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Energy-Efficient Envelope Design for Apartment Blocks—Case Study of A Residential Building in Spain

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Featured Application: Multi-objective optimization problem: to minimize the annual heating demand of the building and the standard deviation of the annual demand of the different dwellings. Avoiding excessive insulation reduces the risk of overheating in summer.

Abstract: Buildings are known to be responsible for about a third of energy consumption in developed countries. This situation, together with the fact that the existing building stock is being renovated at a very slow pace, makes it crucial to focus on the energy retrofitting of buildings as the only way to reduce their contribution to these energy consumptions and the consequences derived from them in terms of pollution and climate change. The same level of insulation and the same type of windows is usually proposed for all dwellings in a building block. This article shows that since the improvements required by each dwelling in the same block are different, the proposed solution must also be different. The methodology is proposed for a practical case consisting of an apartment block in Cádiz, a demonstration building of the European RECO2ST project. To achieve the optimum solution for each case, a multi-objective optimization problem is solved: to minimize the annual heating demand of the building and the standard deviation of the annual demand of the different dwellings. Thanks to the use of the proposed methodology, it is possible to bring the building to a Nearly Zero Energy Building (NZEB) level, while avoiding excessive insulation that causes overheating in summer.

Keywords: retrofitting; energy efficiency of buildings; thermal inertia

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1. Introduction

In Europe and on a global level, the three main energy consuming sectors are: industry, transport, and the residential sector. It is estimated that buildings are responsible for 36% of the final global energy consumption [1], rising to 40% in Europe, as has been reported in many publications, such as the ODYSSEE-MURE report on Energy Efficiency Trends in Buildings [2]. This same report highlights that, although new buildings are more efficient than old ones, they only represent a very small percentage of the existing stock (1.1% in the period from 2000 to 2016). Consequently, a great deal of emphasis is being placed today on energy renovation measures for existing buildings. In 2016, the European Union (EU) launched the EU Building Stock Observatory with the objective of providing the necessary data to direct the policies aimed at reducing energy consumption in this sector [3].

There are several databases in which the actual energy consumption in buildings can be obtained and filtered according to the type of building, the final use of energy, etc. A good example of this is the European Union Buildings Database [4], or the Key World

Energy Statistics (KWES) report produced by the International Energy Agency (IEA) [5]. According to the KWES, 27.1% of the total electricity consumption in 2016 was due to the residential sector and 22.2% to commercial and public services.

Energy consumption in buildings mainly results from the need for lighting, heating and/or cooling, ventilation, and others. All of this, in turn, depends on the type of building, its use, the thermal quality of its exterior envelope, the state of conservation of the building and its facilities, not to mention the climate of the area in which it is located [6].

Many studies have analyzed the causes of the energy consumption of buildings, their findings included climatic reasons, building envelope, building facilities, user behavior, etc. D'Agostino and Mazzarella [7] presented a global vision of energy consumption in buildings in Europe that relates to the aforementioned data. In the case of residential buildings in particular, latitude and therefore the local climate are determining factors of heating and cooling consumption, and for this reason, special emphasis has been placed on the study of how the urban microclimate affects the energy consumption for the conditioning of buildings. With this objective, Sánchez et al. [8,9] proposed a method based on the concept of climatic severity.

The energy demand in residential buildings for lighting, on the other hand, represents only a small part of the total consumption; other uses, such as household appliances and especially the production of domestic hot water require more energy. According to the study of the energy consumption of households in Spain by the SECH-SPAHOUSEC Project [10], this consumption depends fundamentally on the climate (varying from 0.719 toe/year on the Mediterranean coast to 1087 toe/year inland) and on the type of housing: single-family or apartment blocks (varies from 0.649 toe/year for apartments to 1334 toe/year for single-family homes).

According to the analysis performed by Cao et al. [11] on the state of the art of Nearly Zero Energy Building (NZEB) technologies, they can be summarized in three categories: passive energy-saving technologies, energy-efficient building service systems, and renewable energy production technologies. To the first category belong the measures that entail a reduction in the need to consume energy in buildings, such as increasing the insulation of roofs and facade walls. The second category includes measures aimed at improving the efficiency of energy consuming equipment in buildings. And finally, renewable energy facilities belong to the third category.

Among the energy saving measures in buildings, the most effective in the long term are those that reduce the need to consume energy, since they do not depend on any equipment that must be monitored for its proper operation and maintenance. These types of measures are known as passive measures, and mainly comprise the insulation of facades and roofs, the use of windows with low thermal transmittance and the proper use of solar gains. Omrany et al. [12] performed a review of these types of passive techniques, as well as more special ones, such as Trombe Walls, Double Skin Walls, and Green Walls.

In the scientific literature, we found numerous case studies in which the main proposal for the energy renovation of a building is the incorporation of insulation in facade walls. Salvalai et al. presented as a case study the deep renovation of a residential building in the Province of Milan through the placement of prefabricated panels of thermal insulation on the exterior layer of the façade walls [13]. Braulio-Gonzalez and Bovea also presented as the main measure of renovation of buildings the use of insulation, and focuses their study on comparing different types of insulation from the point of view of environmental performance. They concluded that the highest eco-efficient performance corresponds to sheep wool and recycled cotton, jointly with traditionally used mineral and glass wool [14]. Among conventional thermal insulation materials, Kalhor and Emaminejad highlight mineral wool as the most efficient option [15].

In addition, Amani and Kiaee say that adding insulation is an efficient way to upgrade an existing building into a nearly zero-energy building, and present a Case Study for which a 70% reduction in the energy demand is reached [16]. Other researchers, such as

Raimundo et al., proposed to optimize the necessary insulation thickness depending on the use of the building and the climate [17].

At the same time, it should be noted that the insulation that reduces heat losses in winter has the same effect in summer, in this case being an unintended drawback that contributes to overheating [18]. This overheating, more common in well-insulated homes [19], has been observed mainly in top-floor homes of apartment blocks with high solar gains and low ventilation. Thus, the risk of overheating when retrofitting existing homes is especially high, mainly when insulation is placed as the interior layer of facade walls and roofs [20]. In addition, increasing the thermal inertia of the building envelope is known to reduce the energy required for cooling, as well as the peak cooling load [21].

This is a serious problem highlighted by institutions such as the Building Research Establishment Ltd. (BRE) in the United Kingdom, which has recommended that more should be done to address the growing risk of overheating in dwellings and other buildings [22]. A risk that according to CIBSE TM59 occurs in summer when a dwelling fails more than 3% in the number of hours that exceed the comfort temperature in living rooms, kitchens, and bedrooms, or when indoor temperatures in bedrooms exceed 26 °C for more than 1% of the annual hours. This same report points out one of the causes of overheating as the combination of the increase in the facade glazing area along with the use of wall insulation. In fact, it can occur with an outdoor air temperature that is not necessarily high. The problem arises from the solar gains that enter the building and that fails to get out through insulated walls [23]. The same trend was observed by Morey et al. in a monitoring study of 122 social housing units in central England to investigate the overheating risk [24].

On the other hand, it is known that the layers of a wall that are useful for inertia are those that remain from the insulation material to the inside of the building. Thus, if the insulation layer is placed on the outside side of the wall, all its layers are useful as thermal inertia. This type of construction solution is called ETICS (External Thermal Insulation Composite Systems), and guarantees a greater thermal comfort due to the higher interior thermal inertia [25]. As pointed out by Verbeke and Audenaert, thermal mass on the inner side of the thermal insulation appears to be beneficial with regards to improving thermal comfort and reducing the energy demand [26].

This article will focus on this solution given by the external positioning of the insulating material to ensure thermal inertia, while if the building consists of very light structures, there are authors who recommend increasing the thermal mass thanks to the use of Phase Change Materials (PCM) [27]. Other solutions are based on adding a second skin to the building that may be opaque or translucent, and may or may not be ventilated inside. Cabeza and Chafer present a systematic review highlighting the advantages and disadvantages of Trombe walls, green facades, PCM integration in walls, thermally activated building systems (TABS), reflecting coatings, etc. A general conclusion of this work was that there are few studies in the literature regarding the implementation of those technologies for the energy performance of existing buildings towards sustainability [28].

In the search for solutions to reduce the energy consumption of buildings in apartment blocks, it is necessary to take into account the disparities in energy consumption from one apartment to another of the same block. This disparity can be observed even for buildings of similar thermal qualities in its envelope. In these cases, orientation and shape factor or the building's compactness are the main causes related to the geometric characteristics of the building [29].

In view of the above, it is necessary to evaluate the level of insulation required for each home, even for each exterior wall or roof, as well as the most appropriate type of window, and the solution does not have to be identical for every dwelling in the same apartment block.

Consequently, when proposing a measure to reduce the energy needs of a building based on increasing the insulation of the facade, why propose the same level of insulation for the entire apartment block? The proposal should be different from one dwelling to another depending on their individual characteristics.

This article tries to answer the following question: why are the heating and cooling needs in an apartment block very different from one flat to another? They all have the same construction qualities with regard to the level of insulation, type of windows and, obviously, the same outdoor climate. Thus, the answer can only be related to geometric parameters, such as different ratios of windows to facade walls, different compactness factors, different floor positions, different orientation, different solar access, etc.

This article proposes a methodology for optimizing the building envelope with a dual objective: to reduce the total heating demand of the building, while reducing the differences in this heating demand from one dwelling to another. This methodology is applied for an apartment block in Cadiz, a city on the southern coast of Spain with a mild climate in both winter and summer, as part of the European RECO2ST project.

2. Methodology

2.1. Optimum Solution Search Methodology

In this section, the proposed methodology for searching the optimum solution is presented. In its original condition the case study building does not have thermal insulation on the facade walls, roof or the slab on ground, and windows are single-glazed with high thermal transmittance. This results in the building presenting a high global heating demand and a significant difference in the heating demand among different dwellings, some requiring substantial improvement while others require much less intervention. It is this difference that arouses the interest of the authors for which this work focuses. A retrofitting aimed exclusively at reducing the total heating demand of the building would not only reduce the demand for the worst dwellings but would also reduce that of those with a low demand that did not require improvement. This strategy could then involve the unnecessary use of thermal insulation and replacement of windows where it was not really required, resulting in unjustified extra costs in the building renovation. A strategy focused on reducing and leveling the demand of the worst dwellings could be more appropriate, with the solution not being the same for each dwelling of the building. Therefore, this study proposes that the desired optimum solutions are those that result in the lowest total annual heating demand of the building and the smallest differences in the annual demand between the building's dwellings, quantified by the standard deviation.

In this study, the building elements that are to be modified to find the optimal solutions are those that define the thermal envelope of the building (a more detailed explanation on the case study is presented in Section 3). Thus, the parameters and values that were considered include the following, where for each parameter the chosen values come from the existing practices of the Spanish regulations [30]:

1. The insulation thickness of the facade walls: 2, 4, and 8 cm of an expanded polystyrene insulation with a thermal conductivity of 0.036 W/m·K, commonly used as exterior insulation. A distinction was made between the ground floor and the upper floors and, moreover, between the south orientation and the others because the main orientations of the building are North–South.
2. The insulation thickness of the roof: 2, 4, and 8 cm of a polyurethane foam insulation with a thermal conductivity of 0.036 W/m·K.
3. The insulation thickness of the slab on ground: 2, 4, and 8 cm of an extruded polystyrene insulation with a thermal conductivity of 0.034 W/m·K.
4. The thermal transmittance (U-value) of glazing: The building contains windows from 0.55 to 1.64 m^2, and balconies from 1.39 to 7.18 m^2 in all orientations, so a distinction was made between the former and the latter and between those facing south and north or east and west. The glass types and the corresponding U-values considered were:

   A double 4-mm low-emissivity glass ($\varepsilon < 0.03$) with 12-mm air gap (4/12/4): U-value = 1.66 W/m^{2}K.

   A double 4-mm glass with 16-mm air gap and thermal break aluminum frame (4/16/4): U-value = 2.74 W/m^{2}K.

A double 4 mm glazing with 8 mm air gap and thermal break aluminum frame (4/8/4): U-value = 3.19 W/m^{2}K.

Table 1 shows the three different values of U corresponding to each building construction element considered. As a result of 3 levels of insulation for 4 different facade walls, 3 for the roof, 3 for the slab on the ground, and 3 thermal transmittances values for 6 different windows, the total possible building designs are 3 raised to the 12th power, that is 531,441.

Table 1. U-values of the different building construction elements to be modified, in W/m^2·K.

Facade Walls				**Roof**	**Slab on Ground**	**Windows**					
Ground Floor		**Upper Floors**				**Balconies**			**Windows**		
S [1]	**N,E,W** [1]	**S** [1]	**N,E,W** [1]			**N** [1]	**S** [1]	**E,W** [1]	**N** [1]	**S** [1]	**E,W** [1]
1.16	1.16	1.16	1.16	0.81	0.83	3.19	3.19	3.19	3.19	3.19	3.19
0.72	0.72	0.72	0.72	0.57	0.58	2.74	2.74	2.74	2.74	2.74	2.74
0.41	0.41	0.41	0.41	0.35	0.36	1.66	1.66	1.66	1.66	1.66	1.66

[1] N: North, S: South, E: East, W: West.

To find the desired optimum solution, a methodology based on a bootstrap resampling technique with a set of different design combinations was used. This methodology enables different design parameters to be combined simultaneously with many input values. Traditional methodologies are based on resampling Monte Carlo simulations many times and picking the best one each time. The distribution of the best solutions can be obtained [31], where the size of the sample is always the same. In this study, the combinations to be simulated are randomly selected by Monte Carlo between consecutive approximations of increasingly reduced samples, however. This is an advantage as the number of approximations is greatly reduced.

1. First, we defined the target functions and the parameters to be modified and the range of values that they can take. The parameters and the range of values are specified in Table 1, and the target functions are to minimize the annual heating demand of the building and the standard deviation of the annual demand of the different dwellings. The possible combinations resulting from this set of parameters and values form the initial sample of possible design solutions, this number being N_0 = 531,441.
2. Then the optimum searching process by successive approximations was started. The cases to be simulated from the set of designs shown above (initial sample at first approximation) were randomly selected, being $n_i = \sqrt{N_{i-1}}$, where i stands for the current approximation (step 1).
3. The selected n_i cases were then simulated and values of the target functions calculated (step 2).
4. In the next step, bootstrapping was started. In Figure 2, the conceptual approach of the multi-objective optimization problem of two variables (T_1 and T_2 in Figure 2) used in this work is shown (step 3). This figure shows a Pareto front obtained from the points corresponding to each of the simulated design combinations at current approximation, in total n_i points. Then, the procedure is as follows:
    a. Only those solutions of the set n_i with values of the first target function T_1 lower than a certain specified criterion were selected ('Area of target 1′ in Figure 2a). The same is done for the second target function, that is, the valid solutions are found among those whose value of T_2 is less than another specified criterion ('Area of target 2′ in Figure 2b). Solutions that meet both criteria constitute the set of valid solutions ('Area of targets 1 & 2′ in Figure 2c).

   b. Among these valid solutions, only a certain percentage (30% in this study) at the shortest distance from Pareto front were selected (Figure 2d). This set of combinations corresponds to the best solutions at current approximation, n_i^*.

5. Next, for each parameter, the number of times that a certain input value appears among the current best solutions n_i^* was counted. Those values having a percentage of occurrence of less than 50% were then discarded. The new sample N_i to be used for the next approximation comprises the combinations that do not have the discarded values of each parameter (step 4). Thus, the sample used in a certain approximation is smaller than the previous one, that is, the methodology is based on consecutive approximations of increasingly reduced samples.
6. Then, we went back to step 1 to randomly select the new cases to be simulated in the next approximation, and the process was repeated until the sample was no longer reduced.
7. Finally, the last Pareto front was obtained and the optimum solution was selected.

Figure 1 shows a flowchart with the different steps followed to search for the optimal solution:

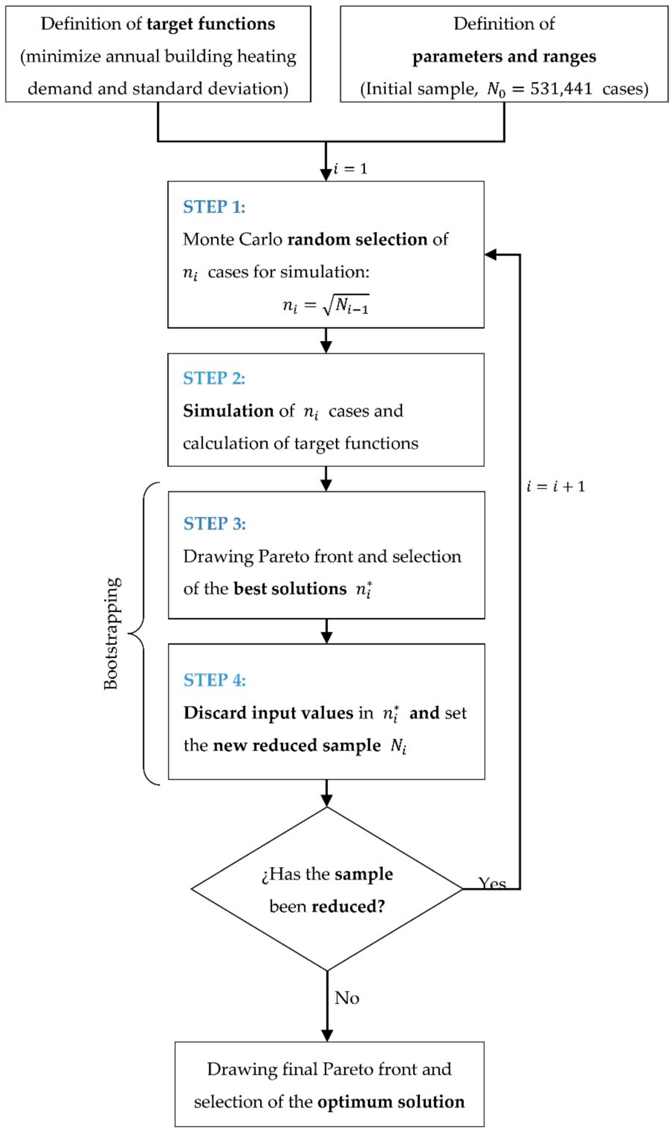


Figure 1. Flowchart of the proposed methodology for searching the optimum solution.

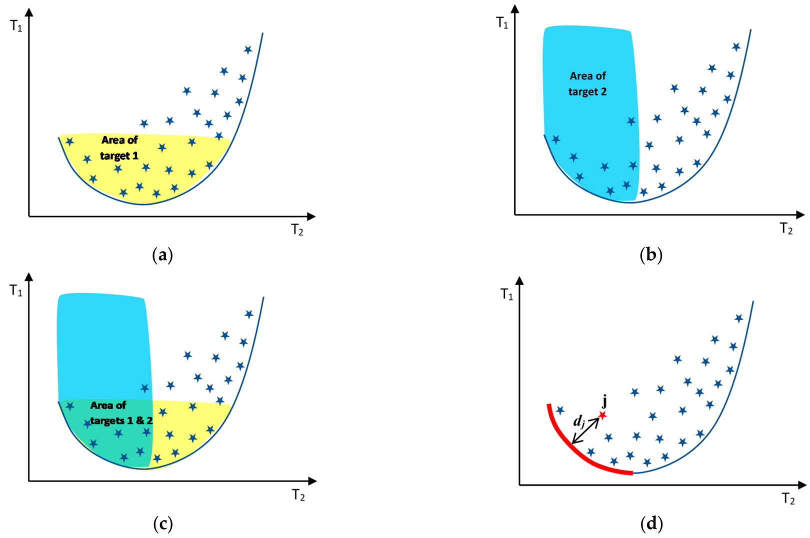


Figure 2. Conceptual approach of a multi-objective optimization problem of two variables T1 and T2: (**a**) Fulfil first target function criterion (T_1); (**b**) Fulfil second target function (T_2); (**c**) Fulfil first and second target functions criteria (T_1 and T_2); (**d**) Selection of best solutions: shortest distance from Pareto front.

2.2. Building Simulation

Many software tools have been developed and used worldwide to simulate the thermal performance of buildings. Crawley et al. [32] compared twenty building energy simulation programs commonly used by researchers and professionals in the field of building energy, with the best-known being EnergyPlus [33], TRNSYS [34], and ESP-r [35]. Among others, the aspects they compared are: the level of detail and hypothesis of modelling (zone energy balance, heat transfer through different building construction elements, solar radiation and shadows, ventilation and infiltrations, Heating Ventilation and Air Conditioning (HVAC) systems, etc.), user interface, reporting of results, validations, and availability. In this study, building simulations were carried out by using the HULC software which has been developed following the previous considerations in terms of modelling [36]. HULC is the building energy simulation program used in Spain for implementing the Energy Performance of Buildings Directive (EPBD) [37]. This tool calculates the transient thermal performance of the building with hourly time-steps. Some features of the program are described in Table 2. More details about the calculation method can be consulted in [38].

Table 2. Main modelling features of HULC.

Simulation Period and Time Step	Hourly-Time Step Yearly Calculation.
Climate	Meteorological files TMY2 for climatic zones of Spain [39]. In this case, study climate A3 was used.
Building thermal envelope	Transient thermal performance of opaque construction elements.
Ventilation and infiltration	The ventilation level is the minimum required by Spanish regulation [40] to ensure the indoor air quality. Infiltration is calculated according to the type of windows
Thermal bridges	Calculation based on an equivalent linear thermal conductivity [41]
Results	In terms of heating and cooling demand.
Validation	According to ANSI/ASHRAE Standard 140–2004, Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs [42].

3. Case Study

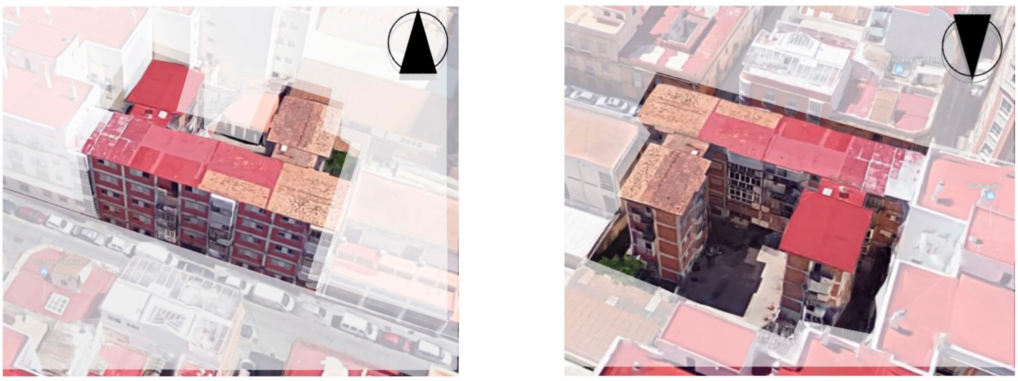
In order to relate the proposed methodology to a real building, in this paper an apartment block located in the city of Cádiz, Spain was selected. It is one of the demonstration buildings on the European project RECO2ST. It is a five-story residential building from the 1960s with a total of 28 apartments and a constructed area of 1873 m^2. At the time of writing this paper the building was uninhabited and the renovation project was underway to bring the building to NZEB consumption levels. The renovation of the building involves, among other aspects, the total replacement of the envelope, maintaining the structure of the building and the incorporation of facilities based on renewable energy.

With this aim, under the RECO2ST project the optimization of the new building envelope was studied with measures devoted to the reduction of heating and of cooling needs. This paper focuses on the improvements to the building envelope, which includes measures such as the addition of an insulation material on exterior walls and roofs on the outer layer of the original envelope and replacement of current windows with new more energy efficient ones. Moreover, to reduce the risk of overheating in the cooling season, the thermal insulation layer will be placed on the outside of the walls and ceilings since, as mentioned above, overheating can be reduced if the building has a high thermal inertia. Laying insulation on the outside helps to increase the thermal inertia of the building.

3.1. Location and Building Characteristics

The study building is located in Cádiz, Spain (36.5°N, 6.26°W) with an orientation of its main facade of 22° east of due south. Figure 3 shows a bird's-eye view of the building prior to the renovation, where the main facade can be seen in Figure 3a, and the inner courtyard on the north side of the building in Figure 3b.

The buildings opposite the main façade are about 10 m away and have three floors so they are lower than the study building, which means that in the heating season the solar radiation falling on the upper floors is a high while the lower floors will be in shade most of the time. Meanwhile, on the north face, due to the shape of the study building and the adjacent buildings to the east and west, solar radiation is distributed in a very different way in each of the dwellings located in this area since the building itself casts shadows on its facades. However, it can be seen that during the heating season solar radiation falls on the upper floors in the early morning and late afternoon, while the lower floors will remain practically in shade at all times.



(**a**) (**b**)

Figure 3. 3D-view of the building: (**a**) south-facing façade and (**b**) north-facing façade.

As a result of the foregoing, the solar irradiation to which a certain floor of this building can be subjected is highly conditioned by its position within it, the orientation of its facade and the floor on which it is located being the most important variables affecting the irradiation and, therefore, its thermal behavior.

The main constructive characteristics of the original building are shown in Table 3. These values were normal for the date the building was constructed, but obviously, they are far from the minimum requirements for the current national standard in Spain.

Table 3. Original building envelope characteristics.

	Opaque Elements	Windows		Total Area	Windows to Wall Ratio
	U (W/(m^{2}K))	U (W/(m^{2}K))	g-Factor	(m^2)	
North	2.97	5.7	0.8	449	0.23
East				324	0.09
South				436	0.34
West				270	0.11
Roof	1.41			328	
Slab on ground	1.49			215	

3.2. Initial Heating Needs

To assess the heating needs of the building in the initial situation, an energy simulation of the building was carried out with the official tool in Spain for the energy certification of buildings. It is the LIDER-CALENER Unified Tool (HULC), which performs a detailed calculation in transitory regime of the building's thermal behavior on an hourly basis [36].

For the simulation of the building using this software tool, the required information can be grouped into its geometry, thermal characteristics of the envelope and interior partitions, operational conditions, and external excitations (climate and surroundings elements casting shadows). The building is calculated with the geometric detail shown in Figure 4.

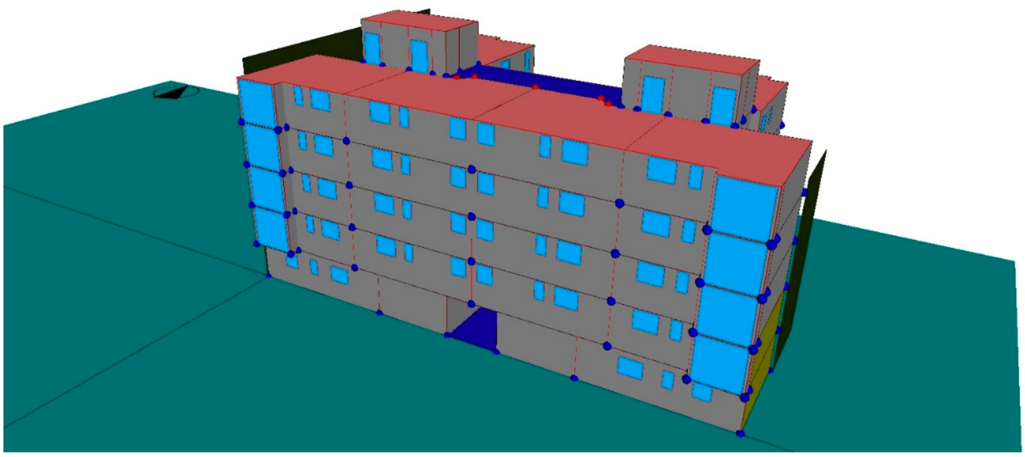


Figure 4. 3D-view of the building model using HULC software tool.

In Figure 5, the energy demand for each dwelling in the winter period is shown. These values are ordered from higher to lower demand. It can be seen that the difference between the apartment with the highest demand and the one with the lowest is almost double, which could be equivalent to one apartment being in a much colder climate than the other.

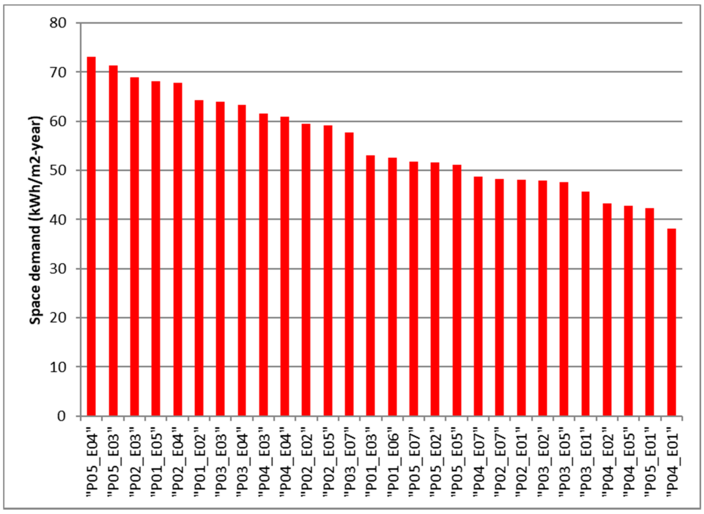


Figure 5. Heating space demand for each apartment (kWh/m^2·year). Ordered list from the worst to the best ("P" refers to the floor and "E" refers to the dwelling).

Figure 6 shows the flats with a heating demand higher than the mean in red. As expected, the ground-floor flats are, in general, those with the highest heating demand, as well as those on the north face of the building, with values above the average.

To answer the question about differences in heating needs, the possible causes are discussed below. Thus, firstly, the north-facing dwellings all have a demand for high heating, due to two reasons: one is the orientation itself, which makes the solar gains in winter less, and the second is that these houses are the ones that present a greater area to the outside for the same volume, that is, a lower compactness. Secondly, there is also an above-average need for heating in dwellings in contact with the ground as they have heat losses towards it, something that does not occur on upper floors. Finally, on the first floor there are dwellings that on their lower face are in contact with the outside air. This fact makes the heat losses through the floor of these dwellings another reason for heating needs that exceed average.

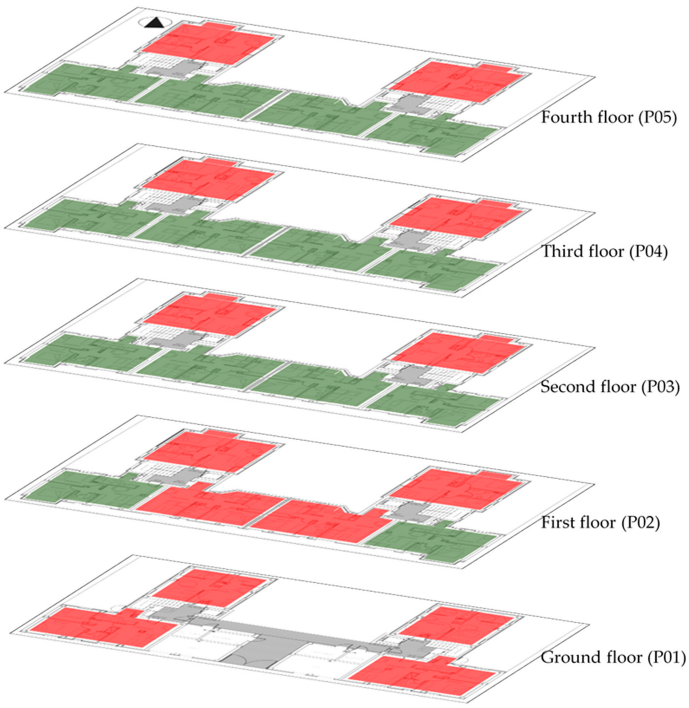


Figure 6. Heating space demand for each apartment: Drawing view.

In view of the previous results, where the differences in the demand for heating can be equivalent to a change of location, and as it is evident that in different locations, the insulation measures and, in general, the renovation measures of a building are different, it seems logical that in a case like this one, the insulation measures should be applied according to the needs of each apartment. Therefore, the ideal way is to propose different solutions for each facade of each flat. As this degree of detail may be impractical, the proposed solutions should probably be made for a group of facades and windows.

4. Results and Discussion

The use of the methodology proposed in this article has made it possible to bring the optimal solution closer with each iterative step. This has been possible by reducing the search sample of independent variables of the optimization problem. As a result, the total number of simulations performed was 934, while the possible combinations were 531,441. Only 0.18% of cases had to be simulated, thus, significant computational time was saved.

The solution reached improves the two optimization variables: the total heating demand of the building and the standard deviation from the heating demands of the individual dwellings. Thus, the optimal solution has a total heating demand of the building of 18.70 kWh/m^2·year, while the initial situation was 55.24 kWh/m^2·year (66% saving). In addition, the final standard deviation is 3.30, compared to its initial value of 9.77 (a reduction of 66%).

Therefore, it has been possible to reduce the building's heating demands, especially where it was most needed, placing all the dwellings of the building in almost zero energy consumption levels for heating with the minimum necessary interventions to its envelope.

Figure 7 shows all the simulated cases throughout the optimization procedure, representing the standard deviation versus the total heating demand of the building. This type of representation makes it possible to observe the so-called Pareto Front, with the cases located in its proximity being those of less standard deviation for each specific total heating demand of the building. Following the methodology described above, the solution was reached after four iterations. In this figure, the simulation cases of the first iteration are represented with grey squares, the cases of the second iteration with red triangles, the third iteration with green circles, and finally the fourth iteration with blue crosses.

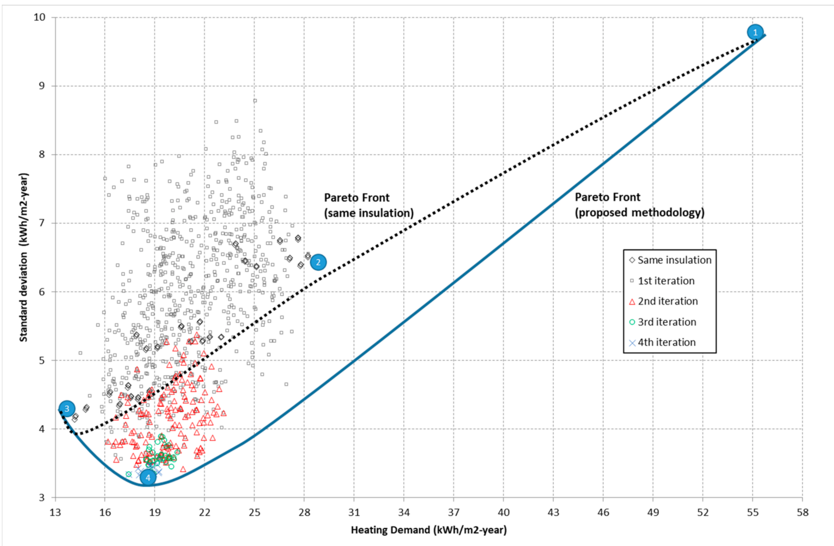


Figure 7. Pareto Front and simulated cases from the 1st to 4th iteration and for same insulation assumption.

Additionally, cases that would be obtained if the entire building had the same level of insulation and type of windows have also been represented in the same figure with black rhombuses. A different Pareto Front corresponding to these cases with the same level of insulation has been represented with a black dotted line. Comparing both Pareto Front lines, it is observed that for equal demand for total heating of the building, the standard deviation would be much greater for the cases with the same insulation level, resulting in some dwellings having a very low demand, while in others it would be very high.

The original case (no insulation) is labelled "1", the case with minimum insulation is labelled "2", the case with maximum insulation level is labelled "3", and the optimal case has label "4".

To show the benefits of the proposed methodology in more detail for finding the optimum case, Figure 8 shows a zoomed display of the area of interest in Figure 7. It shows how the four iterations gradually approached the optimal solution. At the same time the number of simulation cases is smaller for each iteration. In the first iteration the number of simulated cases were 730, in the second iteration the simulated cases were 149, in the third iteration 40 cases, and finally in the fourth iteration only 15 cases were needed.

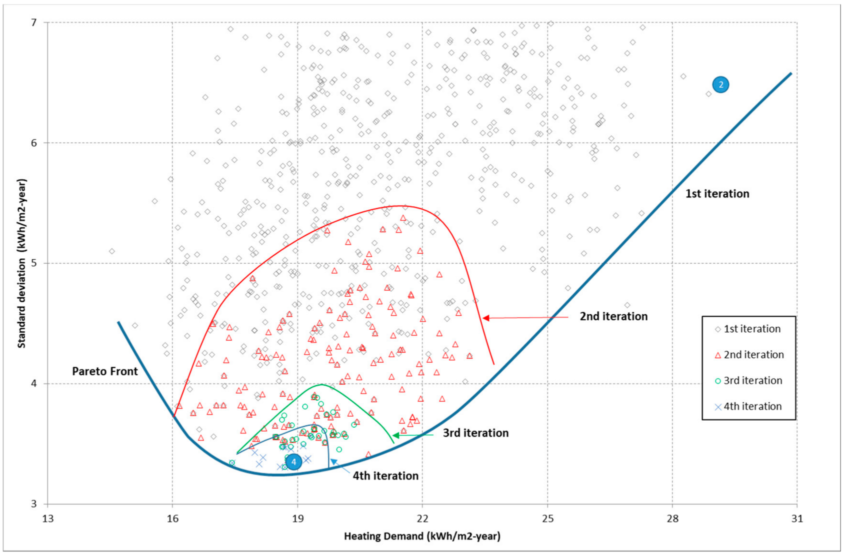


Figure 8. Pareto Front and simulated cases from the 1st to 4th iteration (zoom of the area of interest).

In short, to compare the four most interesting cases, the building heating demand and the standard deviation are shown in Table 4 and Figure 9. As can be seen, with the maximum insulation level it is possible to achieve the lowest heating demand of the building but the standard deviation is higher than that of the optimum case. In this optimum case, the heating demand of the building is low enough to consider that the entire building can be considered a NZEB according to the Spanish regulation, which establishes a maximum value of 25 kWh/m^2·year for the A3 climate zone where the city of Cádiz is located [30]. This optimum case minimizes the disparities among all of the dwellings. Table 5 summarizes the thermal characteristics of the four cases being compared.

Table 4. Building heating demand and standard deviation among dwellings.

		Heating Demand (kWh/m^2·Year)	Standard Deviation (kWh/m^2·Year)
(1)	Original (no insulation)	55.24	9.77
(2)	Minimum insulation level	28.87	6.40
(3)	Maximum insulation level	13.59	4.28
(4)	Optimum	18.70	3.30

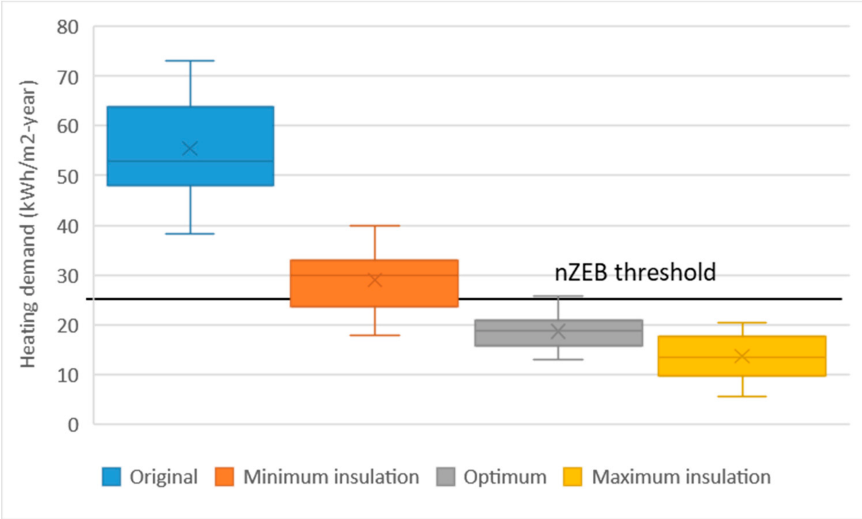


Figure 9. Building heating demand from the original to the optimum solution with indication of the Spanish Nearly Zero Energy Building (NZEB) threshold.

Table 5. U-values of building construction elements of cases 1–4, in W/m^2·K.

	Facade Walls				Roof	Slab on Ground	Windows					
	Ground Floor		Upper Floors					Balconies			Windows	
	S [1]	N,E,W [1]	S [1]	N,E,W [1]			N [1]	S [1]	E,W [1]	N [1]	S [1]	E,W [1]
1	2.97	2.97	2.97	2.97	1.41	1.49	5.70	5.70	5.70	5.70	5.70	5.70
2	1.16	1.16	1.16	1.16	0.81	0.83	3.19	3.19	3.19	3.19	3.19	3.19
3	0.41	0.41	0.41	0.41	0.35	0.36	1.66	1.66	1.66	1.66	1.66	1.66
4	0.41	0.41	0.72	0.41	0.57	0.58	1.66	3.19	2.74	2.74	3.19	3.19

[1] N: North, S: South, E: East, W: West.

Finally, the cooling demand was calculated for the original case, the optimum solution and a case with the same level of insulation as the optimum case but placed in the interior layer of the exterior walls and roof. Figure 10 shows that the best position to prevent overheating in summer is the outer layer of the exterior walls and roofs. This is the optimum solution due to the effect of thermal inertia.

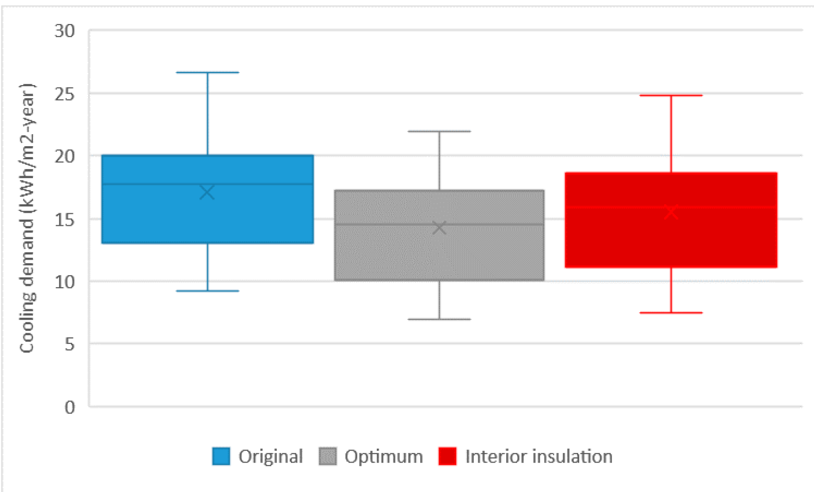


Figure 10. Building cooling demand for the original construction, the optimum solution, and a case with interior insulation.

5. Conclusions

As highlighted in the Introduction, the usual practice is for the whole building to undergo renovation with the same thickness of insulation and the same type of windows. However, not all dwellings require the same level of insulation or windows to achieve the NZEB objective. Furthermore, excessive, unnecessary insulation comes at a higher cost and can lead to an increased risk of overheating in summer. Thus, this article proposes a methodology for optimizing the building envelope with a double objective: to reduce the total heating demand of an apartment block and to reduce the differences in these heating demands from one dwelling to another. In addition, in order to not affect the energy performance of the building in summer, the new insulation should be placed on the outer layer of the exterior walls and roof, thus favoring the thermal inertia of the building.

To implement this methodology, the demonstration building of the European RECO2ST project in Cadiz, Spain, is used as a case study. It is a five-story residential building with 28 dwellings for which a complete renovation of its building envelope is planned.

The Case Study presented in this article has identified the causes of the highest heating demands are mainly the following: north facing dwellings with little solar gain in winter, as well as a low compactness factor.

The proposed methodology requires first identifying both the facade walls and windows that might have a different construction solution to the rest and the possible levels of insulation and glazing. In this sense, different construction solutions are possible depending on the orientation and on the floor of the building in question. It is important that this first step is carried out together with the team of architects and engineers responsible for the renovation of the building to ensure that the aesthetic criteria as well as all of the construction regulations are met. Second, for each opaque element or window, the proposed methodology offers three different options. Thus, given the number of building elements considered, and the number of options for each of them, the total number of possible combinations was 531,441.

The proposed methodology applied for this building, based on a resizing of the sample in four iterations, has enabled the optimal solution to be reached in just 934 simulations. This limited number of simulations performed has been thanks to the novel bootstrap resampling technique developed by the authors and presented in this article for the first time. The optimal solution makes it possible to reduce both the total energy demand of the building and the disparity in demands between dwellings by 66% with regard to the initial values.

Both the methodology explained here and the idea of proposing different solutions according to facade, orientation, type of window, etc. can easily be used in future interventions in buildings with results that guarantee the best possible intervention for each specific dwelling within an apartment block.

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