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Analysis of the Energy Efficiency of Le Corbusier's Dwellings: The Cité Frugès, an Opportunity to Reuse Garden Cities Designed for Healthy and Working Life

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Abstract: This paper looks at the energy efficiency of the Cité Frugès in Pessac, designed in 1924 by Le Corbusier. Many of the innovations introduced by the Modern movement, such as flat roofs, large windows and solar protection elements, are still evident in the way architecture is carried out today. Most of these contributions were implemented in the Cité Frugès. The aim is to evaluate the architectural design criteria that most influenced the energy performance of Le Corbusier's works, and to analyse the improvement that could be achieved by energy rehabilitation. The methodology used consisted of a systematised study of the five dwellings designed by Le Corbusier. For the modelling and calculation of their energy performance the "Líder–Calener unified tool" was used for evaluation, under the standards of compliance with European regulations for nearly zero energy consumption buildings. Energy parameters, such as thermal transmittance, solar gains and overall annual energy demand, were tested. The results obtained provide information on energy performance and allow for the analysis of possible energy refurbishment alternatives. The analysis of the results makes it possible to identify and qualitatively and quantitatively assess the limitations of the most relevant architectural and construction aspects in relation to energy efficiency and to draw up an energy map of the Cité Frugès in Pessac.

Keywords: energy efficiency; sustainable rehabilitation; Le Corbusier; building retrofitting; sustainable construction; resilience; indoor environmental quality

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Citation: González-Avilés, Á.B.; Pérez-Carramiñana, C.; Galiano-Garrigós, A.; Ibarra-Coves, F.; Lozano-Romero, C. Analysis of the Energy Efficiency of Le Corbusier's Dwellings: The Cité Frugès, an Opportunity to Reuse Garden Cities Designed for Healthy and Working Life. *Sustainability* **2022**, *14*, 4537. https://doi.org/10.3390/su14084537

Academic Editors: Alicia Alonso Carrillo and Rocío Escandón Ramírez

Received: 17 February 2022
Accepted: 6 April 2022
Published: 11 April 2022

1. Introduction

The increasing regulatory requirements for energy efficiency in Europe, with the aim of reducing the significant contribution of greenhouse gases from buildings [1], especially since the European Directive 2010/31/EU [2] on the energy performance of buildings and its subsequent amendment by Directive (EU) 2018/844 [3], have led to a significant increase in the insulation and solar control of buildings, and the use of increasingly specialised computerised calculation tools [4–6].

More than 20% of the European building stock have low energy performances and high energy consumption, as they were built before 1945 [7]. In this context, and in order to gain a better perspective of the current situation, it is interesting to recall and analyse the important innovations introduced by the Modern movement at the beginning of the 20th century, which had such an influence on the way architecture is being performed today [8]. The Modern movement introduced new materials and construction systems, and the development of new architectural and constructive solutions that transformed the way architecture was approached at the time, with new concepts such as the flat roofs [9], large windows [10,11] and solar protection elements [12]. Le Corbusier, with his formulation of the five points of modern architecture [13], is one of the most prominent examples [14] of this group of architects.

This article analyses the energy efficiency of houses designed by Le Corbusier, selecting as a case study the villas of the Cité Frugès in Pessac, built between 1924 and 1926, whose design was intended to be an example of standardisation and production line housing and constituted a landmark of social housing typologies [15].

The research about the energy savings and improvement in comfort of the Cité Frugès project allows understanding of an example of "pre-World War Two" buildings, which represent more than 30% of the French building sector [16].

The project, innovative for its time, showed the architect's emerging interest in energy efficiency [17] and proposed, among other aspects, the use of pergolas, blinds and the introduction of thermal insulation. For all these reasons, it is pertinent to analyse the energy performance of Le Corbusier's residential projects in order to be able to compare it with current regulatory requirements.

The aim is to identify and assess the architectural design criteria that most influence the energy performance of Le Corbusier's works. Embodied energy/emissions are not considered, as this is not a life cycle approach study.

By studying all the housing typologies of the Citè Frugés, it has been possible to evaluate the degree of compliance and non-compliance with European regulatory requirements for nearly zero energy consumption buildings, and to analyse the most optimal possibilities for the energy refurbishment of each of the typologies.

Research on social housing built in Spain until the 1980s reveals a widespread urban pattern in contemporary cities [18]. Their constructive solutions [19], with the effects of time, have caused their obsolescence, requiring rehabilitation for their revitalisation.

Desvallees' research [20] shows the determinant character of rent in the insulation of dwellings and in the rate of thermal equipment for heating and air conditioning. Authors such as Sanz Fernández et al. [21] link energy inefficiency with renting as an occupancy regime. Both situations, together with the difficult balance between energy efficiency and the conservation of heritage values in historic buildings [22], are a reality in the Ville de Pessac, leading to the rapid deterioration of its state of conservation.

A balance is proposed between energy efficiency considerations, the essential conservation of the architectural heritage and meeting the needs of occupants. Starting from the original conditions of the project and trying to respect as much as possible the original design, this study proposes the modification of some aspects of the villas to achieve the optimal performance of energy efficiency [23]. There were many solutions to consider, but, based on recent studies on improving energy efficiency [24], it was decided to select a balanced solution to the results of the sensitivity analysis and public retrofit programmes initiatives for social dwellings. Foyers de Seine-et-Marne (FSM), one of the first social housing companies to certify major renovation projects, implements energy saving measures in the improvement of insulation (façades and roofs), windows and heating and ventilation systems [25].

Enhancing the value of Le Corbusier's project in the current context: the pandemic and environmental sustainability

The COVID-19 pandemic and the confinement within dwellings have highlighted the weaknesses of traditional and contemporary architectural design, and have made manifest the population's need for new ways of living, with more flexible and multipurpose residential spaces, which are more suitable and compatible with teleworking, and the possibility of enjoying outdoor spaces with greater contact with nature.

On the other hand, for some years now, new technologies have been generating new social behaviours and new ways of relating between the user and the home, making it possible to combine leisure and work in the same space in a flexible way and consolidating the demand for a growing relationship between users, architecture and nature. These are drastic social changes with important implications for architecture that reproduce and recall the social and urbanistic effects of other pandemics of the past. The promotion of hygiene and sanitation systems for the control of infectious diseases during the Roman Empire was motivated by the spread of dysentery or typhus [26]. The planning of cities outside the walls was to avoid the insalubriousness of medieval streets after the Black Death or Bubonic Plague that devastated Europe in the mid-fourteenth century. The construction of large parks and wide avenues with improved sewage systems followed the outbreaks of cholera between the nineteenth and twentieth centuries [27]. The construction of sanatoriums and the application of hygienist ideas in buildings by the architects of the Modern movement was after the outbreaks of tuberculosis in the mid-nineteenth and early twentieth centuries; these architects advocated for natural light and natural ventilation for their curative properties against disease and greater contact with the natural environment [28]. Le Corbusier was at the forefront of the architectural changes, with his five points of modern architecture [29].

Although the Spanish flu and other pandemics caused by the influenza virus that struck Europe in the early twentieth century [30] did not have a clear impact on architectural measures [31], the recent respiratory pandemic caused by the SARS-CoV-1 coronavirus in 2003 previously raised the possible influence of the built environment in controlling the spread of a pandemic by focusing on improving ventilation and drainage systems [32]. Finally, the current pandemic caused by COVID-19 has revived the debate on the impact of the built environment on health and disease transmission, going beyond strictly health aspects and analysing the relationship between architecture and people's individual and collective way of life [33]. This debate can influence urban and architectural aspects, and offers the opportunity to reconcile the necessary architectural response to the pandemic with healthier and more sustainable development linked to climate change, linking energy efficiency, comfort, air quality and health [34]. An architecture capable of providing a compatible response balanced between health, social transformations, economic interests and environmental sustainability [35].

In this new situation, the increasingly widespread use of housing as a hybrid residential and work space makes the energy refurbishment of the large building stock built decades ago, in times of zero climate awareness and lack of energy saving regulations, much more relevant. The new social context offers new paradigms of use for residential complexes built during the twentieth century that were falling into disuse, such as the garden cities such as the Cité Frugès in Pessac designed by Le Corbusier, which offer urbanised spaces with a better relationship between building and nature, as demanded by today's urbanites. In this sense, there is a clear trend that shows a balance in most of the urban plans designed by Le Corbusier, which tend to balance the surface area destined for residential use, of 50%, with the surface area destined for other urban functions [36]. In the present context, this type of neighbourhood, which have degraded over the last decades, can be reused for residential or tourist purposes, avoiding their abandonment and deterioration, and promoting sustainable urban planning processes and the circular economy, which allow for urban regeneration and rehabilitation compatible with existing buildings.

These advantages are applicable to other residential typologies of the Modern movement, both single family dwellings and large multifamily buildings, with the results of studies showing a lower incidence of the COVID-19 virus [37]. These data help to recover the validity of modern architecture as a paradigm of healthier urban architectural design, revalidating the arguments of the architects of modernity who defended health and hygiene through the circulation of clean air, natural lighting and ventilation in buildings [38]. Many of Le Corbusier's considerations for this urbanization are very much in line with the sustainable development goals of the 2030 Agenda. His approach looked at safe and affordable housing (11.1) with affordable and sustainable transport systems (11.2), generating inclusive and sustainable urbanization (11.3), protecting natural heritage (11.4), reducing the environmental impact of cities (11.6) and providing access to safe and inclusive green and public spaces (11.7). This research presents the energy efficiency improvement of its proposal to contribute to the slowing down of climate change, thus reducing the adverse effects of natural disasters (11.5).

Hygiene and energy efficiency in Le Corbusier's architecture

Given that contemporary architecture today is based on the principles of modernity, in order to understand the relationship between architecture, health and environmental sustainability, it is pertinent to recall the responses that the architects of the Modern movement gave to these aspects [39].

In the current context, Le Corbusier's residential proposals take on renewed relevance, with his advocacy of a more hygienic urbanism, with sunnier dwellings and healthier environments in contact with nature. In fact, the results from the literature before [40] and after the COVID-19 pandemic indicate that indoor air quality is the most researched topic, followed by thermal conditions and lighting and daylighting [41].

The Franco-Swiss architect, one of the pioneers of modern architecture, promoted natural light and natural ventilation in the interior of dwellings, and defined the five points of modern architecture: the *piles*, the *free floor plan*, the *free façade*, the *sliding window* and the *roof garden terrace* [42].

Le Corbusier considered natural light as a fundamental parameter in his projects; by designing large windows according to the sunlight of each place, and the zenithal illumination with skylights and side windows to provide multisided natural light combining direct and diffuse light, he guaranteed homogeneous illumination in all the rooms [43]. Le Corbusier made natural light the main compositional element in his work, defining architecture as the wise, correct and magnificent interplay of volumes assembled under light [44]. His great control over natural lighting has been demonstrated even in all his unrealized residential buildings.

However, Modern architects' concern for lighting was not initially accompanied by a control of energy efficiency, so that the increase in openings in the façades of their buildings had a proportional influence on the increase in cooling consumption in summer due to solar gains and in heating in winter due to the poor insulation of the glazing and joinery of the time [45]. In fact, energy efficiency was not a relevant topic of discussion of architects and engineers with their clients in the middle decades of the twentieth century [46]. Against this background, nowadays it is essential to ensure the development of a resilient built environment and the further development of a networked, integrated sustainability assessment in the design stage of buildings [47].

Later, in 1933, Le Corbusier's work was oriented towards new ways to provide façades with the heating and air-conditioning of the interior spaces and a ventilation mechanism through the exact respiration of the glass panels [48]. The new problems of thermal and light control caused by the large glazing of modern architecture prompted Le Corbusier, from the 1930s onwards, to investigate and reinterpret the overhangs, *loggias* and *muxarabis* of traditional building culture from the renovating perspective of modernity. His ideas gave rise to new passive solar, thermal and natural ventilation control systems—the brise-soleil, the loggia and the aerateur—to guarantee shading and natural air circulation by construction elements that protect the house from the intense sun [49]. These passive systems, based on vernacular architecture, had the objective of greater light control, for visual comfort and the control of the heat energy of direct solar radiation, creating intermediate spaces of thermal transition that better insulate the interior of the dwellings from climatic changes and that ended up defining the formal image of Le Corbusian architecture [50]. New architectural and construction solutions were a modern example of architectural design, with passive cooling strategies for improving the energy efficiency of buildings [51].

In short, Le Corbusier's work constitutes a bridge between the first hygienic responses of modern architects and today's growing challenges of energy efficiency and sustainability in architecture. His research on solar control and natural ventilation in housing is a precursor of today's methodologies of thermal and lighting calculation using computer tools. It is, therefore, pertinent to investigate the advantages of combining the ideas developed by Le Corbusier in his projects with the advantages of new technical possibilities, studying the needed energy rehabilitation of his buildings, by means of a prior analysis that makes it possible to identify the most unfavourable aspects of their energy performance.

La Cité Frugès: an opportunity to reuse garden cities designed for healthy and working life

In 1923 Le Corbusier published his book *Vers une architecture—Towards an architecture*—in which he put forward his idea of modern, social and economic housing, built using new construction methods and materials. Le Corbusier believed in the capacity of the new machine age to create serial and standardised elements, and advocated the mass production of dwellings that would meet the housing needs of the population in the shortest possible time and at the lowest possible cost [52].

Le Corbusier's postulations caught the attention of Henry Frugès, an industrialist who wanted to create affordable housing for his workers on a plot of land surrounded by woods in the French town of Pessac, near Bordeaux, by creating a garden city close to his factory and a tuberculosis hospital, a very common illness among workers at the time. In 1924, Mr. Frugès commissioned Le Corbusier to put his theories on affordable housing into practice, even in their most extreme forms; he wanted to achieve truly conclusive results in the reform of low cost housing, thus, "Pessac should be a laboratory" [53].

As an urban planning project, the design of the neighbourhood was configured as a unitary and ordered landscape [15], combining social and functional programmes and highlighting the modernity of the neighbourhood for its time [14]. The Cité Frugès in Pessac shows the predominance of the open space of the modern cities conceived by Le Corbusier, with large terraces, courtyards, windows and spaces for the car [36].

The dwellings designed for this neighbourhood are based on the prototype of Le Corbusier's Maison Citrohan, with a structure of reinforced concrete porticoes and non-load-bearing walls that allow his concepts of an open floor plan, sliding windows and roof gardens to be applied. Based on these concepts, included in the five points of modern architecture defined by Le Corbusier, and incorporating his ideas of industrialisation, he designed several modular dwellings as standardised prototypes based on simple combinations [54]. His standardised and industrialised design methodology generates a rationalist architecture that combines numerical rules governing space and constructive rules, creating five housing typologies with different dimensional and spatial characteristics [15]. The Cité Frugès in Pessac was the first practical example where Le Corbusier was able to apply his ideas of standardisation, economy and speed of construction in accordance with the way aircraft and automobiles were built. Standardisation was based on dimensional criteria inspired by the human scale and industrialised prefabrication with dry assembly [55]. All the construction elements used are standardised, but the houses are combinable and varied: detached, semi-detached, grouped or in bands of five or six dwellings [56]. It is a field of application of the industrial work organisation method, standardised in its elements: the same 5 m. by 5 m. and 2.50 m. by 5 m. cell, the same window, the same staircase, the same heating system, and the same kitchen and bathroom equipment.

However, the disastrous final result of this neighbourhood, both economically and in terms of a lack of social acceptance, made Le Corbusier understand that the technical and architectural approach must be based on knowledge of the social and industrial reality of the place, and not on the mythification of industrialised architecture [57].

The correct energetic functioning of his dwellings inevitably depended on the necessary adaptation of the residents' way of life to the functional design of these modern dwellings. However, over the years and through self-building, most residents adapted their dwellings by altering the cross ventilation and correct natural lighting [58]. An architectural failure that shows the duality between the intellectual point of view of the designer and the practical point of view of the users, who did not understand Le Corbusier's idea of constructive standardisation and environmental control [58]. This situation is ongoing and even more complex today, with the need for tools to manage the complexity of the design process and compliance requirements and to support transparent communication with stakeholders [59].

Le Corbusier himself came to recognise that the neighbourhood had been an absolute failure, and, for years, the Cité Frugès suffered a progressive deterioration, both constructively and socially. Even in the 1960s, the authorities of the municipality of Pessac considered demolishing the neighbourhood [60].

However, the designation, in 2016, of the Cité Frugès de Pessac as a World Heritage Site, along with other works by Le Corbusier, brought about a very important change in the perception of the neighbourhood, and generated a debate on the possibility of rehabilitating this type of urban planning project of the Modern movement, raising new challenges regarding the reuse, adaptation or readaptation of existing buildings that constitute an architectural legacy with historical value [61]. This reflection raises questions about the need to restore them to their initial state, and to what extent this recovery would be imposing on their users, a century later, the ideas of the Modern movement that led to the construction of these buildings [62].

In the specific case of the Citè Frugés, the authorities tried to find a balanced solution to this problem. A protocol has now been established with a coherent set of measures for the rehabilitation of the neighbourhood. On the one hand, it has been proposed to restore the original polychromy of the façades with the different colours of each façade. On the other hand, neighbours are also allowed to carry out minor alterations that do not distort the original concept [63]. However, the real challenge is to rehabilitate the neighbourhood to meet contemporary standards of comfort and energy efficiency.

Achieving this challenge represents, for neighbourhoods such as the Cité Frugès de Pessac, a new opportunity to reuse garden cities designed for healthy living and working life that are more adapted and resilient to the new social demands generated by the new postpandemic situation.

2. Methodology

2.1. Definition of the Research Scope

The methodology used consisted of a systematised study of all the dwellings in the Citè Frugés, to evaluate them under the standards of compliance with European regulations for nearly zero energy consumption buildings and contemporary construction materials and HVAC systems. Each of the housing typologies of this residential complex was modelled using energy efficiency calculation software. Their geometries, orientations and the architectural composition of their façades were maintained (Figure 1).

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

Figure 1. (**a**) Neighbourhood map and housing typologies; (**b**) aerial view.

2.2. Selection of the Modeling Method

For the modelling and calculation of the energy performance of the dwellings, the "Líder–Calener unified tool" [64] (version 2.0.2253.1167), has been used. This tool includes, in a single platform, the official programmes for energy verification and the evaluation of energy consumption demand.

The Líder–Calener unified tool has been used as it is a free access calculation software that allows the calculation of the energy demand and energy consumption of buildings in accordance with Directive 2010/31/CE, and facilitates the establishment of correlations between the results obtained in this work located in the south-west of France and other social housing studies being carried out in Spain. In addition, this computer programme allows energy calculations in different types of climate, and can perfectly consider climatic characteristics equivalent to those of the town of Pessac.

The selected software uses a calculation engine whose accuracy and reliability is considered to be proven by the public institutions themselves, and allows a quantitative comparison of the proposed energy performance improvements in the houses.

This software uses calculation criteria equivalent to those laid down in the French energy certification standard [65], and is well suited to this research because its calculation procedure takes into account the hourly evolution of thermal processes, the behaviour of installations and the energy input from renewable sources.

Both the French and Spanish standards are based on thermal comfort limits according to the predicted percentage of dissatisfied (PPD) and calculation methods for operating temperature and humidity established by the UNE-EN-ISO 7730 standard [66]. For the same type of climate, the total primary energy consumption requirements of the Spanish standard are similar to the French standard [6].

The Líder–Calener unified tool allows the calculation of the heating demand, which makes it possible to check the maximum threshold set by the French regulations. It also takes into account the same criteria as the bioclimatic design indicator of the French standard (Bbio), such as compactness, window surfaces, orientation, thermal inertia and airtightness of the thermal envelope. At the same time, it distinguishes between habitable and nonhabitable spaces, and distinguishes habitable spaces according to their internal load and whether they are air conditioned or not [67]. Lastly, it makes it possible to take into account the influence of insolation, sun protection systems and natural lighting, which allows Le Corbusier's dwellings to be modelled taking into account their main characteristics.

2.3. Climate Classification

For the energy calculation, the climatic characteristics of the Citè Frugés site, located in the city of Pessac (France), have been taken into account, considering the Cfb climate (temperate oceanic with mild summers) according to the Köppen climate classification, and assimilating it within climate zone C1, according to the Spanish Technical Building Code. This type of climate is strongly influenced by the Atlantic, because the predominance of westerly winds from the ocean causes cool winters, with average temperatures of 7 °C in winter. However, summers are warm and long, due to the influence of the Bay of Biscay, with average temperatures above 20 °C. Rainfall is over 900 mm and insolation is less than 2000 h of sunshine per year, with an average annual relative humidity of 81%.

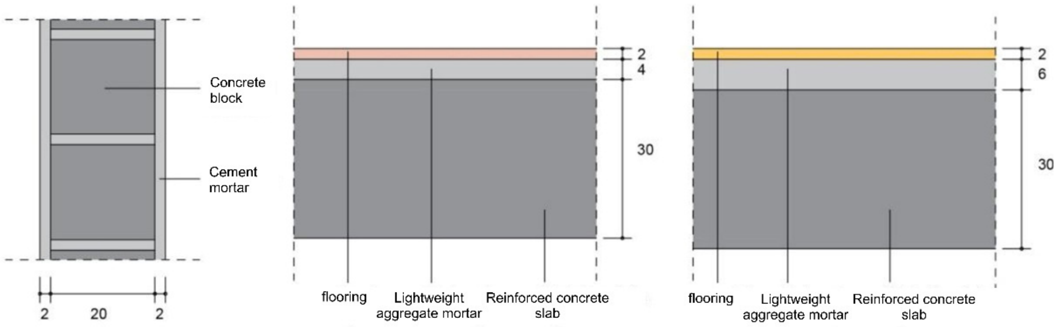
2.4. Construction Composition of the Envelope

The construction characteristics of the original buildings have been analysed (Table 1 and Figure 2). The proposed solution includes an intervention to improve the envelope with external thermal insulation composite system (ETICS), thermally broken joinery, low emissivity double glazing and solar protection. With these constructive improvements, different energy parameters, such as thermal transmittance, solar gains or the overall annual energy demand of the dwellings, are optimised, obtaining an adequate energy rehabilitation.

The same envelope energy improvement solution is studied in a uniform and common way for all the dwellings in the neighbourhood, in order to make global comparisons of the energy performance of each case study. The modelling shows which typology is the most efficient and which is the least.

Table 1. Summary of construction composition of the thermal envelope of the original house.

Composition of the Thermal Envelope of the Original House	Thickness [cm]	Thermal Conductivity [W/m·K]	U [W/m^2·K]	g
Roof:			1.52	
Ceramic flooring	2.0	1.30		
Lightweight aggregate mortar	6.0	0.41		
Reinforced concrete slab	30	0.846		
Walls:			1.06	
Cement mortar	2.0	0.55		
Concrete block	20	0.287		
Cement mortar	2.0	0.55		
Lower slab:			1.37	
Wood flooring (light leafy)	2.0	1.15		
Lightweight aggregate mortar	4.0	1.30		
Reinforced concrete slab	30	0.846		
Window			Uw = 5.68	
Glass (90.5% of the window)			Ug = 5.70	g = 0.85
Frame (9.5% of the winwow)			Uf = 5.50	
Frame absorptivity = 0.96; Frame air permeability = 100.00 m^3/h·m^2 (at 100 Pa)				

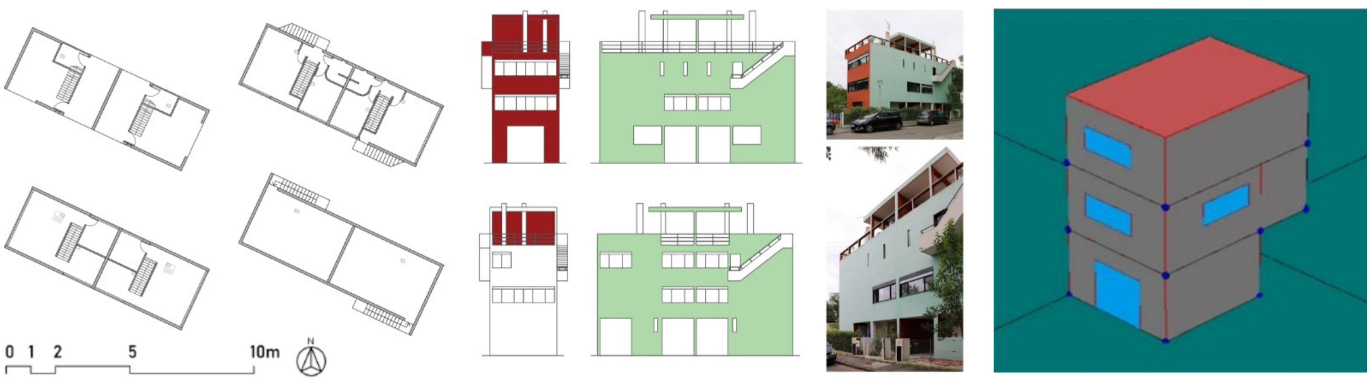


(**a**) (**b**) (**c**)

Figure 2. Construction details of the original houses: (**a**) façade; (**b**) floor slabs; (**c**) roof.

2.5. Modelling of Dwellings

For the modelling of each dwelling, the orientation, geometry, layout and size of the openings in the architectural envelope and the recessing of the glazing with respect to the façade plane were taken into account (Figures 3a, 4a, 5a, 6a and 7a). Each of the houses was modelled in the Líder–Calener unified tool, taking into account the geometrical and constructive data (Figures 3b, 4b, 5b, 6b and 7b).

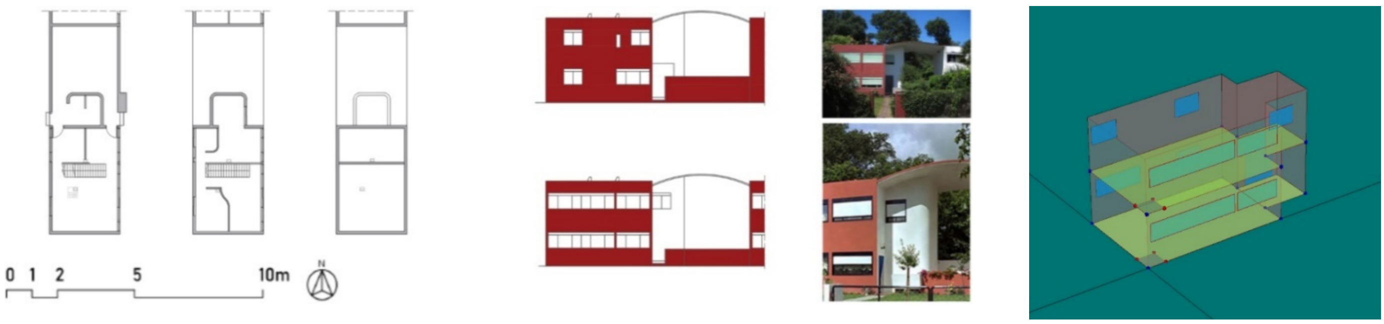


(**a**) (**b**)

Figure 3. (**a**) Plans, sections and photographs of the Villa Gartte-Ciel; (**b**) computer model.

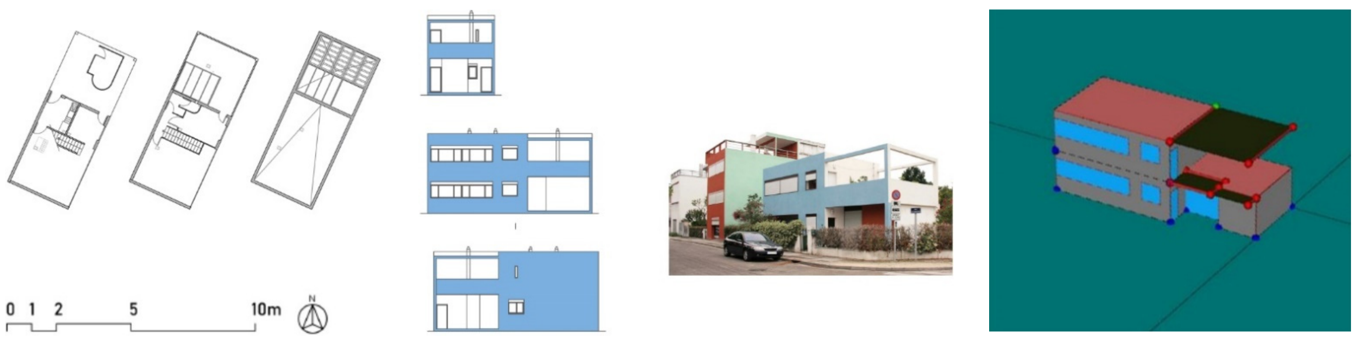
(**a**) (**b**)

Figure 4. (**a**) Plans, sections and photographs of the Villa Vrinat; (**b**) computer model.



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

Figure 5. (**a**) Plans, sections and photographs of the Villa Arcade; (**b**) computer model.



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

Figure 6. (**a**) Plans, sections and photographs of the Villa Zig-Zag; (**b**) computer model.

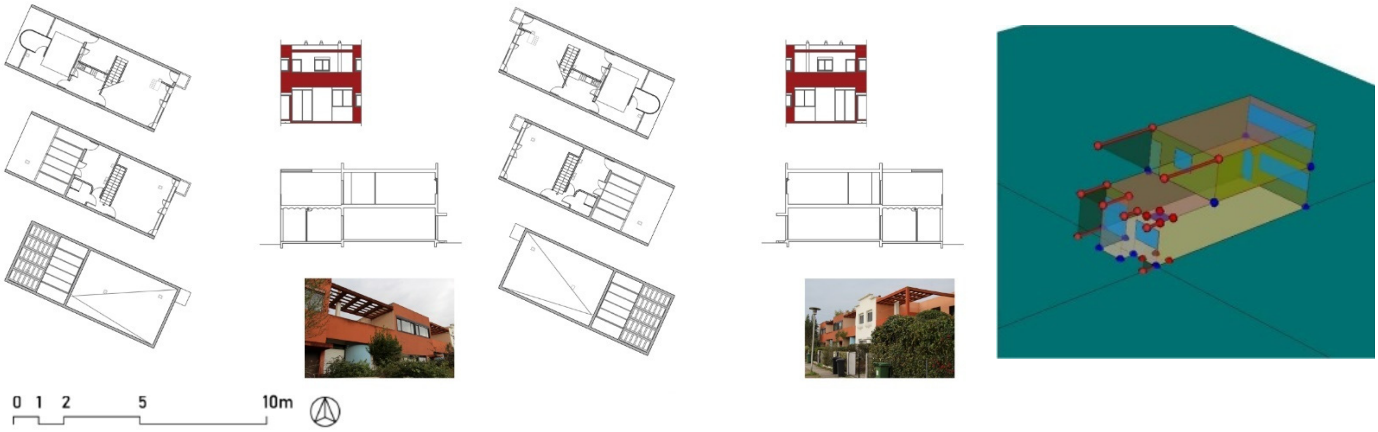


Figure 7. (**a**) Plans, sections and photographs of the Villa Quinonce.; (**b**) computer model.

2.6. Construction Composition of the Thermal Envelope

The improvement proposal consists of incorporating a 10 cm thick layer of expanded polystyrene (EPS) thermal insulation with a thermal conductivity of λ= 0.029 W/m-K into the original single concrete block wall enclosures (Figure 8), either on the inside face of the enclosure by means of wall cladding or on the outside face by means of an ETICS system [68].

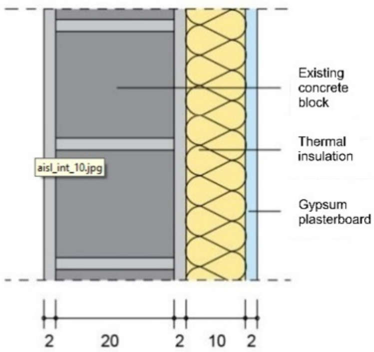


Figure 8. Construction details of the façade of the energy refurbished building.

External insulation has a better thermal performance in contrast to internal insulation [69] and window replacement and roof insulation have a large impact on annual thermal comfort. This solution is used in the social housing literature with a cement mortar finish rather than brick [18,19,70,71]. The frequent reasons are the continuity of the new envelope, the elimination of thermal bridges, and the fact that it works on the outside of the building, safeguarding the inside of the rooms. In other heritage buildings with brick or stone envelopes this would not be possible, but the Citè Frugés lends itself to its use [72].

Many insulation solutions have been considered in other research: vacuum insulation panels [68,73], thermal insulation panels from tree bark [74] or biobased insulation panels [75]. These represent viable alternatives to other conventional insulators but their implementation should be carried out with a deeper analysis due to their hygroscopic properties [76]. In order to identify the volumetric repercussion of their use in the Cité Frugès, the ETICS system has been used with all of them.

With regard to the glazing, low emissivity double glazing with 16 mm argon gas chamber, with values Ug = 1 W/m^2 K and g = 0.58, has been modelled to replace the original monolithic glazing, and aluminium frames with thermal bridge break, with values of Uf = 2 W/m^2 K and with an absorptivity (α) of 0.40, to replace the original iron profile frames. In addition, solar protection louvres have been proposed only in the glazing of the rear façades, so as not to alter the main architectural composition of the dwellings.

With regard to thermal conditioning, all the dwellings have been modelled with multizone air-conditioning systems with two interior units, one for each floor of the dwelling. Each dwelling is equipped with a domestic hot water system (DHW) using a conventional boiler with a calculated demand adapted to the theoretical number of occupants of each dwelling according to its size.

Finally, with regard to the ventilation system, all the dwellings have been modelled with an enthalpy heat recovery system with an energy recovery efficiency of 90%.

3. Results

The results obtained show the need to improve the energy efficiency of the houses originally designed and built by Le Corbusier in order to adapt them to contemporary energy efficiency and comfort standards (Table 2).

Table 2. Comparison of results of the original and energy refurbished dwellings.

Villa Typology	$C_{ep,nren}$	$C_{ep,nren,lim}$	$C_{ep,tot}$	$C_{ep,tot,lim}$	K	K_{lim}	$q_{sol,jul}$	$q_{sol,jul,lim}$
Quinonce (original)	-	-	-	64.00	4.47	0.56	3.95	2.0
Quinonce (refurbished)	24.70	32	55.40	64.00	0.56	0.56	1.56	2.0
Arcade (original)	-	-	-	64.00	2.42	0.53	21.21	2.0
Arcade (refurbished)	22.70	32	63.20	64.00	0.69	0.53	1.74	2.0
Mean value (refurbished)	23.70	32	59.30	64.00	0.60	0.55	1.65	2.0

Indicators and parameters of CTE DB-HE: $C_{ep,nren}$: nonrenewable primary energy consumption of the building [KWh/m^2·year]. $C_{ep,nren,lim}$: limit value for nonrenewable primary energy consumption [KWh/m^2·year]. $C_{ep,tot}$: total primary energy consumption of the building [KWh/m^2·year]. $C_{ep,nren,lim}$: limit value for total primary energy consumption [KWh/m^2·year]. K: overall heat transfer coefficient through the thermal envelope [W/m^2·K]. K_{lim}: limit value for the overall heat transmission coefficient through the thermal envelope [W/m^2·K]. $q_{sol,jul}$: solar control of the building's thermal envelope [KWh/m^2·month]. $q_{sol,jul,lim}$: limit value for solar control of the thermal building envelope [KWh/m^2·month].

The research carried out has revealed the different thicknesses of external insulation used in housing construction that would be necessary to obtain the results shown in Table 2. The study, therefore, allows the determination of the required thickness to achieve thermal conductivity, (λ) between 0.020 W/m-K and 0.050 W/m-K (Figure 9).

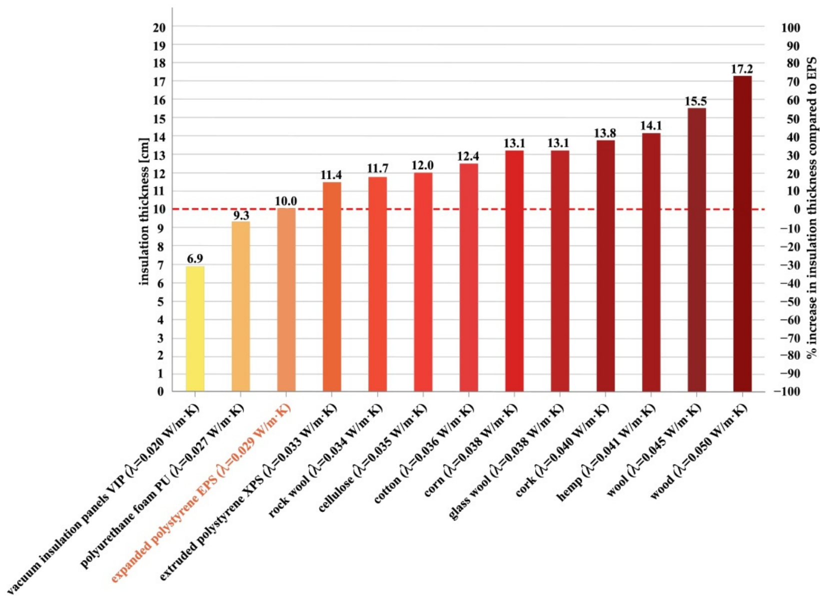


Figure 9. Thicknesses of external insulation and % increase compared to EPS.

Considering the lower visual impact on the volumetry of the energetically refurbished dwellings, it can be observed that the 10 cm of EPS proposed is one of the construction solutions with the lowest visual impact.

The calculations carried out make it possible to quantitatively assess the energy performance of the different types of dwellings according to parameters such as the global thermal transmittance "K", the global solar factor, the global annual demand and energy rating. The results obtained have made it possible to classify the neighbourhood by means of colour gradients that organise the villas from more efficient to less efficient, according to specific parameters.

Considering each of these parameters individually, the results obtained with respect to the global thermal transmittance "K" show that the villas with the highest proportion of glazing and individual houses are the ones with the worst thermal performance in terms of thermal transmittance, having not sufficiently controlled energy losses through the openings in some homes, as the quantity and distribution of the windows has prevailed exclusively on the basis of functional criteria to enhance natural lighting and natural ventilation (Figure 10 and Table 3).

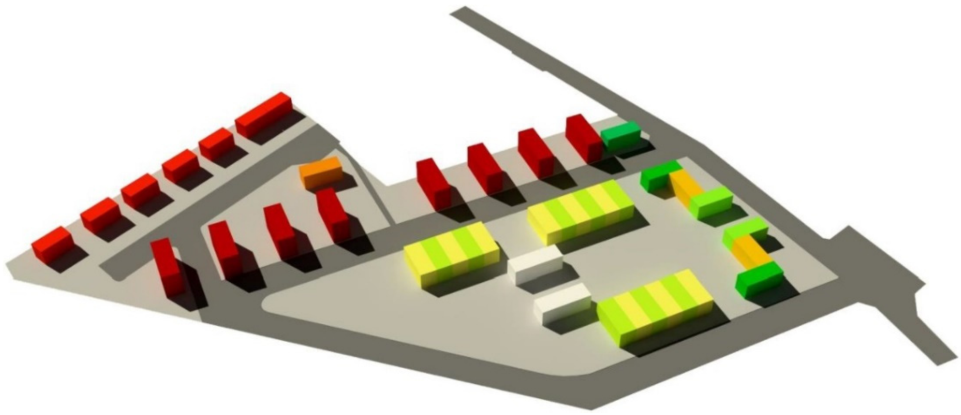


Figure 10. Representation of the results of the thermal transmittance on a 3D view of the Cité Frugès.

Table 3. Comparison of the results of the thermal transmittance of the different dwellings.

Global Thermal Transmittance k[w/m^{2}k]								
Gratte-Ciel	Vrinat	Arcade	Quinonce		Zig-Zag			Isolee
			Type 1	Type 2	Type 1	Type 2	Type 3	
0.76	0.71	0.73	0.56	0.56	0.53	0.60	0.55	0.50

With regard to the global solar factor, the calculations show that dwellings with large glazing without solar protection elements and facing west or south have excessive insolation. The results obtained show the great influence of the orientation of each of the dwellings and typologies, and the insufficient solar protection of windows in houses with more glazing and southern exposure to sunlight (Figure 11 and Table 4).

Table 4. Comparison of the results of the solar factor of the different dwellings.

Solar Factor (kWh/m^{2}k·month)								
Gratte-Ciel	Vrinat	Arcade	Quinonce		Zig-Zag			Isolee
			Type 1	Type 2	Type 1	Type 2	Type 3	
2.04	2.56	3.42	1.36	1.28	2.84	3.26	2.48	3.00

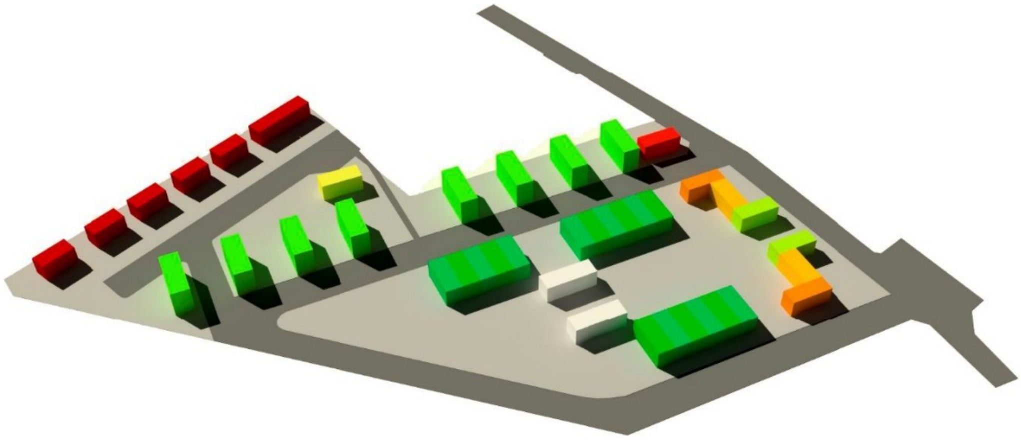


Figure 11. Representation of the results of the solar factor on a 3D view of the Cité Frugès.

As a result of the combination of the above factors, the results obtained for overall annual demand show equally high differences in the energy performance of the different dwellings in the neighbourhood. In all houses, the heating demand is much higher than the cooling demand due to the climate zone where the project is located, and the energy demand in individual houses is much higher. (Figure 12 and Table 5).

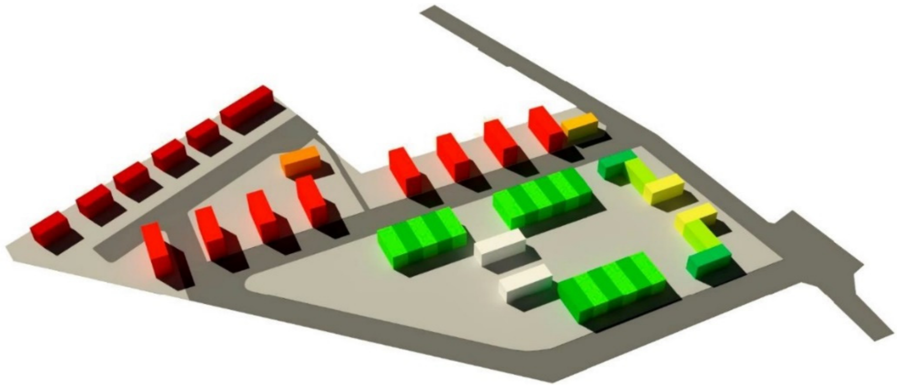


Figure 12. Representation of the energy demand of the thermal transmittance on a 3D view of the Cité Frugès.

Table 5. Comparison of the results of the energy demand of the different dwellings.

	Demand (kWh/m^{2}k·year)								
	Gratte-Ciel	Vrinat	Arcade	Quinonce		Zig-Zag			Isolee
				Type 1	Type 2	Type 1	Type 2	Type 3	
Heating	51.56	38.20	52.60	9.08	10.99	9.47	18.72	21.36	24.95
Cooling	0.17	0.20	0.32	0.07	0.00	0.34	0.31	0.05	0.18

Finally, with regard to the energy rating obtained, after the incorporation in the calculations of similar type installations in all the dwellings, as a result of the diversity of heating and cooling demands, the results obtained also show large differences in the energy ratings obtained in each type of dwelling, being worse in individual houses (Figure 13 and Table 6).

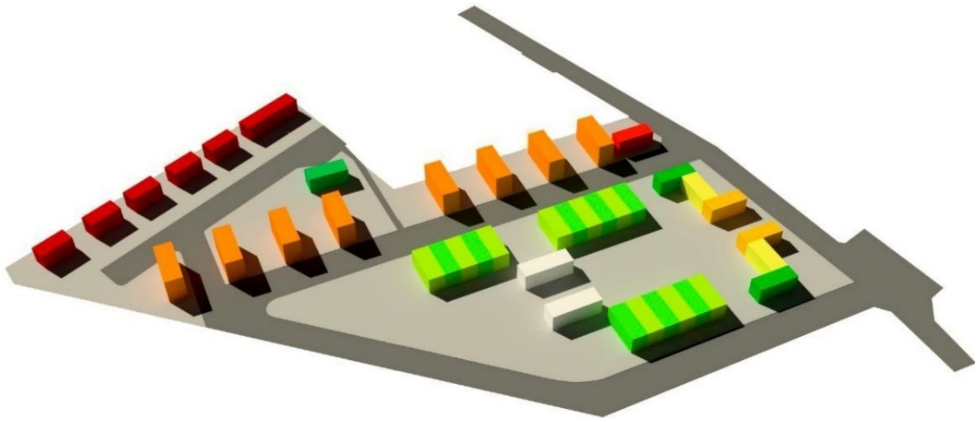


Figure 13. Representation of the results of the energy qualification on a 3D view of the Cité Frugès.

Table 6. Comparison of the results of the energy qualification of the different dwellings.

	Energy Qualification								
				Quinonce		Zig-Zag			
	Gratte-Ciel	Vrinat	Arcade	Type 1	Type 2	Type 1	Type 2	Type 3	Isolee
Non-Renewable Primary Energy Consumption (kWh/m^{2}k·year)	35.53 A	22.28 A	44.92 B	24.74 A	25.53 A	23.34 A	29.40 A	30.76 A	38.73 B
Carbon Dioxide Emissions (KgCO^2/m^{2}k·year)	6.67 A	3.83 A	7.69 A	4.27 A	4.4 A	4.03 A	5.06 A	5.29 A	6.66 A
Total Qualification	A-A	A-A	B-A	A-A	A-A	A-A	A-A	A-A	B-A

4. Discussion

The analysis of the energy efficiency of Le Corbusier's dwellings in the Cité Frugès is carried out as an opportunity to reuse garden cities designed for healthy and working lives.

This is the first evaluation of the energy efficiency of the neighbourhood where Le Corbusier began his research with different housing typologies. Since it is an update of the architectural solutions to the new requirements, the embodied energy/emissions or multiple refurbishment variants will need to be studied in detail in future research. The great differences in the energy performances of the different dwellings in the Cité Frugès require an individual analysis of the thermal performance of each type of dwelling, in order to plan a correct and optimised energy rehabilitation. This will generate greater efficiency in the neighbourhood.

The aim must be to apply the appropriate energy improvement in each case in order to meet the contemporary standards of comfort and energy efficiency in all the dwellings, and to achieve the reuse of this valuable example of a garden city, responding to the new social demands generated by COVID-19 by making contact with nature, health, comfort and energy efficiency compatible.

The results obtained show that there is no uniformity in the energy performance of the different types of housing in the Cité Frugès district. Some housing models offer much better energy efficiency and comfort standards than others, since the same housing typology, such as the Zig-Zag, was used with three different orientations without changes to its envelope. Depending on the proportion of glazing and opaque enclosures, geometry and orientation, and whether houses are individual or not, the different housing typologies offer very different energy performances, considering the different parameters analysed, such as the global thermal transmittance "K", the global solar factor, and the global annual demand and energy rating.

The insufficient solar protection of windows in houses with more glazing and solar exposure to the south has been demonstrated. This is not surprising, because Le Corbusier's concern for this issue would emerge in the 1930s with his trips to South America and Algiers, a period that would mark the transformation of his architecture [77]. The comparative analysis of the results obtained from the energy performance of the different dwellings shows that natural light and natural ventilation in the interior of the dwellings prevailed in the design, over energy aspects.

Le Corbusier had not yet experimented with his passive solar and thermal control systems, such as the brise-soleil. Calculations show that the increase in openings in the façades of his buildings, regardless of the orientation of each dwelling, had a proportional influence on the increase in cooling consumption in summer and heating in winter.

The advocacy of Le Corbusier for a more hygienic urbanism with sunnier dwellings and healthier environments in contact with nature is evident. At the Buenos Aires conference in 1929, Le Corbusier argued: *Before drawing, one must always know "what it is all about", "what it is for", and finally one must learn to look* [78]. According to his understanding of the architect's work, energy efficiency was not yet one of the reasons for the design for Pessac. In the following decades, however, he would address these aspects in his work.

Over the years, the need to reduce the significant contribution of greenhouse gases from buildings by meeting the new technical and regulatory requirements for nearly zero energy buildings (NZEB) make it necessary to propose more efficient architectural designs that avoid energy need and even produce surplus energy. These can include equipping with efficient air conditioning systems to save energy consumption, complemented by the use of renewable energies to offset such consumption. Following low energy passive design strategies such as those proposed in the Kyoto pyramid [79], which has the aim of reducing energy consumption and CO_2 emissions based on higher construction quality, resulting in greater comfort and quality of life for users, the taking into account of thermal and lighting conditions, and is based on the maxim that the cheapest energy is the energy that is not consumed.

The study of different insulation materials makes it possible to determine the thicknesses required for the same energy conditions. The thicknesses range from 7 cm to 17 cm, which shows the importance of studying this factor in the volumetry of renovation works.

At present, concrete, ambitious and resilient measures about sustainability must be taken. Researchers, architects and engineers need progressively better methodologies to visualize the relevant interdependencies between sustainability criteria in building design, depending on the quality levels of the intended functional and technical requirements [80]. New methodologies must assure quality during planning and construction, adopting a holistic perspective with an expanded process model increasing productivity and quality. Architects and engineers should evaluate decision-making processes with maturity levels to decrease pathologies.

5. Conclusions

The key aspect of the Cité Frugès programme was for workers to live with their families near the factory. The social issues and practicality raised by this situation of work, family, human life and leisure intimately linked almost a century ago highlighted the need to rehabilitate the energy use of Le Corbusier's project in the wake of the COVID-19 pandemic, to bring them up to present standards of energy efficiency and comfort.

In the 1920s, energy efficiency was not a priority for Le Corbusier. His priority was, rather, hygiene and the relationship with the environment. The study shows that functional and formal criteria prevailed over energy control aspects in the orientation of dwellings and the distribution of windows. It is also found that the sun protection of the glazing is insufficient. As a result, there are large differences in heating and cooling consumption between dwellings within the same neighbourhood.

Years later, once this concern had been rectified, the Swiss architect devoted himself to this vitally important and committed subject.

Mr. Frugès' objective was to achieve truly conclusive results in the reform of low cost housing, even in its most extreme forms, by turning Cité Frugès into a laboratory [53].

Reasonably, every house behaves like an experiment, in which energy efficiency was not part of the equation.

Le Corbusier's solutions, as a global response, to the climate and adaptation to the environment had not yet been studied by the architect. In the 1930s, the brise-soleil, the aerateur or the roof garden were incorporated into his architecture. That is why the Cité Frugès district could be understood as his own experimental housing laboratory.

A new cartography of the Cité Frugès in Pessac, designed in 1924 by Le Corbusier, has been provided. The new energy map of the Swiss architect's project shows the diversity of energy efficiency of each housing model for the same construction solution.

EPS is the insulating material with the best thermal conductivity, and is among the most commonly used insulating materials in exterior thermal insulation composite system for facades. The study of different insulation thicknesses in the envelope allows us to understand the widespread use of EPS in the ETICS system in this type of renovation.

For the same parameters considered in Section 2.6 of this research, only vacuum insulation panels allows a 30% reduction in thickness, compared to EPS.

Author Contributions: Conceptualization, Á.B.G.-A.; methodology, Á.B.G.-A. and C.P.-C.; software, C.P.-C., F.I.-C. and C.L.-R.; validation, C.P.-C., Á.B.G.-A. and A.G.-G.; formal analysis, F.I.-C. and C.L.-R.; investigation, C.P.-C., Á.B.G.-A., A.G.-G., F.I.-C. and C.L.-R.; resources, F.I.-C. and C.L.-R.; data curation, Á.B.G.-A. and C.P.-C.; writing—original draft preparation, Á.B.G.-A. and C.P.-C.; writing—review and editing, C.P.-C. and Á.B.G.-A.; visualization, A.G.-G.; supervision, C.P.-C., Á.B.G.-A. and A.G.-G.; project administration, C.P.-C. and Á.B.G.-A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

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