The Cost-Optimal Optimization of public buildings in cold and warm climates: two case-studies in Germany and Italy

F Ascione1 *, N Bianco1, O Boettcher2, T Iovane1, M Mastellone3, G M Mauro4 and J Muehle2

1 Department of Industrial Engineering – DII, Università degli Studi di Napoli Federico II, Naples, 80125, IT
2 BBSR - Federal Institute for Research on Building, Urban Affairs, and Spatial Development - Division WB 7 - Energy-Optimized Building, Berlin, 10785, DE
3 Department of Architecture – DIARC, Università degli Studi di Napoli Federico II, Naples, 80134, IT
4 Department of Engineering - DING, Università degli Studi del Sannio, Benevento, 82100, IT
* fabrizio.ascione@unina.it, Olaf.Boettcher@BBR.Bund.de

Abstract. Directive EU 844/2018, in the matter of energy performance of buildings and future goals of energy efficiency for the EU Member Countries, extends the standard of nearly zero-energy building goals to the existing building stock, with the mandatory aim of almost complete decarbonization of the whole sector within 2050, and thus a strong reduction of greenhouse gas pollution of about 80-95% compared to the levels of ’90s. In this frame, the present study purposes the multi-objective optimizations of two office buildings, located in Berlin (Germany, European backcountry, “Cfb” climate in the classification of Köppen and Geiger) and Naples (Italy, Mediterranean coast, “Csa” climate classification), with the aim of finding the best trade-off between two couples of contrasting targets, representative of private and public interests, respectively: minimization of indoor thermal discomfort and operational costs, and minimization of indoor thermal discomfort and environmental impact. In addition, an investment cost analysis is performed by optimizing operational costs and total construction costs. The explored and investigated energy conservation measures, to apply during the building retrofit, involve the main levers of energy efficiency, and thus the building envelope, and the active energy systems. The results underline that the cost-optimal energy measures to apply during the building refurbishments deeply differ based on the building usage, the intensity of required indoor comfort, and depending on the climatic peculiarities and building construction technologies.

Keywords: building simulation, energy refurbishment, office buildings, multi-objective optimizations, cost-optimal analysis.

1. Introduction
A sustainable future must necessarily pass through the energy efficiency of the built environment, which features ancient buildings, above all inefficient from both energy and well-being points of view. In Italy, about 55% of the buildings were built between the 40s and 80s, without any thermal insulation and on a European scale, the energy consumption for heating and cooling is around 50%, of which, 80% is for
buildings [1]. Buildings in Europe are also responsible for about 38% of global CO₂-emissions [2], a percentage that is bound to increase as the world is becoming more and more urbanized. For this reason, the European community had taken action by issuing directives aimed at regulating the energy performance of buildings and energy efficiency, firstly with the Energy Performance of Building Directive (EPBD) 2002/91/EC [3], followed by its recast in 2010 [4], and by the Directive 2012/27/EU [5]. The Directive EU 844/2018 [6], which modifies those of 2010 and 2012, has set even higher objectives giving a higher priority to the energy refurbishment of existing buildings. The European Union is committed to achieving a sustainable and almost completely decarbonized system by 2050. As regards the construction sector, by virtue of these objectives, there are two paths to follow. In the first instance, new buildings must be highly efficient, and thus nearly zero energy buildings (nZEB), as introduced in the Directive 2010/31/EU. On the other hand, considering that in 2050 about 75% of the present buildings will continue to exist [1], they must be energetically redeveloped. According to the provisions of Directive 844/2018, the average annual renewal rate of the built environment should be equal to 3%/a, to guarantee the objectives set.

By 2021, this rate is still too low, estimated at around 1%/a. To accelerate the decarbonization process in the building sector the European Commission has presented a recovery and resilience plan: Next Generation EU. A large part of the resources is reserved for the mission of green revolution and ecological transition. About 30% of the European funds are remarked for the fight against climate change [1]. Given the role played by buildings in this issue, as discussed above, a huge set of resources is devoted to energy efficiency and building renovation. The renovation of a building can be performed through different interventions, employing different materials, or different technical systems, and obviously, the aim is not only to reduce the energy demand of the building but also to limit the intervention cost, the CO₂-emissions, or to improve the indoor thermal comfort. Therefore, when an energy refurbishment is carried out, a multi-objective problem is incurred, and the intent is to find the best trade-off between these conflicting aspects.

Optimization problems can be addressed through several procedures and Nguyen et al. [7] presented a review of the optimization methods by collecting the most widespread concepts, procedures, and techniques, while in [8] seven energy optimization tools for buildings are analyzed based on four criteria: data wholeness, degree of interoperability provided, parameters that can be optimized and post-processing capacity. Genetic algorithms (GA) represent the most popular approaches in the field of building simulations. In [9], the logic behind this type of algorithm is described and then a collection of the studies on the optimization of buildings using GA are provided. In [10], the optimization is performed by combining EnergyPlus and Matlab, implementing a GA. Yu et al. [11] use the multi-objective genetic algorithm model NSGA-II combined with an artificial neural network. Even in [12] EnergyPlus is coupled with Matlab, and NSGA II is used for the optimization process. The objective is to find the trade-off between the primary energy consumption for space conditioning and the percentage of thermal discomfort hours. The annual energy consumption for heating, cooling, and lighting are chosen as objective functions in [13] and the optimization is performed by combining EnergyPlus with a multi-objective particle swarm optimization algorithm. In [14] the NSGA-II algorithm is implemented in Matlab to identify the optimal solutions for minimizing energy consumption, hours of discomfort, and economic investments. In [15], the functions to be minimized are the consumption of heating and cooling, maximizing the comfort for the occupants, and guaranteeing the conservation of the historic building under investigation. Several tools can be used for the optimization phase, and Tian et al. [16] conducted a survey with the aim of identifying the most used ones. The optimization module provided by DesignBuilder resulted in the most used, followed by Matlab. Usually, the analyzed objective functions are in contrast with each other, and for this reason, the solution of an optimization process is never unique. The result is a set of optimal solutions that compose the Pareto front, the set of non-dominated solutions. In order to find the optimal configuration, a certain criterion must be chosen. In [17] the utopia point method is used. Among the solutions of the Pareto front, the one closest to the utopia point is selected. This point is the one that minimizes both objective functions. Alternatively, the method of minimum comfort can be used [12].
In this frame, this paper deals with the multi-objective optimization of two office buildings located in Berlin and Naples. The investigated objective functions are divided into two groups: discomfort hours and emissions, and operational costs and discomfort hours. Depending on the ownership of the building, public or private, the focus shifts from one group of objective functions to the other. Two optimization processes are then conducted for each building, to identify the best energy efficiency solution.

2. Methodology

Usually, the modelling of a building requires a collection of data, and in this case, the data refers to the main characteristics of the building constructions of the 60s. This is both for the energetic quality of the building envelope, opaque and transparent, and the technical systems installed. The investigated building is intended for office spaces and therefore the occupancy profiles and electrical systems (lights and equipment) are typical for such use. The building models were developed in DesignBuilder® modeling software [18], which implements EnergyPlus as a simulation engine [19]. The data were assigned through the following tabs: activities, construction, openings, lighting, and HVAC. The energy consumption, obtained through the dynamic energy simulation, was validated through a comparison with the typical energy consumption of office buildings. The validation process is necessary to ensure reliable results, especially when energy efficiency measures are applied. Once the model was validated and, the energy consumption of the two buildings was assessed, the optimizations – focusing on building-related measures - were performed. For this purpose, the optimization module provided by DesignBuilder was used. This module uses Genetic Algorithms based on the NSGA-II method to find the optimal solutions. The data required for the optimizations are the objectives of the analysis, any limits, and the project variables with the corresponding values. The objective functions investigated are:

- total discomfort hours evaluated on the base of the ASHRAE 55 method [20]. In this study, the discomfort hours are calculated over the year, without differentiating between occupied and not occupied hours and thus this indicator has a relative (i.e., indicative) and not absolute value;
- operational cost: the annual cost of the energy sources required for the operation of the building. For this evaluation, it is necessary to define the tariff for the different energy sources (€/kWh), in this case, natural gas, district heating, and electricity;
- operational CO\textsubscript{2}-eq emissions: the annual carbon emissions. For this evaluation, it is necessary to define the emission factors (tCO\textsubscript{2}-eq/MWh).

For each building, two optimizations are carried out by grouping the objective functions:

- minimization of discomfort hours and operational costs in the interest of private ownership;
- minimization of discomfort hours and CO\textsubscript{2}-eq emissions in the interest of public ownership.

The results that meet these objectives create a region and all optimal solutions lie on the Pareto front. For the choice of the optimal solution, among those present on the Pareto front, it is possible to use the utopia point method. The utopia point corresponds to the ideal solution that minimizes both objective functions. The point of real optimum is the point on the Pareto front positioned at the minimum geometric distance from the utopia point. The optimal point can also be identified through other methods, for example by setting the maximum limit of the annual hours of discomfort or by setting a threshold for CO\textsubscript{2}-eq emissions. For publicly owned buildings, it is possible to adopt a compensation CO\textsubscript{2} criterion to select the optimal point; for instance the CO\textsubscript{2} absorption of planted trees.

3. Case study

The building under investigation is occupied by offices. It has a rectangular plan and a total height of 20 m. It consists of 5 floors with a common internal distribution. The longest facades, of about 50 m, are oriented to North-West and South-East respectively (figure 1). The conditioned area is 2,166 m\textsuperscript{2}.

The same building is located in two different cities, Berlin and Naples, and it presents the following thermophysical properties for the opaque building envelope, summarized in table 1:

- the external walls consist of brick layers. This is plastered on both sides. The thermal transmittance (U-value) of the wall is 0.93 W/m\textsuperscript{2}K;
• the roof slab consists of many layers, with concrete slabs and blocks, internal plaster below, and a waterproofing membrane on the outer side. The U-value is 0.94 W/m²K;
• the ground floor is composed of tiles, blocks, and reinforced concrete slabs, with a waterproofing layer. The U-value is 0.98 W/m²K.

As previously specified, the investigated building is representative of the building constructions of the 60s. The thermal transmittances of the building components are perfectly coherent with those reported by the UNI TS 11300-1/2008 standard.

![Figure 1: Investigated building, rendered by DesignBuilder®](image)

### Table 1. Building features for the building energy analysis.

| BUILDING GEOMETRY          | Value |
|----------------------------|-------|
| Total Building Area [m²]   | 2,735 |
| Gross Roof Area [m²]       | 600   |
| Net Conditioned Building Area [m²] | 2,166 |
| Conditioned total volume [m³] | 8,120 |

| THERMAL TRANSMITTANCES     | Value   |
|----------------------------|---------|
| External walls [W/m²K]     | 0.93    |
| Roof floor [W/m²K]         | 0.94    |
| Glass (windows) [W/m²K]    | 3.16    |
| Frame (windows) [W/m²K]    | 5.88    |
| Ground floor [W/m²K]       | 0.98    |

| INTERNAL GAINS AND BOUNDARY CONDITIONS IN OFFICES | Value |
|---------------------------------------------------|-------|
| Lighting systems power [W/m² – 100 lux]           | 3     |
| Light control according to the daylight illuminance| 0.7   |
| Infiltration rate [h⁻¹]                           | 0.11  |
| Electric equipment [W/m²]                         | 4     |

*These gains were scheduled according to typical office programs*

| EMISSION FACTORS AND ENERGY COSTS | Naples | Berlin |
|-----------------------------------|--------|--------|
| Emission factors [tCO₂eq/MWh]     |        |        |
| Natural gas                       | 0.24   | 0.042  |
| District heating                  | 0.424  | 0.404  |
| Electricity                       |        |        |
| Energy unitary costs [€/kWh]      |        |        |
| Natural gas                       | 0.09   | 0.09   |
| District heating                  |        |        |
| Electricity                       | 0.399  | 0.26   |
Unlike the building envelope, the location of the building influences the microclimate control system, in particular:

- in Naples: the building is served by a centralized gas boiler and a chiller coupled with in-room fan coils. The heating system has a nominal efficiency of 0.62 and the cooling system has a rated EER of 2.5. The heating period runs from November 15th to March 31st. The heating setpoint was set as 21°C. The cooling period runs from June 1st to September 15th, with a cooling setpoint of 25°C.
- in Berlin: the space heating during the cold seasons is guaranteed by district heating, from October 15th to April 30. No mechanical cooling is considered.

### 3.1. Baseline energy consumptions for building in Naples and Berlin

The annual baseline energy consumptions for the building located in Naples are:

- 87,656 kWh for natural gas, or 40 kWh\textsubscript{gas}/m\textsuperscript{2}.
- 110,083 kWh for electricity (including the electric energy demand from all the electrical devices), or 50 kWh\textsubscript{el}/m\textsuperscript{2}. More in detail, an average power density has been multiplied by the area and schedules according to typical profiles of office buildings.

Considering a cost of 0.09 €/kWh for natural gas, the annual operational costs for gas are around 365 €/100 m\textsuperscript{2}. Statistically, this is a reliable and common value for an office building located in the same climatic zone. For what concerns the cost of electricity (0.399 €/kWh\textsubscript{el}, very high today), is about 2,030 €/100 m\textsuperscript{2}. The annual baseline energy consumptions for the building located in Berlin are:

- 152,886 kWh for thermal energy from district heating or 70 kWh/m\textsuperscript{2}.
- 90,931 kWh for electricity or 42 kWh\textsubscript{el}/m\textsuperscript{2}.

The annual costs for district heating are around 635 €/100 m\textsuperscript{2}, considering a unitary cost of thermal energy from district heating of 0.09 €/kWh. Clearly, since the climate in Berlin is more rigid than that of Naples, and since the heating season is longer, we have higher costs for the building in Berlin compared to the building in Naples. At the same time, it is noted that the electricity consumption for the building in Naples is higher than for the building in Berlin, this is due to the presence of a summer air conditioning system in Naples, which is instead absent in Berlin.

### 4. Cost-optimal retrofit

The optimization process is performed through the optimization module of DesignBuilder. The objective functions of the analysis are divided into the following two groups, the first one reflects the private interests, the second one the public interests:

- Minimization of the operational costs and the discomfort hours according to the standard ASHRAE 55 discomfort model [20].
- Minimization of operational CO\textsubscript{2-eq} emissions and minimization of discomfort hours according to the standard ASHRAE 55 discomfort model [20].

The optimization variables correspond to the following interventions, and these are selected by establishing minimum performance thresholds, according to the laws.

- the thermal insulation of the opaque building envelope both for walls and roof. Table 2 reports the proposed measures specifying the thickness of the insulation layer, with mineral wool (mean thermal conductivity), the corresponding costs (for the whole retrofit), and the thermal transmittance values,
- the replacement of the transparent building envelope, with new windows and the installation of external shading systems with an activation set point of 120 W/m\textsuperscript{2}. The proposed windows and shading systems, with the corresponding costs and the thermal transmittance values, are reported in table 3,
- the replacement of the lighting system by varying its normalized power density from 1.5 to 4 W/m\textsuperscript{2} – 100 lux, with intermediate steps of 0.5.
Table 2. Proposed measures for the opaque building components

| Insulation thickness [cm] | Wall Cost €/m² | Wall U-value W/m²K | Roof Cost €/m² | Roof U-value W/m²K |
|---------------------------|----------------|------------------|---------------|------------------|
| Base wall/roof            | 0              | 0.95             | 0             | 0.94             |
| Mineral wool              | 10             | 117.2            | 58            | 0.30             |
| Mineral wool              | 12             | 135.2            | 66            | 0.25             |
| Mineral wool              | 14             | 153.2            | 74            | 0.23             |
| Mineral wool              | 16             | 171.2            | 82            | 0.20             |
| Mineral wool              | 18             | 189.8            | 90            | 0.18             |
| Mineral wool              | 20             | 207.2            | 98            | 0.17             |
| Mineral wool              | 22             | 225.5            | 106           | 0.16             |
| Mineral wool              | 24             | 243.2            | 114           | 0.14             |
| Mineral wool              | 26             | 261.2            | 122           | 0.13             |
| Mineral wool              | 28             | 279.2            | 130           | 0.13             |
| Mineral wool              | 30             | 297.2            | 138           | 0.12             |

Table 3. Proposed windows and shading systems

| Type                          | Costs €/m² | Uₜ-value W/m²K |
|-------------------------------|------------|----------------|
| Base glazing                  | 0          | 3.2            |
| Double glazing type with PVC frame | 273      | 1.5            |
| High performance glazing type 3, with PVC frame | 488      | 1.1            |
| High performance glazing type 4, with PVC frame | 750      | 0.8            |
| Shading systems               | 240        | -              |

Only for the building located in Naples, to the previous interventions, it was added also the replacement of the heating generation system with more efficient ones. In particular, the proposed alternatives have an efficiency varying between 0.62 and 0.98, with intermediate steps of 0.09. Definitely, the new gas boilers and sub-systems of the heating systems have the following efficiencies: 0.71, 0.80, 0.89, and 0.98.

The performed analyses refer to the operational phase of the building, by considering the CO₂ emissions and costs during the post-retrofit stage of the buildings, and not by taking into account the life cycle. However, in recent years a great deal of attention has been paid to the other phases of the life cycle of a building, and in particular to the energy and carbon embodied in the materials used. Nowadays, the impact related to the operational phase of the building represents almost 80% of the impact in the whole life cycle, and only 20% is related to embodied energy in the materials. With the application of energy efficiency interventions on the existing buildings, needed to reach the European target of decarbonization, the contribution related to the operational stage will decrease, with a consequent increase in the contribution related to embodied energy [21]. For this reason, this optimization process is only the first part of a future analysis that will consider the entire life cycle of the building and its materials.

5. Results of the optimization process

As mentioned above, two optimization processes are conducted for each building, with the two different objective function groups.

5.1. Optimization process for building in Naples

Figure 2a shows the results for the following objective function group: operational costs and discomfort hours, of interest for private property. All the solutions on the Pareto front, and therefore the optimal
solutions, have the highest level of insulation both for external vertical walls and for the roof, i.e., 30 cm of insulation with mineral wool. The solutions that maximize thermal comfort are characterized by high power lighting systems, i.e., 3.5 and 4 W/m²-100 lux. The effect of the lighting system on the thermal comfort can be attributed to the convective rate that affects the air temperature, as the light degrades into heat, and to a radiative rate that affects the mean radiant temperature. Once the insulation level is pushed to the maximum, the energy demand for heating is largely decreased, and the weight assumed by the efficiency of the heating system is minimal, therefore on the Pareto front, there are also solutions with minimal efficiency of the heating system, i.e., 0.62. All other configurations with lower insulation levels move away from the Pareto front. The optimal solution identified through the utopia point method is characterized by the maximum level of insulation, a glazed component with a U = 1.5 W/m²K with an external shading system, a lighting system with a power of 2.5 W/m²-100 lux, and a heating system efficiency of 0.8.

Figure 2. a) Pareto front of Operational annual cost and Discomfort hours, and b) CO₂ eq annual emission and Discomfort hours for building in Naples

Figure 2b shows the results for the following objective function group: emission and discomfort hours, of interest for public property. Even in this case, all the optimal solutions, located on the Pareto front, are characterized by the maximum insulation level for the external vertical walls and the roof. Solutions that maximize thermal comfort are once again characterized by lighting systems that require high power. However, inefficient lighting systems determine a greater quantity of emissions and for the public property, the amount of CO₂ eq emissions is the determining factor in choosing the optimal solution. To select the optimal solution, the utopia point method could be even used in this case, but it would lead to a solution with higher CO₂ eq emissions, which as just mentioned is the most important aspect for public properties. For this reason, we proceeded according to a different criterion, setting the threshold value for the CO₂ eq objective function and then choosing the solution with the lowest value of the second objective function (hours of discomfort).

The adopted method is the compensation criterion of CO₂ by trees. It represents a method to compensate the CO₂ building emission in a sustainable way, which even improves the environmental quality, and contributes to the reforestation. Considering an average value of CO₂ emissions among those that characterize the solutions on the Pareto front, a threshold of 40 tons per year is set. According to [22], 4.5 hectares of forest can guarantee a CO₂ absorption of about 40 tons/year. Once this threshold is respected, the solution that guarantees the maximum thermal comfort is chosen on the Pareto front. The optimal solution is characterized by the maximum insulation level, by a glazed component with U=1.1 W/m²K with an external shading system, a lighting system with a power of 2.5 W/m²-100 lux, and a heating system efficiency equal to 0.8, and it is evidenced in figure 2b.
5.2. Optimization process for building in Berlin
For the first group of objective functions, of private interest, the results are shown in figure 3a. The maximum level of insulation characterizes all the optimal solutions. Due to the cold climate of Berlin, it is also necessary to maximize the insulation of the transparent components. All the optimal solutions have high-performance glazing. The difference in the level of comfort is given, also in this case, by the lighting system power. Less efficient systems, which therefore require more power, can guarantee greater comfort but this is not rational, given the higher energy, economic and environmental costs. The optimal solution identified through the utopia point method is characterized by the maximum level of insulation for the roof and walls, by a glazed component with a $U = 0.8 \text{ W/m}^2\text{K}$ with external shading systems, and a lighting system with a power of $2.5 \text{ W/m}^2$-100 lux.

Figure 3b shows the results for the second group of objective functions of public interest. Even in this case, the insulation for the optimal solutions is the maximum available and the lighting systems have a relevant influence on thermal comfort. By comparing the two extreme points on the Pareto front, an increment in the hours of discomfort, about 120 h for the whole year, is observed, but at the same time, an annual CO$_2$-eq emissions reduction occurs, from 48 tons to 28 tons. The attention of public institutions is focused on the reduction of CO$_2$-eq emissions, therefore, solutions with more efficient lighting systems are preferred. The fact that this involves a slight increase in the number of hours of annual discomfort is not significant. Indeed, the improved comfort due to the inefficiency of lighting systems is not a valuable solution or strategy to consider.

To identify the optimal solution, the compensation criterion is also used in this case, with the same approach adopted for Naples, and thus the average value of CO$_2$ emissions among those that characterize the solutions on the Pareto front. The average value of CO$_2$ emissions is approximately 35 tons per year. If the property decides to commit 4.0 hectares of the forest [22] (on-site or off-site), it can guarantee a CO$_2$ absorption of about 35 tons/year.

Once this threshold is respected, with a CO$_2$ compensation measure, the solution that guarantees the maximum thermal comfort is chosen on the Pareto front (figure 3b). The optimal solution has the maximum insulation level, glazed components with $U=0.8 \text{ W/m}^2\text{K}$, and a lighting system with a power of $2 \text{ W/m}^2$-100 lux.

Figure 3. a) Pareto front of Operational annual cost and Discomfort hours, and b) CO$_2$-eq annual emission and Discomfort hours for building in Berlin

5.3. Investment cost analysis
The optimal solutions evaluated for both cities and objective function groups are always characterized by the maximum insulation level. Clearly, these interventions require high costs. For the public and private interests, it is also necessary to consider the cost of the investment. For this reason, a further optimization process is carried out by setting the total construction costs and the operational costs as objective functions. For the case of Naples, this process is performed by fixing the overall heating system efficiency as the value of the optimal solution from the emissions point of view (efficiency 0.8).
From the results of the two optimizations, it is observed that all the solutions on the Pareto front have the base glazing type. So, the interventions on the transparent component are the most expensive and at the same time determine high operational costs. It is also observed that the maximum level of insulation characterizes a small number of solutions of the Pareto front, the most expensive ones.

As regards the lighting system impact, a more efficient system involves a greater investment cost and guarantees a minor operational cost.

**Figure 4.** Pareto front of Operational annual cost and Total construction costs in a) Naples and b) Berlin

In Naples (figure 4a), two optimal solutions are identified by the Utopia point method and are both characterized by non-insulated walls and roof, a glazed component with a U=3.16 W/m²K, and a lighting system with a power of 1.5 W/m²-100 lux or 2 W/m²-100 lux.

For the building in Berlin (figure 4b), the optimal solution is characterized by a non-insulated wall, a 10 cm insulation for the roof, a glazed component with a U=3.16 W/m²K, and a lighting system with a power of 2 W/m²-100 lux.

**5.4. The lighting system impact on the optimization results**

It is observed the important effect of the lighting systems. In particular, a less efficient system, with higher energy demand, can guarantee greater comfort in the face of an increase in emissions. Figure 5 shows the percentage weight of the individual consumptions of the building, for the two extreme cases on the Pareto front, and thus the configurations with the highest and lowest CO₂-equ emissions in comparison with the base cases.

By considering the results of the optimization in Berlin with the objectives for a public interest, in the refurbished building with the lowest emissions (depicted in figure 5, right side), with a more efficient lighting system, and with the highest level of insulation, the weight assumed by the lighting system on the total energy consumption of the building, is lower if compared to the base building. In Naples, by considering the warm climatic conditions and thus the different heating needs of the building, in the low emission building with an efficient lighting system, the weight assumed by the lighting is the same as the base building with an inefficient lighting system. This is due to the high level of insulation of the building which greatly reduces the heating demand.
6. Conclusions
In this study, a multi-objective optimization process is proposed for two office buildings located in Berlin and Naples. The optimization variables for this process concern the opaque and transparent envelope, the lighting system, and the heating system only for the building in Naples. The objective functions investigated are divided into two groups:

- operational costs and discomfort hours for private property,
- CO$_2$-eq emissions and discomfort hours for public property.

The results show that, in buildings, even the lighting systems can have a role in thermal comfort. Indeed, in winter conditions, not efficient lighting induces a raising effect both on the air temperature and on the mean radiant temperature. Of course, this cannot be a driving fact, due to the irrational energy, economic and environmental costs, even in terms of high emission of CO$_2$-eq. Indeed, for public property, the most interesting objective function is precisely the reduction of CO$_2$-eq emissions. Therefore, it is preferable to make the lighting system more efficient in the face of a slight increase in the hours of annual discomfort. The optimal solutions obtained from both optimization processes and for both cities are always characterized by the highest level of thermal insulation. Greater insulation requires higher investment costs. This factor cannot be overlooked. Therefore, a further optimization process is implemented, setting investment and operational costs as objective functions. In this case, it is observed that the solutions on the Pareto front with the highest level of insulation are few. Furthermore, it is observed that the replacement of the windowed components is never selected. While as regards the lighting system, greater efficiency requires a higher investment cost and determines a lower operating cost. Depending on the optimization objectives, and thus according to the interests of private or public owners, the optimal solution can be very different.

The analyses were performed referring to the operational phase of the building, this with reference both to the energy consumption and to the CO$_2$ emissions. However, by considering a great deal of attention that, in recent years, has been paid to the other phases of the life cycle of a building, and in particular to the energy and carbon embodied in the materials used, future developments of the study will consider the entire life cycle of the employed materials to identify the optimal solutions and to verify if the results are comparable. Furthermore, to appreciate the optimal solutions obtained, from a future perspective, other variables could be examined and evaluated.

References
[1] Available online at www.ec.europa.eu (Last access: 02/02/2022)
[2] Available online at www.globalabc.org (Last access: 02/02/2022)
[3] EU Commission and Parliament. Directive 2002/91/EC of 16 December 2002 (EPBD).
[4] EU Commission and Parliament. Directive 2010/31/EU of 19 May 2010 (EPBD Recast).
[5] EU Commission and Parliament. Directive 2012/27/EU of 25 October 2012 on the Energy Efficiency
[6] EU Commission and Parliament, Directive 2018/844/EU of 30 May 2018
[7] Nguyen A T, Reiter S, and Rigo P (2014). A review on simulation-based optimization methods applied to building performance analysis. Applied Energy, 113, 1043-1058
[8] Tian Z C, Chen W Q, Tang P, Wang J G and Shi X (2015). Building energy optimization tools and their applicability in architectural conceptual design stage. Energy Procedia, 78, 2572-2577
[9] Li T, Shao G, Zuo W and Huang S (2017, February). Genetic algorithm for building optimization: State-of-the-art survey. In Proceedings of the 9th international conference on machine learning and computing (pp. 205-210)
[10] Ascione F, Bianco N, De Stasio C, Mauro G M and Vanoli G P (2015). A new methodology for cost-optimal analysis by means of the multi-objective optimization of building energy performance. Energy and Buildings, 88, 78-90
[11] Yu W, Li B, Jia H, Zhang M and Wang D (2015). Application of multi-objective genetic algorithm to optimize energy efficiency and thermal comfort in building design. Energy and Buildings, 88, 135-143
[12] Ascione F, Bianco N, De Masi R F, Mauro G M and Vanoli G P (2015). Design of the building envelope: A novel multi-objective approach for the optimization of energy performance and thermal comfort. Sustainability, 7(8), 10809-10836
[13] Delgarm N, Sajadi B, Kowsary F and Delgarm S (2016). Multi-objective optimization of the building energy performance: A simulation-based approach by means of particle swarm optimization (PSO). Applied energy, 170, 293-303
[14] Penna P, Prada A, Cappelletti F and Gasparella A (2015). Multi-objectives optimization of Energy Efficiency Measures in existing buildings. Energy and Buildings, 95, 57-69
[15] Roberti F, Oberegger U F, Lucchi E and Troi A (2017). Energy retrofit and conservation of a historic building using multi-objective optimization and an analytic hierarchy process. Energy and Buildings, 138, 1-10
[16] Tian Z, Zhang X, Jin X, Zhou X, Si B and Shi X (2018). Towards adoption of building energy simulation and optimization for passive building design: A survey and a review. Energy and Buildings, 158, 1306-1316
[17] Ascione F, Bianco N, Iovane T, Mauro G M, Napolitano D F, Ruggiano A and Viscido L (2020). A real industrial building: Modeling, calibration and Pareto optimization of energy retrofit. Journal of Building Engineering, 29, 101186
[18] DesignBuilder 6.0.1 Available online at: https://designbuilder.co.uk//software
[19] EnergyPlus 8.9.0 Available online at: https://energyplus.net
[20] ASHRAE Standard 55 (2020) Thermal environmental conditions for human occupancy
[21] Vilches, A., Garcia-Martinez, A., & Sanchez-Montanes, B. (2017). Life cycle assessment (LCA) of building refurbishment: A literature review. Energy and Buildings, 135, 286-301.
[22] Bernal B, Murray L T and Pearson T R (2018). Global carbon dioxide removal rates from forest landscape restoration activities. Carbon balance and management, 13(1), 1-13.