Beyond the very good fit, the investigations, carried out for three different climates, *i.e.*, Cairo (hot), Naples (Mediterranean), and Munich (cold), showed the profitability of the dynamic insulation of the building envelope because it provides significant benefits in the cooling period, with a reduction of indoor air temperatures.

Eventually, Yao [37] emphasized another crucial point in the thermal design of the building envelope by pointing out that the best design should aim not only to decrease the whole building energy demand, but also to minimize the "energy performance difference between housing units" (EDH). This generally implies a heterogeneous building envelope with different thermal and optical properties for different exposures. For instance, in the same study, Yao showed that the optimal building design for a typical residential building in China included movable shading for east- and west-facing windows as well as reduced *U*-values for east walls and west-facing windows. Definitely, the EDH-based design improvement ensures higher energy, economic, and environmental performance than potential improvement options commonly adopted in China, as also evidenced by Yao in [38]. Furthermore, the EDH-based approach provides flexible options that address the different demands for building aesthetics, function, *etc.*, even in the presence of few available improvement actions.

The described background shows that the design of the thermal characteristics of the building envelope is a very complex task that requires a holistic and integrated team approach. Also, in the presence of very efficient and high-tech solutions, the choice of the optimal thermal envelope is a crucial issue. Moreover, the concept of "optimal" itself is relative, since different competitive objectives subsist simultaneously in the building design, such as the minimization of energy consumption and/or of the polluting emissions, the maximization of economic benefits, and/or thermal comfort. Finally, a mathematical approach, based on multi-objective optimization, is fundamental because the domain of possible solutions is very large and different goals occur concurrently.

Starting from this observation, the proposed paper provides an original approach, based on multi-objective optimization, for the thermal design of the building envelope in order to minimize the energy demand for space cooling and, at the same time, the thermal discomfort.

3. Methodology: Multi-Objective Optimization

A multi-objective optimization is applied in order to identify, once we fixed the climate, the best compromise between the thermal insulation, the thermal mass of the building, and the radiative characteristics of the external surface. This kind of study can be useful for providing guidelines for both new design and refurbishment of buildings. The methodology combines, interactively, EnergyPlus [39], used for building performance simulation, and MATLAB® [40], used for solving the optimization problem. The authors have applied a similar approach for the detection of the cost-optimal package of energy efficiency measures at the building level in [9]. Therefore, the framework of the methodology is detailed in [9], so only a brief summary will be proposed here. The selection of EnergyPlus is due to its authoritativeness and to the possibility of defining building energy models by means of text-based inputs and outputs. This allows the coupling with MATLAB®, in which a Genetic Algorithm (GA) is implemented in order to solve the optimization problem. The adopted GA is a variant of sorting genetic algorithm II (NSGA II) [41]. It provides a continuous and iterative improvement of the building model, with the final aim of identifying a set of solutions that optimize both energy performance and thermal comfort.

The first phase requires the definition of a base building model, where the main boundary conditions for the simulations are assigned (thermal envelope, HVAC systems, occupancy, and profiles of use of the building and set point temperatures). Then, the decision variables are identified and parametrized in the building model. They delineate the thermal characteristics of the building envelope to be optimized, such as the solar absorptance and thermal emissivity of the external coatings, the thickness and density of the masonry layers, the thickness of the thermal insulation, and the type of windows. The value assumed by each variable corresponds to a design decision and this can be changed by replacing the default value defined in the base building. Each variable can take sundry discrete values that should be defined on the basis of expertise and the reasonability of the designer.

In the proposed multi-objective optimization framework, the two chosen conflicting objectives are those that commonly are taken into consideration by building owners and occupants: the energy requests for microclimatic control and the thermal comfort. In further detail, in order to evaluate the optimal solutions, the following two objectives are considered:

- Minimization of annual primary energy for space conditioning per unit floor area—EP [kWh/m^2·a], which is the annual primary energy demand for indoor microclimatic control, and thus the sum of the primary energy required by the heating and cooling systems, respectively, per unit of conditioned area;
- Minimization of percentage of thermal discomfort hours—DH [%], which represents the annual percentage of occupied hours characterized by conditions of thermal discomfort. The weighted-under-or-over-heating/cooling-hours criterion is used for the assessment of the thermal comfort because it gives a function that should be minimized [9]. Briefly, it is assumed that thermal discomfort occurs when the average Predicted Mean Vote (PMV) in the building's thermal zones is not included in the range of −0.85, 0.85, with a consequent Predicted Percentage of Dissatisfied (PPD) greater than 20%. This range of PMV is the one that ensures the minimum level of comfort according to the Standard ANSI/ASHRAE 55 [11].

Once defined, the GA optimization algorithm is implemented in MATLAB® and it automatically interrogates EnergyPlus in order to evaluate EP and DH. A summarized flow-chart of the procedure is shown in Figure 1, where $\underline{x}$ is the vector of encoded decision variables, $\underline{F}$ is the vector of objectives ($\underline{F}$ = [EP, DH]), the *.csv* is the file in which the outcomes of the simulations are reported, and the *.idf* is the model input file for EnergyPlus. In vector $\underline{x}$, each design variable is coded with a string of n_i bits, in such a way that it can assume 2^{n_i} different discrete values. A key role is played by the "function for coupling EnergyPlus and MATLAB®", which converts the $\underline{x}$ vector into an EnergyPlus input file (*.idf*) and an EnergyPlus output file (*.csv*) into the vector of the objectives $\underline{F}$.

MATLAB® sees EnergyPlus as a generator of hidden functions and this implies the use of heuristic and iterative optimization algorithms, such as the GAs. The final goal of the multi-objective programming problem is the achievement of the Pareto front, which represents the set of non-dominated (*i.e.*, "the best") solutions. GAs, and heuristic methods in general, do not ensure the detection of the real Pareto front, but produce a good Pareto front (sub-optimal) that is close to the real one in a reasonable computational time.

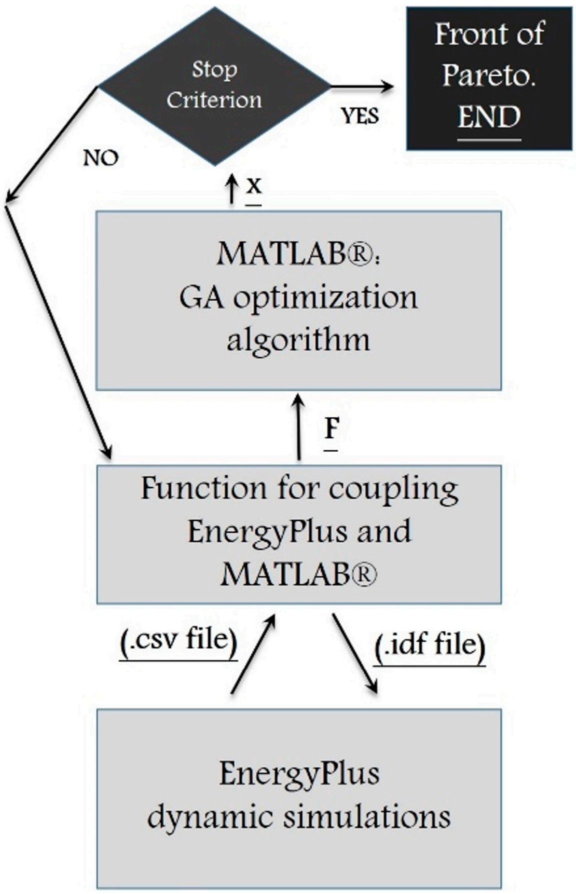

Figure 1. Scheme of coupling of MATLAB® and EnergyPlus.

A GA is a stochastic evaluation-based method that realizes the iterative evolution of a population of individuals ("chromosomes"). Each individual is defined by a set of values of the vector x, thereby corresponding to a certain configuration of the building thermal envelope. At each iteration (*i.e.*, "generation"), the genes of some chromosomes are combined and/or mutated for achieving new chromosomes that provide improved outcomes for the objective functions. In further detail, starting from a random generation of a population of individuals, the objective functions are evaluated and, based on the results (definition of a non-dominated rank) and by taking into account an established average crowding distance, some individuals ("parents") are selected. The following generations are composed of the best of these ("elite") and by the "children". The latter are defined partly by means of crossover and partly by the mutation processes. The "Darwinian" evolution of the population ends when one of the following conditions is verified:

(a) a maximum number of generations is achieved;
(b) the change in the spread of the Pareto front is lower than an established tolerance.

In greater detail, the GA operates according to the following scheme, already proposed in [9], where τ represents the generations' index.

Note that Ascione *et al.* [9] proposed this scheme (Scheme 1).

$\tau = 1$
Create the initial population $P^{(1)} \equiv \{\underline{x}_i^{(1)}\}_{i = 1, \ldots, s}$ of s individuals
Calculate $\underline{F}(\underline{x}_i^{(1)})$ for $i = 1, \ldots, s$
Evaluate the rank value and the average crowding distance for each individual of $P^{(1)}$
DO UNTIL at least one stop criterion is satisfied
$\tau = \tau + 1$
Select the parents from $P^{(\tau-1)}$
Generate $P^{(\tau)} \equiv \{\underline{x}_i^{(\tau)}\}_{i = 1, \ldots, s}$ from crossover and mutation of the parents: elite parents survive
Calculate $\underline{F}(\underline{x}_i^{(\tau)})$ for $i = 1, \ldots, s$
Evaluate the rank value and the average crowding distance for each individual of $P^{(\tau)}$
END
Return the Pareto front

Scheme 1. Sequence of the optimization procedure by means of the applied Genetic Algorithm.

Once the Pareto front is obtained, this is investigated in order to select a solution (*i.e.*, a point on the graph) that represents the best configuration of the building envelope.

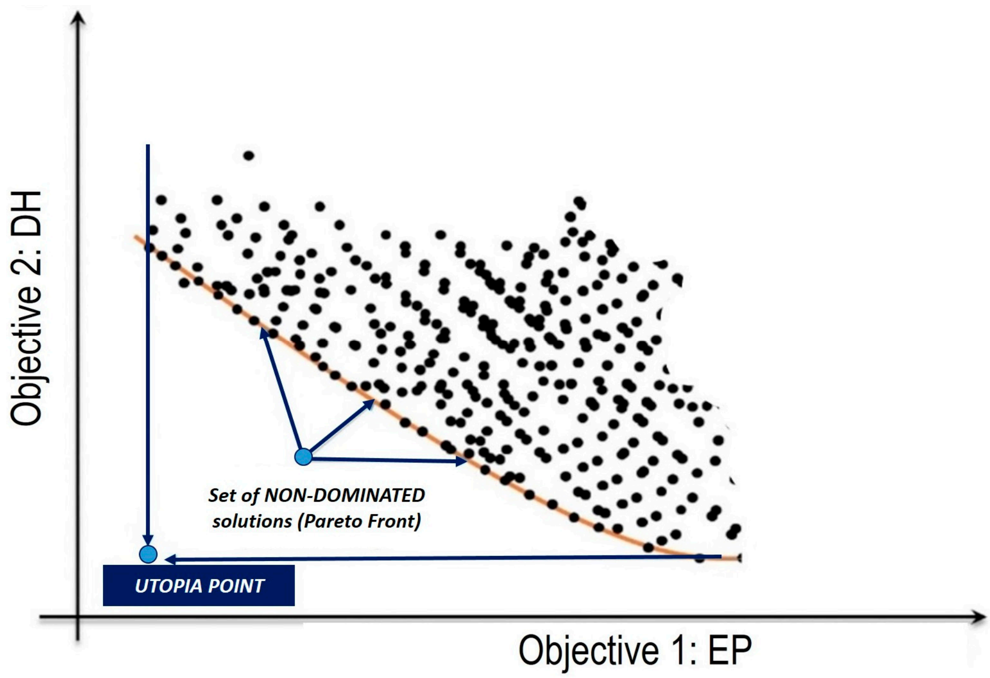

Figure 2. Pareto front and MCDM by means of the utopia point method.

This process is called "Multi-Criteria Decision Making" (MCDM). The stakeholder can adopt different criteria for the MCDM. For instance, the occupant could select the solution that minimizes the thermal discomfort, and the owner could select the one that reduces the energy demand. In intermediate situations, other methods can be used for the MCDM. In particular, in our investigation, the two methods below described are adopted and compared.

(1) *The utopia point method*: the "best" set of design variables is the closest to the ideal point (utopia point) that minimizes both objective functions (see Figure 2). As stated in [42], this approach has already been used in many engineering applications since it gives an equal importance/weight to all objectives.

(2) *The minimum comfort method*: a maximum value of admitted discomfort (DH_{max}) is set and the "best" solution is the one that satisfies this constraint and minimizes EP. This second method is more suitable for building applications since a minimum level of comfort must be usually guaranteed.

In the next sections, the proposed methodology is applied for the optimal design of the thermal envelope of a residential building. Two different climates are investigated in order to explore the impact of weather conditions on the optimal solution.

4. Introduction to the Case Study

The investigated building (Figure 3) in the next step, diversified on the basis of the variation of the main parameters affecting energy performance, has a common shape, geometry, and structural composition. In greater detail, a residential building is considered. It has six floors above the ground, each one with four apartments. This typology is quite common in all European countries where, starting from the reconstruction following the end of the Second World War, a large use of reinforced concrete has characterized the new texture of the cities. The characteristics of the new technology, lightweight and suitable for multistory buildings, answered the deep demand for dwellings due to great urbanization because of the new job opportunities in urban areas. The building is considered as standing alone, without contiguity or proximity to other buildings, because the objective of this study is the evaluation of the individual edifice and not of its characteristics in relation to others, which could change during the building lifespan. As shown by the admirable review of Nguyen *et al.* [42], this assumption is adopted in most studies provided by the current scientific literature concerning the optimization of the energy performance of single buildings. A further investigation could consider the same optimization in a dense urban context, and thus by also evaluating the role played by the presence of surrounding buildings (inter-building effect) and urban vegetation.

It is noticed that the software DesignBuilder [43] has been used for the definition of the building geometry and for the assignment of suitable profiles of building use.

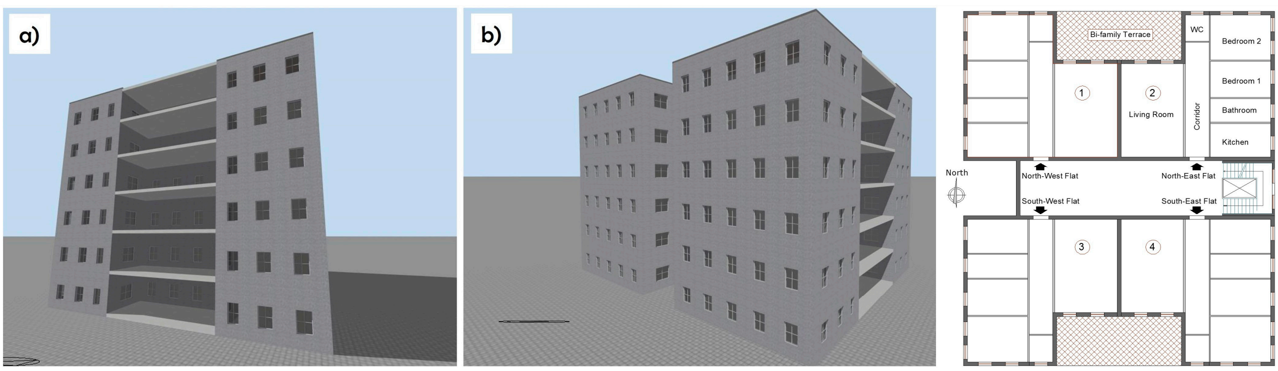

Figure 3. The case study building: (**a**) north and (**b**) west facades.

The building has an overall usable floor area of around 3250 m^2, with 24 apartments, each one of about 110 m^2. The single apartment has two exposures because it is located at a building corner, characterized by an inner height of 3.3 m (net). Detailed information concerning the building dimensions is reported in Table 1. The terminal units of the HVAC system are fan coils, fueled by hot water (45 °C, ΔT = 5 °C between supply and return sides) in the heating season and cold water (7 °C, ΔT = 5 °C) during the cooling period. The generation of hot and chilled water is provided respectively by means of a condensing boiler (fired by natural gas, η = 1.0, with respect to the lower calorific value of the fuel) and of an air-cooled chiller (energy efficiency ratio, at rated conditions, (EER) equals to 2.5). At each floor, a common space, where the elevator and stairs are located, has microclimatic control as well. The heating period has been fixed between 16 November and 31 March, while, with reference to the space cooling, a conventional season starting from 1 June and ending at 30 September has been defined. Of course, the aforementioned time periods are theoretic boundary conditions. In further detail, these are mere "availabilities" and, thus, if the indoor temperature in winter is higher than 20 °C, or lower than 26 °C in summer, the heating and cooling systems, respectively, do not operate. Moreover, for both the space heating and cooling, a maximum operation of 10 h per day has been established, with this kind of approach being common in Mediterranean climates.

According to the peculiarities of the building energy performance simulation (BEPS), all other parameters and boundary conditions affecting building energy behavior and indoor thermal comfort have been considered on an hourly basis. In particular, suitable hourly schedules for endogenous heat gains, artificial lighting (according to different values depending on the rooms' intended use), air changes due to infiltration, and/or voluntary opening of windows and doors, as well as occupant behavior, have been defined according to the databases provided by DesignBuilder [43] (*i.e.*, ASHRAE databases). The potentialities of BEPS have been shown in many studies, mainly when properly calibrated and, if necessary, coupled with specific computational fluid dynamic (CFD) investigations, also suitable for taking into account the lack of homogeneity of indoor conditions in some situations (e.g., high inner heights, big volumes, and so on) [44,45].

Table 1. Building information and geometrical characteristics.

Length (South-North)	23.8 m		**Width (East-West)**		28.4 m
Height	22.8 m		**Gross volume**		12,395.7 m^3
Surface-to-volume ratio	0.318 m^{-1}		**Building net floor area**		3262.0 m^2
Geometry	Total	North (315° to 45°)	East (45° to 135°)	South (135° to 225°)	West (225° to 315°)
Gross wall area [m^2]	2859.8	617.9	812.0	617.9	812.0
Window opening area [m^2]	444.4	95.6	127.7	95.6	125.5
Window-wall ratio [%]	15.5	15.5	15.7	15.5	15.5

4.1. Thermal Characteristics of Opaque and Transparent Building Envelopes

In order to provide useful guidelines for the design of new buildings and for the refurbishment of existing ones, by also taking into consideration the high variability of the thermo-physical properties of the building envelope (mainly related to the age of construction), various levels of thermal insulation of the building will be taken into account. In greater detail, the optimization study will move across the following combinations of typical buildings' stocks:

- buildings built in reinforced concrete, before 1975, and thus when energy saving prescriptions were not mandatory. These architectures have U_{values} of the opaque envelope around 1.2 W/m^2·K (hollow block, no insulation) while the windows' thermal transmittance U_w (single layer, no thermal break) is around 6 W/m^2·K, with a *g*-value (the solar energy transmittance of a glazed system, even called "solar factor") equal to 0.85. With reference to this last term, the *g*-value is a very important characteristic of windows, expressing the amount of solar energy passing through the transparent part, both for direct transmission and as secondary effect due to absorption and emissions inside. Normally, the *g*-value decreases with decreasing U_g (thermal transmittance of the glass).
- buildings built after the energy legislations following the oil crisis due to the Kippur war, in the second half of 1970 and before 2000. These architectures have low values of thermal insulation of the opaque envelope ($U_{value} \approx 0.7$ W/m^2·K) and simple double-glazed windows ($U_w = 3.3$ W/m^2·K, *g*-value = 0.76).
- buildings born under the prescriptions of the EPBD 2002/91/EU, with more than 6–10 cm of insulating layers. The U_{value} of the opaque envelope is commonly lower than 0.45 W/m^2·K, the windows have double glass with argon-filled cavities and frames with thermal breaks (U_w= 2.5 W/m^2·K, *g*-value = 0.70).
- buildings designed in order to meet the standard of nearly zero-energy buildings, strongly insulated, born under the prescriptions of the EPBD Recast 2010/31/EU with more than 10 cm of insulating layers. The U_{value} of the opaque envelope is lower than 0.30 W/m^2·K, the windows have low-emissive (with good reflective properties) triple-glass and high-tech frames ($U_w = 1.35$ W/m^2·K, *g*-value = 0.56).

In the optimization study, the decision variables will be properly set in order to cover the described configurations. The last outcome will be an optimal building envelope that optimizes energy performance and thermal comfort. Such an optimal solution is not obvious because it should provide the best trade-off between heating and cooling needs.

The base composition of the envelope is shown in Figure 4. Note that for some layers, the thickness (t) is not reported because it will be a decision variable during the optimization phase.

4.2. Spectral Characteristics of the External Coatings

In the optimization study, as mentioned, a wide range of the thermal insulation levels of the building envelope will be analyzed in order to find the best compromise in combination with the other variables. With reference to the radiative behavior of the sun-, sky-, and wind-exposed surfaces, multiple sets of solar absorptance and infrared emissivity have been considered. The heat transfer between the indoor space and the outdoor environment is due to both radiation to/from sky and sun, as well as to the different temperatures between the air-conditioned rooms and the outside spaces. In this regard, the outer surface temperatures highly influence the heat losses in wintertime and the heat gains during the warm season. In order to take into account the surface temperature, several methods can be applied, such as the one based on the concept of sol air temperature (Equation (4)) or the cooling load temperature difference/cooling load factor/solar cooling load factor - CLTD/CLF/SCL.

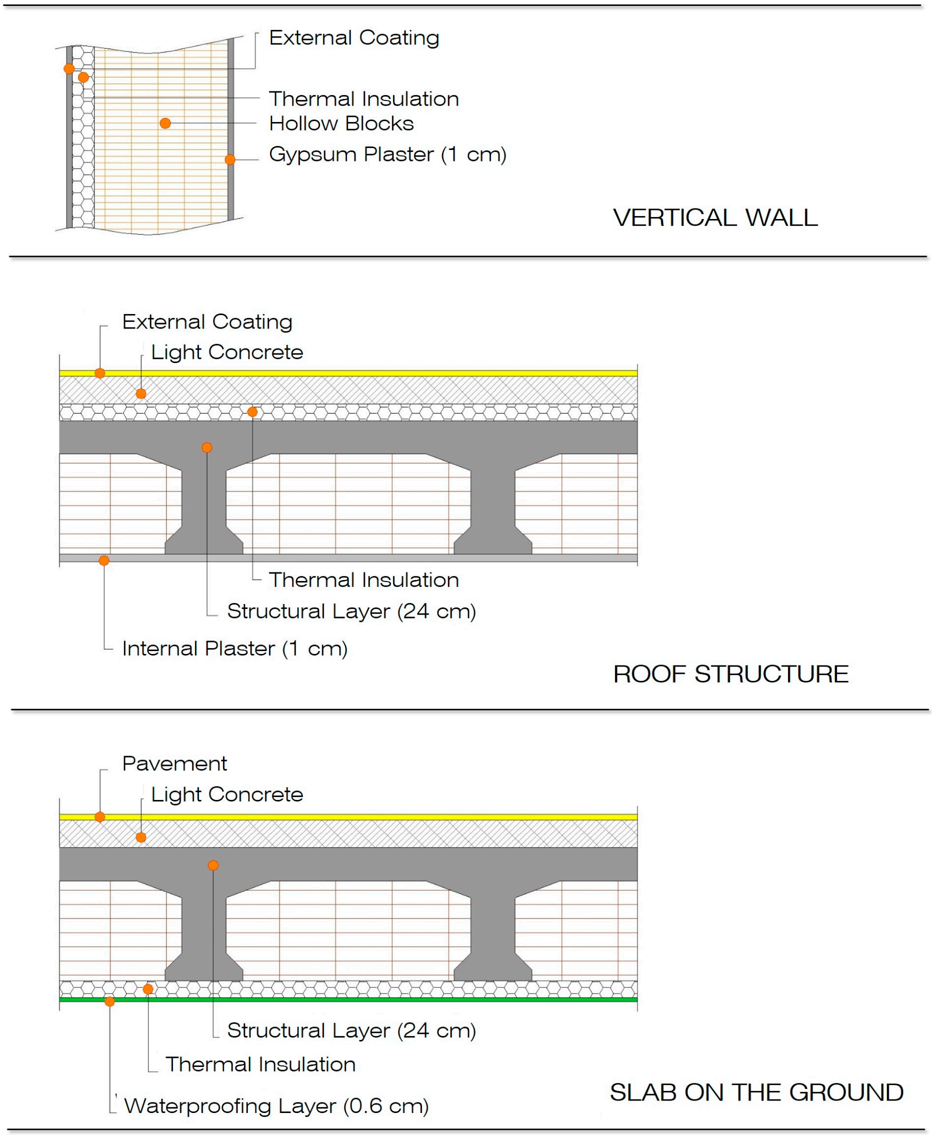

Figure 4. Base composition of the building envelope.

$$\theta_{sol-air} = \theta_{outdoor} + \frac{I \cdot \alpha_{solar}}{h_{ext}} - \frac{\Delta R \cdot \varepsilon_{infrared}}{h_{ext}} \quad (4)$$

In Equation (4), the following terms are defined:

- $\Theta_{outdoor}$ is the outdoor air temperature [°C];
- I is the solar irradiance, and thus the total solar radiation incident on the surface [W/m^2];
- ΔR is the difference between radiation emitted by a blackbody at the outdoor air temperature and long-wave radiation incoming on a surface from the sky and the surroundings [W/m^2];
- h_{ext} is the global heat transfer coefficient of the external surface for convection and radiation [W/m^2·K];

- α_{solar} is the absorptance coefficient of the external coating referred to the wavelengths of the solar spectrum [-]; afterwards, it will be simply indicated with α;
- $\varepsilon_{infrared}$ is the emissivity of the surface referred to the far-infrared wavelengths [-]; afterwards, it will be simply indicated with ε.

If the heat transfer between the building and external environment (ambient, sky, and sun) is evaluated by means of the sol air temperature, the role played by the external coating is easy to understand. In both the heating and cooling seasons, it affects the solar energy absorbed by the surfaces (that rises the temperature) and the heat emitted back to the environment, related to the emissivity.

Conversely, the CLTD/CLF/SCL method evaluates a proper temperature difference by also considering the solar radiation (in the term CLTD or Cooling Load Temperature Difference), the time lag due to the thermal capacity (in the term CLF or Cooling Load Factor), the gains through glazed parts (in the term SC or Shading Coefficient).

All told, the proposed optimization will take into consideration these phenomena in order to provide guidelines for a proper choice of levels of insulation, thermal capacity of the envelope, and spectral coefficients of the outer building surfaces, with respect to the climate. Therefore, α and ε will represent two decision variables: α will range between 0.1 and 0.9, ε will range between 0.4 and 0.9. For instance, white/cool plasters can have $\alpha = 0.1$ and $\varepsilon = 0.9$, while metallic coatings in new aluminum can have $\alpha = 0.7$ and $\varepsilon = 0.5$. Due to the large experimental research in this field (for instance, see the study of Song *et al.* [46,47] on the matter of non-white cool materials), all combinations among the aforementioned values of α and ε will be considered in the optimization.

4.3. Thermal Capacity of the Building Envelope

According to the building structures proposed in Figure 4, a wide combination of thicknesses and various densities of the masonry layers can characterize the bricks. In particular, even if the structural frame of the building is based on the use of reinforced concrete, the vertical wall as well as the ceiling can be characterized by different values of thermal capacity due to various densities (ρ) of adopted materials or thicknesses (t) of the layers. In this case study, by taking into consideration typical bricks used in the constructions sector, densities ranging between 800 and 2000 kg/m^3 have been considered. Moreover, the thickness of masonry layer of the walls has also been assumed variable between 10 and 25 cm, while, with reference to the roof and basement slab, this is a mixed layer of 24 cm. Finally, densities and thicknesses of the brick layers will influence the areic mass of the envelope and, thus, the thermal capacity of the opaque building shell.

4.4. Investigated Climates

This study aims to define both a novel methodology for combining thermal physical properties of the building envelope and, at the same time, to provide useful guidelines to be adopted in Mediterranean climates. Therefore, by fixing the 41st parallel north as the latitude, two European cities have been selected: (a) Naples (Italy) and Istanbul (Turkey). The main climatic peculiarities of these localities are shown in Figure 5, in which it is clear that Istanbul is characterized by a colder climate. In greater detail, according to the Köppen-Geiger classification [48], Naples is “Csa” (interior Mediterranean, mild with dry, hot summer), Istanbul is "Cfa" (humid subtropical, mild with no dry season, hot summers). It means that both cities can be classified as characterized by a moderate Mediterranean climate. Naples has mild winters and dry, hot summers because of the subtropical high-pressure system. Istanbul, conversely, has a colder winter season, with year-round rainfall, and hot, muggy summers, often characterized by thunderstorms.

Climate parameter	INVESTIGATED CLIMATES		
		Naples	Istanbul
Heating Degrees Day	[K*Day]	1365	1885
Max Direct Normal Solar Radiation	[kWh/m^2]	8.7 (9 May)	8.1 (24 July)
Winter Design Outdoor Temperature	[°C]	1.9	-1.0
Cooling Design Outdoor Temperature	[°C]	31.9	30.0

Figure 5. The two investigated climates at 41°N in latitude: Naples and Istanbul (from the IWEC—International Weather for Energy Calculations-methodology [49], the baseline for the calculation of heating degrees days–HDD is 18.3 °C).

The colder climate of Istanbul can also be understood by analyzing the heating degrees days (HDD index) of the cities, as well as the outdoor design temperature, for evaluating the heating load at the peak and, thus, for sizing the heating systems. With reference to the cooling period, the instability of the weather of Istanbul also causes summer conditions less critical compared to Naples, with a lower design temperature for cooling and lower solar radiation at the peak.

5. Results and Discussion

5.1. Parameters of the Genetic Algorithm

In this study, the control parameters of the GA assume the values reported in Table 2, where s is the size of the population, c_e is the elite count, f_c is the crossover fraction, f_m is the mutation probability, g_{max} is the maximum number of generations, and tol is the tolerance in the average change of the spread of Pareto front. Such values derive from both previous studies [9,50,51] and from some tests preliminarily performed by the authors in order to obtain a satisfactory compromise between the computational burden and the reliability of the results.

Table 2. Definition of the control parameters of the Genetic Algorithm.

s	c_e	f_c	f_m	g_{max}	**tol**
25	2	0.6	0.1	30	0.001

5.2. Decision Variables

The decision variables are reported in Table 3, which also shows the respective ranges of variability and the number of bits that are required for the coding of the variables. The thermal insulation is applied externally (see Figure 4) and it is installed on the whole opaque external envelope (walls, roof, slab on the ground). A common thermal insulating material is considered, *i.e.*, expanded polystyrene (EPS), characterized by a thermal conductivity (k) equal to 0.04 W/m·K. The optimization study considers the four window types previously described in Subsection 4.1.

Table 3. Characterization of the decision variables.

Decision Variables	**Range of Variability**	**Number of Possible Discrete Values**	**Number of Bits for Variable Coding**
Solar absorptance of the external plastering (a)	From 0.1 to 0.9 with a step of 0.05 (the values 0.45 and 0.55 are excluded)	15	4
Infrared emittance of the external plastering (ε)	From 0.4 to 0.9 with a step of 0.05	11	4
Thickness of the thermal insulant (t_i) [m]	From 0.03 m to 0.18 m with a step of 0.01 m	16	4
Thickness of the brick (t_b) [m]	0.10, 0.15, 0.20, 0.25	4	2
Brick density (ρ) [kg/m^3]	600, 800, 1000, 1200, 1400, 1600, 1800, 2000 *	8	3
Thermal transmittance of windows (U_w) [W/m^2·K]	1.35, 2.5, 3.3, 6 **	4	2

* Please note that there is a relation between density and thermal conductivity. In greater detail, in correspondence with the eight different values of ρ, the brick thermal conductivity (k [W/m·K]) assumes the following values: 0.25, 0.30, 0.36, 0.43, 0.5, 0.59, 0.72, 0.90; ** As shown in Subsection 4.1, there is a relation between windows' thermal transmittance and solar factor. In greater detail, in correspondence with the four values of U_w, the *g*-values are, respectively, equal to: 0.56, 0.70, 0.76, 0.85.

It is noted that the number of the possible configurations of the building thermal envelope is equal to $15 \times 11 \times 16 \times 4 \times 8 \times 4 = 337{,}920$, whereas the maximum number of configurations investigated by the GA is equal to $g_{max} \times s = 750$. Therefore, the proposed methodology ensures a saving of computational time of about 99.8% compared to an exhaustive search.

5.3. Main Outcomes

The Pareto front, which shows the non-dominated configurations of the thermal envelope for the investigated building located in Naples, is proposed in Figure 6. The values of the objective functions and decision variables in correspondence with these solutions are reported respectively in Tables 4 and 5.

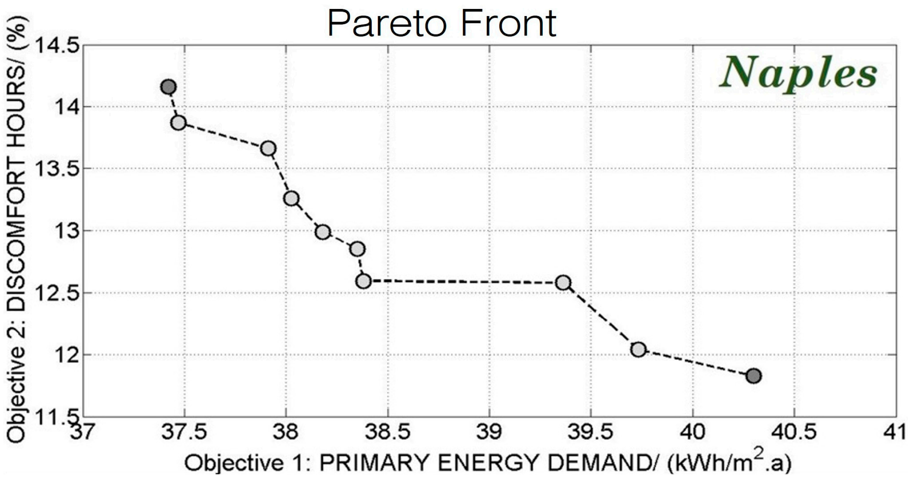

Figure 6. Pareto front: non-dominated configurations of the building thermal envelope for Naples.

Table 4. Values of the objective functions on the Pareto front for the building located in Naples. The solutions selected for the comfort criterion (DH_{max} = 13.5%) and the utopia point criterion during the MCDM are highlighted.

	EP [kWh/m²·a]	DH [%]	
1	37.42	14.16	
2	37.47	13.87	
3	37.91	13.67	
4	38.03	13.26	→ COMFORT CRITERION
5	38.18	12.99	
6	38.35	12.85	
7	38.38	12.60	→ UTOPIA CRITERION
8	39.36	12.58	
9	39.73	12.04	
10	40.30	11.83	

All optimal solutions are characterized by the same values of α (equal to 0.1) and ε (equal to 0.9). It happens because of the high impact of space cooling for the considered geographical location, with a consequent need for the reduction of the solar heat gain. Thus, it can be generalized that cool coatings and cool materials are, for the foreseeable future, suitable for optimizing the overall building energy performance.

With reference to the thermal quality of windows, all the points on the Pareto front present the same window type, characterized by low values of U_w (equal to 1.35 W/m²·K) and *g*-value (equal to 0.56), because the adoption of highly efficient windows, with low-emissive and reflective coatings, is advantageous for residential buildings in both cold and warm seasons. This induces lower thermal losses in winter, as well as an increment of the indoor mean radiant temperature, by improving the thermal comfort. In summer, conflicting effects happen. The coatings (low-emissive and reflective) reduce the entering gains due to solar radiation since the *g*-value is equal to 0.56, even if the thermal losses from inside to outside during some hours (mainly in the intermediate seasons) are lowered. In any case, at least for residential buildings, the first beneficial effect prevails. Furthermore, most solutions (eight of 10) provide a high value of ρ (*i.e.*, density) of the brick layer, equal to 1800 kg/m^3. This is justified by the exigency of providing the building envelope with an adequate thermal resistance in wintertime and with a satisfactory thermal capacity in summertime. In other words, high values of the envelope density, in the presence of a layer of thermal insulation, ensure a good trade-off between the different needs of the heating and cooling seasons for a balanced climate (like the one investigated).

Table 5. Values of the decision variables on the Pareto front for the building located in Naples. The solutions selected for the comfort criterion (DH_{max} = 13.5%) and the utopia point criterion during the MCDM are highlighted.

	a [-]	ε [-]	t_i [m]	t_b [m]	ρ [kg/m^3]	k [W/m·K]	U_w [W/m^2·K]	
1	0.10	0.90	0.14	0.25	1800	0.72	1.35	
2	0.10	0.90	0.13	0.25	1800	0.72	1.35	
3	0.10	0.90	0.13	0.25	1600	0.72	1.35	
4	0.10	0.90	0.14	0.15	1800	0.72	1.35	→ COMFORT CRITERION
5	0.10	0.90	0.13	0.15	1800	0.72	1.35	
6	0.10	0.90	0.14	0.10	1800	0.72	1.35	
7	0.10	0.90	0.13	0.10	1800	0.72	1.35	→ UTOPIA CRITERION
8	0.10	0.90	0.08	0.25	1600	0.59	1.35	
9	0.10	0.90	0.08	0.15	1800	0.72	1.35	
10	0.10	0.90	0.06	0.10	600	0.25	1.35	

Finally, the solutions show different combinations of the thicknesses of brick and thermal insulation in order to ensure a suitable compromise between the heating and cooling energy demands.

The specific stakeholder can prefer any of the points on the Pareto front by keeping in mind an opportune criterion for the Multi-Criteria Decision Making (MCDM). For instance, the utopia point criterion or the minimum comfort criterion can be adopted, as shown in Figure 7. For the comfort criterion, the maximum acceptable level of DH is set equal, for the sake of the example, to 13.5%, which is an intermediate value among those characterizing the non-dominated solutions (DH_{max} = 13.5%).

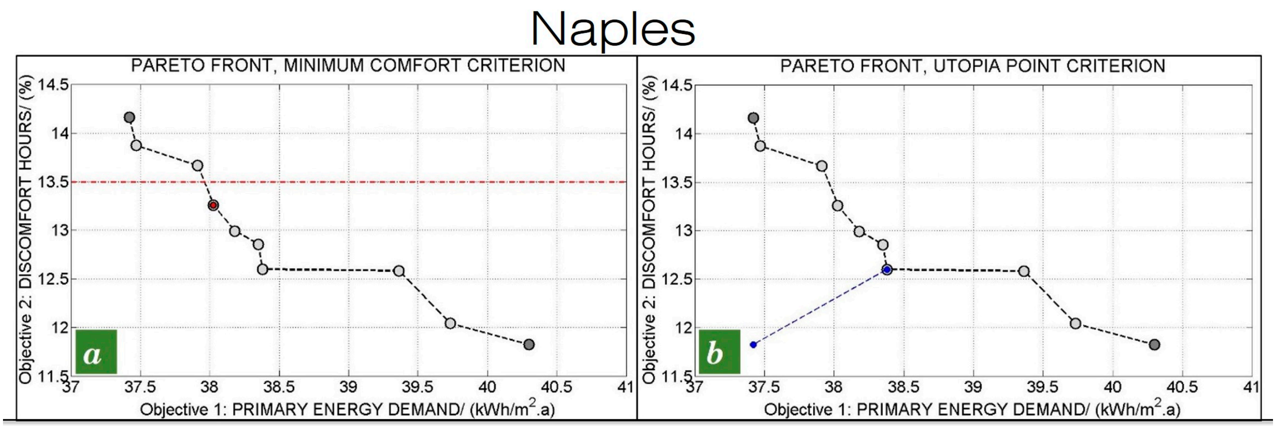

Figure 7. MCDM for selecting a solution from the Pareto front related to the building located in Naples: (**a**) minimum comfort criterion (DH_{max} = 13.5%); (**b**) utopia point criterion.

Furthermore, in order to verify the uniformity of the results in another climate of the same Mediterranean area at the same latitude, the same investigation has been carried out by considering the same building located in Istanbul. This is also a way to verify the consistency of the proposed procedure. The results are summarized in Figure 8, Tables 6 and 7.

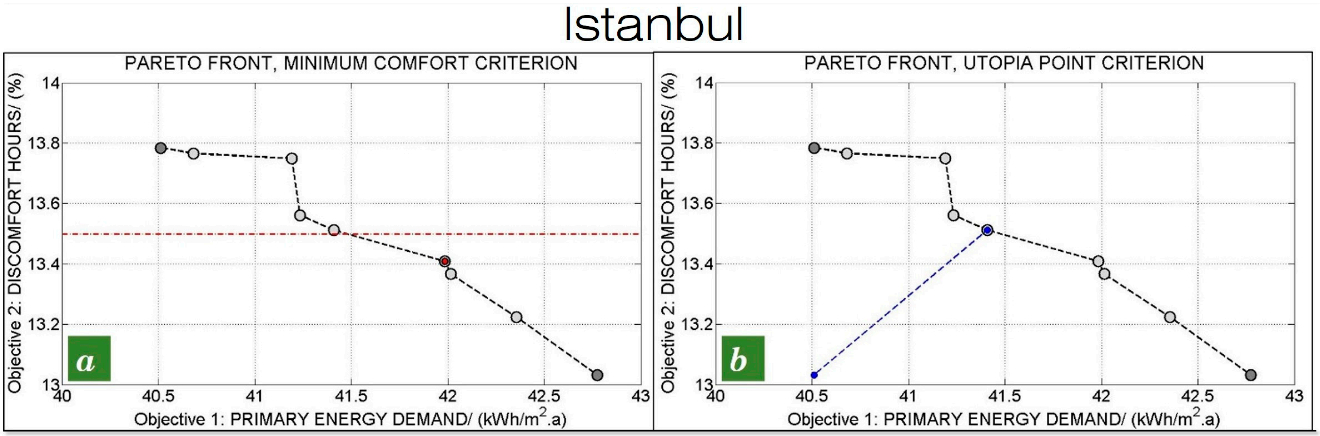

Figure 8. MCDM for selecting a solution from the Pareto front related to the building located in Istanbul: (**a**) minimum comfort criterion (DH_{max} = 13.5%); (**b**) utopia point criterion.

The outcomes for Istanbul are quite similar to those obtained for Naples. In particular, these differ mainly for the higher values of the thickness of the thermal insulation. This is reasonable and occurs because Istanbul is characterized by a more significant heating demand compared to Naples, due to a colder winter season: the EP values are higher, as well as the Heating Degrees-Day reported in Figure 5. Finally, the results show the reliability of the proposed methodology.

Table 6. Values of the objective functions on the Pareto front for the building located in Istanbul. The solutions selected for the comfort criterion (DH_{max} = 13.5%) and the utopia point criterion during the MCDM are highlighted.

	EP [kWh/m²·a]	DH [%]	
1	40.51	13.78	
2	40.68	13.77	
3	41.19	13.75	
4	41.23	13.56	
5	41.41	13.52	→ UTOPIA CRITERION
6	41.99	13.41	→ COMFORT CRITERION
7	42.01	13.37	
8	42.36	13.22	
9	42.36	13.22	
10	42.78	13.03	

Table 7. Values of the decision variables on the Pareto front for the building located in Istanbul. The solutions selected for the comfort criterion (DH_{max} = 13.5%) and the utopia point criterion during the MCDM are highlighted.

	a [-]	**ε** [-]	$\mathbf{t_i}$ [m]	$\mathbf{t_b}$ [m]	**ρ** [kg/m^3]	**k** [W/m·K]	$\mathbf{U_w}$ [W/m^2·K]	
1	0.1	0.9	0.18	0.25	2000	0.90	1.35	
2	0.1	0.9	0.17	0.25	2000	0.90	1.35	
3	0.1	0.8	0.18	0.20	2000	0.90	1.35	
4	0.1	0.9	0.18	0.25	1600	0.59	1.35	
5	0.1	0.9	0.17	0.25	1600	0.59	1.35	→ UTOPIA CRITERION
6	0.1	0.8	0.18	0.15	1600	0.59	1.35	→ COMFORT CRITERION
7	0.1	0.9	0.18	0.15	1600	0.59	1.35	
8	0.1	0.4	0.06	0.10	600	0.25	1.35	
9	0.1	0.9	0.17	0.10	1600	0.59	1.35	
10	0.1	0.9	0.17	0.25	800	0.30	1.35	

6. Conclusions

The paper presents a novel optimization procedure for designing the thermal characteristics of the building envelope, with reference to both new and refurbished buildings, by means of a multi-objective approach. Several parameters characterize the thermo-physical performance of the building shell, such as the thermal transmittance, the thermal capacity, the behavior of the transparent envelope, and the radiative properties of external coatings. That is why the design of the building thermal envelope is a complex task. Furthermore, today, given the high diffusion of the system and equipment for space cooling, the building energy demand has to be minimized on the basis of both winter and summer seasons. Therefore, the old approach, which merely focused on the reduction of heating demand, is not proper for balanced climates such as the Mediterranean ones. Starting from this observation, a new approach is proposed here.

The methodology is based on the coupling between EnergyPlus and MATLAB®, which allows us to solve a multi-objective optimization problem by means of the implementation of a Genetic Algorithm. The thermal design of the building envelope is optimized in order to pursue two objectives: the minimization of primary energy demand for the annual space conditioning and the minimization of thermal discomfort hours. The decision variables concern different parameters characterizing the thermal envelope of the building, and thus: the aptitude to absorb or reflect the solar radiation, the infrared emission, the thickness of the insulation, the density and thickness of the masonry layers, and the quality of the windows. The methodology is applied to a residential building by taking into consideration two different Mediterranean climates: Naples and Istanbul (colder climate). The results show that for Naples, because of the significant incidence of the cooling demand, cool colors and cool materials are always suitable. Diversely, the insulation of the walls should be high but not excessive (no more than 13–14 cm), even if the Pareto front has solutions with 6 cm. The importance of high-reflective coating is also clear in colder Mediterranean climates, such as Istanbul, where the coatings should reflect the solar radiation in order to improve the summer comfort and to reduce the cooling demand even if the most suitable thicknesses of thermal insulation are higher (around 16–18 cm). In both the climates, the thermal envelope should have a significant mass, obtainable by adopting dense and/or thick masonry layers.

In general, the methodology can be considered solid and effective from the point of view of the computational effort by requiring only 0.22% of the building energy simulations (EnergyPlus) required for an exhaustive search.

Future studies will concern the enhancement of the proposed methodology in order to allow a more flexible optimization by varying the thermal and optical characteristics of the building envelope, depending on the exposure, thereby aiming not only to decrease the whole building's energy demand, but also to minimize the "energy performance difference between housing units" (EDH) [37,38].

Author Contributions

The proposed study is part of a research carried out by all authors, within a synergic collaboration, with continuous reciprocal feedbacks during the literature studies, the development of the numerical methodology, the selection of parameters and criteria of the optimization study, the writing of the text. Indeed, optimization of energy performance, in terms of energy savings and improvement of thermal comfort in buildings, are topics largely investigated, in several studies, by the research group. Finally, all authors contributed in all phases of the work.

Conflicts of Interest

The authors declare no conflict of interest.

Nomenclature

DH	Percentage of annual discomfort hours [%]
DH_{max}	Maximum value of DH, using the minimum comfort level
EER	Energy efficiency ratio [-]
EP	Annual primary energy for space conditioning per unit floor area
$\underline{F}$	Vector of objective functions $\underline{F}$ = [EP, DH]
GA	Genetic algorithm
g-value	Solar factor of a glazed system [-]
HVAC	Heating, ventilating, and air conditioning
k	Thermal conductivity [W/m·K]
MCDM	Multi-criteria decision making
t	Thickness [m]
U_{value}	Thermal transmittance [W/m^2·K]
U_w	Thermal transmittance of the windows (glass + frame) [W/m^2·K]
$\underline{x}$	Vector of decision variables
Greek symbols	
α	Solar absorptance [-]
ε	Thermal (infrared) emissivity [-]
η	Boiler nominal efficiency [-]
ρ	Density [kg/m^3]
Subscripts	
b	Referred to bricks (masonry layers)
i	Referred to thermal insulant

References

1. European Commission and Parliament. *Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the Energy Performance of Buildings*; European Commission and Parliament: Brussels, Belgium, 2002.
2. European Committee for Standardization. *Explanation of the General Relationship between Various European Standards and the Energy Performance of Buildings Directive (EPBD)—Umbrella Document*; Technical Committee CEN/SS B09, CEN/TR 15615; European Committee for Standardization: Brussels, Belgium, 2008.
3. European Commission and Parliament. *Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the Energy Performance of Buildings (EPBD Recast)*; European Commission and Parliament: Brussels, Belgium, 2010.
4. European Commission. *Commission Delegated Regulation (EU) No 244/2012 of 16 January 2012 Supplementing Directive 2010/31/EU of the European Parliament and of the Council on the Energy Performance of Buildings*; European Commission: Brussels, Belgium, 2012.
5. Buildings Performance Institute Europe (BPIE). Implementing the Cost-Optimal Methodology in EU Countries. Available online: http://bpie.eu/cost_optimal_methodology.html#.UxS0s_l5OCk (accessed on 5 August 2015).
6. Pikas, E.; Thalfeldt, M.; Kurnitski, J. Cost optimal and nearly zero energy building solutions for office buildings. *Energy Build.* **2014**, *74*, 30–42.
7. Ferrara, M.; Fabrizio, E.; Virgone, J.; Filippi, M. A simulation-based optimization method for cost-optimal analysis of nearly Zero Energy Buildings. *Energy Build.* **2014**, *84*, 442–457.
8. Pikas, E.; Kurnitski, J.; Liias, R.; Thalfeldt, M. Quantification of economic benefits of renovation of apartment buildings as a basis for cost optimal 2030 energy efficiency strategies. *Energy Build.* **2015**, *86*, 151–160.
9. Ascione, F.; Bianco, N.; de Stasio, C.; Mauro, G.M.; Vanoli, G.P. A new methodology for cost-optimal analysis by means of the multi-objective optimization of building energy performance. *Energy Build.* **2015**, *88*, 78–90.
10. European Parliament. *Directive 2012/27/EU of The European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC*; Official Journal of the European Union L 315, 14.11; European Parliament: Brussels, Belgium, 2012.
11. American National Standards Institute and American Society of Heating, Refrigerating and Air-Conditioning Engineers. *Thermal Environmental Conditions for Human Occupancy, American Society of Heating*; ANSI/ASHRAE 55; American National Standards Institute and American Society of Heating, Refrigerating and Air-Conditioning Engineers: Atlanta, GA, USA, 2004.
12. CEN- European Committee for Standardization. *EN 15251: Energy Performance of Buildings—Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings- Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics*; CEN—European Committee for Standardization: Brussels, Belgium, 2007.

13. International Organisation for Standardization. *Ergonomics of the Thermal Environments—Analytical Determination and Intrepretation of Thermal Comfort using the PMV and PPD Indices and Local Thermal Comfort Criteria*; ISO—International Organisation for Standardization: Geneva, Switzerland, 2005.
14. Kolokotroni, M.; Ren, X.; Davies, M.; Mavrogianni, A. London's urban heat island: Impact on current and future energy consumption in office buildings. *Energy Build.* **2012**, *47*, 302–311.
15. Jenkins, D.P.; Patidar, S.; Banfill, P.F.G.; Gibson, G.J. Probabilistic climate projections with dynamic building simulation: Predicting overheating in dwellings. *Energy Build.* **2011**, *43*, 1723–1731.
16. Santamouris, M.; Kolokotsa, D. Passive cooling dissipation techniques for buildings and other structures: The state of the art. *Energy Build.* **2013**, *57*, 74–94.
17. Santamouris, M.; Kolokotsa, D. On the impact of urban overheating and extreme climatic conditions on housing, energy, comfort and environmental quality of vulnerable population in Europe. *Energy Build.* **2015**, *98*, 125–133.
18. Santamouris, M.; Cartalis, C.; Synnefa, A.; Kolokotsa, D. On the impact of urban heat island and global warming on the power demand and electricity consumption of buildings—A review. *Energy Build.* **2014**, doi:10.1016/j.enbuild.2014.09.052.
19. Porritt, S.M.; Cropper, P.C.; Shao, L.; Goodier, C.I. Ranking of interventions to reduce dwelling overheating during heat waves. *Energy Build.* **2012**, *55*, 16–27.
20. Ascione, F.; Bellia, L.; Mazzei, P.; Minichiello, F. Solar gain and building envelope: The surface factor. *Build. Res. Inf.* **2010**, *38*, 187–205.
21. Ascione, F.; Bianco, N.; de Masi, R.F.; de Rossi, F.; Vanoli, G.P. Energy refurbishment of existing buildings through the use of phase change materials: Energy savings and indoor comfort in the cooling season. *Appl. Energy* **2014**, *113*, 990–1007.
22. Mlakar, J.; Štrancar, J. Overheating in residential passive house: Solution strategies revealed and confirmed through data analysis and simulations. *Energy Build.* **2011**, *43*, 1443–1451.
23. Badescu, V.; Laaser, N.; Crutescu, R. Warm season cooling requirements for passive buildings in Southeastern Europe (Romania). *Energy* **2010**, *35*, 3284–3300.
24. Bellia, L.; de Falco, F.; Minichiello, F. Effects of solar shading devices on energy requirements of standalone office buildings for Italian climates. *Appl. Therm. Eng.* **2013**, *54*, 190–201.
25. Katunský, D.; Lopušniak, M. Impact of shading structure on energy demand and on risk of summer overheating in a low energy building. *Energy Proc.* **2012**, *14*, 1311–1316.
26. Yao, J. An investigation into the impact of movable solar shades on energy, indoor thermal and visual comfort improvements. *Build. Environ.* **2014**, *71*, 24–32.
27. Yao, J. Determining the energy performance of manually controlled solar shades: A stochastic model based co-simulation analysis. *Appl. Energy* **2014**, *127*, 64–80.
28. Yao, J.; Chow, D.H.C.; Zheng, R.Y.; Yan, C.W. Occupants' impact on indoor thermal comfort: A co-simulation study on stochastic control of solar shades. *J. Build. Perform. Simul.* **2015**, doi:10.1080/19401493.2015.1046492.
29. Cotana, F.; Rossi, F.; Filipponi, M.; Coccia, V.; Pisello, A.L.; Bonamente, E.; Petrozzi, A.; Cavalaglio, G. Albedo control as an effective strategy to tackle Global Warming: A case study. *Appl. Energy* **2014**, *130*, 641–647.

30. Pisello, A.L.; Taylor, J.E.; Xu, X.; Cotana, F. Inter-building effect: Simulating the impact of a network of buildings on the accuracy of building energy performance predictions. *Build. Environ.* **2012**, *58*, 37–45.
31. Pisello, A.L.; Castaldo, V.L.; Taylor, J.E.; Cotana, F. Expanding Inter-Building Effect modeling to examine primary energy for lighting. *Energy Build.* **2014**, *76*, 513–523.
32. Salata, F.; Golasi, I.; Vollaro, A.D.L.; Vollaro, R.D.L. How high albedo and traditional buildings' materials and vegetation affect the quality of urban microclimate. A case study. *Energy Build.* **2015**, *99*, 32–40.
33. Kamali, S. Review of free cooling system using phase change material for building. *Energy Build.* **2014**, *80*, 131–136.
34. Inard, C.; Pfafferott, J.; Ghiaus, C. Free-running temperature and potential for free cooling by ventilation: A case study. *Energy Build.* **2011**, *43*, 2705–2711.
35. Shaviv, E.; Yezioro, A.; Capeluto, I.G. Thermal mass and night ventilation as passive cooling design strategy. *Renew. Energy* **2001**, *24*, 445–452.
36. Ascione, F.; Bianco, N.; de Stasio, C.; Mauro, G.M.; Vanoli, G.P. Dynamic insulation of the building envelope: Numerical modeling under transient conditions and coupling with nocturnal free cooling. *Appl. Therm. Eng.* **2015**, *84*, 1–14.
37. Yao, J. Energy optimization of building design for different housing units in apartment buildings. *Appl. Energy* **2012**, *94*, 330–337.
38. Yao, J. A multi-objective (energy, economic and environmental performance) life cycle analysis for better building design. *Sustainability* **2014**, *6*, 602–614.
39. EnergyPlus, the Official Building Simulation Program of the United States Department of Energy. Available online: http://www.eere.energy.gov/buildings (accessed on 5 July 2015).
40. MATLAB®-MATrixLABoratory (2010)—7.10.0. User's Guide MathWorks. Available online: http://it.mathworks.com (assessed on 7 August 2015).
41. Deb, K. *Multi-Objective Optimization Using Evolutionary Algorithms*; John Wiley & Sons: Chichester, UK, 2001; Volume 2012.
42. Nguyen, A.T.; Reiter, S.; Rigo, P. A review on simulation-based optimization methods applied to building performance analysis. *Appl. Energy* **2014**, *113*, 1043–1058.
43. DesignBuilder. *DesignBuilder V 3.2.0.067*; DesignBuilder Software Ltd.: Gloucestershire, UK, 2013.
44. Ascione, F.; Bellia, L.; Capozzoli, A. A coupled numerical approach on museum air conditioning: Energy and fluid-dynamic analysis. *Appl. Energy* **2013**, *103*, 416–427.
45. Ascione, F.; Minichiello, F. Microclimatic control in the museum environment: Air diffusion performance. *Int. J. Refrig.* **2010**, *33*, 806–814.
46. Song, J.; Qin, J.; Qu, J.; Song, Z.; Zhang, W.; Xue, X.; Shi, Y.; Zhang, T.; Ji, W.; Zhang, R.; *et al.* The effects of particle size distribution on the optical properties of titanium dioxide rutile pigments and their applications in cool non-white coatings. *Sol. Energy Mater. Sol. Cells* **2014**, *130*, 42–50.
47. Song, J.; Qin, J.; Qu, J.; Song, Z.; Zhang, W.; Xue, X.; Shi, Y.; Zhang, T.; Ji, W.; Zhang, R.; *et al.* A systematic investigation of the factors affecting the optical properties of near infrared transmitting cool non-white coatings. *Sol. Energy Mater. Sol. Cells* **2014**, *125*, 206–214.
48. Kottek, M.; Grieser, J.; Beck, C.; Rudolf, B.; Rubel, F. World map of the Köppen-Geiger climate classification updated. *Meteorol. Z.* **2006**, *15*, 259–263.

49. American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). *International Weather for Energy Calculations (IWEC Weather Files) Users Manual and CD-ROM*; ASHRAE: Atlanta, GA, USA, 2001.
50. Li, Y.F.; Ng, S.H.; Xie, M.; Goh, T.N. A systematic comparison of metamodeling techniques for simulation optimization in decision support systems. *Appl. Soft Comput.* **2010**, *10*, 1257–1273.
51. Li, Y.F.; Xie, M.; Goh, T.N. A study of project selection and feature weighting for analogy based software cost estimation. *J. Syst. Softw.* **2009**, *82*, 241–252.