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Energy and economic assessment of the envelope retrofitting in residential buildings in Northern Spain

J. Terés-Zubiaga (1), A. Campos-Celador (2), I. González-Pino (1), C. Escudero-Revilla (1)

(1) ENEDI Research Group, Department of Thermal Engineering, Faculty of Engineering of Bilbao, University of the Basque Country UPV/EHU, Alda. Urquijo s/n, 48013 Bilbao, Spain.

(2) ENEDI Research Group, Department of Thermal Engineering, Faculty of Engineering of Eibar, University of the Basque Country UPV/EHU, Avda. Otaola 29, 20600 Eibar, Spain.

Abstract

In this paper, potential energy savings by implementing different energy saving methods to enhance the building envelope are presented and calculated through dynamic simulations using TRNSYS software. With this aim in mind, a reference building was selected. In order to develop an accurate model, a dwelling of that building was monitored during three months, and data obtained in that monitoring study was used to calibrate and adjust the simulation model. The monitoring study as well as the definition of the building model and the different assumed hypothesis are presented in this paper. Then, different Energy Saving Measures are defined for roof, façade and windows, and 64 combinations are simulated. Those results, which are evaluated under economic and energy criteria, are assessed using as reference thermal requirements fixed by Spanish regulation (both for new buildings and for building renovations). These results show how energy renovations in buildings involve important benefits not only under an energy or environmental approach, but also considering economic issues.

Keywords: *Thermal Performance, Energy Renovation, Energy Efficiency, Building Envelope, Energy Savings*

1 Introduction

Nowadays, it is broadly known that the building sector is responsible of 40% of overall energy consumption in Europe [1]. Thus, any action directed towards increasing the energy efficiency of buildings can be considered of great importance. This explains the fact that since year 2000 many regulations have been set up in order to take advance of such potential. As a way of example, an interesting renovation policies review was presented in 2012 by Baek and Park [2].

In this way, many measures have been taken to enhance energy efficiency in new buildings but, at the same time, it is recognized that the biggest challenge concerns existing building stock, becoming retrofitting a key aspect to improving its energy efficiency. In the case of Spain, there were more than 26 million dwellings in 2011, according to data from Spanish Ministry of Public Works [3], and about 56% of the Spanish dwelling stock was built up before 1980, just when the first Spanish thermal regulation (NBE-CT 79) became effective [4]. Therefore, in order to reduce energy consumption, the main effort must be focused on the existing stock, being the implementation of Energy Savings Measures (ESM) in building renovation of great importance for meeting the European energy targets.

ESM in existing buildings can be divided into three categories: energy savings owed to the thermal performance of the building envelope (reducing energy demand), savings by upgrading heating systems (reducing energy consumption) and energy savings by supplying the total or part of the energy demand by renewable resources (reducing primary energy consumption).

This paper focuses on building envelope ESMs, as a first step for energy renovation of buildings. Several references are found in literature dealing with this issue, many of which are related to insulation materials. Several state-of-arts in thermal insulation materials can be found [5, 6], where the main characteristics and applications of common building thermal insulation materials are gathered.

More specific studies dealing with insulation layer optimization thickness have been thoroughly developed, and many references are found, such as [7-11]. Another important change in building envelope is the windows replacement, whose effects have been widely studied. Studies focused on windows influence on the building thermal performance can be found in several papers, such as [12, 13], to name but a few.

Many studies of this kind are based on theoretical calculations. However, important differences can be obtained when experimental and theoretical analyses are compared. This fact underlines the need for monitoring which is carried out in several studies. The work developed by the Danish researchers P. Bacher and H. Madsen in 2010 is noteworthy. They presented a procedure to identify models for the heat dynamics of buildings. An office building called "Flex House" was previously monitored and the results of monitoring and model development were published in [14]. More leaded to commercial usages (ESCOs and similar) is the IPMVP, a protocol of the Office of Energy Efficiency and Renewable Energy developed by the U.S.

Department of Energy [15]. It documents the state-of-art and defines common terminology, with the purpose of publishing current good practices for verification and measuring.

The integration of dynamic calculation by simulation and experimental studies makes the validation and tuning of the former possible. This procedure allows checking the validity of the simulation models and evaluates the performance of the buildings and ESMs under conditions different to those used in the validation. There are many simulation programs to develop this kind of models, such as TRNSYS [16, 17] or Energy Plus [17-19], to name but two of the most known.

The aim of this paper is to validate a TRNSYS simulation model by detailed experimental measurements. Once the model is validated it is used for carrying out the energy and economic analysis of several ESM covering insulation change and windows replacement. One of the main contributions of this paper is that the selected building used for the analysis is an existing building placed in Bilbao (northern Spain), which can be representative of the existing building stock of the 50s-60s period. Therefore, the obtained results can be regarded as very useful for assessing the actual potential of ESM. Moreover, the energy results are compared to those limits imposed by the new Spanish Regulation.

Thus, the paper has the following structure. In Section 2 the case study is presented, remarking the relevance of the selected building as representative of the buildings of the 50s and 60s. Section 3 presents the monitoring of the building specifying the selected sensors and their location for the sought objective. The TRNSYS modelling and its validation routine are presented in Section 4, where the tuning of the model is carried out. Once the model is validated, the ESMs to be evaluated are briefly presented in Section 5, covering insulation addition and windows replacement. Results of the energy and economic evaluation are presented in Section 6. Finally these results are discussed in Section 7, ending up with main conclusions in Section 8.

2 Choice of the case study

2.1 Building stock in the region

A thoughtful analysis of the building stock was recently carried out by the authors and presented in [20]. As a conclusion of that analysis, a multi-family building located in a significant district of Bilbao, known as Otxarkoaga, was selected as representative for the building stock of the area. It is well known the complexity and heterogeneity of the building stock and the subsequent difficulty of defining a "standard building" as model of the total building stock. However, the building selected for this work is quite from a specific construction period of the 20th century, the 60s. It was in this decade when a significant number of today's buildings, especially in industrial cities, were built up. In the case of Bilbao, around 20% of the current building stock was constructed in this decade. Moreover, the need for fast growing in that period (especially in many industrial, urban areas) leaded to homogeneous construction, giving rise to really similar constructive features in many buildings of that period.

2.2 The case study building

The studied building was built in 1959-1961. Some recent photos are presented in Figure 1. The building contains 36 dwelling units. Each dwelling has a net floor area of 50-55 m^2 and its floor to ceiling height is 2.47 m.

Figure 1. General view of the case study building

According to information provided by Bilbao Social Housing (local institution for social housing), external walls of the dwelling are composed by two layers of hollow bricks separated by an air gap. The indoor surfaces of walls consist of plaster over gypsum. On the other hand, as far as windows features are concerned, two different kinds of windows could be found in the majority of the dwellings, both of them with aluminium frame without thermal break. Some windows are single glazing, whereas others are double glazing.

Like many buildings built up in the region during those years, the building was constructed with reinforced concrete structure. Horizontal structure is composed by hollow-tiled floors, as usual in that construction period.

3 Monitoring

One of the dwellings of the building was monitored in order to have data to calibrate and validate the building simulation model. This dwelling has 3 external façades, oriented East, West and South, but only two of them (E and W) have windows as presented in Figure 2.

Detailed measurements of indoor and outdoor temperatures were collected using 53 PT100 sensors. Both surface and air temperatures were measured with these sensors. Reflexive tape was used to protect the sensors from direct solar radiation. Sensors were fixed using conductive plaster, in order to guarantee a good surface-sensor contact. Data obtained by the meteorological station of the Basque Meteorology Agency were also taken into account in this study.

On the other hand, five electrical heaters, each rated at 400W, were used for heating the dwelling. Their heat inputs were measured using a SINEAX M561 single phase power meter and they were controlled by a combination of a Randomly Ordered Logarithmic distributed Binary Sequence (ROLBS, a high frequency routine, with a 30 min. step) and a Pseudorandom Binary Sequence (PRBS, a low frequency routine, with a 60 minute step). Air temperature next to each heater was also gathered, in order to check that all of them were working properly. A layout of the dwelling can be seen in Figure 2, where each sensor position is shown.

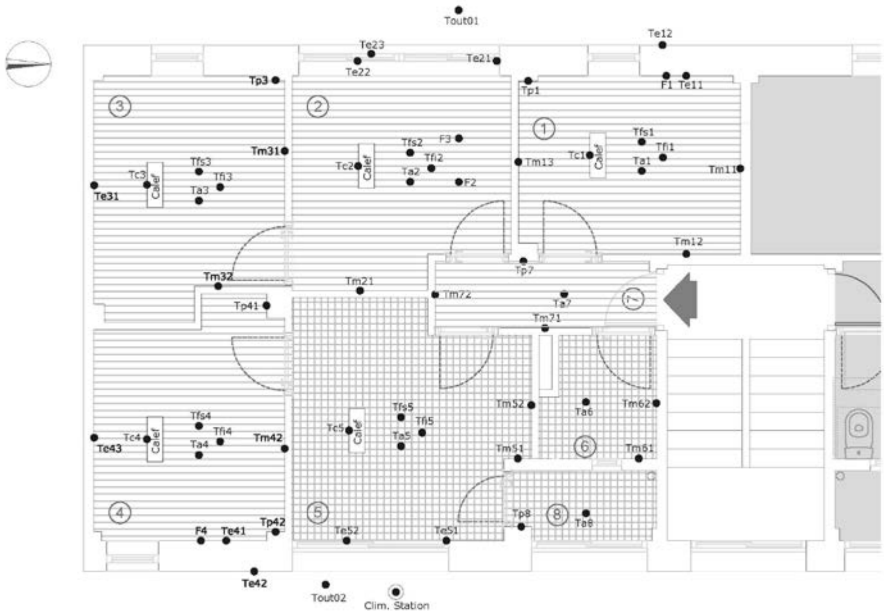

Figure 2. Layout of the studied dwelling before retrofitting works

An Agilent 34980A Data Acquisition and Switching system was used for logging measured values, with 34921A channel armature multiplexer and 34921T terminal block. All sensors and instrumentation were previously calibrated and validated with traceability by means of international patterns according to an internal procedure, in the Laboratory for the Quality Control in Buildings (LCCE) of the Basque Government, Detailed information on instruments characteristics is presented in Table 1.

Parameter	Units	Sensor	Uncertainty
Temperature	[°C]	PT100. A class (4 wire)	± 0,2 °C
Heat Flux	[W/m²]	Ahlborn FQA-0801-H	± 5 %

Anemometer	[m/s]	Meteo Multi FMA510	± 0,5 / ± 0,3 m/s
Barometric pressure	[bar]	Meteo Multi FMA510	± 0,5 mbar
Relative humidity	[%]	Meteo Multi FMA510	± 3 %
Solar Irradiation	[W/m^2]	Kipp and Zonen CMP11	± 3 %
Electrical power (heaters)	[W]	Sineax M561 single phase power meter	± 0,2 %

Table 1. Characteristics of the used sensors

Data were collected during 3 months (February – April 2012). The dwelling was empty during the monitoring period. Measurements were taken every 1 minute, since this frequency allowed checking the measurements in detail. After this first checking, data were integrated in 10 minute periods (more suitable frequency for buildings), by calculating the average value of each period. Outdoor conditions were also measured with a 10 minute frequency. This way, heating demand, outdoor and indoor conditions were measured simultaneously, guaranteeing the quality of the obtained data.

4 Model definition and validation

4.1 Model definition

The whole building was geometrically defined using Google Sketch Up with TRNSYS 3d plug-in, based on data obtained from plans provided by Bilbao Social Housing and on-site measurements. Two snaps of the model are depicted in Figure 3.

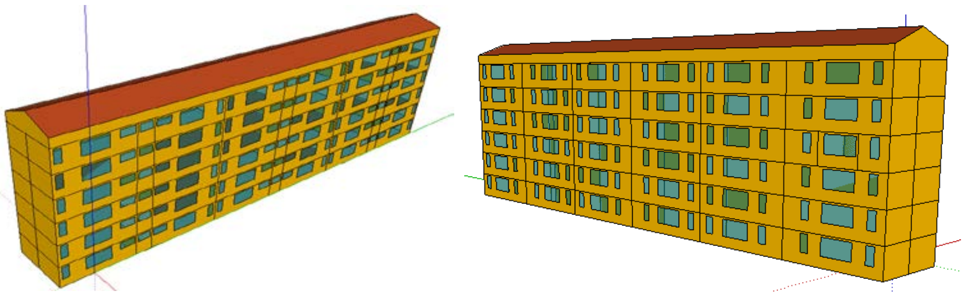

Figure 3. Snaps of the Sketch Up 3D model of the building

Dwellings were defined as different thermal areas. The importance of selecting a suitable division in thermal areas is shown in literature, such as in [21]. Each modelled dwelling encompasses two thermal areas: one of them corresponds to the west side of the dwellings, i.e. bedrooms; the other one, to the east side, which includes living room, kitchen, bathroom and drying area.

Similarly, the part of the building model which represents the monitored dwelling was divided more in detail considering four different thermal areas: one per each bedroom and other one which includes living room, kitchen, bathroom and drying area. Finally, staircase was considered as an independent thermal area.

Detailed description of the construction data assumed in the TRNSYS model is presented in the forthcoming Table 2. It is based on data provided by Bilbao Social Housing.

	e [cm]	Conductance [kJ/hmK]	Capacitance [kJ/kgK]	Density [kg/m³]	Thermal Resistance [hm²K/kJ]
EXT_WALL (Façade)					
Gypsum	1	1.8	1	900	-
Hollow Brick	4.5	1.76	0.9	1200	-
Vertical Air Gap (NoVent)	4	-	-	-	0.047
Hollow Brick	12.5	1.76	0.9	1200	-
Fibre Glass	2	0.144	0.84	12	-
Hollow Brick	4.5	1.76	0.9	1200	-
Cement Mortar	3.5	5.04	1.1	2000	-
Façade U-value	*0.74 W/m²K*				
EXT_ROOF (Roof)					
Cement and sand Mortar	1	3.6	1	1800	-
Hollow Brick	4.5	1.76	0.9	1200	-
Cement and sand Mortar	1	3.6	1	1800	-
Horiz. Air Gap (Lig.Vent)	2	-	-	-	0.022
Roof tile	1	3.6	0.8	2000	-
Roof U-value	*2.7 W/m²K*				
ADJ_WALL (Indoor walls)					
Cement and sand Mortar	1	3.6	1	1800	-
Hollow Brick	12.5	1.76	0.9	1200	-
Cement and sand Mortar	1	3.6	1	1800	-
Adjacent walls U-value	*2.25 W/m²K*				
ADJ_CEILING (Floors and ceilings)					
conifer wood flooring	1	0.504	2.8	600	-
Horiz. Air Gap (NoVent)	1	-	-	-	0.042
Hollow tilled Floor (20+4)	24	3.75	1	1500	-
Gypsum covering	1	1.44	1	1000	-
U-value	*2.27 W/m²K*				

Table 2. Detailed construction data

Likewise, the main characteristics of the windows are presented in Table 3.

Frame (30%)	U_{frame} [W/m².K]/[kJ/h.m².K]	Glass	U_{glass} [W/m².K]
Metallic without TB	5.7 / 20.52	4/6/4	3.44

Table 3. Windows considered in TRNSYS model

4.2 Model validation

Data corresponding to the first days of February (from 1st to 9th of February, 2012) obtained by the monitoring study were used as a reference to calibrate and validate the TRNSYS model. This period was selected since it was considered as representative, with variable weather conditions. Measured heat inputs were included as internal gains in the TRNSYS model validation.

The weather data file was defined taking the real outdoor environmental conditions recorded during the monitoring period. To do that, data gathered by the climate station of the Basque Meteorology Agency located in Bilbao was introduced in the TRNSYS weather data file.

Some significant data which could play a significant role in the simulation, such as capacitance, coupling air flow between different adjacent air nodes, or adjacent dwellings temperatures could not be monitored. They were used as parameters for the validation and were combined by means of an iterative process. The infiltration rates were measured during the monitoring period resulting in very low values. Different values of it were also taken for the validation routine ranging from 0.05 to 0.2 air changes per hour.

Even though only one dwelling was used as a reference in the validation, adjacent dwelling temperatures play a very important role in indoor air temperature of the mentioned dwelling. Since it is virtually impossible to know the heat routines in adjacent dwellings during the monitoring period (they were not measured), different constant set-point values were assumed in the validation.

Thus, about forty different parameter combinations were simulated in the model. Indoor air temperature was used as a reference to compare calculated values by the model and measured data. Model checking was carried out for indoor air temperatures in each air node of the dwelling, as well as the average value of the whole dwelling.

	Room1	Room2	Room3	Living Room
Infiltration (from outdoors) [vol/h]	0.1	0.1	0.1	0.1
Capacity [kJ/K]	100	120	164	650
Infiltration (from Staircase) [vol/h]	-	-	-	0.26
Convective heat transfer coefficient of wall (Façade) [kJ/h.m^2.K]	24			

Table 4. Final parameters assumed in the building model

According to the described analysis, model with parameters presented in Table 4 was selected as the most adjusted. Calculated versus measured air temperature for one room (in this case, room 2) and calculated versus measured surface temperature for the whole dwelling are depicted in Figure 4, where measured and calculated values are depicted in the left axis, and residual in the right axis.

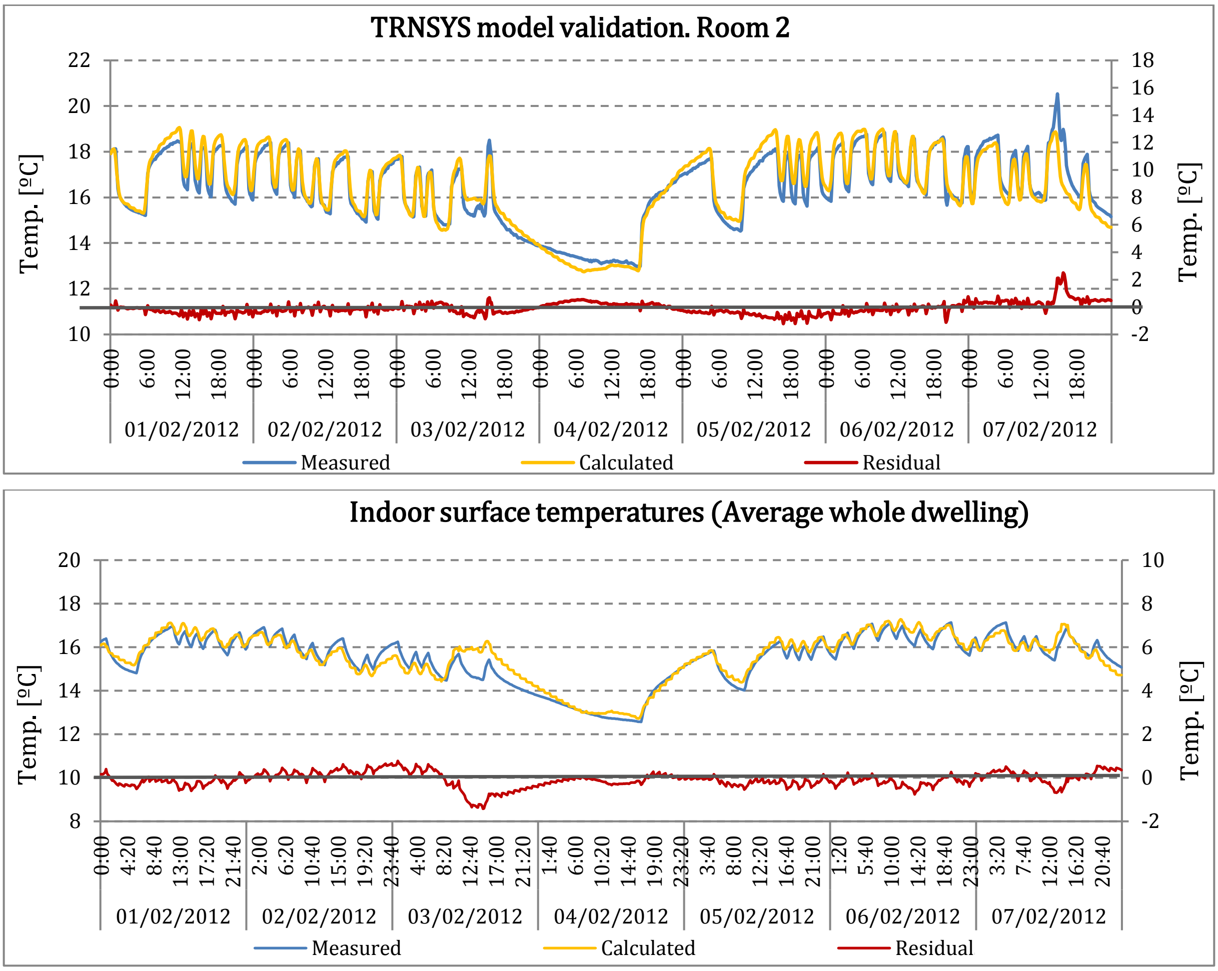

Figure 4. a) Calculated Vs Measured data and residual (Room 2); b) Indoor surface temperatures. Measured VS Calculated, and residual

Looking at these results, and taking into account the analysis of the residual, the model accuracy was assumed as acceptable. Some general values of the analysis of residuals are presented in Table 5.

	Analysis of residuals (Selected model)		
	Average (abs. Values)	Average (Real Values)	Standard Deviation
Dwelling	0.39	0.16	0.46
Room 2	0.34	-0.02	0.43

Table 5. Some statistical values of obtained residuals with the selected model

Thus, taking into account all mentioned uncertainties and their influence on the final performance of the studied dwelling, it can be affirmed that there was a good approximation between the monitored data and the simulation results. The model was subsequently compared with the experimental data of the whole monitored period and similar agreement was found.

5 Energy Saving Measures

Different ESM were laid and studied for ameliorating the building envelope elements. These ESM were addressed to improve the thermal behaviour of windows, roof and/or façade. Energy savings and initial investments were assumed taking into account the fact that many of these improvements are usually carried out taking advantage of required maintenance works of the building envelope. That is, economic data (initial investment) as well as obtained results (payback or NPV) were assumed to be the cost increase due to the implementation of the specific ESM. Thus, in the case of the façade, to name an example, assumed costs in each scenario were the insulation material and secondary material costs (materials needed to lay the insulation layer) and the labour cost (only the share devoted to lay the insulation layer). Other costs (e.g. scaffolding or finishes) are assumed to exist in the building maintenance work (with or without improving thermal performance), and for that reason, they have not been taken into account to make the calculations.

According to this premise, four scenarios were assumed for each element: scenario 0, when no thermal improvement is carried out; scenario 1, when a typical improvement is carried out (business as usual, BAU); scenario 2, when BAU scenario is slightly improved; and finally, scenario 3, when a "high standard" solution is assumed. Resulted models were named according to the combinations of the ESM adopted in each case. Thus, Model 1.2.0 represents façade scenario 1, roof scenario 2 and windows scenario 0. In Table 7, each scenario is described. Different costs were obtained from the ITEC database [23].

ESM in Façade	Addition of EPS in façade			
	Currently	**BAU**	**Improved Scenario**	**High Standard**
Scenario	0	1	2	3
Thermal ins. thickness [cm]	2 (+0)	6 (+4)	8 (+6)	14 (+12)
U [W/m².K]	0.74	0.43	0.36	0.24
Investment [€/m²]	-	6.46	8.42	14.94
ESM in roof	**Addition of fibreglass in roof**			
	Currently	**BAU**	**Improved Scenario**	**High Standard**
Scenario	0	1	2	3
Thermal ins. thickness [cm]	0	6	14	20
U [W/m².K]	2.7	0.53	0.26	0.19
Investment [€/m²]	-	10.05	20.81	29.11
Window scenarios	**Windows improvement**			
	Currently	**BAU**	**Improved Scenario**	**High Standard**
Scenario	0	1	2	3
Frame material (30%)	Metal (without TB)	PVC	PVC	PVC
U_{frame} [W/m².K]	5.7	2.2	2.2	2.2
Glass	4/6/4	6/12/6	3/12/3 Low-E	4/16/4/16/4
U_{glass} [W/m².K]	3.44	3.0	1.76	0.7
U_{wind} [W/m².K]	4.12	2.76	1.89	1.15

Table 6. Summary of data regarding ESMs in façade, roof and windows

It is seen that there is no economical assessment for windows. As mentioned before, in the case of roof and façade, costs assumed in scenario 1, 2 and 3 are actually the difference between each scenario and a reference maintenance work with no thermal improvement (which corresponds to case 0 or reference case). For the windows, since no costs were assumed to occur in the reference case, all costs are attributed to other scenarios. This fact contributes to making energetic measures on the windows apparently less cost-effective. For this reason, windows replacement was evaluated independently. Moreover, in the majority of the cases, windows improvement is not motivated by obtaining a quick payback of the investment, but other aspects, such as thermal and acoustic comfort. In this case, it is not possible to share out the investment corresponding to improving the energy performance and the investment devoted to other issues, as done for roof and façade improvements.

Financial help and other usual incentives promoted by different institutions for this kind of works were not considered. Thus, economic results presented in this paper would be even better if any kind of economic incentive would be applicable when the energy renovation is carried out.

As far as infiltration rates are concerned, a constant flow rate of 0.6 vol/h was assumed in the dwellings, and 0.9 vol/h in the stair case for all simulations. Even though there is no single standard value defined for the infiltration rate, the considered ratio is into the commonly used range for existing buildings [24]. No mechanical ventilation was considered, only manual ventilation (opening windows) was assumed for an hour (7 am – 8 am) with an air change rate of 4 vol/h in the dwellings, which is a common assumption for natural ventilation [21]. The internal gains were defined taking into account the hourly values given by IDAE [22]. The temperature set-point selection was adapted from the same document, considering that no set-point temperature is included during the ventilation period. Thus, 20ºC was set from 8.00h to 23.00h, being 17ºC the rest of the hours except from 7.00 to 8.00 when the natural ventilation takes place. For all the simulation Bilbao weather data file from Meteonorm Data Base was considered [25], which represents a typical meteorological year, generated from a data bank of many years in duration.

6 Results

Once validation was carried out, it was simulated under several scenarios. The assumed operating conditions and internal gains were defined according to those values proposed by IDAE [22], based on an hourly schedule. Thus, different simulations were carried out, using a 1h time step.

Therefore, the 64 possible retrofitting actions resulting from the combination of the presented ESMs were simulated with TRNSYS software. The results obtained from these simulations were thoroughly assessed afterwards.

In order to carry out the economic assessment of the different ESM combinations, some assumptions had to be made with regard to some energy and economic values. As far as energy values are concerned, the energy performance of the considered heating system was assumed to be 0.9 [26]. Concerning economic values, the assumed natural gas cost was 5.0 c€/kWh [27], different values of r were assumed (4-5-6-7-8%, based on values used in [28]), and three scenarios of expected annual increasing of natural gas price were evaluated: 0-4-8%.

6.1 Energy results

With regard to energy issues, energy demand, demand reduction and PE savings were assessed. Specific energy demand obtained for each simulated combination, as well as the achieved specific energy savings in relation to the base case (0.0.0.) are presented in Figure 5.

Two green lines are depicted in this graph. They represent the limit thermal demand imposed by the recently approved update of the Spanish Building Regulation [29], for both new and renovated buildings. In the case of new buildings, this limit would be 20.5 kWh/m^2 per year for the assessed building in the location under study. In the case of a retrofitted building, that limit (which must actually be fulfilled when more than 25% of the building envelope is affected by renovation works) is fixed in relation with a reference building (with the same geometrical characteristics). In this case, it would be around 83,500 kWh per year (40kWh/m^2), as obtained when those minimum thermal requirements were simulated in the model. It is observed that new energy demand limits for existing buildings can be easily reached by reducing 10% energy demand, but the limit for new building requires getting a reduction over 50% in the reference case energy demand.

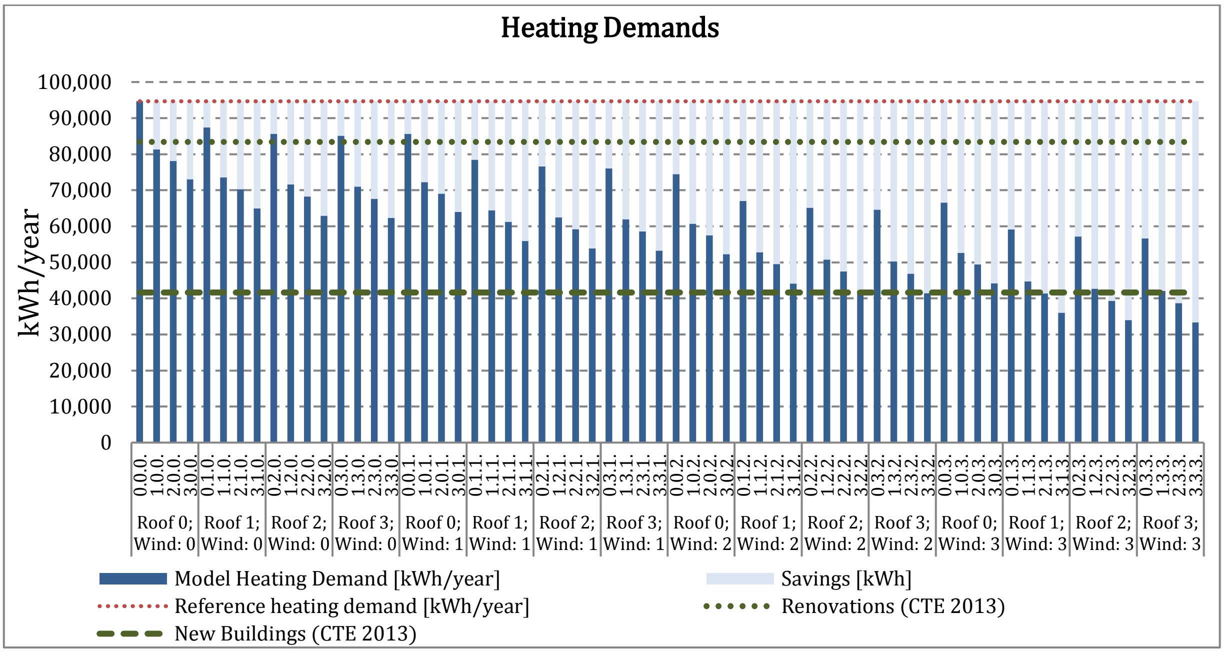

Figure 5. Yearly heating demands

From the analysis of the results, it can be deduced that, from all the selected cases, only four of them would not reach the energy demand limit for existing buildings. These cases are based on roof renovation which, nevertheless, would not reach the renovation size for being affected by the new regulation (25% of the total envelope).

Regarding the limits for new buildings, it is seen that, even being much lower than the demand of the reference case, it can be reached when high standards are applied on renovation, being 7 the ones that reach that limit (3.3.2, 2.1.3, 3.1.3, 2.2.3, 3.2.3, 2.3.3 and 3.3.3). Six of them are based on the implementation of high standard windows which are not commonly found in Spanish buildings. However, this fact underlines the potential of windows for getting very significant reductions in energy demand. The other one (3.3.2) presents “high standard” renovation works in roof and façade.

From a general analysis, it is concluded that the best combination scenario (3.3.3) achieved savings of almost 65% respect to the base case. But significant savings were also obtained when only acting on one element. Typical windows replacement (0.0.1.) achieved savings around 10%. Savings obtained by windows replacement were triple with the best windows scenario (0.0.3). When the façade is the only improved element, obtained savings on energy demand ranged from 14.15% (1.0.0) to almost 23% (3.0.0.)

Effects of roof retrofitting were slightly less significant when the total energy demand of the building was analyzed, from 7.64% (0.1.0) to 10.10% (0.3.0). Savings were obviously more significant when only the upper floor is considered; in these cases energy savings reached values from 26.31% (0.1.0) to 34.60% (0.3.0).

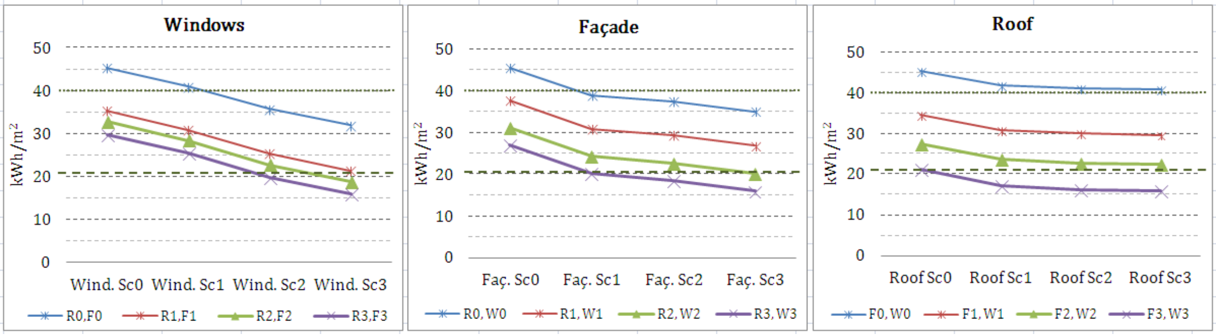

Figure 6. Energy demand of scenarios improving windows, façade and roof

In Figure 6 the influence of windows (left), façade (centre) and roof replacement (right) on the energy demand is analysed in detail in order to obtain direct conclusions of the performance of each action. In the case of windows replacement, energy consumption is almost linearly reduced when the window quality is improved, being no depletion in the energy demand reduction. Nonetheless, that effect does not occur with the façade and roof renovation. In these cases it can also be appreciated that every action produces a demand reduction, but this is more effective when changing from scenario 0 to 1. This is especially evident in the roof renovation, where not significant improvement is achieved when scenarios 2 and 3 are assessed.

6.2 Economical issues

Although energy regulation aims to decrease the energy demand and improve the energy performance of existing buildings, the implementation of ESM usually needs to be backed by economic assessment. Payback and NPV are selected as financial parameters for evaluating the economic feasibility of different approaches.

The economic analysis was carried out as follows. First, ESM combinations of roof and façade scenarios were evaluated. That economic assessment was carried out under the premise presented in section 5. Afterwards, windows replacement was assessed. This is owed to the fact that window replacement cannot be shared out like those costs associated to roof and façade improvements. Moreover, as previously mentioned, window replacement is not only motivated by energy demand reduction, but other aspects are sought, for instance, thermal and acoustic comfort.

Hence, the 15 possible combinations of ESM for roof and façade were economically evaluated using previously mentioned parameters. In this section, an assessment of those combinations assuming a 4% discount rate value and an increment of 4% in the natural gas cost is presented. The so obtained cash flows are depicted in Figure 7, where only some of the cases are analysed for the sake of clarity.

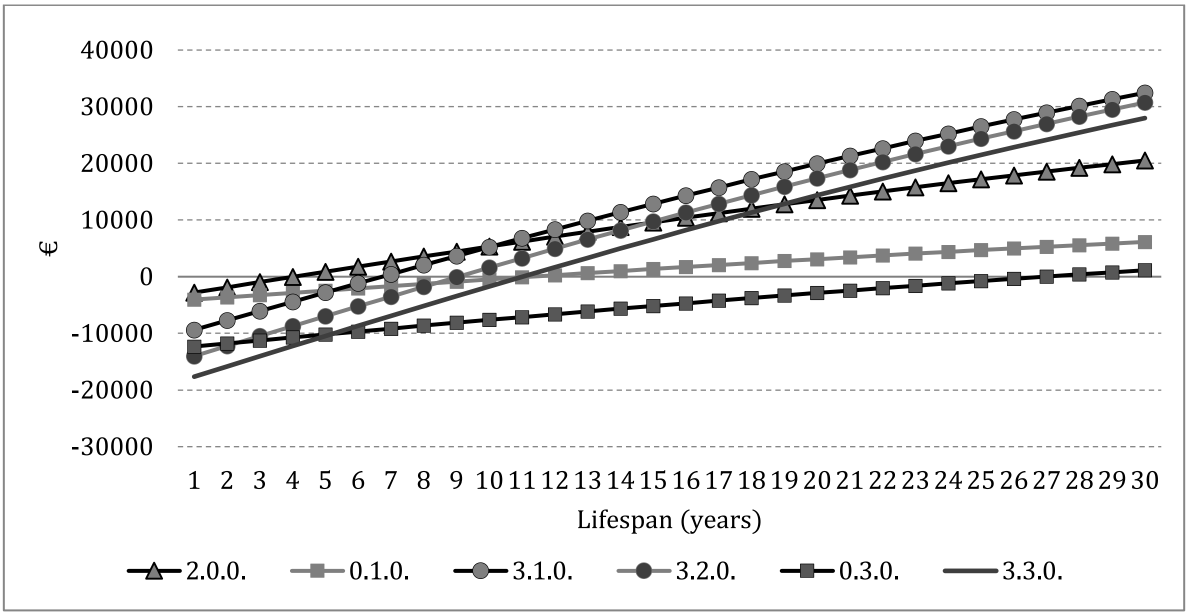

Figure 7. Cash flows of the selected ESM

These 6 cases are enough in order to identify the three trends that were found. There are some actions which are barely feasible for 30 years lifespan and the investment is only recovered at the end of its life. These correspond to those actions where only the roof renovation was considered (0.1.0, 0.2.0 and 0.3.0). On the other hand, any renovation on the facade produces significant savings. There are some actions which produce a faster recovery of the investment with a moderate NPV (2.0.0, in the case of those depicted in Figure 7), while there are some others with a slower recovery of the investment but a higher NPV at the end of its life (combinations 3.1.0, 3.2.0 and 3.3.0 in Figure 7). All these effects should be considered when assessing a building renovation, and the discussion of the aforementioned results is carried out in next section.

6.3 Discussion

When the different proposed combinations were evaluated taking into account energy issues, it was seen that minimum energy requirements in renovations established by the Spanish Regulation can be easily met if proper ESMs are applied to existing buildings. However, the standards established for new buildings by Spanish Technical Building code could be only fulfilled if a deep renovation project following high standards was carried out.

Several ideas can be highlighted when assessing these simulation results:

- The ESM based on façade renovation are the most cost-effective and the ones that offer the best relationship between economic feasibility and energy savings.

- It was obtained that energy renovations in roof are less cost-effective than ESM in façade. This is mainly due to the fact that this building typology has a low roof-to-façade ratio, around 0.20, which is typical for constructions in that period. However, the cost of the action is interesting when other renovation works are carried out on it.
- A moderate ESM on as many envelope elements as possible is better, than a high standard one over a single element.
- Windows replacement is less cost-effective ESM when compared to the other proposed ESM, and its economic analysis has not been performed in this paper since it is an independent action itself. However the energy demand reduction is very significant and would have been even higher if the associated reduction of infiltration rate had been included in the analysis. Besides, one could not forget other non-economic benefits such as noise reduction and thermal comfort improvement.

The feasibility of the ESM can be also analysed from a user's point of view, which can be introduced by Figure 8, where specific investment and profitability per dwelling are related. The profitability has been defined as the NPV-to-investment ratio. Two different trends can be identified in the figure, both decreasing exponentially as the investment increases, being the upper trend of higher feasibility than the lower.

The lower set of ESM (0.1.0, 0.2.0 and 0.3.0) are those covering only roof renovation. Amongst them, only the basic ESM on the roof (0.1.0) presents significant profitability while the others only allow recovering the investment at the end of its lifespan. Moreover, other fact should be considered. In this analysis both the investment and the NPV are equally distributed amongst all the dwellings. However, as the reduction of the energy demand mainly affects to the dwellings in the last level, depending on the cost distribution carried out by the investors, the afore defined profitability would vary significantly. That is a fact that should be known in advance when a feasibility study is carried out for an ESM that does not affect equally to all the dwellings of a building,

The rest of the ESM lay on the upper trend and it is clearly seen that the ESM covering only façade renovation are the most profitable for the user and moreover, the effect of the ESM are more equally distributed (1.0.0, 2.0.0 and 3.0.0) with great profitability ratios. The rest of the cases include the roof ESMs as well, and although they require a bigger initial investment, they also offer higher economic benefits.

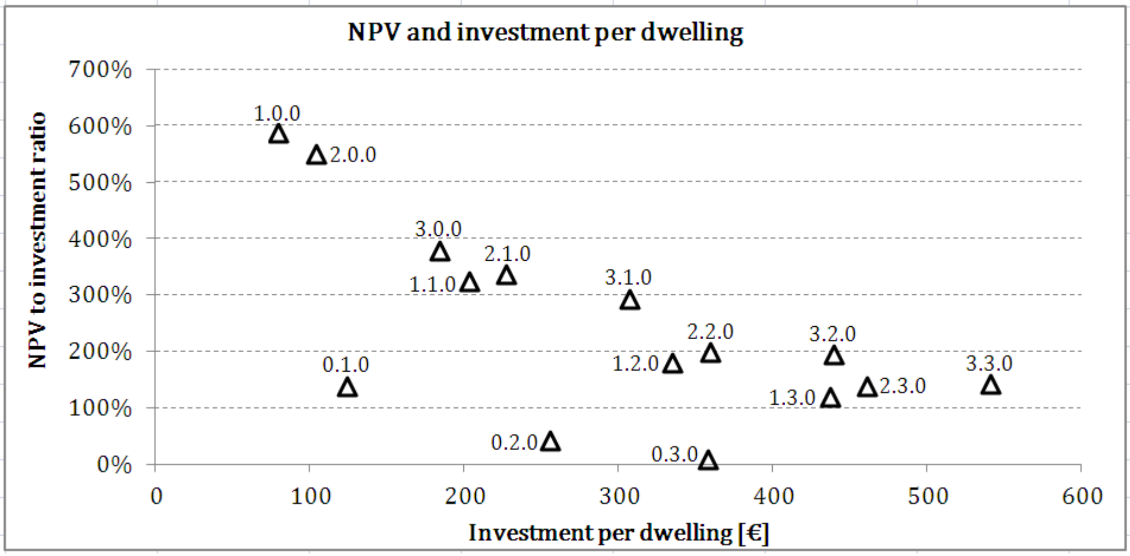

Figure 8. Investment and NPV per dwelling

It must be remarked that, as mentioned before, economic results were obtained based on the cost increment linked to the thermal enhancement when required envelope maintenance works are carried out. Thus, results presented in this paper, mainly those related to roof improvements, must not be considered as unfeasible or uninteresting works. Results presented in this paper, indeed, remark that even in the case of the roof, where ESM are less cost – effective, cost increase related to thermal improvement is paid back over its lifespan. Moreover, the addition of insulation layer in roof involves other benefits; especially remarkable is the increasing of the lifespan of the roof, since it reduces the thermal gradient of the waterproof layer (when thermal improvement is laid on the external side of it) reducing then the maintenance cost of the roof (since frequency required for roof maintenance is reduced). Results related to façade thermal improvements show that carrying out a façade maintenance work and not taking advantage to improve the thermal performance of the façade makes no sense, taking into account the low cost increase, the short payback periods obtained and the reasonable NPV obtained for thirty years.

Finally, other positive effects must be taking into account when renovation works are carried out in buildings, such as improving thermal comfort and indoor air quality, reduction of the noise or improving the building aesthetics and architectural integration, to name but a few. It would be interesting to explore the way of considering these benefits (both for building owners, promoters and users) when different ESM are evaluated. That point is also object of study in different researches, e.g. those carried out by Annex 56 "*Cost-effective energy and carbon emission optimization in building renovation*" [30].

7 Conclusions

The modelling and experimental validation of an existing building is presented in this paper, being that building representative of the construction in the 60s in northern Spain. Then, this model was used for implementing different ESM in the envelope, covering façade, roof and windows replacement.

Results of 64 possible combinations of ESM were firstly presented and their energy and economic results were thoroughly assessed. Results showed that, in the majority of the cases, thermal improvement of roof and façade is beneficial under energy and economic approach. Obtained economic indicators were clearly favourable, even under conservative assumptions (assumed natural gas cost was lower than the actual cost in January 2014, no kind of financial or economic incentives were considered…).

Results also showed that, for the case of northern Spain, fulfilling energy requirements established by Spanish regulations for existing buildings is accessible and even thermal requirements for new buildings could be fulfilled if a deep energy renovation was carried out. Thus, it can be affirmed that although thermal requirements have been increased in Spain in last years, Spanish thermal regulation needs to be toughened in order to meet European goals, especially when the building sector has been widely recognized as a key sector for energy consumption reduction and CO_2 emissions mitigation.

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