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Method for the economic profitability of energy rehabilitation operations: Application to residential dwellings in Seville

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Abstract

This work proposes a method based on a computer model to assess the economic profitability of energy rehabilitation operations in the envelope of a block of residential dwellings (Virgen del Carmen) in Seville (Southern Spain). The work evaluates the influence that certain hypotheses of interventions in the opaque part of the envelope exert on the annual energy demand: better insulation of the façade, interior partitions, roof and ground floors, in addition to its semi-transparent part: improvements in the airtightness of the building openings, the glass windows, and the thermal conductivity of its frame. These interventions arise from strict compliance with the Spanish regulatory framework. This model has been designed for the context of a Mediterranean climate, (mild winters and hot summers). The simulation tool Design Builder 3.4.0.041, which uses the calculation engine Energy Plus 8.1, has been selected to generate the computing model and establish its energy demand. The amortization of the economic costs of rehabilitation is quantified by the net present value (NPV) index, in accordance with the savings in the bills of energy consumption due to the reductions in demand for heating and cooling in the building, thereby obtaining an amortization period which exceeds 22 years.

Keywords: Passive thermal energy; dwelling envelope; energy rehabilitation; energy demand reduction; Mediterranean climate.

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1. Introduction

In Spain the existing building stock is inefficient, uncomfortable and causes excessive energy consumption. The residential sector is of the greatest impact since it represents 85% of total construction, against the remaining 15%

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Nomenclature

D_r	discount rate (%)
FB_i	flow of benefits in the period i (€)
I_0	total initial investment costs (€)
NPV	net present value (€)
U	thermal transmittance (W/m^2·K)
Greek letters	
λ	thermal conductivity (W/m·K)

which corresponds to the tertiary sector. Residential construction resulted in approximately 25 million dwellings in 2011, from which 72% were first residences[1], and accounted for 19% of the total energy consumed in the country in the same year[2] and was also responsible for 32% of the greenhouse gas emissions of the total allocated to Spain for the 1990-2009 period.

Tackling the problem requires the thermal rehabilitation of the existing housing, especially those dwellings built prior to 1979 (year of the introduction of the first legislation for thermal conditions of buildings[3]), and which accounts for 58% of all registered houses as of 2011. To achieve these objectives, several policies and regulations have recently been launched in Spain. Among these are the Construction Technical Code (Código Técnico de la Edificación CTE[4] (2006)), and subsequent updates of its documents (the latest update directly affects the subject of this study, the DB HE[5] September 2013), as well as the incorporation of the basic procedure for certification of energy efficiency of existing buildings[6].

In this field of research, many studies have appeared that are focused on the Mediterranean climate due to the growing interest in energy efficiency and environmental sustainability in buildings. From among these numerous studies, we highlight the work by Jaber *et al*.[7] who performed an analysis for the energy optimization of the design in residential buildings, the work by Olivieri *el al.*[8] on the thermal energy performance of insulated vegetal façades, and the contribution by Evola *et al*.[9] to define a standard for low-rise residential net zero energy buildings (NZEBs). In southern Spain (Seville), work by León *et al.*[10] evaluates the influence of various types of solar protection on a block of flats in the city, and a study by Domínguez *et al.*[11] evaluates the savings in annual energy demand through the alteration of the properties of the windows on a multi-family residential building. In cost studies, work carried out on continental and Mediterranean climates in Portugal[12,13] and in northern Spain[14,15] deserves mention.

This work focuses on developing and implementing a methodology for assessing the energy performance through computer simulation on a specific case. The aim is to establish an energy rehabilitation hypothesis adjusted strictly to Spanish legislation (acting only with passive improvements in the envelope) to evaluate the savings produced. Solar protection, despite its utility in this climate, does not feature among the compulsory elements that must comply with current regulations, and hence it is disregarded herein. This energy saving is reflected in electric and diesel oil bills (2014 prices). By counterpoising the cost savings with the cost of the initial investment to undertake the intervention (2014 prices), a value for the benefit of the overall operation can be reached expressed as a period of amortization. Thus, the feasibility of this type of operation is analysed in the absence of external funding sources, and evaluating whether a particular community of neighbours could undertake this operation autonomously. The model used is that of one of the H-shaped blocks of the residential neighbourhood of *Virgen del Carmen* in Seville (Southern Spain), built between 1955 and 1960. Although this analysis cannot be considered representative for all buildings constructed at that time in this city (for differences in architectural type, orientation, solar obstacles, etc.), it acts both as a methodological example and an indicative reference, and is generalizable to other buildings and hypotheses of thermal refurbishments in the Mediterranean area.

2. Model description

The *Virgen del Carmen* neighbourhood consists of a set of 636 flats designed by the architect Luis Recasens[16], where the rigorous geometric arrangement of linear blocks of five storeys conjugates with others of greater height: ten-storey symmetrical H-shaped blocks around the perimeter of the neighbourhood, creating a wide network of

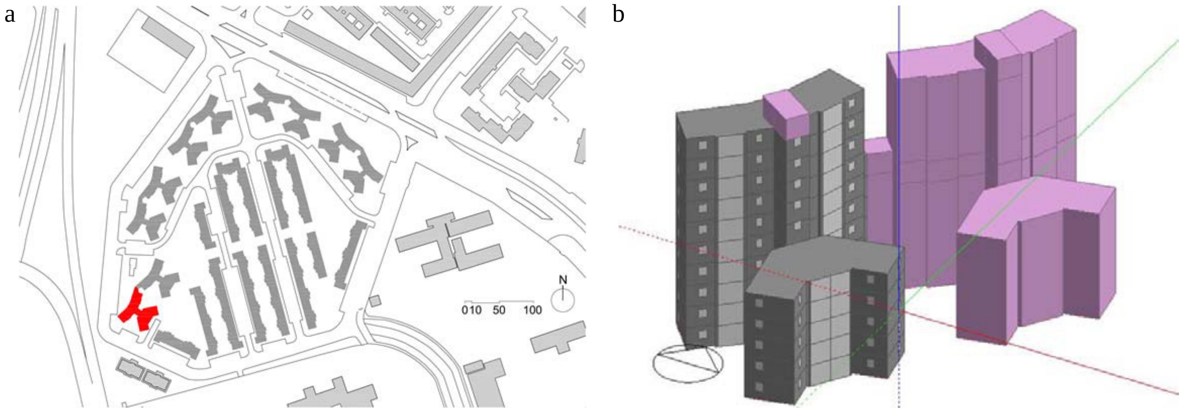

Fig. 1. (a) Neighbourhood plan with the location of the block (in red) to be simulated. (b) Image of the block edited by the simulation programme.

public spaces between them.

These dwellings were built on the land reclaimed from the various reductions of the Guadalquivir River, as the last building phase carried out in the neighbourhood of *El Tardón* between 1955 and 1960, and occupies the area which adjoins the city wall. Currently, the blocks have an acceptable degree of conservation thanks to a reform in the façades and enclosure of the balconies performed in 1983 by the architect Enrique Taviel de Andrade[17].Although the set of dwellings consists of two edificatory types, the description of only the H-shaped block is given, since this constitutes the object of study in this research. These are blocks of 10 storeys that present a variant for the standard H-shaped type: two slightly curved wings in search of greater sunlight, in which the outside wing has the aforementioned height and the interior wing resembles the scale of the rest of the neighbourhood, with a ground floor plus four upper storeys. These blocks are grouped in pairs and at the point of contact between the two blocks a volume is added that makes up an extra room in the first six storeys. The connection between blocks enables the creation of transition spaces between the complete public sphere and the interior of buildings (Figs. 1a and 1b).

By observing the configuration of the neighbourhood, it follows that, for the H-shaped blocks, two fundamental provisions exist (Fig. 1a): three pairs of blocks directing their tallest façade (10 storeys) to the west and two pairs of blocks with the mentioned body facing towards the northeast. Due to their placement, the influence on sunlight of each pair on the rest remains negligible. In addition, based on the analysis of the sunlight of openings, the shadow cast by the blocks farther south (in each pair) onto the adjacent block generally exerts a very small influence on the demand, both for cooling and heating. Hence, the block located further south, as highlighted in Fig. 1a, is the only one assessed.

The interior layout of flats starts with the main room, which is broken into two enclosures, each linked to an orientation but united diagonally. The centred position of this piece divides the dwelling into two zones, interpretable as a parents' area (1 room) and a children's area (2-3 rooms), instead of the typical modern division of day and night areas. The kitchen and dining area are associated with the terrace, and hence is understood as a utility terrace. The average size of dwellings stands at around 70 m^2 of useful surface, and there is a great perimeter surface of the façade of all the flats in the neighbourhood; the block under consideration has a total floor area of 2351.46 m^2, the surface of the opaque part of the façade is 2511.98 m^2 and the total surface of openings is 310.27 m^2.

3. Simulation: methods

Simulations were carried out with the DesignBuilder programme in its 3.4.0.041 version. This programme works as a graphical interface of the calculation engine Energy Plus 8.1, designed by the US Department of Energy[18], which is one of the most advanced dynamic simulation tools of phenomena related to the environmental and energy performance of buildings, whether they operate in mechanical mode (with air conditioning systems), in passive mode (using only natural resources, such as wind and solar radiation), or in mixed mode.

3.1. Simulation configuration

Given that the study sample must be comparable with the standard case studies, simulation conditions are established by the document "Condiciones de aceptación de programas informáticos alternativos”[19,20] on the conditions for acceptance of alternative computing programmes:

- Setting temperatures for cooling and heating throughout the year:
    - Cooling (June - September): 27 ºC (23:00 to 8:00), free running (8:00 to 16:00), 25 ºC (16:00 to 23:00).
    - Heating (October - May): 17 ºC (23:00 to 8:00), 20 ºC (8:00 to 23:00).
- Sensitive and latent loads due to occupation throughout the year:
    - Sensitive (weekday): 2.15 W/m^2 (23:00 to 8:00), 0.54 W/m^2 (8:00 to 16:00), 1.08 W/m^2 (16:00 to 23:00).
    - Sensitive (weekend): 2.15 W/m^2 (00:00 to 24:00).
    - Latent (weekday): 1.36 W/m^2 (23:00 to 8:00), 0.34 W/m^2 (8:00 to 16:00), 0.68 W/m^2 (16:00 to 23:00).
    - Latent (weekend): 1.36 W/m^2 (00:00 to 24:00).
- Sensitive loads due to lighting equipment throughout the year:
    - 0.44 W/m^2 (00:00 to 8:00), 1.32 W/m^2 (8:00 to 19:00), 2.20 W/m^2 (19:00 to 20:00), 4.40 W/m^2 (20:00 to 23:00), 2.20 W/m^2 (23:00 to 24:00).
- Sensitive loads due to electronic equipment throughout the year:
    - 0.44 W/m^2 (00:00 to 8:00), 1.32 W/m^2 (8:00 to 19:00), 2.20 W/m^2 (19:00 to 20:00), 4.40 W/m^2 (20:00 to 23:00), 2.20 W/m^2 (23:00 to 24:00).
- Operating conditions of ventilation and infiltration throughout the year:
    - Ventilation (June - September): 4.0 ac/h (00:00 to 8:00), 1.25 ac/h [21] (8:00 to 24:00).
    - Ventilation (October - May): 1.25 ac/h [21] (0:00 to 24:00).

The building is located in Seville (Latitude: 37.38º N, Longitude: −5.99º W), a city with a typical Mediterranean climate which is part of the B4 zone (according to the Spanish climatic zoning), with moderately cold winters and hot summers, which corresponds to Csa in the Koppen climate classification[22]. In this way, the weather data template used for this research was “ESP Seville.swec” (Spanish Weather for Energy Calculations)[23].

3.2. Constructive description of the existing building model

The composition of the envelope is typical of the dwellings of this period (Table 1) and there are thermal bridges, both for slab edges and façade pillars, as well as in the windows and door jambs. Ventilation (window openings and infiltration): 1.25 ACH throughout the year and 4 ACH from 00:00 to 08:00 local time in summer, in accordance with the “Condiciones de aceptación de programas informáticos alternativos” document[19,20].

Simulation reports show differences of minor significance between the two blocks of each pair, thereby establishing the following values for the block under study: Annual cooling thermal demand 28.52 kWh/m^2; Annual heating thermal demand 46.39 kWh/m^2.

Table 1. Envelope description.

Element	Composition	Transmittance U (W/m^{2}K)
Façade	6-inch-thick brickwork, air chamber and a ceramic inner partition	1.39
Dividing wall	Ceramic-brick inner partitions of brick-width thickness	2.05
Horizontal partitions	Unidirectional concrete slab with ceramic filler block and ceramic floor tiling	1.58
Roof	Non-trafficable, with lightweight concrete slope formation and without thermal insulation	1.80
Ground floor	Reinforced concrete base without thermal insulation	2.59
Windows	Sliding window with metal frame without thermal break	5.88
	Simple glass panes and solar factor 0.82	5.80

4. Proposed improvements for the envelope

In the field of rehabilitation, it is possible to perform thermal demand reduction operations in four ways: by improving the insulating capacity of the opaque envelope; by improving the insulating capacity and the airtightness of windows and doors; by controlling the solar radiation incidence on the building using solar protection devices; and, finally, by changing the reflectivity of the walls and roofs. Of these four approaches, the latter two have been left out of this study: the fourth since the long-term effectiveness of radiant heat reflective insulation materials has been insufficiently tested for rehabilitation purposes.

4.1. Rehabilitation hypothesis: Results and discussion

The methodology followed consists of performing an energy renovation operation in order to strictly cover the requirements of the current thermal regulations[5], see Table 2.

With these assumptions for improvement, the simulation results yield the following data for the new model (Fig. 2): Annual cooling thermal demand 20.25 kWh/m^2; Annual heating thermal demand 19.04 kWh/m^2.

The cost of the proposed improvements in the building envelope amounts to I_0= 315,745 €, (material and manpower) according to the database "Banc BEDEC" from ITE[24] and "Database Building Materials" from the Junta de Andalucía[25]. Of this cost, 56% is for thermal insulation of exterior walls and partitions (177,343 €), 37% for the treatment of openings (117,790 €), 4% for ground floor insulation (11,315 €), and 3% for the roof (9,297 €).

Figure 3 compares the simulation results for the current model of the building and for its proposed thermal improvements, and shows the annual heating and cooling demand and consumption in terms of primary energy. To this end, the protocol of acceptance of software tools[19,20] is used in accordance with:

Heating (diesel oil boiler of performance consistent with COP 0.7): Final energy consumption (kWh/m^2) ·1.081

Cooling (heat pump of performance consistent with EER 1.7): Final energy consumption (kWh/m^2) · 2.603

The major savings in primary energy consumption of heating should be especially borne in mind, (see Fig. 3), which produce a net saving of 42.23 kWh/m^2 of primary energy in heating and a net saving of 12.67 kWh/m^2 in cooling. This results in total savings of 54.9 kWh/m^2. It is noted that, in the current situation, the primary energy consumption of heating (71.63 kWh/m^2) is much greater than that of cooling (43.67 kWh/m^2), but with the improvements introduced, heating consumption (29.4 kWh/m^2) is slightly lower than that of cooling (31.00 kWh/m^2).

In order to conduct a study on the economic profitability of rehabilitation carried out, use will be made of what is known as the Net Present Value (NPV).

Table 2. Envelope refurbishment.

Element	Composition	Thermal conductivity λ (W/m·K)	Transmittance U (W/m^{2}K)
Façade	External thermal insulating composite system (ETICS) with 3 cm-thick XPS	0.038	0.66
Thermal bridge in façade	Calculated as 10% of the total wall surface		1.5
Dividing wall	Wall cladding addition of 2 cm-thick EPS and plasterboard cladding on one side	0.037	0.99
Roof	External reinforcement of 8 cm-thick EPS	0.037	0.37
Ground floor	Internal reinforcement of 6 cm-thick XPS	0.038	0.45
Windows	Metal frame without thermal break, Ventilation of 0.8 ACH by infiltrations		3.30
	4/6/4 double-glazed windows with solar factor 0.88.		4.00

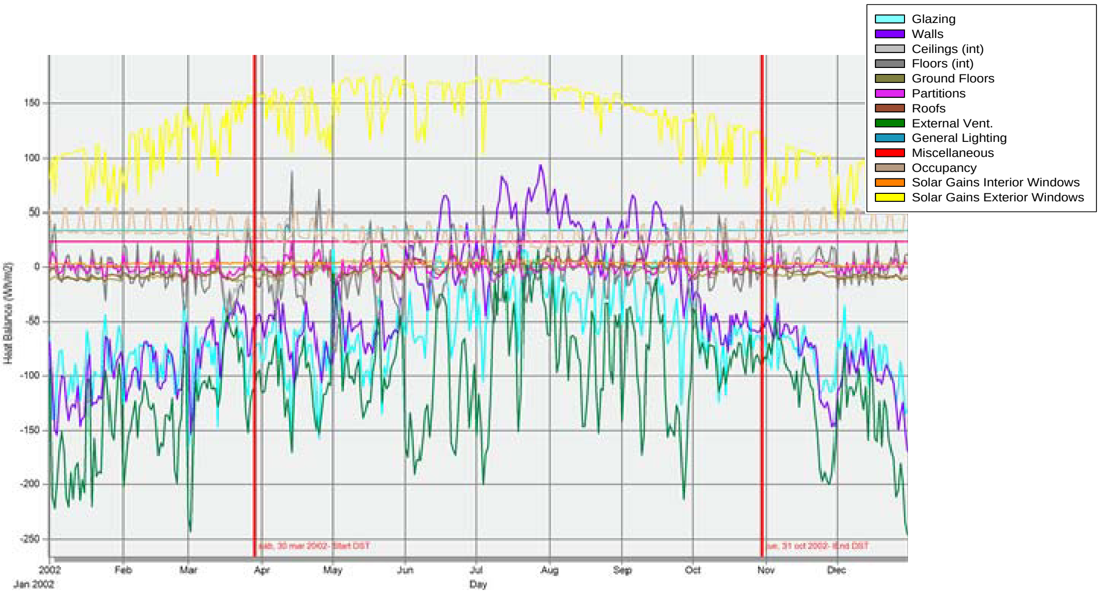

Fig. 2. Heat balance with the proposed thermal rehabilitation throughout the year, in the building studied.

This concept measures the return on the investment for a given value of years[26]. Its mathematical expression is Eq. (1):

$$NPV = -I_0 + \sum_{i=1}^{n} FB_i \Big/ \left(1 + D_r\right)^i \tag{1}$$

where I_0= Total initial investment costs; FB_i= Flow of benefits corresponding to year i, in this case these are the savings produced in the annual diesel oil bill for heating and the annual electricity bill for cooling due to the intervention; i= Year of study of the investment; n = Project horizon (for this study it can be likened to the life of materials used in the interventions, it seems reasonable to consider a maximum of 25 years, if the operation does not make a profit in this period it would be considered that is not depreciable); D_r= Discount rate or interest rate. In the present study two values of discount rate are considered: a more conservative value of 2.1% as used for energy enterprises; and a 3% value, as many energy studies assume[15].

In addition, it should be borne in mind that the flow of benefits ($\mathrm{FB_i}$) is subject to fluctuations in the price of energy. The higher the price, the more savings each year and thus the contribution to the NPV becomes positive faster. In the case of diesel oil, annual price fluctuation is subject to many variables, especially the price of crude oil, and is therefore very difficult to predict. The upward trend of energy prices is especially noticeable when considering a period of 25 years. Having consulted numerous official sources, an annual increase of 5.15% for the cost of diesel oil[26] and an annual increase of 6.3% for electricity[27] is considered. In the calculation of the average annual value of diesel oil for heating[26] corresponding to 2014, the assumed value amounts to 0.834 €/l, and for electricity[27], 0. 217 €/kWh. Under these conditions, the flow of benefits corresponding to year i is:

$$FB_i = \left(\frac{39.07 \cdot 0.834 \cdot 1.0515^{i-1}}{9.98} + 4.86 \cdot 0.217 \cdot 1.063^{i-1} \right) \cdot 2351.46 \quad (€) \tag{2}$$

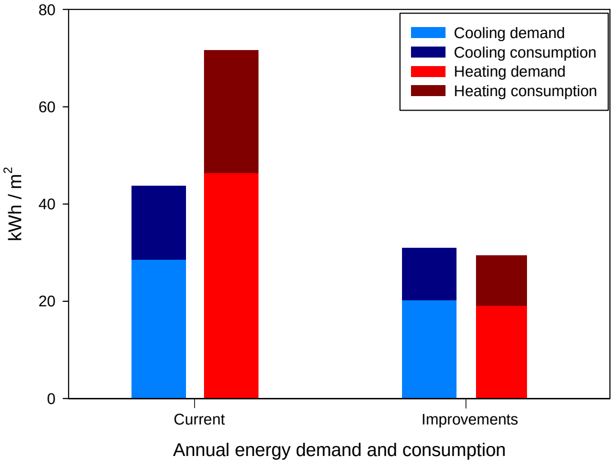

Fig. 3. Comparison of annual primary energy consumption and energy demand for cooling and heating of the current model of the building, and of the proposal of thermal rehabilitation of the envelope.

Assuming a lower heating power value for diesel oil: 9.98 kWh/litre. In summary, through Eqs. (1) and (2), the value of investments to date is obtained according to the year in which we find ourselves. Since the initial investment at the beginning of the process is large and has a negative value, several years have to pass before a positive NPV is reached. In the year in which the sign of the NPV changes from negative to positive, the operation begins to be profitable.

This NPV coefficient, in the case of the proposal of energy rehabilitation in the building envelope, begins to be positive from year 23, going from -2164.99 € in year 22, to +18100.29 € in year 23 when a 2.1% value of discount rate is considered; and begins to be positive from year 25 when a 3% discount rate is assumed, in this case going from -1514.65 € in year 24 to +15855.46 € in year 25.

These results clearly show that, for poorly insulated dwellings in a climate with moderately cold winters and hot summers, an energy rehabilitation of this scale, conducted outside the building (on the façade), is more economically expensive, although it enjoys the advantage of not interfering in the lives of neighbours and protects thermal bridges with maximum efficiency. However, this type of rehabilitation cannot be undertaken by counting on only the economic contribution of the building users but also requires a source of funding or external financial support.

5. Conclusions

In this paper, an energy model of a building under study (an H-shaped block of the residential complex Virgen del Carmen, in Seville, Spain) has been generated by DesignBuilder-Energy Plus software, as an illustration of the proposed methodology. This building has a large envelope surface, and was constructed before the implementation of the first Spanish regulations concerning thermal conditions of buildings, and therefore presents excessive energy consumption and should be subjected to energy refurbishment operations.

To this end, interventions in the envelope of the building are proposed: those that affect the insulating capacity of the entire envelope including the façades (openings and opaque part), roof, and floor in contact with the ground; as well as the overall airtightness of the building. These interventions are in strict compliance with the current Spanish regulatory framework.

Thermal results indicate that these improvements produce a significant reduction in demand and consumption of primary energy for the cooling and especially heating of the building model. This study also assesses the economic costs due to the operation of the rehabilitation studied and the repayment period of the intervention due exclusively to the savings in annual diesel oil (heating) and electricity (cooling) bills. The study of the Net Present Value coefficient has revealed that the repayment period for this model, considering a conservative hypothesis of discount rate, is 23 years and, consequently, the undertaking of this rehabilitation remains unfeasible when counting exclusively on the economic contribution of the residents of the building. This conclusion is also transferable to other poorly insulated dwellings in the Mediterranean area. External funding is therefore required in order to help reduce costs in the initial investment of energy rehabilitation by the owners.

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