Procedure for evaluating and refurbishing envelopes of obsolete buildings in warm regions

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Abstract

This research develops a procedure to evaluate and refurbish obsolete buildings obliged to comply with the Spanish Technical Building Code (STBC). This procedure matches the building typologies selected to the optimal solution for each case. The analysis focuses on buildings constructed between the 1960s and the 1980s in Castellón, Spain. The buildings selected are representative of the period, of compact cities, and of the Mediterranean climate region.

Three types of intervention on the envelope have been considered. The analysis for the most appropriate intervention in each case was based on economic, environmental, technical and social factors. It shows that the best solution for Terraced Houses (TH) and Multi-family Houses (MH), is exterior refurbishment with additional insulation on the façade. This solution is achieved at reasonable cost by reducing one third of the primary energy consumed. The best solution for Apartment Blocks (AB) is exterior retrofitting with ventilated façades, which offers the best performance from a technical, environmental and economic perspective. In all cases interior retrofitting is ruled out given that exterior retrofitting with additional insulation provides greater energy savings at a similar cost.

Key words: Obsolete buildings, Warm regions, Envelope intervention, Energy consumption, Building retrofitting.

1. Introduction

This research analyses the potential reduction of CO_2 equivalent emissions in urban areas in warm regions by analysing specific solutions for building retrofitting in the Urban Planning of Castellón. Current research examines the resilience of specific Mediterranean residential building stock to the impact of global warming taking into account technical, economic, environmental and social criteria (Kolokotsa, Diakaki, Grigoroudis, Stavrakakis, & Kalaitzakis, 2009). Strategies and measures involving urban fabric simulation are considered for the adaptation of building envelopes to diminish Heating Ventilation and Air-conditioning (HVAC) energy demands (Papadopoulos, 2007).

Some authors have spoken of the potential of retrofit programmes (Karvonen, 2013) in promoting socio-technical and technical-innovative change (Seyfang & Haxeltine, 2012) (Vergragtand & Brown, 2012). However, before proceeding it is essential to characterise and understand the long-term timeframe of the fabrics, forms, and systems of built environments (Eames, Dixon, May, & Hunt, 2013) (Newton, 2013), taking into account societal behaviour, ascertaining whether or not each regional development is ready for such a 'commitment'. This should be understood as a way of re-engineering the existing urban environment (Cole, 2012)

Previous studies based on the effect of occupancy and building characteristics on energy use showed that although occupant profile -recording age, marital status, or membership of family- and behaviour significantly affect energy use (4.2%), building characteristics still determine a large part of energy use in apartments (42%). Further analysis showed that certain types of occupant behaviour are determined by the type of dwelling, so that the effect of the occupant profile might be greater than expected (Guerra Santin, Itard, & Visscher, 2009) (Meir, Garb, Jiaoandand, & Cicelsky, 2009). This paper analyses different solutions to meet the recommendations of the International Energy Agency (IEA, 2008) on the renovation of existing buildings in order to save a significant portion of this energy.

Building renovations which are usually unstructured and non-optional are conditioned by knowledge and subjective preferences. The end user's criterion is viewed as the sole economic aspect of the overall procedure and is probably the overriding criterion (Leal, Granadeiro, & Azevedoandand, 2014). In this respect, this research is based on a set of previously outlined criteria, and available options and constraints. Simulation and multi-criteria decision-making are focused on solving the evaluation and retrofit of building envelopes in key areas taking into account the social context for evaluation (Hauge, Thomsen, & Berker, 2011), while the process of moving into an energy-efficient building and prior knowledge of environmental issues influence the Post-Occupancy Evaluation of the building (Voelker, Beckmann, Koehlmann, & Kornadt, 2013).

2. Methods

2.1 Building typologies. Selection and characteristics

The study was carried on a set of buildings dating from the 1960s to the 1980s in Castellón, Spain. The first construction norms, CT79, established the characteristics of building envelopes for improving comfort conditions in multi-family houses and apartment blocks. However, CT79 made no reference to eco-efficient refurbishments.

The areas for study were selected taking into account previous studies on the age of the neighbourhoods of Castellón. A list of buildings was drawn up by using the online dataset from the Ministry of Finance and Public Administration (MFPA) (2006). The study was based on 1,146 buildings with a total of 7,652 apartments. There were three different typologies found among the buildings analysed: 1. Terraced Houses (TH) with one apartment per storey; 2. Multi-family houses (MH) with two or more apartments per storey and up to four storeys; 3. Apartment Blocks (AB) with several apartments per storey and more than four storeys (Episcope, 2009). Typology 1 represents 11% of the buildings analysed, typology 2 80.5% and typology 3 8.5%.

Conservation Reports of Building and Energy Certification (CRBEC) from the Valencian Regional Government and Valencian Institute of Building (IVE, 2011a) were produced for some buildings, accessing several buildings and residential units and collecting all the necessary data. BCRs were created for 5 type 1 buildings (TH), 1 type 2 building (MH) and 1 type 3 building (AB). Initially, given the predominance of TH in the centre of Castellón five buildings from typology 1 were analysed. As part of the surveying process neighbouring buildings were inspected visually to extrapolate the intensity and scope of pathologies and deficiencies associated with these building types.

BCRs and Energy Assessments were carried out using a tool developed by the Valencian Regional Government. The results of the BCRs awarded the buildings analysed an energy rating of E on a scale ranging from A (best) to F (worst).

In order to reduce CO_2 equivalent emissions and the E energy rating of the entire residential stock built between 1960 and 1980 retrofitting interventions were necessary. To carry these out the Valencian Regional Government developed the Retrofit Building Solutions Catalogue (RBSC) (IVE, 2011b) which covers the different options for improving building envelopes in energy retrofitting. The data compiled in the CRBEC and the RBSC showed that there were three possible interventions for façades and roofs: the addition of thermal insulation from inside (solution 1), the addition of exterior insulation (solution 2) and the creation of a ventilated exterior façade (solution 3).

An approximate simulation of original and hypothetical post-intervention conditions was carried out by using the Energetic Residential Rating Abbreviated Method provided by CERMA-R (2013). The results obtained with this tool were the energy rating in relation to total CO_2 equivalent emissions (kg/m^2) for the building envelope, individual energy ratings for heating ventilation, air conditioning, and ACS (CO_2 equivalent emissions), the noticeable demand in heating ventilation, air conditioning, and ACS (gross) in kWh/m^2, and the emission percentages for heating and air conditioning.

CERMA-R software is widely recognised for the energy efficiency certification of newly built and older residential buildings. Given that this software considers the building as a single thermal zone, the components of the envelope that limit the zone with the exterior need to be defined. Other inputs such as climatic zones, building orientation, surrounding obstacles, and heating and cooling equipment need to be specified. Outputs detail the estimated energy consumption, providing not only a global rating based on total CO_2 equivalent emissions per year, but also the CO_2 equivalent emissions per year based on an element-by-element consideration: opaque and semi-transparent elements, ventilation, thermal bridges, internal loads, and domestic hot water. Other outputs are monthly and annual energy demand and consumption for heating, cooling, and hot water.

2.2. Environmental pre-existences

This research seeks to analyse the extent to which CO_2 equivalent emissions can be diminished by means of different energy efficiency measures simulated in consolidated urban areas on the Mediterranean coast. The study focuses on analysing the incidence of summer climatic conditions. Taking this into consideration, the study examines the retrofitting of the most exposed elements of buildings in summer, the roof, and the east and west façades. Most, if not all, the HVAC installations in multi-family buildings are individually controlled in each apartment. Units can either be completely ventilated or partially ventilated, resulting respectively in overventilation with the consequent higher energy consumption, or underventilation which causes an accumulation of contaminants.

The climate of Castellón is Mediterranean, mild and wet. The average temperature exceeding indoor comfort limits is subject to seasonal peaks and occurs during the months of June, July, August and September, when indoor temperatures can reach 30ºC. The monthly mean values of solar radiation in Castellón have been calculated using daily global radiation data from the Spanish Meteorological Agency. These data show more than 6.0 Kwh/m^2 of solar radiation from early May to late August. In these months the city is prone to heat waves caused by incoming warm fronts from the Sahara. As regards sun exposure, Castellón has 2,660 hours of sunshine a year, the equivalent of 300 days a year. The Köppen climate classification places Castellón in a Csa geographical area.

The incidence of wind on housing causes heat exchanges between surfaces in contact. This is reflected in increased superficial transmission coefficients of heat, both in façades and roofs in summer. In the warmer months (June, July, August and September) the wind direction is principally from east to west.

Table 1. Climatic data for Castellón de la Plana

The façades most in need of protection from solar radiation in summer are east and west, with an average solar radiation of 2.98 kWh/m^2. However, if taking into account the positioning of the plots, the urban fabric, and the values obtained in the warmer months, it could be stated that at times south façades have the greatest potential for solar irradiance, with peaks of 305 W/m^2 from 12:00 to 1:00 pm, higher than the peaks of the west and east façades. In this regard, a lower figure for hours of solar radiation was obtained by studying the different typologies of buildings protected from solar insulation by other buildings.

2.3. The three envelope interventions

Multi-criteria analysis was used in the research on technical, economic, environmental, and social factors for all the types studied in relation to the three possible interventions for each case to evaluate which cost-optimal rehabilitation for energy performance requirements would be the most. The different factors were analysed in four buildings, one per building type and two for type 1 (TH) to ensure results in better keeping with the heterogeneous nature of these buildings.

Table 2. U values table

2.3.1 Technical factor

The roofs and floors in TH, MH, and AB are flat ventilated roofs which can sometimes be accessed. Some buildings included unventilated roofs in interior courtyards and lift shafts, elements which are not in direct contact with occupied spaces. In types 1 (TH) and 2 (MH) the lower horizontal enclosure of the building was 20cm deep concrete slabs in direct contact with the ground. Type 3 buildings (AB) included a basement, which acted as a thermal buffer between the ground and the inhabited space directly above.

There are four different building solutions used for vertical enclosures. Three of these can be observed in types 1 (TH) and 2 (MH): perforated brick enclosures rendered on the outside and coated on the inside with sheets 12 and 24 cm thick (solution 1); dividing walls are enclosures between 24 and 48 cm thick, in perforated brick, masonry, adobe, or even rammed earth (solution 2); the remaining enclosures, main façade, and courtyards are hollow brick rendered on the outside and coated on the inside with 12 cm thick sheets (solution 3). Solution 4 is only found in the case of type 3 (AB) and consists of a double-sheet enclosure with an unventilated air cavity. The outer sheet is perforated brick and the inner sheet is rendered 4cm hollow brick. This enclosure is between 25 and 27 cm thick. The most widespread type of exterior joinery (90% of all types) consists of aluminium window frame structures with 4 or 6mm single glazing and no thermal bridge rupture.

The technical assessment suggested similar solutions for all three building types. In all cases the simplest and most immediate technical solution is to add thermal insulation from inside (1), as the only scaffolding required would be to avoid thermal bridges on the slab faces. The other two solutions are much more complicated and require occupancy permits and the aesthetic modification of buildings. In any case, as regards durability the best solution would be to create a ventilated façade (3). Finally, the addition of insulation from outside (2) would require the earliest inspection for retrofitting.

As regards the roof, the simplest technical intervention would be from inside, but just as with the façade an intervention from the outside would increase the useful life of buildings, guaranteeing improved behaviour. When considering the maintenance of material, interventions from inside always seem more suitable as they subsequently enable easy access. In the case of the slabs in types 1 (TH) and 2 (MH) it is best if these are insulated on the upper face. In type 3 (AB) it is best to insulate the ground floor from below.

2.3.2 Economic analysis

To analyse the economic factor Arquimedes (1983) was used to draw up the estimates for the three hypothetical interventions on the different building type envelopes, obtaining 12 variants. For the financial assessment all building envelope elements - façades, dividing walls, roofs and floors - were considered. In addition to each possible intervention, changes in joinery and the elimination of pre-existing pathologies and other actions characteristic of interventions were taken into account.

Arquimedes is a Quantity Surveying and Project Management software developed by CYPE Engineering. By using this software with an updated version of the Guadalajara Building Surveyors Construction Prices Database, the e2co2cero (2014) application in Arquimedes allows the user to calculate the embedded energy and the Carbon footprint of a building taking into account the materials of the original and the retrofitted envelope. The tool allows users to successively evaluate the different stages of the retrofitting project and the different ranges of retrofits, according to materials to be used and position in the envelope as in the case of this study.

Table 3. Results from Morella St (AB) building considering an estimate of investment and payback from a static analysis with an actualization rate of 3%.

The prices obtained for the three types of intervention, interior or exterior, not only included the general vertical insulation of façades, dividing walls and the roof, but also the thermal bridges; including the insulation of balcony fronts, paving and roof, and considering the extra cost of demolitions and railings. The eventual reinforcement of the structure of the building was also considered due to new estimated wind suction forces in the ventilated solutions and the weight loads of the new systems in both the interior and exterior ventilated solutions, forces and loads not considered in the original design of the structure. PVC joinery was considered optimum. Nonetheless, as will be shown, cheaper solutions for joinery would probably allow the investment to be recovered, although they were not used in this case. The insulation of slab foundations in contact with the ground was considered for all interventions, involving demolition of paving and modifications of interior joinery.

The economic assessment offered a hierarchy of solutions based on building type. For types 1 (TH) and 2 (MH), solution 1, the addition of thermal insulation from inside, is the cheapest, followed by solution 2, the addition of insulation from outside. In this case, although it is slightly costlier than the previous solution, the cost decreases proportionally as the height of the building increases. Finally, solution 3, the creation of a ventilated façade, is the most expensive by far, although the cost decreases as with solution 2.

Table 4. Financial assessment of every possible intervention according to type.

Solution 2, the addition of insulation from outside, is the most cost-efficient solution for type 3 (AB), while solution 3, the creation of a ventilated façade, although costlier has a longer useful life with economic repercussions following intervention. Finally, solution 1, the addition of thermal insulation from inside would be the least suitable for this type given the previous observations.

2.3.3 Environmental factor

The CERMA-R software was used in the analysis of the environmental factor to calculate the emissions of buildings prior to interventions and to analyse potential savings after intervention. Intervention emissions were calculated by using the e2CO2cero (2014) application which makes it possible to calculate the embodied energy and the carbon footprint for a given building depending on the materials added and construction processes followed during retrofitting. Based on 12 economic assessments the tool calculates the embodied energy and the total CO_2 equivalent emissions for each, taking into account the Life Cycle Analysis of materials and their implementation.

Environmental analysis offered a hierarchy of solutions depending on the building type. For types 1 (TH) and 2 (MH), solution 3, the creation of a ventilated façade, is optimal as it provides the greatest reduction in emissions and in primary energy consumption in both cases. With solution 2, the addition of insulation from outside, there is less of a reduction, while solution 1, the addition of thermal insulation from inside, has the least effect on the reduction of emissions and primary energy consumption.

Although the three possible interventions for type 3 (AB) result in practically the same reduction in CO_2 equivalent emissions and primary energy consumption, solution 1, the addition of thermal insulation from inside, is the optimal solution as there are fewer CO_2 equivalent emissions and proportionally less embodied energy than the others. With solution 3, the creation of a ventilated façade, the proportion of CO_2 equivalent emissions is greater, while solution 2, the addition of insulation from the outside, causes most pollution and has a shorter life cycle.

Table 5. Embodied energy and total CO_2 equivalent emissions according to type of intervention and building.

2.3.4 Social factor

In order to assess a possible procedure for action depending on the optimal solution for each building type the study included quantitative analysis based on data from surveys of building owners. Thus, the social factor was based on a simple random sample of 300 surveys of owners with an estimated error of 5.5% for a confidence interval of 95%. Data was collected in person on a door-to-door basis using a structured questionnaire.

The general survey's economic, environmental, and technical results aimed to determine an integrated action and showed that 80% of those surveyed believed economic criteria to be the most important consideration when deciding on retrofitting buildings. 22.3% of those surveyed considered technical criteria important, while environmental criteria were considered of little or no importance, with 17.7% of those surveyed admitting to feeling indifferent towards these.

Non-hierarchical or cluster analysis allowed the market to be segmented, identifying underlying groups displaying homogeneous behaviour depending on the importance attached to the different criteria. A total of three groups of surveys were extracted, with percentages showing a very heterogeneous sample: Group 1 (4.3%), Group 2 (71.7%), and Group 3 (24%).

When all three groups were questioned on the measures already implemented in the retrofitting of residential units, Group 1 had given the least thought to measures for retrofitting dwellings. Group 2 claimed to take measures and change living habits in order to implement them. Group 3 admitted to being most conditioned by the seasons of the year, as they changed measures depending on the season.

Those questioned were asked about the possible sources for funding an hypothetical retrofit. Over 40% of those surveyed would not make any investment as they would not be able to exchange a second home as payment, they had no money specifically for this, or they did not think they would be able to obtain money from other sources such as the sale/rental of a second home, a bank loan, a family loan or savings. In all cases the results for the different groups show a certain degree of willingness. Group 1 is the least predisposed to invest in apartments since 100% would not give up a second home to cover costs, 69.2% would have no access to funds for energy improvements in the apartment and 84.6% would have no other sources of funding.

Group 2 considered the greatest number of options for obtaining funding. 25.6% would be willing to use land in the country as payment, 5.1% a second home in the country, and 4.6% one on the coast or in the city. 39.1% of the group claim to have access to money for the energy improvement of the apartments. The bracket most commonly mentioned is that of up to 1,000€, while 15.3% could afford up to 3,000€, 6% up to 5,000€, and 5% up to 10,000€. As regards the sources of funding, 29.8% would be willing to rent out a second home and 16.3% would have access to funding in the form of savings, 15.8% would consider applying for a loan or requesting family help.

26.3% of Group 3 consider that the best options for funding the investment would be to apply for a mortgage loan or request help from family. 63.9% of this group would not have money for energy improvements on the dwellings, although 26.4% would have access to up to 1,000€. In addition, 87.5% were unable to consider payment exchanging a second residence as an option.

Another result worth noting is that associated with giving up square metres (surplus buildable area) to pay for the energy retrofitting. 74% of those surveyed would not be willing to live in a smaller apartment to ensure energy efficiency (less heating and air conditioning expenses). 22% would be willing to reduce their apartment by up to 10m^2 if this represented a saving of up to 8,000€. Although there is no significant difference between the groups, Group 2 showed most willingness to live in an apartment with fewer m^2, with 22.8% in favour. 4% of those surveyed would be willing to reduce their apartments by more than 20m^2.

3 Discussion

3.3 Optimal intervention for each building type

In Europe, Directive 2012/244/UE (2012) developed a methodology that compares and rates the minimum criteria for energy efficiency in buildings based on the Net Current Value aftermath. The economic estimates require certain hypotheses to be assumed, especially in the long-term investment analysis and dynamic calculus. The analysis of global costs was based on the macroeconomic version of Directive 2012/244/UE (2012) because of related social costs. The cost of maintenance, elimination or removal considering 50 years as the expected lifespan, the emission cost for 20€/tonne, the annual costs, tax adjustment (3%) and adjustment factor (table 3) were all considered for the purposes of analysis.

It is not easy to reach an agreement regarding the expected lifetime of the refurbished buildings. In several cities, there are buildings over a century old that are perfectly functional if maintenance and retrofitting are executed correctly. Although some authors quote a period of a hundred years and others of fifty, Directive 2012/244/UE (2012) quotes 30 years as the eventual economic lifespan of the housing unit. This figure represents the time an owner could live in the same place, although the expected lifetime of some measures such as thermal insulation exceed this timeframe, reaching fifty years. It is considered that the investment of most interventions, with the exception of joinery and façade and structural interventions, can be recovered. In this respect, it should be noted that interventions on façades are considered the worst scenario for a set of buildings directly exposed to wind action or for structures unprepared to withstand the dynamic and static loads derived from a contemporary retrofitting.

Table 6. Multi-criteria assessment of the solutions considered depending on building type and factors involved in decision-making.

3.3.1 TH Type: (single-family residence between dividing walls)

In technical terms, the most suitable intervention would be from inside. However, the economic investment required from residents would be so high that it would fail to cover a considerable part of the intervention, and subsidies would not cover the costs. In environmental terms, solution 1, the addition of thermal insulation from inside, would reduce emissions by over 50%, and the emissions generated by the retrofitting would be amortised in 8 to 14 years. Given the above, the intervention in this type of buildings is not viable and only leaves room for the preliminary actions included in the procedure, in accordance with current legislation and the wishes of owners.

Image 1: From left to right: (a) calle Enmedio 47 (TH), (b) calle Tenerías 44 (MH), (c) calle Morella 22-30 (AB)

3.3.2 MH Type: (multi-family dwellings between dividing walls)

For this building type the most economical solution was an intervention from inside, and the exterior additional solution was minimally less costly. An exterior intervention with a ventilated façade represented a considerable increase in the final total cost. For this type the most plausible interventions in economic terms, halving emissions, were the addition of thermal insulation from inside (solution 1) and the addition of insulation from outside (solution 2). The amortisation of emissions is similar, as it is 5 years for solution 1 and 6.4 for solution 2.

In technical terms the best solution would be 1, the addition of thermal insulation from inside, while solution 2, the addition of insulation from outside, would be less favourable. However, it should be noted that thermally solution 2 provides better energy characteristics for the building, making it the most suitable for implementation in MH buildings as it is believed the investment would be accepted with relative ease in view of the willingness observed among those surveyed.

3.3.3 AB Type: (multi-family dwellings in standalone block)

Solution 2, the addition of insulation from outside, is the best in technical and economic terms for multi-family dwellings over 4 storeys high (AB). As regards environmental factors, solution 1, the addition of thermal insulation from inside is the first to amortise the emissions caused by the intervention, calculated at 7.5 years. However, building obsolescence and advisability of investing should be taken into account when considering solution 3, the creation of a ventilated façade, since despite the 12.5-year-long amortisation of emissions this solution presents the best thermal behaviour, reducing the consumption of primary energy and with it long-term CO_2 equivalent emissions.

Depending on the values obtained in the social factor, solution 3 is an option considered for few buildings given its high cost. Equally, despite the loss of square metres in the apartment solution 1 would be the most accepted. In any case, the best course of action for AB, given its high solar exposure, would be to implement solution 2, the addition of insulation from outside, on the east and west façades and solution 1, the addition of thermal insulation from inside, on the north and south façades.

A final remark on the optimal intervention for each building type looking for an standardised intervention procedure is that the initial investment, vertical insulation, could be one of the cheapest measures if specific constraints such as those considered in this study, thermal bridges and building exposure to dominant winds, are well managed and specifically analysed.

Having said that, it can be stated that investments can be recovered for all elements considered in the analysis except for the joinery. Nonetheless, the recovery of the investment will depend on more accurate solutions according to the specific characteristics of each building. Payback periods can be easily assumed for solution 1, Insulation from the inside, and solution 2, Additional exterior insulation, although as stated previously, joinery is not included.

The payback period analysis has not considered the result of the social factor surveys, and therefore it has not considered the financial costs from a possible loan to finance the investment. The financial cost will obviously delay the payback period. The multi-criteria analysis has demonstrated the importance of social awareness, possible income sources, accurate technical advice to owners, and specific analysis of each building as an individual case study, not only because of the solutions to be implemented, but also for the specific preconditions of façade design, solar exposure, and winds. In this regard, this multi-criteria analysis has shown how an eventual building retrofitting would allow neighbours to decide the type of refurbishment according to the economic, social, and environmental constraints mentioned above.

3.4 Action procedure

The outlined procedure focuses on highlighting the relevance of merging the different factors in a unified approach to a building. The procedure stresses the importance of the social factor, which indicates the extent of inhabitants' awareness of urban retrofitting. This shows the difference in individual behaviour when comparing neighbourhoods in terms of residents' “cultural” literacy and welfare. In this regard, the procedure emphasises that despite the energy deficiencies found in the building stock analysed, it is ineffective to approach the problem solely from a technical perspective. This is why this study has compared a set of decision-making factors according to pre-existing material, physical and social elements in buildings. Consequently, the above procedure does not aim to represent standard practice, but refers to the importance of establishing the relevance of each factor and its final impact in solving a problem directly affected by pre-existing constraints. Approaches such as those proposed are outlined to incorporate intuition, rationality, and irrationality when making such a complex technical decision.

Table 7. Action procedure

4 Conclusions

The study has shown the need to analyse, evaluate, and understand the willingness of individuals to adopt solutions for building envelope improvement. The study shows that economic factors and social conditions are major conditioning factors for the feasibility and implementation of improvements. The optimal solution is not always technically the best and it may be preferable to implement building efficiency on an intermediate scale while taking into account funding measures resulting in decreased energy consumption. In conclusion, there is a need to review aid and action plans in place for urban regeneration where in-depth socio-economic analysis, studied building by building, prompts an action procedure specific to type, obsolescence, and investment capacity of owners. Current legislation in energy ratings for buildings should also be considered in order to encourage or impose global certification actions relating to the best course of action for each type. Thus, buyers and sellers of apartments should undertake the improvements to be implemented in the building to improve energy ratings. Qualified teams of municipal specialists, building administrators, and technical architects specialising in the evaluation and rating of housing stock should be in charge of prioritising the building types and solutions to be adopted following the procedure.

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	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year Ave.
Average Temperatures ˚C	10.6	11.3	13.4	15.4	18.5	22.5	25.3	25.6	22.9	19.0	14.3	11.4	17.5
Average Max. Temperatures ˚C	13.0	14.2	17.4	17.5	20.5	26.5	27.4	28.1	24.3	21.2	16.5	13.5	18.6
Average Min. Temperatures ˚C	7.4	9.2	10.9	13.3	15.6	19.4	22.4	23.6	21.1	16.9	12.2	9.6	16.1
Average relative humidity %	67	66	64	63	63	63	64	66	68	69	68	68	66
Average rainfall mm	35.7	31.0	30.8	41.6	43.9	19.4	8.6	24.1	71.2	69.9	48.8	42.2	38.9
Hours of sun Monthly average	179.8	179.0	209.1	234.7	271.9	296.0	328.6	290.0	229.3	203.2	173.0	164.0	229.8
Direct Irradiancy Monthly average Kwh.m2.day	2.43	3.34	4.53	5.88	6.52	7.24	7.48	6.38	5.03	3.63	2.55	2.08	4.76
Wind Monthly average km/h	10.1	10.2	11.3	12.2	11.2	10.7	10.9	11.1	10.5	10.2	9.1	10.0	10.6
Calm winds %	17.2	12.3	7.7	5.9	7.9	8.9	6.9	4.2	5.5	14.0	16.7	17.4	10.4

Table1. Climatic data for Castellón de la Plana

Type of refurbishment	U values (W/m2K) Structures of the thermal envelope				
	Façades	Patios	Dividing walls	Roofs	Floors
ENMEDIO 47 Multi-family building (1apartment/storey) (TH)					
Initial situation	2,73	2,73	0,82	1,71	3,13
Insulation from inside	0,43	0,43	0,31	0,37	0,48
Additional exterior insulation	0,47	0,47	-	0,43	-
Ventilated exterior façade	0,38	0,38	-		-
ENMEDIO 110 Multi-family building (1apartment/storey) (TH)					
Initial situation	1,90	2,70	1,90	1,71	3,13
Insulation from inside	0,40	0,43	0,40	0,53	0,48
Additional exterior insulation	0,44	0,47	-	0,43	-
Ventilated exterior façade	0,36	0,38	-		-
TENERÍAS 44 Multi-family building (2 or more apartments/storey) (MH)					
Initial situation	1,93	-	1,93	1,48	2,68
Insulation from inside	0,49	-	0,49	0,37	0,86
Additional exterior insulation	0,39	-	-	0,43	-
Ventilated exterior façade	0,36	-	-		-
MORELLA 22-30 Multi-family building more than 4 floors (AB)					
Initial situation	1,58	-	1,58	1,71	2,17
Insulation from inside	0,39	-	0,39	0,37	-
Additional exterior insulation	0,37	-	-	0,43	0,41
Ventilated exterior façade	0,40	-	-		-

Table 2. U values

MORELLA 22-30	S1 - Insulation from inside, €	S2 - Additional ext. insulation, €	S3 - Ventilated ext. façade, €	Payback in years S1	S2	S3
Façade & structure	150,120.43	87,954.80	203,398.64	>50	20	>50
Dividing walls	9,085.44	19,333.44	30,141.60	4	5	6
Roof	2,488.08	12,569.54	12,569.54	1	4	4
Ground floor	11,412.02	23,087.85	23,087.85	4	6	6
PVC Joinery	127,801.95	127,801.95	127,801.95		>50	
Others	8,652.08	8,477.42	8,525.42	2	2	2
Total	**309,560.00**	**279,225.00 €**	**405,525.00 €**	**12.2**	**7.4**	**13.6**

Table 3. Results for calle Morella (AB) building considering estimated investment and payback from a static analysis and an adjustment rate of 3%.

Building Typology	Building	Intervention Type	Total amount (€)	m^2 usable surface area	Cost per m^2 (€/m2)	No. of Units	Cost per Unit (€/apartment)
Multi-family building (1 apartment/storey) (TH)	Enmedio 110	Insulation from inside	163,823	474	346	3	54,608
		Additional exterior insulation	175,674		371		58,558
		Ventilated exterior façade	189,729		400		63,243
	Enmedio 47	Insulation from inside	105,134	416	253	5	21,027
		Additional exterior insulation	110,681		266		22,136
		Ventilated exterior façade	136,998		330		27,400
Multi-family building (2 or more apartments/storey) (MH)	Tenerías 44	Insulation from inside	92,293	559	165	8	11,537
		Additional exterior insulation	103,443		185		12,930
		Ventilated exterior façade	143,212		256		17,902
Multi-family building (over 4 storeys) (AB)	Morella 22/30	Insulation from inside	309,560	1,877	165	19	16,293
		Additional exterior insulation	279,225		149		14,696
		Ventilated exterior façade	405,525		216		21,343

Table 4. Financial assessment of every possible intervention according to type.

Type of refurbishment	Building		Retrofit	
	Total CO_2 equivalent emissions (kg/m^2)	Total Primary Energy (kWh/m^2)	CO_2 equivalent emissions (equivalent kg CO_2/m^2)	Embodied Energy (MJ/m^2)
ENMEDIO 47 Multi-family building (1apartment/storey) (TH)				
Initial situation	40.3	155.5	-	-
Insulation from inside	23.5	91.7	113.39	2186.00
Additional exterior insulation	23.5	91.7	140.74	2444.96
Ventilated exterior façade	23	90	162.13	2833.60
ENMEDIO 110 Multi-family building (1apartment/storey) (TH)				
Initial situation	49.9	246.9	-	-
Insulation from inside	19.1	88.2	203.49	3780.70
Additional exterior insulation	16.7	80.2	236.83	4164.79
Ventilated exterior façade	16.4	79	249.22	4389.95
TENERÍAS 44 Multi-family building (2 or more apartments/storey) (MH)				
Initial situation	44.5	170.2	-	-
Insulation from inside	23.7	92.1	93.14	1805.05
Additional exterior insulation	22.9	89	122.09	2075.45
Ventilated exterior façade	22.7	88.1	154.57	2665.48
MORELLA 22-30 Multi-family building more than 4 floors (AB)				
Initial situation	30.8	102.1	-	-
Insulation from inside	21	83	49.00	895.10
Additional exterior insulation	21	82.8	102.10	1817.84
Ventilated exterior façade	21.1	83.3	81.02	1360.06

Table 5. Embodied energy and total CO_2 equivalent emissions according to type of intervention and building.

Building	Technical factor	Economic factor	Environmental factor
Type TH	1. / 3. / 2.	1. / 2. / 3.	1. / 2. / 3.
Type MH	1. / 3. / 2.	1. / 2. / 3.	1. / 2. / 3.
Type AB	2. / 3. / 1.	2. / 1. / 3.	1. / 3. / 2.
Social factor	22.3%	60%	17.7%

Table 6. Multi-criteria assessment of the solutions considered depending on building type and factors involved in decision-making.

Basic action 1. **To be implemented throughout building stock**	Regulation: State legislation
- Social training and awareness - Installation of thermostats in buildings - Inspection and maintenance of installations and envelope	Investment from the owner and National Housing Plan Types: TH, MH, AB
Complementary action 2. **Depending on income and properties**	Regulation: Regional legislation
Action 2.1. - Renovation of joinery and seals - Elimination of thermal bridges	Investment from the owner and Subsidy Programme Type: TH
Action 2.2. - Action 2.1. - Improvement of envelope 1. Interior	Investment from the owner and Subsidy Programme Type: MH
Action 2.3. - Action 2.1. - Improvement of envelope 1. Interior and/or 2. Exterior	Investment from the owner and Subsidy Programme Type: AB

Table 7. Action procedure