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RENFE, 80 V. Vilanova i la Geltrú. 1957.
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When construction was linear. Analysis of the energy sustainability of social housing in Spain (1939-1989)

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Abstract: Building circularly means thinking and designing for the future, so that, in addition to sustainability in construction, use and possible reuse, at the end of the building's useful life, all the elements can be usable. Since Pearce and Turner (1995) put forward their ideas on the circular economy, this approach has gained prominence in other disciplines, such as architecture. (McDonough y Braungart, 2005). However, until very recent times architecture has been "linear" if we understand this as the opposite of the aim of reduce-reuse-recycle: the initial purpose was disconnected from the final one. In the case of social housing, there are still no examples built according to the principles of circular architecture, nor are there any studies that verify whether it is possible to apply it to social housing built in previous decades. Thus, to have elements of analysis and comparison, we will approach the way of building in Spain in the 20th century focusing on the case of railway social housing, which had an abundant production (around 20,000 dwellings) in the period 1939-1989, within the framework of the existing housing legislation at that time in which there was no purpose of any of the principles encompassed within the concept of circular architecture, as the context and needs were different. However, these are dwellings that are still in use and the question of this study is whether, at least in terms of energy savings, it is possible to optimise the lifespan of these dwellings without compromising the current way of life and the associated comfort demands. The article is based on the analysis of the thermal envelope carried out based on the projects available, as well as the study and application of the regulations on thermal insulation in the period under study, which specifically did not exist until the 1979 basic standard on thermal conditions (NBE-CT-79). The aim is to simulate, after the study carried out and after the recent update of the basic document on energy saving, (CTE DB-HE 2019) what renovation actions are necessary in these dwellings to ensure compliance with the new and rigorous standards set with the aim of reconciling these dwellings, which are still in use and were built under criteria of minimum cost, with the lowest energy consumption and therefore with greater energy efficiency and environmental sustainability.

Keywords: social housing; thermal insulation; construction materials; sustainability.

1. Introduction

Building circularly means thinking and designing for the future, so that, in addition to sustainability in construction, use and possible reuse, at the end of the building's useful life, all the elements can be usable. Since Pearce and Turner (1995) set out their ideas on the circular economy, this approach has gained prominence in other disciplines, such as architecture (McDonough and Braungart, 2005). However, until very recently architecture has been 'linear', if we understand this as opposed to that end of reduce-reuse-recycle: the initial purpose was disconnected from the end.

There are numerous experiences with circular architecture¹, but none of them have so far materialised in the construction of social housing. In addition to applying the design methodology of "shearing layers" (Brand, 2018), it requires solving issues such as installations as well as complying with increasingly stringent regulations. Therefore, the starting question is whether it is possible to apply circular architecture to the construction of social housing and, beyond that, to what extent it is possible to implement some of its associated principles in social housing that has already been built.

Recent regulatory changes in housing construction pose a new scenario that brings our society closer to a protectionist awareness that could at least reduce the speed of deterioration. This raises a relevant question about what to do with the tens of thousands of social housing units that have been built up to now, when there was no approach to either reuse or recycle of their components, and volume, economy and speed in construction were paramount. Therefore, from a realistic approach considering the historical context in which these dwellings were built as well as considering the relevance of the building skin as a determining layer in terms of compliance with energy efficiency standards (Pushkar y Verbitsky, 2014), we consider whether it is technically feasible to update the group of dwellings under study in order to extend their useful life and thus collaborate with this concept integrated within the principles of circular architecture.

In this text, we will focus on the study of railway social housing², the characteristics of the non-existent or precarious insulating materials applied during their construction and the opportunities that arise for the application of current regulations and thus improve their situation. The data have been obtained from the information gathered from projects and reports of the different social railway housing developments that we have studied so far: 99 cities, 260 developments and 19,198 dwellings³.

Regarding the structure of the text, first, we will review the evolution of regulations and the use of insulating materials in dwellings. Then, we will classify the different cases of railway housing studied and group them according to the regulations in force during the construction period. Based on this information, we will apply a thermal analysis model simulated using the CERMA programme to find out how far these buildings are from the current regulations on the subject. Finally, the conclusions will frame what has been studied in this article.

2. Regulations and insulating materials

The technical regulations governing housing projects and construction in Spain began with the approval of the standards drawn up by the Ministry of Housing - the well-known M.V. standards - around 1962. They are actually a set of four families of standards covering: the actions to be considered for structural calculations, steel structures, brick masonry load-bearing walls and the waterproofing of roofs with bituminous materials.

There is no specific mandatory regulation regarding thermal insulation until the approval of the Basic Standard on Thermal Conditions (NBE-CT-79) approved in 1979. This regulation was in force until the approval of the Technical Code in 2006 and its recent modification in 2019 contemplates an update of the basic energy saving document, motivated both by the need to mitigate the effects of climate change and to reduce the energy dependence of buildings.

As a background to these regulations and with an ambiguous and general character, there was, firstly, the Order of 29 February 1944⁴, which consisted of a compendium of 14 precepts aimed at improving the hygienic conditions of dwellings. With regard to the envelope, it was necessary to make dwellings on the ground floor independent by means of a chamber or impermeable layer, but it did not establish any limit values for the conductivity of the different elements.

With regard to the need for thermal insulation, it was extremely ambiguous as it only mandated to ensure thermal insulation "to protect against the rigours of the temperatures typical of the region" where the building was located.

The next antecedent was the Technical Ordinances and building standards for "limited income housing"⁵ of 1955, because the vast majority of housing being built in the country in those years was subsidised.

These ordinances and standards distinguish between dwellings belonging to the first or second group. In our case study, all the dwellings belong to the second group and to the 2nd or 3rd category. In relation to these dwellings and with regard to insulation, this regulation establishes some more precepts and includes more casuistry as well as greater specificity than the previous regulation, although it is still not very specific with regard to the solutions to be applied.

It introduces prescriptions regarding maximum block heights with respect to the street width, block layout for better sunlight, prescription of double bay block width in newly created nuclei so that as many rooms as possible are directly ventilated, and establishes the minimum courtyard dimension depending on the block height.

The 8th ordinance is specifically dedicated to thermal insulation but the prescription consists of dividing Spain into two groups, the first grouping regions with temperatures between 30°C and -5°C and the second grouping the rest. It also defines areas with a benign climate as those where it is possible to be and work outdoors at least 300 days a year and where temperature differences in the shade do not exceed 8°C. Specifically, this includes the Balearic and Canary Islands, the coastal area of the provinces of Huelva and Cadiz and the Mediterranean up to the province of Castellon. It establishes the following conditions for walls and roofs (Table 1):

The technical solutions to achieve these values were limited to the thickness of the walls and, in the case of roofs, to the roof finishing material and insulation elements used. It also did not prescribe any particular roof finish or insulation material.

Therefore, these brief prescriptions regarding thermal insulation were those that governed the construction of low-income housing between 1955 and 1969, when the Order of 20 May 1969 was approved, adapting these ordinances and a specific modification of the same to the so-called subsidised housing (VPO) at that time. With regard to energy efficiency issues, it maintains the free floor heights, the dimensions of the interior courtyards in relation to the height of the block, although with the

exception of establishing an interior courtyard with a minimum side of 3 m, as long as the main rooms of the dwelling (bedrooms and living-dining room) do not lie within it, admits ventilation chimneys by general collector, prescribes the south orientation of the buildings as far as possible or, failing that, the most favourable, and maintains the minimum ventilation dimension of each room at one tenth of its surface area.

Regarding the related construction issues, it prescribes the need for walls to be stable, as well as to comply with insulation and waterproofing conditions.

Ordinance 32 is dedicated to thermal insulation, dividing Spain into two climatic zones (zone I: between 30 and -5°C; zone II, the rest), establishing maximum conductivity depending on the zone and type of space, which is somewhat more restrictive than in the previous ordinance (Table 2) and, for dwellings located on the ground floor, requires a sanitary floor slab separated by a minimum of 30 cm from the ground. It does not provide either types of insulation or construction solutions that guarantee the prescribed conductivity.

Thus, this was the background to the above-mentioned basic standard for thermal conditions, which already represents a substantial change of criterion with clear practical application.

Note that in the case of free housing, until the approval of the basic regulation of 79, there was only the succinct ambiguity of the 1944 order, that is to say, technically nothing.

The Basic Building Standard for compliance with thermal conditions in buildings (NBE-CT-79)⁶ represents a substantial change with respect to the above because, in addition to being applicable to all newly constructed buildings and being the first Spanish regulation specifically dedicated to thermal insulation, it is a regulation of practical application.

The basic objective of the standard was to adopt measures in the construction of buildings that would lead to lower energy consumption in the face of rising energy

Table 1 | Maximum thermal conductivities (W/mK). Order 1955. Own elaboration.

	Benign climate		
	Group I	Group II	zones
Walls	1.4	1.8	2.5
Flat roofs and habitable roofs	1.4	2.5	3.0
Non-habitable roofs	1.8	2.5	3.0

Table 2 | Maximum thermal transmittance (W/m²K). Order 1969. Own elaboration.

	Zone I	Zone II
Walls	1.2	1.6
Flat roofs and habitable roofs	1.2	1.8
Non-habitable roofs	1.6	1.8

prices. Mechanisms are also adopted to improve the hygrothermal performance of building envelopes in order to improve habitability.

The application of the standard requires the inclusion in the projects of the detailed calculation of the kg coefficient, which is the global transmission or transmittance of heat through the enclosure as a whole. As in the previous regulation, climatic zones are distinguished, although now instead of two zones, six are established: from A (milder climates) to E (more severe climates), leaving the Canary Islands aside. Two cases are also distinguished according to the type of energy used for heating or in unheated buildings. Finally, a building form factor is established.

This is a practical application standard that includes tables with thermal conductivity and water permeability values of the materials commonly used in construction, as well as classification of window and door frames according to their permeability and air tightness (classes A-1, A-2 and A-3), with one or the other to be used depending on the climate zone.

Of these, in the projects analysed and only in those corresponding to this last stage, the most commonly used insulation materials are sprayed polyurethane and fibreglass or rock wool sheets in thicknesses of 2.5-3 cm.

Finally, 27 years later, in 2006, the Technical Building Code was approved⁷, which complies, among other things, with the basic safety and suitability requirements that had been prescribed by Law 38/1999, on building regulations, in view of society's growing demand for quality in buildings.

The change in approach with respect to the two previously analysed regulations is essential: while these prescribed specific technical solutions, which greatly constrained both the designer and technical development, the technical code proposes the fulfilment of objectives but leaves open the way to achieve them, which gives freedom to the designer and to the incorporation of a variety of solutions.

In essence, the basic requirements with regard to energy saving are concretised in a practical way in the basic document DB HE on energy saving. The aim is rational use by reducing consumption and achieving the partial use of renewable energy sources. After the modifications in accordance with RD 732/2019, to achieve this purpose, basically the six basic requirements in force limit energy consumption according to the climatic zone, dividing Spain, in this case, into five climatic zones that become twelve subzones depending on the altitude; it

requires buildings to have a thermal envelope⁸ that limits energy demand without compromising thermal comfort, paying special attention to thermal bridges and avoiding heat transfer between the different units; demand energy-efficient lighting systems and, lastly, require that, as far as possible, both DHW (domestic hot water) demand and high electricity consumption be covered by renewable energies.

In this case, the thermal transmittance (U) (W/m^2K) of the different construction elements that make up the thermal envelope of the building, established according to the climatic zone and the type of construction element, is as shown in table 3.1.1.a of the basic document DB HE section H1 (Dec, 2019).

With regard to compliance with these basic requirements, none of the dwellings under study could meet them, as none of the requirements existed prior to the approval of the technical code, in addition to the fact that the total thermal transmission requirements are increasingly more restrictive and, therefore, more distant from those applicable at the time of the construction of the dwellings where, as we have observed in the regulatory evolution presented, there were hardly any restrictions. Another of the considerations of interest is the evolution in the attention paid to the adequate treatment of thermal bridges⁹, an issue that was also not addressed at the time of construction of the dwellings under study.

The aim of this article will be to show how far these dwellings are from these objectives and what construction solutions can be implemented to guarantee thermal comfort and, therefore, to update, as far as possible, the dwellings in order to promote their sustainable use.

3. The thermal envelope of railway social housing in Spain

The dwellings under study were built between 1949 and 1989. The application of the aforementioned regulations was mandatory as follows in the different developments throughout the period studied (Figure 1):

It should be noted that only 9% of the total number of dwellings analysed were built when the basic standard for thermal conditions was in force. Of the remainder, 11% of the cases are governed by the generic requirements of the 1944 Order. Another 24% are governed by the 1955 Order, which is somewhat more specific than the previous one, and 56% by the 1969 Order which, in terms of insulation, the most significant changes compared to the previous one are the division into two climatic zones (the mild climate zone disappears), the search for block orientations

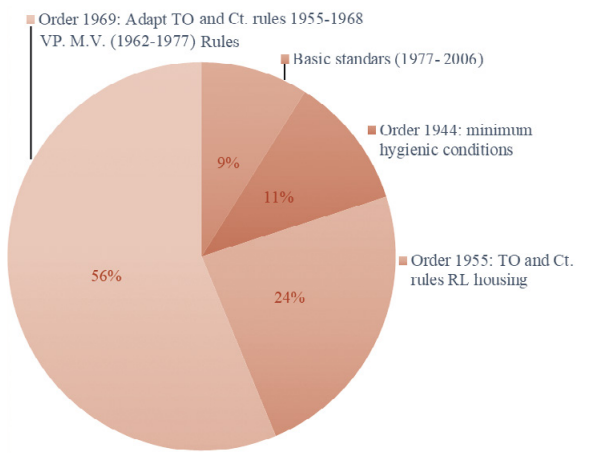


Figure 1 | Regulations applicable to the dwellings under study. Own elaboration.

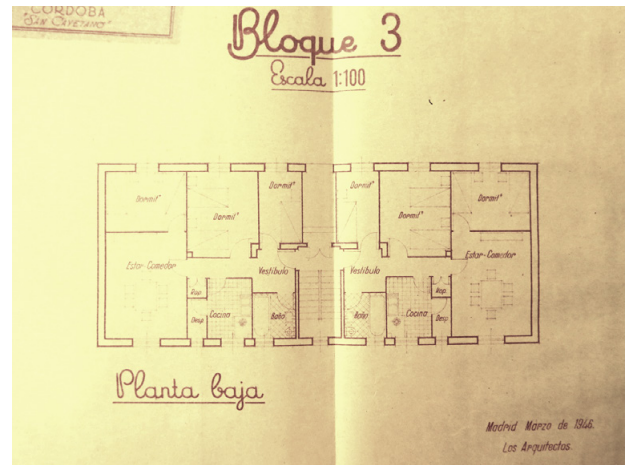


Figure 2 | Floor plan of 48 RENFE subsidised housing project block in Córdoba, 1952. (AMF. CO-1571-VP).

preferably South/East, somewhat lower conductivity of walls and roofs, and the obligation to use a sanitary floor slab if there are dwellings on the ground floor.

With regard to the group of dwellings built under the 1944 order, there are 26 developments with a total of 1,959 dwellings. Of these, only 120 dwellings (6%), corresponding to three developments located in Estación de Vadollano (Jaén) and Córdoba, have been demolished, being the rest in use and with little intervention with respect to the envelope. With the exception of an early cooperative¹⁰, 90 % of the dwellings were built in numerous cities and railway enclaves by the public company RENFE¹¹, being the project type detailed below (Table 3):

It should be noted that there is no separation from the ground, nor are there any insulating materials in the thermal envelope. There is also no heating and DHW is produced by an economical cooker using coal or

firewood. In short, these dwellings are far from current thermal comfort standards. In the following section we will analyse the thermal behaviour of the envelope of this type of project and what improvements can be implemented since the houses are still in use today.

The following figures (Figure 2 to 4) show the plan, elevation and original and current appearance of the defined project type of the dwellings built in this period.

The uniformity of the standard project is due to the fact that the developer, except in one atypical case for the time, is RENFE, which had a group of architects on staff who repeated many of the design and technical characteristics in the different locations. This repetition of technical solutions without taking into account the different climatic zones leads to the conclusion that the thermal performance of the dwellings was not a de facto premise and that the performance will differ depending on the climatic zone where the dwellings are located.

Table 3 | Enveloping basic features. Project type I. Own elaboration.

Building typology: open-plan building (94 %), double bay blocks (96 %). Project type height: four storeys (69 %). (Weighted average height: 4.45 storeys).
Structural typology: load-bearing walls (100 %) with intermediate structural line (25 %), made of ceramic brick (93 %). Average thickness of 1 foot. Average slab thickness: 15 cm.
Surface in contact with the ground: concrete slab with an average thickness of 15 cm (75 %).
Enclosures: 0.5-1.5 ft thick load-bearing walls without interior bending. (1 foot average thickness). Double hollow brick in upper floors (93 %). Finished with cement mortar rendering and paint outside (93 %), plastering and paint inside (100 %).
Carpentry: wood, hinged, without blinds or shutters (95 %), with an average hollow surface of 1.20 m. x 1.40 m
Glazing: single, 2 mm and colourless (100 %).
Roof: sloped (84 %), four-sloped (58 %). Slope formation: timber; one-piece fill with rubble or rasilla board. Roof finish based on Arabic tiles (74 %).
Ground floor dwellings: yes (94 %).



Figure 3 and 4 | Original and Current status 64 dwellings Albacete, RENFE, 1952. (AHF-FV-0033 -Own archive).



Figure 5 | RENFE, 76 subsidised housing in Valencia-Alameda, 1954. (AHF FV-0042).

For the modelling of the envelope, we will adopt the most common and favourable climatic zone, although the dwellings studied in the four periods studied were built throughout Spain. With respect to the shape coefficient, the most commonly used building typology in this period is the rectangular detached block with 4 floors (2.50 m, free, 0.15 m, and slab edge). The estimated floor plan dimensions correspond to two dwellings per stairwell, with respective external dimensions of 10×8 m. This block typology and floor plan dimensions are maintained for the following cases, as it has been found to be frequently repeated throughout the period under study. The only difference is in the heights, which, as we shall see, increase over the period analysed.

The next regulatory leap is the housing built under the 1955 Order. In this case, the group is made up of 52 developments spread throughout Spain, with a total of 4,182 dwellings. Of these, 97% are still in use. Unlike the previous case, in this new time period, the promotion of these groups of dwellings is more distributed, with 67% being built by RENFE (Figure 5 and Figure 6), while 18% were built by other companies in the sector (Economic



Figure 6 | RENFE, 224 subsidised housing in Madrid-Delicias, 1954. (AHF-ADC-0180).

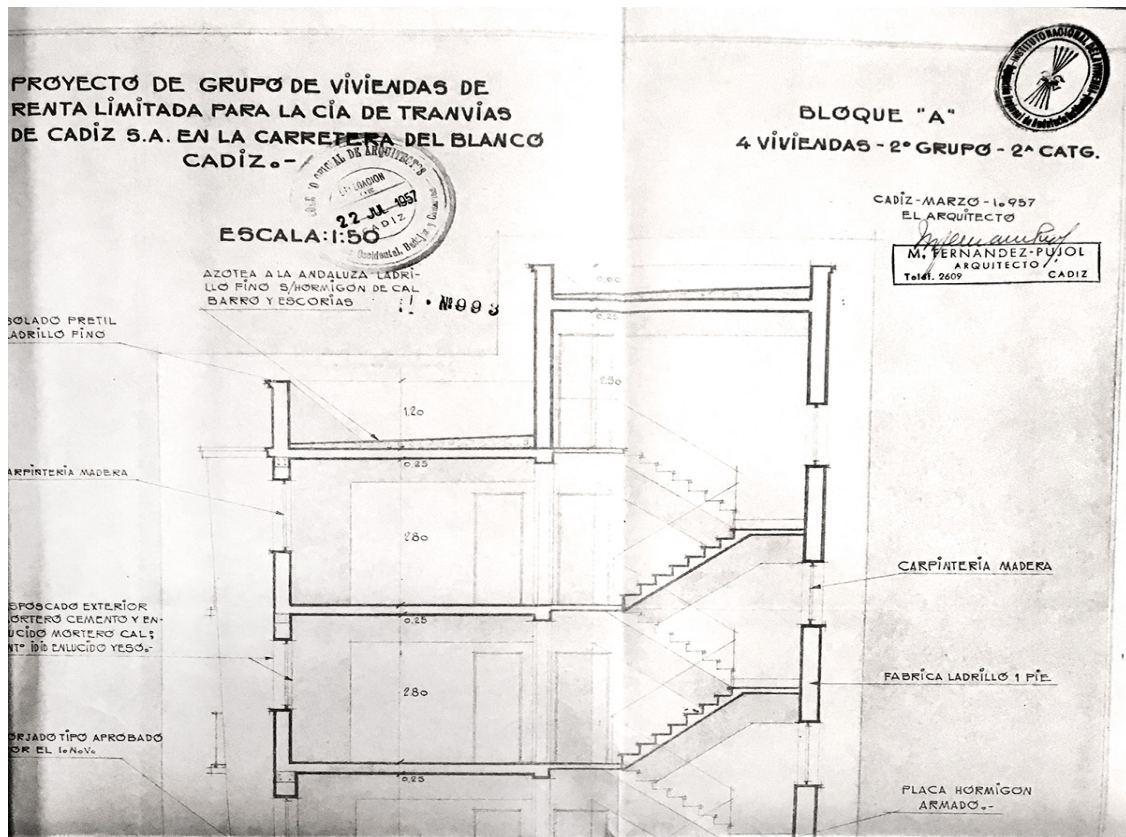


Figure 7 | Design section project type II. Project for 24 low-income housing units for the Cadiz tramway company, 1957. (AMF Project nº 6073).

railways of Asturias, MACOSA or Barcelona trams, among others) and the remaining 15% were promoted by railway workers' cooperatives.

This greater diversity of developers also leads to greater diversity in terms of design, construction solutions, materials and finishes. Based on the analysis of the variables studied, the project type of housing block (Figure 7) for the simulation of the thermal performance calculation is shown in Table 4.

With regard to the ground floor, in the previous period analysed there were no cases of only ground floor premises and, in only 5% of cases, ground floor premises were shared with a dwelling where the separation from the ground consisted only of a concrete slab of an average thickness of 15 cm. In this period, 16% of the buildings already have ground floor premises not shared with a dwelling and there is also a significant increase in the use of the sanitary floor slab compared to the previous period (from 25% to 35%) which, other things

Table 4 | Enveloping basic features. Project type II. Own elaboration.

Building typology: open-plan building (78 %). Double-bay block (93%). Block type height: 5 storeys. (weighted average: 4.89).
Structural typology: 1 ft. ceramic brick load-bearing walls of average thickness (78%). No cavity or interior bending. Average floor slab thickness: 15 cm.
Surface in contact with the ground: concrete slab (65%). 15 cm. average thickness. Mass concrete.
Enclosures: 1.5 ft-1 ft-1/2 ft thick bearing walls with exterior side to be clad (69%), no interior bending and no air space (92%). 1 ft. average thickness. Finished with exterior cement mortar render and paint (73%). Plastered and paint on the inside (100%).
Carpentry: wood. Folding (88 %). No blinds or shutters. Average opening surface: 1.20 × 1.40 m.
Glazing: single (2 mm) or semi-double monolithic (3 mm) ¹² . Colourless (99%)
Roof: sloped (71%). Four-sloped (69%). Slope formation: partition walls and rasilla board. Tile finish (60%).
Ground floor dwellings: yes (84%).

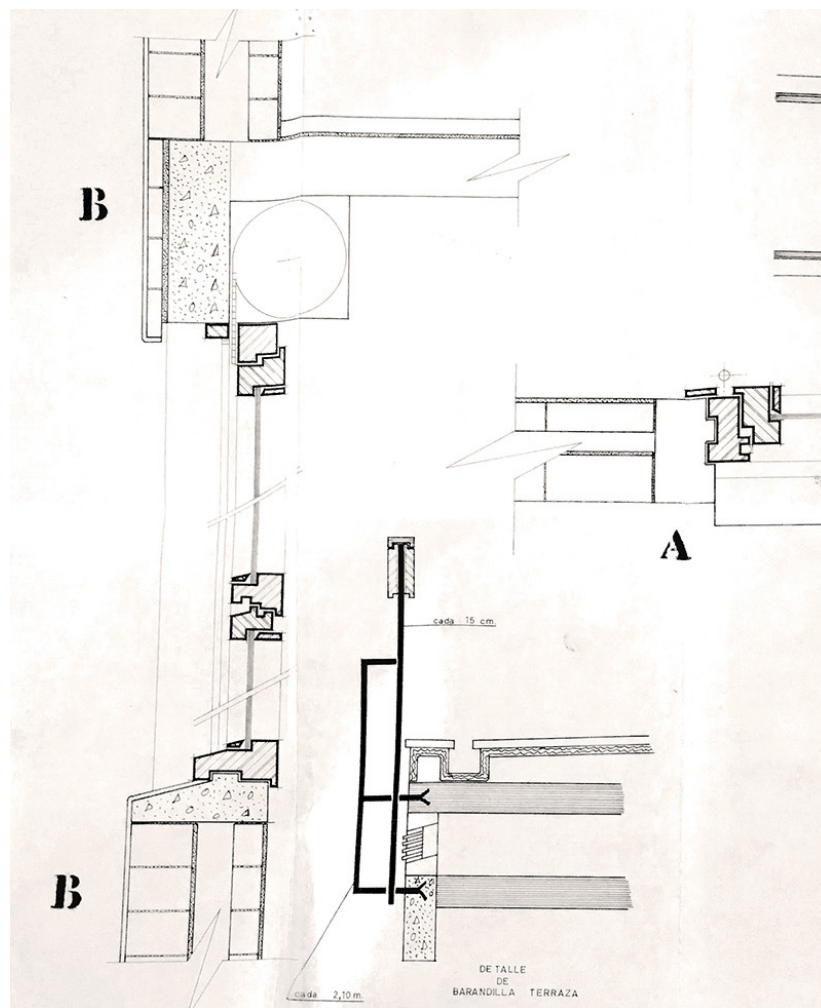


Figure 8 | Design section of project type III. Project for 81 dwellings in Bilbao. “Amézola” cooperative, 1967 (AMB sig. C-2533-002).

being equal, improves the thermal performance of the ground floor.

Regarding enclosures, in some developments, interior bending or an air chamber is applied and, with regard to glazing, the incorporation of semi-double glazing (3 mm) is beginning to be observed, as opposed to the single glazing (2 mm) which had been used exclusively until then.

The third group is made up of 124 developments with a total of 9,918 dwellings, also with a varied geographical distribution, 99% of which are still in use and where the 1969 Order is already applicable.

In this case, the majority of developers are railway workers' cooperatives, which account for 79% of the

dwellings under study, compared to 20% of the dwellings developed by RENFE.

More pronounced than in the previous period is the diversity of design, construction and materials derived from the fact that each cooperative chooses its own architect (there is no longer a company architect who systematically repeats projects and solutions, as was the case with RENFE) and that there is also a greater variety and availability of materials derived from the economic context.

Thus, weighting the different parameters to be studied, the project type for the purposes of the subsequent calculation of the thermal envelope is as shown in Table 5.

Table 5 | Enveloping basic features. Project type III. Own elaboration.

Building typology: Open-plan building (85 %). Double-bay block (69%). Project type block height: 7 storeys (weighted average: 7.04).

Structural typology: reticular (80%). Slab edge: 20 cm.

Surface in contact with the ground: concrete screed (0.20 cm) on top of charcoal or gravel backfill (58%)¹³.

Enclosures: Multilayer. (79%). Outer layer based on 12 cm thick perforated brick covered with cement mortar or facing brick or mixed of both (78%), non-ventilated air chamber and inner layer based on single hollow brick partition wall. Plastering and painting. Average thickness: 25 cm.

Carpentry: iron frames¹⁴ or aluminium sliding frames (75%). Wooden/plastic roller shutters.

Glazing: monolithic double glazing (4 mm). Colourless (100%)

Roof: flat roof with rasilla-based finish (49%) and sloped roof on partition walls with tile-based finish (49%). Mixed option (2%). Therefore, the type building has a mixed roof: flat roof with waterproofing and rasilla finish and sloped roof with ceramic tile finish.

Ground floor dwellings: 44% premises, 43% housing and 11% mixed use housing and premises. Therefore, we envisage mixed use housing and premises for the project type.

A particularity of this period with respect to the facing in contact with the ground is the introduction of basements or semi-basements, mainly for garage use, in the buildings (16%). This, together with the change in the trend of ground floor use for commercial premises and the transfer of residential use to the first floor and above, considerably changes the thermal conditioning of the dwellings, other things being equal, compared to the previous periods analysed.

With regard to the envelopes (Figure 8) the most common case is the independence with respect to the structure, which becomes a grid structure. The creation of thermal bridges (slab fronts, structure-enclosure junctions, roof-enclosure junctions, opening contours, shutter boxes, among others) will be frequent, as there is no specific regulation in this regard in this period. This will be one of the main aspects when dealing with possible refurbishment actions to improve energy performance.

Finally, the fourth group is made up of developments built when the 1979 Basic Standard on Thermal Conditions was in force. As mentioned above, this was the first standard in Spain in terms of thermal insulation. This group includes 1,576 dwellings with a total of 17

developments, all of which are still in use. With regard to the developer group, the previous evolution is confirmed and all the projects come from cooperative groups. Thus, as in the previous case, the diversity of projects and solutions will be the dominant trend.

In this case, the project type (Figure 9) is shown in Table 6.

The increase in height of the blocks over the period under study is relevant, which leads to changes in the shape coefficient of the type building and, therefore, variations in the thermal behaviour. In the same way, the ventilation and lighting conditions both to the façade and to the interior courtyards (the minimum side of 3 m for the interior courtyard remains) are affected.

The change to a grid structure, preferably of reinforced concrete, is consolidated, which implies a higher risk of thermal bridges between the enclosure and the structure.

The presence of ground floor premises as well as the growing number of basements and crawl spaces is also being consolidated.

Table 6 | Enveloping basic features. Project type IV. Own elaboration.

Building typology: Open-plan block (79%). Multi-bay block. Project type block height: 12 storeys (weighted average: 11.69).

Structural typology: reticular (99%). Slab edge: 25 cm.

Surface in contact with the ground: basement wall (50%).

Enclosures: Multilayer. (99%). Outer layer based on half-foot-thick perforated brick coated on the inside with cement mortar, or face brick, or a mixture of both (98.71%). Non-ventilated air chamber with thermal insulation based on 2.5 cm thick polyurethane or fibreglass panels and inner layer based on double hollow brick partition wall. Plastering and painting. Average thickness: 29 cm.

Carpentry: aluminium sliding doors (96%). plastic roller shutters.

Glazing: monolithic double glazing (4 mm). Colourless (100%).

Roof: unventilated/ventilated flat roof with thermal insulation (2-3 cm). Ceramic tile (rasilla) finish (63%).

Ground floor dwellings: Premises (91%)

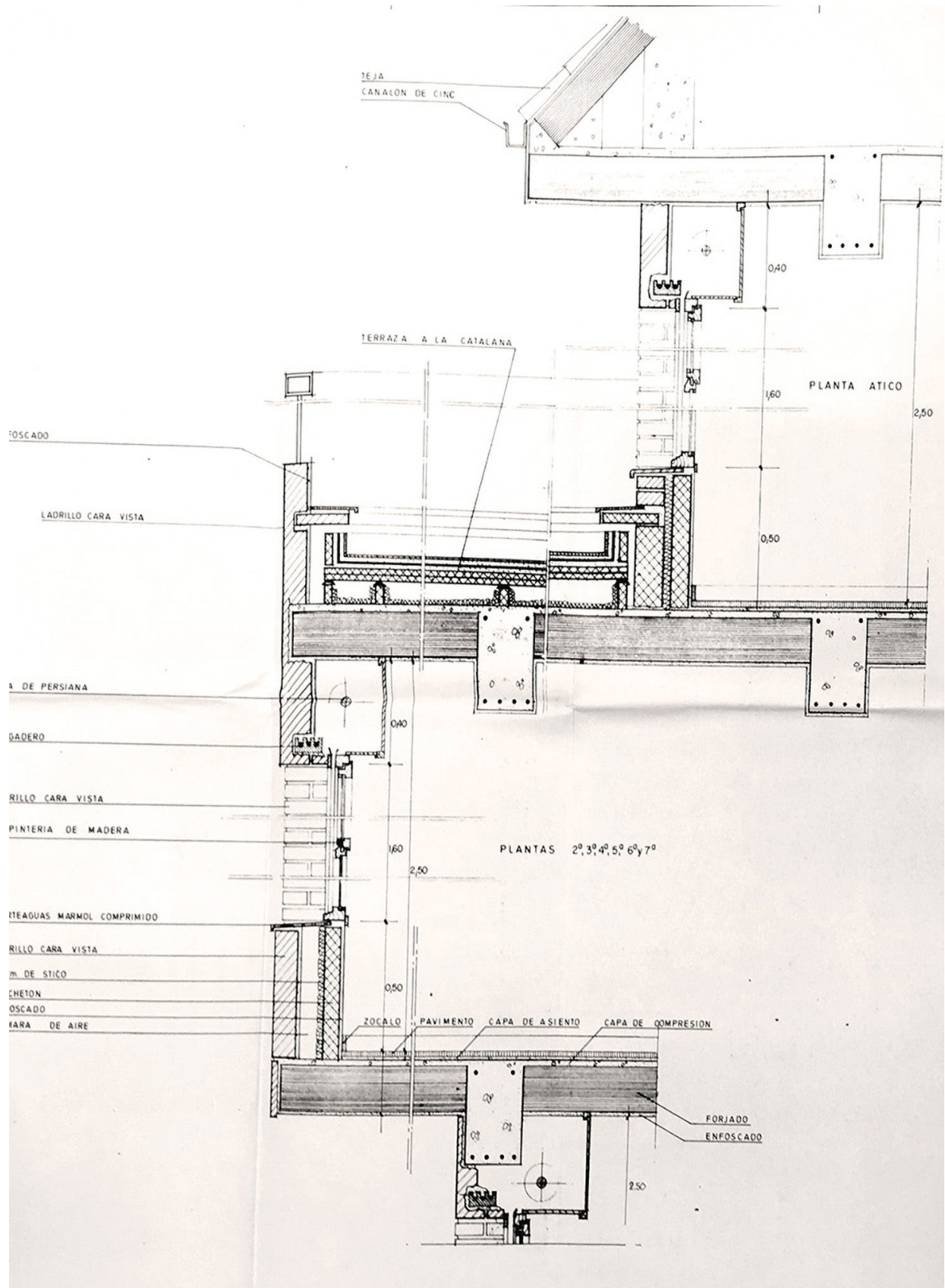


Figure 9 | Construction cross-section of the project type IV. Project for 64 dwellings in Oviedo. Coop. "Sagrada Familia", 1980 (AMO. Exp- 1/81).

In terms of carpentry, there is a transition from wooden hinged frames, through iron hinged frames, to aluminium sliding ones with 4 mm monolithic glazing.

Regarding the presence of thermal insulation in enclosures and roofs, only at this stage do some of the projects consulted include it. Although this is an ongoing investigation, with the data analysed to date, the introduction of thermal insulation in social railway housing was late.

The following table (Table 7) summarises the four cases under study:

Table 7 | Summary of the grouping of project types of the different railway housing developments (1949-1989). Own elaboration.

Rule	Developments (n°)	Dwellings (n°)	Project type
Order 1944	26	1.959	PT I
Order 1955	52	4.182	PT II
Order 1969	124	9.918	PT III
NBE CT79	17	1.576	PT IV
	219	17.635	

4. Simulated thermal analysis

Using the simplified calculation programme for the residential energy rating (CERMA V. 5, December 2020), the data of the four project types previously elaborated are introduced. In all four cases, favourable climatic conditions have been adopted (Valencia, zone B3), as well as identical typology, block dimensions, opening sizes and distance to obstacles. The modifications are those specified in the previous section and refer to the heights, the use of the ground floor and the construction and installation characteristics.

With regard to the limitations on non-renewable primary energy consumption established in the 2019 modification of the CTE, none of the four project types comply, being far from the current limitations for the climate zone under study (Table 8).

Table 8 | Summary results of non-renewable energy consumption. Comparison with CTE limit values.

Project type	Maximum consumption limit EPNR (kWh/m ² year) (CTE 2019)	Real consumption EPNR (kWh/m ² year)
PT I	28	121.73
PT II	28	121.19
PT III	28	93.41
PT IV	28	64.78

However, in order to be able to compare with the reference values of the regulations or orders applicable at the time of construction of the dwellings, we must establish the transmittance values of the elements of the envelope of the dwellings for the case under study, referring to façades, openings, roofs and elements in contact with the ground or with other premises (Table 9).

Table 9 | Transmittance (U) (W/m²K envelope elements in project types. Own elaboration using CERMA V.5, Dec, 2020.

Project type	Façades	Openings	Sloped roofs	Flat roofs	Ground contact/ others
PT I	2.77	5.14 (*)	2.10	-	3.46
PT II	2.77	5.14 (*)	1.47	-	3.46
PT III	1.34	5.70	1.80	1.58	2.39
PT IV	0.79	5.70	-	0.73	1.95

(*) In project types I and II, the assumed glazing thickness is 4 mm, as this is the minimum allowed by the programme. The real thickness was 2-3 mm.

Therefore, dwellings built under the 1944 standard comply with this standard regardless of the transmittance value obtained, given that the aforementioned standard does not establish limit values or any specifics. However, compared to the values obtained with current requirements, it requires, as a minimum (in addition to complying with the energy demand), integral intervention on the entire envelope, which would include, for example, the execution of a 5 cm thick expanded XPS insulation with external rendering. A 7 cm XPS sheet is also installed in the false roof ceiling to comply with current requirements. With regard to the carpentry, it would be necessary for all of them, if they are metallic, to have thermal bridge breakage and, assuming 9+4+9 low emissivity double glazing, they would comply with the limit value established for the openings.

However, the requirement of the wall in contact with the ground would be unfeasible to meet in ground floor dwellings with a very low clear height, as it would require the floor to be raised by 10 cm to incorporate the insulation. It would also require careful attention to thermal bridges. Another front that would remain to be resolved would be the energy demand issues which, among other things, would require serious interventions with regard to the heating installation.

For dwellings built under the 1955 Order, the solution set out above can be extrapolated. The problem of ground floor dwellings and the issue of energy demand also arises.

For the dwellings in the period of validity of the 1969 order, as a possible solution for the opaque part of the enclosures, we propose the installation of insulation based on XPS expanded with carbon dioxide, 4 cm thick, plastered on the outside with cement mortar and paint. With regard to the openings, opting for PVC joinery (more thermally efficient than its metallic counterpart), we could have double-chamber frames with 4+6+4 low emissivity glazing.

On the flat roof, after the corresponding repairs and preparation of the support, it is proposed to spray polyurethane sprayed on the outside in a 5 cm thick layer and on the same polyurethane elastomer for protection against UVA rays. With regard to the sloped roof, in this case on partition walls and not accessible from the inside, to avoid raising the roof, it is proposed to use polyurethane foam projection in a 4 cm thick layer protected with polyurethane elastomer as in the previous case.

With regard to the facing in contact with the ground, in the case of ground floor dwellings, this is the same as in the two previous periods. The establishment of a clear height of 2.50 m makes it impossible for us to take any action, as the necessary heightening implies the loss of habitability due to non-compliance with the minimum clear height in dwellings.

In the last period under study, where there is already the incorporation of insulating materials in enclosures and roofs, achieving compliance with current transmittance requirements could be done by applying the previous solutions with less thickness of the respective insulating materials installed. With regard to the openings, where there is no improvement in thermal insulation with the change of material used for frames, we would opt for the replacement of these with a solution such as that proposed for period III above.

The selection of proposed solutions is based on widely used materials and solutions with a view to lowering the cost for low-income housing such as many of those analysed.

With regard to the improvement actions related to thermal insulation (Figure 10) carried out, the analysis shows that changes have been made in practically all the dwellings. In this sense, the refurbishment of buildings is an option as it represents a 60% saving compared to the construction of an equivalent new building (De Luxán García de Diego, Gómez Muñoz and Román López, 2015). Two integral actions of reference to the case study can be found in the neighbourhood of San Martín de Porres in Córdoba (Serna and Galadí, 2015) or in post-war

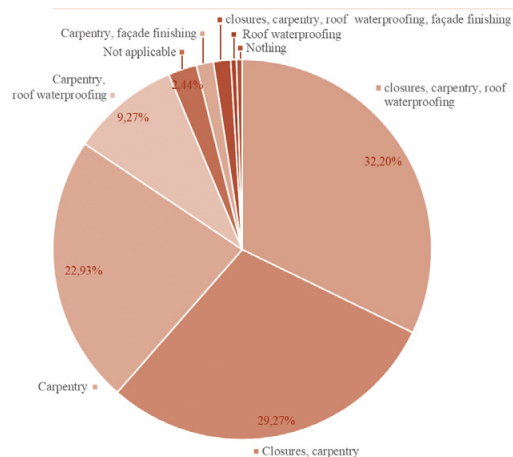


Figure 10 | Improvement actions carried out on the thermal envelope. Own elaboration.

housing in vulnerable areas in Zaragoza (Kurtz, Monzón and López-Mesa, 2015).

Specifically, there have been changes in the carpentry in 96% of the developments. These changes consist of folding the carpentry on the outside, or replacing higher quality carpentry with double glazing, among other things¹⁵.

The second most frequently carried out action was the closing of balconies or verandas, which occurred in 63% of cases. The third improvement action noted is the waterproofing of both flat and pitched roofs (43% of cases), generally using chlorinated rubber paints, which can provide practically no thermal improvement.

Comprehensive actions affecting the entire thermal envelope have been carried out in only 3% of the cases. In most cases, the actions have consisted of covering the façades, originally of exposed brick, with single layer, replacing carpentry, closing galleries and waterproofing roofs. For example, the Vicálvaro dwellings of the Compañía de los Ferrocarriles de Tajuña or those of RENFE in San Cristóbal de los Ángeles, both in the industrial belt of south-southeast Madrid.

In the case of the San Sebastián cooperative, the pre-existing façade, which was plastered and painted, was covered with a ventilated façade (e.g. Faveton type). (Figure 11 and 12).

Finally, as a partial action, on the façade of the “San Carlos” cooperative development in Tarragona, it was decided to cover the parapets with aluminium panels.



Figure 11 and 12 | Original and current view of the façade of the 60-housing development of the San Sebastián railway cooperative. AHF-A-MSS-Own Archive.

5. Conclusions

The result of the analysis carried out shows that none of the standard projects meet or even come close to meeting the requirements of the current regulations regarding thermal insulation and that comprehensive interventions on the building envelope would be necessary. Although it would be necessary to analyse each case, given that this is a representative sample of social housing in Spain built between 1939-1989, such interventions would require a significant economic effort that would be difficult to assume for the average income of the inhabitants of these dwellings and, in the case of ground floor dwellings, would be impossible to apply. Therefore, although only the energy saving aspect has been analysed with the aim of extending the useful life of the dwellings in order to meet the comfort needs of today's society, the fact is that it would be difficult to apply in many of the cases studied.

However, a simulation of reality has been carried out with simplified calculations and model blocks in a favourable climatic situation. In a likely scenario of progressive global warming, this simulation still falls far short of what the real situation could be, especially in some climatic zones (De Luxán García de Diego, Gómez Muñoz and Román López, 2015).

For the real case, it is necessary to carry out concrete and individualised audits with detailed studies taking into account social as well as economic and energetic factors (Fernández Ans, 2019) and (Fernández, Rubio and Guevara, 2019).

In our case study, the values obtained show a high unfeasibility of comprehensive corrective actions. Furthermore, it should be borne in mind that 32% of the dwellings are located in very low-income neighbourhoods and another 49% are located in low-income areas, according to data published by the INE, which adds an economic barrier that makes any action more difficult. However, the low energy quality of the project types (in all cases, energy ratings E) indicates that any action in this direction will be an improvement.

The paradox is that, from an exclusively energy point of view, actions on the envelope become more necessary in cases of energy poverty where users cannot afford to spend on air-conditioning installations (De Luxán García de Diego, Gómez Muñoz and Román López, 2015). This situation is not unusual for almost three quarters of the dwellings studied. In this sense, passive strategies can be essential, although they require a high degree of subsidy.

An attempt has been made to apply the principles of circular architecture to these dwellings that are still in use, in this case to improve and adapt them to regulations on energy saving, with the intention of making their continued use more sustainable, considering the limitations and impediments that this entails. It is a difficult transition from linear to circular construction, especially in this type of housing where the income barrier is an additional limiting factor.

Therefore, with regard to the question raised at the beginning about the possible application of the principles of circular architecture to pre-existing social housing, the truth is that it still seems more of a dream than a reality.

Notes

- ¹ Some examples of circular architecture are the prototypes of Circular Building, by ARUP associates (2016); ICEhouse, by William McDonough+Partners (2016) or Dashilar Pavilion, by Dotmake (2016), among others.
- ² For an approach to the way of building and the materials used in the context of the period, see (Martínez-Corral & Cuéllar, 2020).
- ³ For an overview of railway social housing in Spain in the second half of the 20th century and the methodology and sources used, see (Cuéllar & Martínez-Corral, 2021).
- ⁴ BOE, nº 61, 1 March 1944.
- ⁵ BOE, nº 296 of 10 December 1976 and nº 141 of 14 June 1977 respectively.
- ⁶ NBE-CT-79 (RD 2429/1979, of 6 July) (RD 1650/1977, of 10 June).
- ⁷ Technical Building Code: RD 314/2006 of 17 March.
- ⁸ The terminology used is set out in Annex III of the RD.
- ⁹ Annex A. Terminology DB-HE Technical Code.

- ¹⁰ This was the "Hermandad Católica Ferroviaria" cooperative in Valencia, which built 192 homes in 1955 in Mistral st.
- ¹¹ RENFE (National Network of Spanish Railways) was created in 1941 to integrate into its management all the broad-gauge railway lines, see (Muñoz Rubio, 1995).
- ¹² We have omitted the name given to the glazing at the time (single, semi-double and double) which, in any case, was monolithic glazing, and referred to the thickness of the pane (2, 3 and 4 mm. Respectively) so as not to confuse it with the current terminology, present in the CTE, where double glazing is always a glass composed of two panes and an intermediate chamber.
- ¹³ In the case of dwellings located exclusively on the ground floor, the standard requires a sanitary floor slab separated by at least 30 cm from the ground.
- ¹⁴ Iron carpentry, known as the "Mondragon type", was very popular, although the first types did not have the watertight joints that the earlier wooden ones did. They also represent a deterioration in thermal conductivity compared to their predecessors.
- ¹⁵ The variability encountered is very large and it is impossible to pinpoint the solutions adopted.

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