CivilEng

Article

Precast Concrete Building Construction and Envelope Thermal Behavior: A Case Study on Portuguese Public Social Housing

Pedro I. Brandão * and João C. G. Lanzinha

C–MADE—Centre of Materials and Building Technologies, LABSED, Department of Civil Engineering and Architecture, University of Beira Interior (UBI), 6201-001 Covilhã, Portugal; jcgl@ubi.pt
* Correspondence: pedro.isaac.brandao@ubi.pt

Abstract: A considerable part of Southern European countries building stock was constructed before the implementation of national thermal regulations, and as such, it is currently exposed to challenges such as energy poverty and climate change. Portuguese public social housing presents a significant variety of construction systems and applied typologies. Among them, the "Novobra NK1", a precast concrete construction system that exploits some innovative features in envelope components, has been used in several projects. Considering the importance of retrofitting to improve and adapt the thermal behaviors of buildings to face the aforementioned challenges, this article aims to provide an understanding of the behavior of a NK1 thermal envelope of a dwelling located in Covilhã, Portugal, and the impact of some constructive envelope retrofit measures applied. Results show that existing opaque envelope elements and glazed areas present characteristics that are no longer able to provide proper responses to contemporary building constructive requirements. External insulation was identified as a key retrofit measure, window replacement also being an advised solution for rigorous heating seasons. Improvements from the internal side of windows, such as roller shades, may provide few benefits during cooling seasons, and applying solar films is not advised without a proper thermal repercussion analysis.

Keywords: social housing; precast concrete constructive systems; building envelope; thermal behavior; thermography

Citation: Brandão, P.I.; Lanzinha, J.C.G. Precast Concrete Building Construction and Envelope Thermal Behavior: A Case Study on Portuguese Public Social Housing. *CivilEng* **2021**, *2*, 271–289. https://doi.org/10.3390/civileng2020015

Academic Editors: João Castro-Gomes, Cristina Fael, Miguel Nepomuceno and Pedro Raposeiro da Silva

Received: 25 January 2021
Accepted: 25 March 2021
Published: 9 April 2021

1. Introduction

A decrease in energy consumption, the mitigation of climate change, and the eradication of energy poverty are currently considered significant challenges related to the building sector, especially regarding its energy, thermal and comfort performances [1]. Southern European countries (SEC) building stock was mainly constructed before the implementation of national thermal regulations [2], therefore with constructive solutions that may not assure favorable thermal indoor conditions. SEC vulnerability to the energy poverty phenomenon and climate change worsens this scenario. Exposure to energy poverty results in limited use of active systems to somehow correct existing problems in building thermal performances, making heating and cooling habits intermittent or insignificant [3]. Moreover, current comfort requirements in buildings are expected to increase due to the impact of climate change, where predictions for SEC indicate considerable adverse effects [4,5].

The European Union (EU) has implemented relevant legislative framework, such as the Energy Performance of Buildings Directive 2010/31/EU and the Energy Efficiency Directive 2012/27/EU, amended by the Directive (EU) 2018/844, defining those measures needed to improve the energy performance of buildings and achieve thermal comfort which should focus, among other things, on the building envelope [6]. Thus, additional strategies [7] aim to achieve an improved building stock, highlighting the specific field of envelope refurbishment to improve building energy and thermal performances, which has become a relevant field of study, particularly as regards the examination of proper constructive retrofit measures for both actual [3,8,9] and future [2] climate scenarios. Within building envelope components, the façades—understood as the vertical envelope components—play a decisive role in energy and thermal performances because their thermal transmittance can contribute to 30% of total energy consumption [10]. Possible façade constructive retrofit interventions can be organized as in the work of Sarihi et al. [11]. Highly common interventions are the application of external/internal insulation and window improvements, and conclusions in studies reporting positive results for several options are extensively described in papers [11] and [11,12], respectively.

Therefore, SEC social housing buildings require particular attention in solving or minimizing the aforementioned problems. Two main fields can be specified regarding the importance of retrofit in these buildings:

- Firstly, one related to relevant social housing retrofit projects, where the recognition of the importance of a successful intervention in these contexts is growing, as proved by the 2019 Mies van der Rohe Award, awarded to a constructed retrofit project of 530 dwellings in the Grand Parc Bordeaux [13]. Here, a key strategy was to rethink the existing envelope regarding specific measures to improve habitability, such as introducing flexibility in spaces for balconies or winter gardens, alongside other relevant features such as window improvements. Another example can be observed in the Municipality of Covilhã (where the present study took place) for a social housing building neighborhood, which is currently being retrofitted under the European Union (EU)-supported "Portugal 2020" program, directed at energy efficiency improvement regarding actions in the building envelope such as the introduction of external insulation and window replacement (Figure 1);
- Secondly, one related to specific literature developed for several SEC such as Portugal, Spain, or Italy, regarding, among others, retrofit interventions in vertical envelope components. The work from Oteiza et al. [14] provides a general approach to retrofit these types of buildings, highlighting envelope interventions such as exterior enclosing walls retrofit as appropriate examples of combined actions to improve both energy performance and other relevant needs such as building and neighborhood images. The work of Suarez and Fragoso [15] studied the repercussion of envelope retrofit measures such as insulation, solar protection, and window improvements. For the latter, specific recommendations are made to achieve air infiltration reduction through the frames, glass solar control improvements using solar films, and window U-value reduction through the higher spacing between glass panes. A combination of all those measures alongside other relevant passive strategies such as ventilation can reduce heating energy demand by 3–6 kWh/m^2 and cooling energy demand by 5–6 kWh/m^2. Alonso et al. [16] propose a methodological approach for monitoring energy refurbishment, applying it in a case study in which several actions were detected as necessary to minimize opaque and open envelope sections debilities, for both winter—increased insulation, window air infiltration control compatible with low risk of condensation, elimination of thermal bridges and advantages from solar gains through glazing elements; and summer—the role of solar protection to reduce the effect of climate change frequent extreme events. The aforementioned studies approached envelope retrofit through a combination of specific measures. However, other approaches have also been studied regarding the effect of a specific measure. Curado and Freitas [17] present an analysis on thermal comfort for a reference dwelling in representative Iberian climate scenarios without heating/cooling energy consumption, considering only the effect of external insulation in facades, and the results show that additional insulation alone may be unnecessary or insufficient for winter/summer mild and severest scenarios, respectively. Literature such as that by Boeri et al. [18] should also be mentioned considering its importance in the field of social housing, mainly for its focus on economic conditioning of envelope retrofit interventions.

Figure 1. Retrofit intervention in a social housing neighborhood located in Covilhã.

Referring to Portuguese public social housing, a relevant part of the actual building stock was constructed during the 20th century when a considerable number and variety of national housing guidelines were set out [19]. Many of those buildings were constructed before the implementation of the first national thermal regulation in 1990 (D.L. 40/90 of 6 February) [20], which led to constructive systems applied without proper thermal criteria. Among the variety of construction systems and typologies that were considered, a national program created in 1976 called CAR (Comissão para o Alojamento de Refugiados), which consisted of a refugee housing commission to provide a quick answer to housing needs of Portuguese families returned during the decolonization process [19], used interesting and innovative solutions for some of its projects. They were designed considering the need to obtain short construction timings and feasibility to be quickly replicated across several Portuguese locations, and precast concrete constructive systems were often chosen to provide a quick constructive response to this need. In fact, precast concrete buildings are more abundant in Eastern Europe, a result of an intensive socialistic construction approach directed to residential buildings, resulting in solutions with high final energy demand [21]. Therefore, works regarding retrofit of this type of buildings can be found for some of these locations. Nikolic [22] approached retrofit possibilities regarding several building subsystems, where refurbishment scenarios for the envelope are also considered. Matic et al. [21] approached this subject, putting high relevance on feasible energy-efficient envelope interventions, such as the installation of thermal insulation and window/door glazing/frame replacement, which alongside other strategies resulted in a satisfactory increase in energy efficiency.

Within used precast concrete constructive systems, the “Novobra NK1” system (NK1) consists of an interesting example, not only for its representativeness regarding the application in projects replicated in Portuguese territory—beyond the locations [19], climates [23], and socio-economic scenarios [24] mentioned in the present study—but also because of some innovative features applied in the envelope components. This is an old constructive system that was not extensively used in Portugal, so the available information about its characteristics is not abundant as original documentation is hard to find, and studies regarding this system are also rare. Therefore, by considering the actual role of retrofitting in Portuguese national strategies for housing buildings [25] that can properly be applied to improve and adapt building thermal behavior [26] to face current SEC challenges regarding energy poverty and both actual and future climate scenarios, this article aims to provide an understanding of the thermal behavior of the NK1 envelope. It focuses on the impact of some constructive envelope retrofit measures applied to a social housing dwelling located in Covilhã, Portugal, using quick, non-destructive procedures.

Results show that external walls present general and some specific characteristics that are no longer able to provide proper responses to contemporary building constructive requirements, even with insulation features compared to other constructive solutions applied before [27]. Moreover, solutions applied to glazed areas also present some weaknesses regarding the thermal characteristics of the building envelope. External insulation was identified as a key retrofit measure, window replacement also being an advised solution for severe heating seasons. Improvements from the internal side of windows, such as roller shades, may provide few improvements during cooling seasons, and solar films should not be applied without proper thermal repercussion analysis. Nevertheless, a thermography survey of the entire building envelope is necessary to confirm the extension of the detected anomalies, as well as to allow the identification of new ones. Thus, experimental campaigns and building simulations are suitable studies to perform for social housing contexts to properly quantify the envelope performance alongside the influence of climate and occupancy.

2. Materials and Methods

The main objective of this study is to provide a quantitative and qualitative understanding of the thermal characteristics of the NK1 envelope applied to a specific CAR project. In turn, it proposes some constructive retrofit guidelines to improve weaknesses and potentials detected. This section provides information about the materials and methodology used.

2.1. Case Study

The case study consists of a CAR project where the NK1 was applied, which was found to be replicated in several Portuguese locations—Covilhã, Fundão, Castelo Branco, Lourinhã, Torres Vedras, and Moita [19]. These locations present two distinct climatic zones: inland, with both severe winter and summer seasons; and coastal, with milder winter seasons and severe summer seasons. Figure 2 represent climate severities in winter (I) and summer (V) seasons according to the Portuguese national building energy performance certification system (SCE), levels 1 and 3 being the least and most severe, respectively [28].

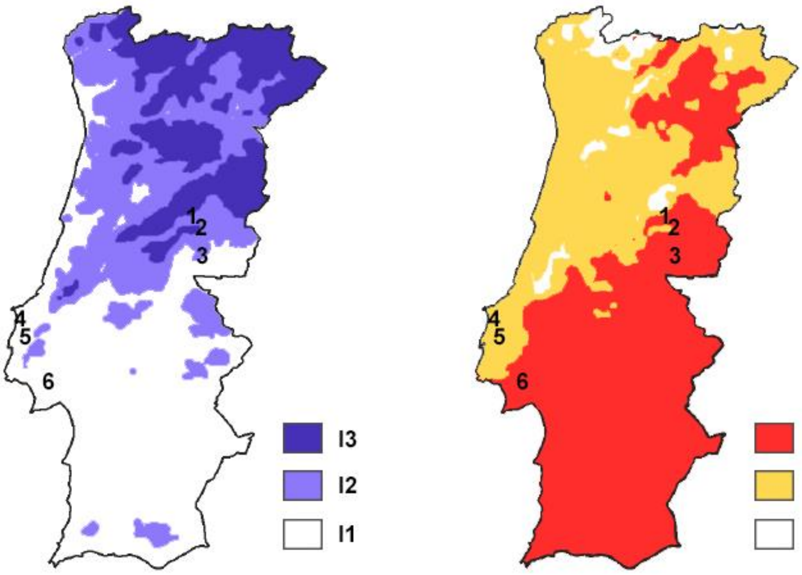


Figure 2. Portuguese climate severities in winter (I) and summer (V) seasons for each building location: Covilhã (1), Fundão (2), Castelo Branco (3), Lourinhã (4), Torres Vedras (5), Moita (6) (adapted from [28]).

Nevertheless, SCE defines that climate severities should be adjusted according to the site altitude where the building is constructed [28]. Table 1 provides both winter and summer adjusted scenarios for each one of the mentioned building locations, recurring to the "SCE.CLIMA" software [29]. According to the results obtained, it is noticeable that a proper response to obtain proper thermal performance is required for both Portuguese most severe winter and summer scenarios.

Table 1. Winter and summer adjusted scenarios for each building location.

Location	Position	Reference Altitude (m)	Building Site Altitude (m)	Winter Severity	Summer Severity
Covilhã	Inland	507	620	I3	V2
Fundão	Inland	507	480	I2	V3
C. Branco	Inland	328	375	I2	V3
Lourinhã	Coastal	99	30	I1	V2
T. Vedras	Coastal	99	50	I1	V2
Moita	Coastal	47	25	I1	V3

Figure 3 presents photos and a ground floor plan of the studied building, located in Covilhã and constructed in 1979. The building consists of four residential floors with all its façades exposed. Each floor has four areas, with a living/dining room, one (T1) or two (T2) bedrooms, a bathroom, and a kitchen with a laundry area. The average area is 47 m^2 for T1 and 62 m^2 for T2. The analyzed dwelling, marked in Figure 3, is a T2 located on the 2nd floor, and due to building geometry, presents 5 external walls: 2 north orientated, 2 east orientated, and 1 south orientated. It is currently managed by the local municipality, which conceded temporary access to perform the study considering that it was currently unoccupied. No indoor elements (like furniture) were noticed, and no electricity was available.

Figure 3. The CAR (Comissão para o Alojamento de Refugiados) studied project: photos and typical floor plan of the building located in Covilhã.

2.2. Methodology

Methods and techniques applied in the analysis and diagnosis of buildings can be classified as destructive, semi-destructive and non-destructive [30]. Non-destructive procedures are usually used to investigate building energy use, fuel poverty, and thermal comfort issues [31,32]. Among many possibilities available, these procedures can be categorized according to the time required to obtain relevant data: the ones by which data are immediately obtained (such as appropriate software [33], in-situ visits, thermography, or specific assessments), and the ones by which data are obtained requiring a specific period (such as monitoring or computational simulations that require calibration procedures).

Considering the scope of this study, only procedures regarding quick or immediate obtained data were considered. Therefore, the following stages were undertaken:

- Stage 1 was a preparation stage, consisting of assessments resorting to Municipality Archives, other entities, and in-situ visits to obtain quantitative and qualitative data that make it possible to perform the next stages;
- Stage 2 was a diagnosis stage, where quantitative and qualitative assessments were performed—verifying U-value requirements defined by SCE and an indoor thermography survey, respectively—to properly identify existing physical and thermal envelope characteristics;
- Stage 3 was a testing stage, resorting to the SCE framework to evaluate the impact of feasible constructive envelope retrofit measures regarding potential overall energy savings for this type of building in both coastal and inland Portuguese climates.

Two relevant issues regarding the proposed methodology must be mentioned:

- The first concern is related to performing the study in an unoccupied dwelling. For the specific case of social housing buildings, occupancy also plays a vital role in the building's overall thermal performance, mainly because of passive strategies used to control indoor environments. Studies such as that by Serrano-Jiménez et al. [34] resort to indoor measurements to investigate indoor environmental quality in social housing dwellings, and the used methodology includes high relevance on occupancy regarding issues such as ventilation patterns and window habits. Curado and Freitas [17] performed building energy simulations for a reference social housing dwelling, and an experimental campaign was performed alongside extensive interviews with the residents, to clearly define occupancy profiles to perform a successful calibration of the simulation model. Nevertheless, this was not the scope of the present paper. As the focus was to analyze the existing thermal envelope characteristics, common non-destructive procedures, such as indoor measurements and building energy/thermal modelling techniques were not applied as they are more suitable for studies on the thermal performance of a building where the influence of occupancy is also considered;
- The second refers to the study's comprehensiveness. Although this study aims to present the analysis of NK1 thermal characteristics focusing on the building envelope, restrictions in accessing dwellings and other parts of the building limited this intention, especially regarding in situ visits and the thermography survey. On the other hand, the scope of this study is centered on the thermal characteristics of specific envelope components, and this is the reason why other relevant fields related to indoor thermal performance, such as ventilation, indoor partitions, or internal gains were not studied. Therefore, the envelope analysis was made only of the vertical envelope's components, such as walls and glazed areas, and of the envelope's connections between vertical components, indoor floors/ceilings, and the building structure.

2.2.1. Stage 1

Assessments resorting to Covilhã and Fundão Municipalities Archives were undertaken to provide relevant quantitative and qualitative data about the building constructive components, as well as to detect if some relevant retrofit action had taken place before the present moment. The research was also performed in the Laboratório Nacional de

Engenharia Civil (LNEC) to obtain homologation documents related to the constructive system used.

Regarding quantitative data, thermal properties of materials of each component were investigated, especially those related to U-value and thickness, as well as expected air infiltration rates. Regarding the latter, this information was considered relevant due to the influence of glazed areas on indoor thermal conditions—Sadineli et al. [35] highlight the probable energy consumption increase in buildings where infiltration and exfiltration are frequent due to improper airtightness—and indoor air quality (IAQ)—the work of Fisk et al. [36], in which a review considering the association of residential energy efficiency retrofits with IAQ is performed, identifies the fact that in some situations envelope sealing measures may increase indoor concentrations of air pollutants emitted from indoor sources.

Regarding qualitative data, technical information about the NK1 used was investigated via architectural drawings and descriptive texts related to the project to obtain detailed specifications about each component layer, as well as the connection and/or joint solutions applied.

2.2.2. Stage 2

Assessment Resorting to SCE (Energy Performance Certification System)

The SCE defines maximum U-values that must be achieved by buildings to be constructed [37] or retrofitted [38]. Although practically, only U-values applied to retrofitted buildings would require assessment, the values for new construction were also mentioned in this study as they are defined as more demanding by SCE. Therefore, also a comparison between the original construction values and those required for new buildings was performed to understand if NK1 can still be considered a valid solution under contemporary requirements.

Thermography Survey

Among the possible thermal anomalies and defects that a building may present, the case study dwelling was analyzed to identify relevant conduction heat losses in reachable constructive components. According to [32], the following basic decisions were needed to define the thermography survey—the measurement method, the definition of the analysis scheme and the location where the survey must be performed:

- Regarding the measurement method, it was selected to be qualitative, so color patterns obtained in recorded thermal images were evaluated to detect relevant superficial temperature differences to identify where and how possible anomalies may occur;
- Regarding the definition of the analysis scheme, the limitation of an unoccupied dwelling without electricity made it impossible to provide heating recurring to electrical devices. Therefore, passive thermography—by which the target is observed with temperature gradients resulting from current temperature states [32]—was selected instead of active thermography, in which the target is observed exposed to an external stimulus to obtain relevant temperature gradients [32]. Thus, the following targets of qualitative analysis were used to detect the existence of individual or repeated anomalies [31]: target symmetry, when the thermography is performed on different areas of the same surface; and target comparison, when the thermography is performed on surfaces located in different elevations with common constructive properties;
- Regarding the location where the survey was to be performed, two main procedures needed to be selected. The first consisted of selecting the approach to perform the survey. The traditional method, walk-through thermography, the most popular passive method used, which consists of a technician scanning relevant building envelope components from both internal and external sides using a thermal camera to detect thermal anomalies, which are then recorded as thermal images for analysis and inclusion in a report [31], was selected instead of street pass-by thermography, a quicker and cheaper procedure which consists of driving past buildings to capture single thermal images of elevation external surfaces, obtaining a considerable amount of information [31].

Studies performed comparing both methodologies have shown that walk-through thermography is more suitable for qualitative analysis [31], besides other aspects like the study feasibility. The second procedure consisted of selecting the possibilities within the previously selected approach, considering that the walk-through methodology means that surveys can be performed from the inside, outside or both. Some authors [39] defend the position that internal inspections should only be performed to validate the findings of external surveys. Other authors state that anomalies are more clearly shown in internal thermography [31,40], and some internally identified anomalies are not always detected in external surveys [31]. For these reasons, internal thermography itself was selected as adequate to the study.

In what refers to the selected equipment, a recently calibrated "Testo 885" thermal imager was used to perform the survey, using both single-handed mode and attached to a tripod, according to the recommended procedures [41]. The technical specifications of the equipment are described in the instructions manual [41].

The walk-through thermography method is defined by entities such as the American Society for Testing and Materials (ASTM) and the Residential Energy Services Network (RESNET), as well as by proper regulation such as the British Standard BS EN 13,187:1999. Considering that several sources define processes for thermography surveys [31], alongside recommendations and requirements to avoid the influence of adverse effects on the recorded images obtained, the ones defined in BS EN 13,187:1999 [42] and the "Testo 885" instructions manual [41] were considered for conducting the thermographic surveys in this study. The camera emissivity value was set to 0.93, which matches with most existing construction materials [41]. Afterwards, all recorded thermal images were submitted for analysis using the post-processing software "Testo IRSoft" [43], which is available from Testo to evaluate and edit the images obtained.

Another relevant issue refers to existing climatic conditions and foreground obstructions. Considering that access to the analyzed dwelling was dependent on the temporary authorization from the municipality, granted only during the last days of September, thermography planning proved to be particularly challenging for obtaining the most favorable conditions that could match the mentioned recommendations, especially as weather conditions have an important influence in a successful survey. As ensuring a suitable thermal gradient between the inside and the outside can contribute to easily identifying potential anomalies, local weather forecasts were observed daily to identify days with ideal conditions regarding temperature and the absence of precipitation and wind. A specific day was selected with considerable daily thermal variability, a common occurrence during September months in this region [23], to make it possible to perform the survey during the daily warmer period, mid-afternoon, while indoor conditions were still with lower temperature values. This way, the required thermal gradient and further conditions were matched, even considering the existing limitations.

The last main consideration is related to exposure to solar radiation and the presence of indoor foreground obstructions. Considering the need to perform the survey during mid-afternoon, building geometry, neighboring buildings and other elements such as trees were considered regarding their impact on shading. Elevations exposed to solar radiation at the time the survey took place—the southern façade—were studied, and it was perceived that the shading produced by those obstacles was partial. Nevertheless, recommendations from BS EN 13,187:1999 could not be fully matched regarding this point. In what refers to foreground internal obstructions, as the dwelling was currently unoccupied, the survey could take place with no restrictions.

2.2.3. Stage 3

To perform the analysis of potential energy savings by constructive envelope retrofit measures, the SCE framework was applied. Nevertheless, the methodology quantifies the required nominal energy consumption to achieve predefined comfort conditions, assuming permanent heating/cooling habits. To avoid the influence of heating/cooling systems in complementing existing thermal envelope debilities, the present analysis only considers two specific items calculated by the framework: the nominal useful energy required for heating (*Nic*) and the nominal useful energy required for cooling (*Nvc*)—associated with specific heating or cooling season periods, respectively, depending on location and altitude—to define the required kWh/m^2·year values to accomplish the predefined 18 °C and 25 °C indoor comfort conditions for heating and cooling seasons, respectively. Therefore, energy values associated with conduction/ventilation heat transfer and solar/internal gains were calculated to identify and test the corrective measures related to the building envelope.

On the other hand, when applying the framework to existing buildings, it is defined that some predefined values are to be used in some specific parameters related to heat transfer and gains. For those related to envelope components, this requirement was not considered when real data was available. That being so, the obtained *Nic* and *Nvc* for this study will differ from those obtained in the case of hypothetical certification procedures.

Another relevant issue concerns dwelling orientation, which differs from each building according to its location. For this reason, a common orientation was considered for all calculations that could involve the impact of glazed elements with effectiveness. Therefore, the dwelling was considered south orientated, that is, with the bedrooms and kitchen windows exposed to the south and the living-room window exposed to the west.

Nic and *Nvc* were then calculated for the dwelling identified in Figure 2 for both Covilhã and Moita locations, those representing the most severe winter and summer climate scenarios for inland and coastal locations, respectively. To test the impact of individual representative constructive envelope retrofit measures, *Nic* and *Nvc* were also calculated for each location according to the following individual cases—selected among the number of available options [11,12] and regarding their feasibility to be applied in the analyzed building project—to provide an understanding of their suitability for each location and season:

- Case A: the application of external insulation, with repercussions in both heating/cooling seasons for opaque envelope elements;
- Case B: the substitution of existing windows by new ones, considering the effect in both heating/cooling seasons for glazed envelope elements.
- Thus, two more cases were analyzed considering their usefulness in cooling seasons as economical alternatives to window replacement in residential buildings [12]:
- Case C: the application of solar films in existing glazed elements;
- Case D: the application of rolling shades on the internal side of the existing windows.

3. Results

3.1. Stage 1

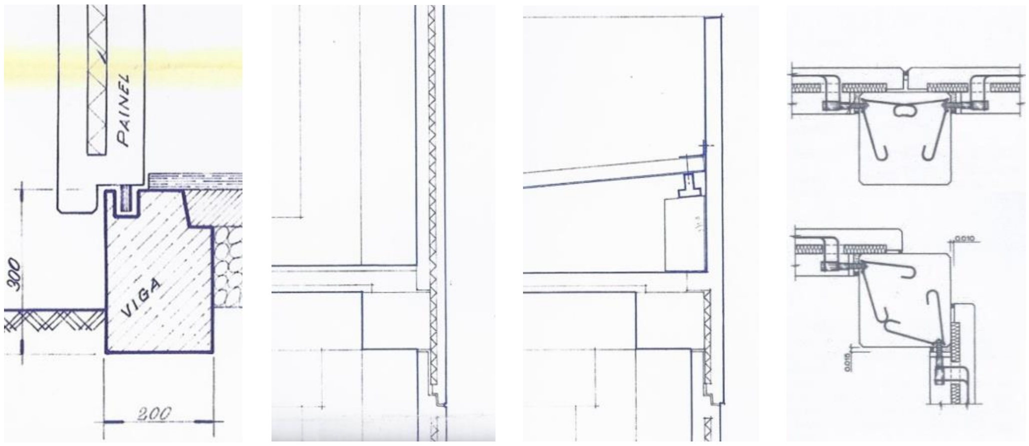
Quantitative data achieved regarding vertical envelope components' physical and thermal characteristics are summarized in Table 2.

Data related to opaque components' U-values was found in the LNEC homologation documents; however, they had already expired as the constructive system is no longer used. Nevertheless, those documents provided the global U-value, although information about windows could not be found. Therefore, in situ visits were carried out to confirm the physical and material characteristics of the frames, glass, and shutters, in order to perform a proper match with indicative literature of reference values [44]. Regarding presented U-value ranges, the lowest value refers to casement window type, while the higher value refers to sliding window type. No relevant modifications regarding the external envelope were identified.

Regarding qualitative data, Figure 4 shows drawings that, although at distinct scales, are representative of the aforementioned constructive composition of building components, as well as the connections and joints used between them.

Table 2. Envelope vertical components: physical and thermal characteristics.

Component	Description	Thickness (mm)	U-Value (W/m^2 °C)
External walls	Precast sandwich panel (outermost to innermost): 50 mm reinforced concrete 30 mm Expanded Polystyrene (EPS) 70 mm reinforced concrete	150	0.99
Glazed areas	Outside uninsulated PVC roller shutters Aluminum frame (no thermal break) Single clear 3 mm glazing	-	U_{wdn}: 3.90–4.10 U_w: 6.20–6.50



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

Figure 4. NK1 constructive details: (**a**) section representing the connection between external wall, structural beam, and ground floor; (**b**) section representing the connection between external walls, structural beam and internal floors; (**c**) section representing the connection between external wall, structural beam and roof; (**d**) plan representing the connections between columns and external walls (source: Covilhã and Fundão Municipalities Archives).

In summary, the NK1 applied consists of a concrete reticulated structure with beam-to-column connections, the thermally insulated concrete external wall panels and concrete beam and block slabs of which are connected to. Information found in architecture drawings and descriptive texts provides relevant details that are described below.

Regarding the vertical envelope component "external walls":

- The connections between both concrete layers are made during the industrial production process recurring to galvanized metallic clamps that go through the insulation layer;
- External walls accommodate both electric and domestic water supply infrastructures at specific points, and in some interventions where larger volume components must be installed, the insulation layer may be removed to accommodate them.

Regarding the vertical envelope component "glazed areas":

- Window U-value corresponds to the mentioned Uw value in Table 2. Nevertheless, considering that existing PVC roller shutters improve Uw value when activated, the Uwdn value is presented, which consists of a daily average value considering the activation of shutters during night periods;
- The glazed area corresponds to almost 13% of the dwelling exposed area;
- Among others (such as building exposure to wind or the existence of kitchen ducts), the type of window installed highly affects the expected air infiltration rates in buildings. As no information was found about this value in related documents, an SCE recommended LNEC tool [45] was used to calculate it as predicted. The value obtained was 0.98 ac/h for Covilhã, which is considerably high according to its potential impact on dwelling indoor thermal behavior;

- No information about the connections between glazed areas and external walls was found.

Regarding connections between vertical components and indoor floors/ceilings and/or the building structure:

- In the points of the building envelope where the connections between external wall panels are located, the correspondent thermal insulation is not continuous, although it is partially or totally achieved in the connections with structural elements such as beams and columns;
- Vertical and horizontal joints between the panels and/or structural elements were made using a sealed insulation strip, normally mastic-based.

Regarding other existing construction elements:

- Internal partitions were found to be constructed using precast concrete panels, while internal wall and ceiling surfaces were found to be finished with thick paint. Alongside the external wall panel solution, the dwellings may benefit from the effect of the high thermal mass;
- The ground floor is constructed with a concrete slab on a gravel base, with textile flooring or ceramic tiles as floor finishing;
- Internal floors are constructed with beam and block slabs, with textile flooring or ceramic tiles as floor finishing;
- The roof is constructed with beam and block slabs with fiber cement roofing. Thermal insulation is sometimes applied depending on the location of each project, although no information was found regarding its application in this specific building.

3.2. Stage 2

3.2.1. Assessment Resorting to SCE

Table 3 allows the comparison between SCE required maximum U-values for both new construction and retrofit and U-values for each of the analyzed envelope components. It is important to remember that SCE establishes a maximum U-value for each building component according to the winter location severity level. Regarding maximum U-values for glazed areas, SCE requires the accomplishment of maximum Uw value and Uwdn value for new construction and retrofit, respectively.

Table 3. Assessment resorting to SCE (Energy Performance Certification System) regarding building envelope U-values.

Component	New Buildings [35]			Retrofit [38]			Analyzed Building
	I1	I2	I3	I1	I2	I3	
External walls	0.50	0.40	0.35	1.70	1.50	1.40	0.99
Glazed areas	2.80 (U_w)	2.40 (U_w)	2.20 (U_w)	4.50 (U_{wdn})	4.00 (U_{wdn})	4.00 (U_{wdn})	6.20–6.50 (U_w) 3.90–4.10 (U_{wdn})

3.2.2. Thermography Survey

The survey was performed on 30 September 2020, between 3.30 pm and 4.30 pm. On that day, data on internal/external air temperatures and further weather conditions was collected to confirm the existence of ideal conditions. Figure 5 presents some representative thermal images resultant from the survey, according to the applied target symmetry and target comparison approaches. For the presented images, the thermal camera was positioned according to Figure 3 (ground floor plan). Thermal scales were adjusted according to the wall orientation to allow a better understanding of identified anomalies.

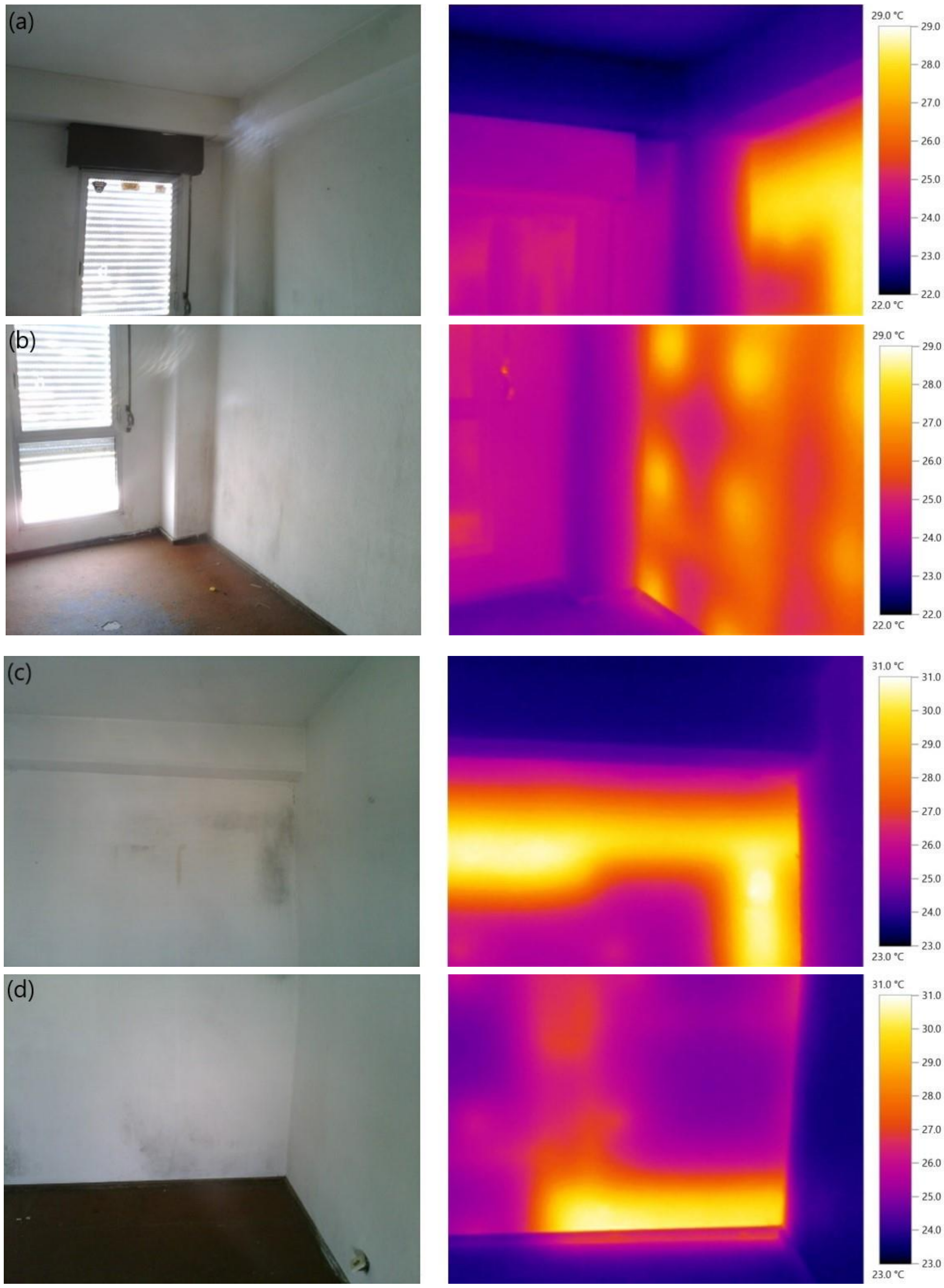


Figure 5. Representative surveyed photo (left) and thermal image (right): (**a**) 1—Northern and eastern façades: connection ceiling/external wall; (**b**) 1—Northern and eastern façades: connection external wall/internal floor; (**c**) 2—Southern façade and internal partition: connection ceiling/external wall; (**d**) 2—Southern façade and internal partition: connection external wall/internal floor.

The main results obtained from the survey are as follows:

- In northern orientated façades, no relevant anomalies were identified;
- In eastern orientated façades, two commonly anomalies related to high superficial temperatures were detected: (1) a considerable and continuous thermal bridge area below the beam, which matches the zone where the connection between external wall panels is made; (2) regular disposition of high-temperature points that were detected only in some of the surveyed façades, which may correspond to the points where the metallic clamps were applied to connect both panel's concrete layers;

- In the southern orientated façade, two main anomalies related to high superficial temperatures were identified: (1) a considerable and continuous thermal bridge area below the beam, with the same characteristics of observed anomalies in eastern façades; (2) an isolated area detected above the floor, and that was not identified in any other surveyed envelope component, and that might be related to damage or no insulation due to the accommodation of specific infrastructure, according to the available data.

3.3. Stage 3

The following criteria and characteristics were applied to define each of the studied constructive envelope retrofit measures:

- Case A: the ETICS (External Thermal Insulation Composite System) system was tested as external insulation, using EPS 100 (20 kg/m^3) with a 0.036 W/m °C thermal conductivity and 60 mm thickness. This system is a common wall insulation type in Portugal; the mentioned characteristics are the same as used in the example of Figure 1;
- Case B: the new windows tested consist of a PVC frame with clear double glazing of 6mm (outside) and 5mm (inside) and a 6 mm space between the panes. This solution was selected as its current market cost is moderate, compared to other available solutions. The possibility of highly efficient solar films was not applied to evaluate it separately from frame and double-glazing performances, as made in Case C. Therefore, the solar factor used was 0.75. Further related values were taken from the SCE database and indicative literature [44] once both already considered proper market information;
- Case C: the tested solution of solar films applied to existing glazing aimed to decrease the existing solar factor from 0.10 to a final 0.78 value as the building´s existing windows still use clear and uncoated glass. This value was taken from pertinent market information;
- Case D: the tested solution for internal rolling shades considered the possibility of considerable solar radiation restriction while allowing proper daylighting. Therefore, a solution was retrieved from the SCE database presenting solar transmittance between 0.15 and 0.25 and an absorbing factor of 0.50.

The results for *Nic* and *Nvc* calculations are presented in Table 4, as well as the respective energy demand difference (D) of each constructive envelope retrofit measure impact when compared with the existing dwelling.

Table 4. *Nic* and *Nvc* results for the existing dwelling and considering each envelope constructive retrofit measure.

City	Moita (Coastal)				Covilhã (Inland)			
kWh/m^2·Year	*Nic*	D	*Nvc*	D	*Nic*	D	*Nvc*	D
Existing dwelling	43.2	–	16.4	–	92.6	–	10.6	–
Case A	31.7	−11.5	15.2	−1.2	70.0	−22.6	10.1	−0.5
Case B	40.9	−2.3	13.3	−3.1	86.5	−6.1	8.4	−2.2
Case C	46.9	+3.7	14.1	−2.3	98.8	+6.2	8.8	−1.8
Case D	43.2	0.0	15.9	−0.5	92.6	0.0	10.2	−0.4

The influence of each climate severity is noticeable in the resultant *Nic* and *Nvc* values for the existing dwelling. In the heating season, Covilhã's dwelling *Nic* more than doubles Moita's. In that cooling season, Moita's dwelling *Nvc* is 35% higher than Covilhã's.

For both locations, Case A presents considerably higher heating season savings than those from the remaining studied cases. In fact, its impact in decreasing energy demand is significantly relevant (particularly in inland climate scenarios), with a *Nic* reduction of 11.5 kWh/m^2·year and 22.6 kWh/m^2·year for Moita and Covilhã, respectively. In the cooling season, the *Nvc* decrease is much more moderate, resulting in a reduction of 1.2 kWh/m^2·year and 0.5 kWh/m^2·year for Moita and Covilhã, respectively.

Case B present satisfactory results in the cooling season, with *Nvc* reductions of 3.1 kWh/m^2·year and 2.2 kWh/m^2·year for Moita and Covilhã, respectively. Nevertheless, the highest value of energy saving is achieved in Covilhã's heating season, with a *Nic* reduction of 6.1 kWh/m^2·year.

For Case C, although satisfactory results were obtained in cooling seasons, with registered *Nvc* reductions of 2.3 kWh/m^2·year and 1.8 kWh/m^2·year for Moita and Covilhã, respectively, solar gain restriction in heating seasons increases considerably with the *Nic* at 3.7 kWh/m^2·year and 6.2 kWh/m^2·year for the same locations.

Case D presents slight improvements in cooling seasons, with registered *Nvc* reductions of 0.5 kWh/m^2·year and 0.4 kWh/m^2·year for Moita and Covilhã, respectively. In heating seasons, as the SCE methodology considers that existing solar protections are not activated for these periods, no improvements are registered for both locations.

4. Discussion

The results obtained from the diagnosis stage (Stage 2) made it possible to identify several main features for the analyzed envelope components:

- Regarding external walls, the sandwich solution clearly benefits NK1 compared to other constructive solutions applied until then [27], as it contributes to achieving U-values compatible with SCE requirements for retrofitting in any of the aforementioned locations. Nevertheless, the achieved values are considerably far from SCE required maximum U-values for new buildings, and this is the reason why it is advised that improvements are made. On the other hand, the use of metallic clamps to connect concrete layers may pose a weakness if the observed anomalies detected in some external wall panels during thermography surveys are considered. Improvements to solve this issue are strongly advised, considering the potential heat gain/loss through these components;
- In what concerns glazed areas, it is noticeable that existing U-values are problematic when compared to SCE required maximum U-values for both new buildings (Uw) and retrofit (Uwdn). For new buildings, the existing values are considerably far from SCE requirements applied to all winter scenarios. For retrofit, SCE requirements are achieved only in coastal locations (I1 climate zone) for both sliding and casement window types, while for regions with harsher winters, only casement window types achieve the required values. Thus, reducing high air infiltration is the most likely window solution, considering few other existing possibilities of air infiltration;
- Regarding connections between vertical components, indoor floors/ceilings and/or building structure, the solution applied in connections between external wall panels presents a considerable weakness regarding discontinuous thermal insulation, resulting in pronounced anomalies related to high conductivity gains due to thermal bridges. Nevertheless, the solutions applied in connections and/or joints between external wall panels, internal ceilings/floors, and the building structure (columns and beams) seem to obtain positive results, although a more complete thermography survey of the entire building envelope would be essential to confirm this assumption.

The results obtained in Stage 3 identified appropriate measures to correct weaknesses detected in NK1 envelope components. Considering potentialities related to the high thermal mass of both external wall panels and indoor partitions, the introduction of external thermal insulation may contribute to simultaneously resolving the identified anomalies and obtaining satisfactory indoor environments with low daily thermal variability. Regarding possible effects on energy savings, Case A results show the high potential of insulation use, something also confirmed by studies that achieved a considerable reduction of heat transmittance across the façades, as well as heating and cooling demands decrease [11], particularly in locations with severe winter and summer seasons [46]. Thus, high effectiveness in locations with high heating degree days—such as inland locations—was obtained, matching the results mentioned in the article [11]. Nevertheless, the following issues must also be considered when using external insulation:

- Regarding the influence of façade orientation, Alonso et al. [46] studied the specific effect of external insulation in buildings located in Madrid, a city with severe winter and summer seasons, concluding that 15.4% energy demand reduction is achievable by adding external insulation to south-facing facades; nevertheless, this solution is not as effective when applied in facades exposed to solar radiation in warm climate conditions. For this reason, this is an issue that must be regarded for both coastal and inland locations;
- In terms of possible effects on thermal comfort, the work of Curado and Freitas [17] highlights the effect of this measure in several Iberian climate contexts. Results show that additional external insulation alone may be unnecessary for winter/summer milder scenarios to achieve thermal comfort. For severe winter/summer scenarios, this measure only constitutes an improvement, being that heating/cooling is required. Thus, the effect of occupancy should be considered when sizing this measure for both coastal and inland locations climates;
- Concerning possible effects when combined with the existent thermal mass, the work of Gonçalves and Graça [47] strongly advises the combination of these measures for locations with high annual and daily temperature variability. Nevertheless, some issues must be regarded. As stated by Stazi et al. [48], recommending adaptable constructive measures to find a proper solution for both winter and summer seasons can constitute a major challenge in Mediterranean climates. The study of Tribuiani et al. [49] highlights the importance of the type of insulation material used to achieve optimal construction solutions on high thermal mass walls in Mediterranean climates with warm summers. Therefore, different external insulation solutions may need to be studied for each one of the mentioned locations.

Regarding window interventions, the existence of architectural drawings and other technical information about applied window systems could provide more details regarding proper solutions, and this is the reason why future work related to research in all the municipality archives where the analyzed project was constructed is advised. Nevertheless, considering results obtained from Stages 2 and 3, the advised solution is the substitution of the existing windows. Besides other relevant variables such as air leakage or condensation resistance, Case B suggests a simple improvement solution regarding frames, double-glazed windows, and an appropriate air gap. Satisfactory results can be achieved particularly for heating seasons, matching the results obtained in other studies. Suárez and Férnandez-Agüera [50] highlight the improvement of thermal properties and energy consumption decrease relating to systems with improved frames or space between the panes of glass. Blecich et al. [51] refer to the effectiveness of multi-glazed windows, which means all these possibilities are very suitable for buildings constructed in inland locations.

Regarding alternatives to window substitution, glazing improvements studied in Case C provide satisfactory results for cooling seasons, matching results mentioned by Ascione et al. [52] and Ariosto et al. [12] with the focus on solar control properties using coated glass or solar films, and applying low-emissivity films as a valid solution to control solar energy and infrared heat, respectively. Nevertheless, due to solar gain restriction during heating seasons, this measure is not recommended for any of the aforementioned locations without detailed studies such as dynamic thermal simulation to confirm if sufficient heat gains are available during these periods.

Regarding improvements from the internal side of the windows, the use of internal rolling shades studied in Case D can be applied for each of the mentioned locations. Although the results of its benefits are slight considering that the SCE methodology defines relevant usage time for external roller shutters, a higher impact is expected in cases where they are not activated or do not exist. Other significant results can be obtained using similar systems for coastal locations with milder winter seasons, avoiding condensation issues [12]. Interior curtains are effective examples to provide insulation besides solar shading. Studies have concluded that the use of particular fleece curtains using THERM can achieve 38% and 17% improvements over double-pane and triple-pane windows, respectively [12].

Cellular shades are also a valid option as regards to thermal comfort improvement, mainly those that are conceived to create a sealed air gap or integrated reflective polyester layer on the side of the blind facing the window to serve as radiant barriers [12].

Additional comments must be made on the following issues:

- The first regards the influence of existing rolling shutters. Being part of the existing dwelling envelope, their inclusion in the study somehow conditioned the impact that glazing improvements and internal roller shades might have. On the other hand, improved results might be obtained using other similar solutions, such as exterior insulated rolling shutters, a very suitable option considering that the existing wall system already presents the space needed for its application. The benefits of this system are described in the work of Ariosto et al. [12], being identified as a remarkably effective solution for thermal efficiency and low risk of condensation when the system features an insulating foam core and is placed on the outside face of the window. The use of sealed tracks can also improve air leakage issues. Among other positive effects, such as simultaneously controlling daylight and allowing ventilation, all these features make this measure very suitable to be applied in any of the mentioned locations;
- The second regards the influence of insulation and window substitution in IAQ. This issue is particularly relevant in Mediterranean contexts for residents who usually reside in reduced spaces for long periods, such as the elderly. Therefore, further studies are advised to be carried out, such as those from Canha et al. [53] and Serrano-Jiménez et al. [34], the latter related to Spanish social housing, which identified excessive CO_2 levels in indoor measurements with elderly occupants, especially in winter seasons. Therefore, studies regarding building airtightness before and after window retrofit also gained importance within Mediterranean climates to prevent such problems. Alfano et al. [54] recommend that proper window sealing must be selected considering possible IAQ and/or condensation issues, while Ghoreishi et al. [55] suggested that proper air renewal may be achieved using non-related window solutions, such as solar air collectors;
- The third regards the NK1 roof solution. If not already applied, a constructive intervention related to thermal insulation increase is strongly advised to improve this solution, especially to resolve probable summer overheating of dwellings located on the last floors.

5. Conclusions

This article aims to provide an understanding of the behavior of the NK1 thermal envelope and the impact of constructive envelope retrofit measures applied to a social housing dwelling located in Covilhã, Portugal, using quick, non-destructive procedures.

Although offering some potential, external walls present general and some specific characteristics that are no longer able to provide proper responses to contemporary building constructive requirements, considering their detachment from key SCE requirements for new buildings. Glazed areas were also identified as a weakness.

Therefore, four individual retrofit interventions were tested for two coastal (Moita) and inland (Covilhã) locations: (1) external insulation—as a retrofit measure to resolve identified anomalies in opaque envelope components; (2) window substitution—as an advised measure considering benefits that commonly commercialized fenestration systems present regarding their frame, glazing and space between pane characteristics; (3) glazed area improvements with solar films; and (4) internal roller shades—considering their economic suitability for some social housing contexts. The following results were obtained:

- For coastal locations, external insulation is a strongly advised retrofit solution, considering its potential in decreasing energy demand, especially during heating seasons. Window replacement may present satisfactory results for both heating and cooling seasons, the latter being internal roller shades and other solutions which might be applied to glazed areas from the inside. These achieve interesting results considering their economic feasibility;

- For inland locations, external insulation is also a key retrofit solution to decrease energy demand for both heating and cooling seasons, window replacement being also advised as a strong retrofit solution for its performance during heating seasons. Nevertheless, although some caution must be considered with these two measures regarding their repercussion in IAQ during colder periods. Internal roller shades can provide little improvement during cooling seasons, although they do not present relevant condensation issues, as in alternative solutions;
- For both locations, glazing improvement through solar films presents some benefits for both coastal and inland cooling seasons, although its use must be carried out with some caution, considering heat gains conditioning during heating seasons.

Based on these results and proposals, an experimental campaign in occupied dwellings is proposed as future work, alongside questionnaires to occupants about their heating/cooling habits, to provide more precise data that will increase the understanding of occupancy influence in the thermal dwelling behavior and IAQ, mainly as regards the use of specific components that require opening and closure procedures. Thus, the data obtained may also be used for building thermal simulations, allowing proper model construction and calibrations. For this reason, the retrofit proposals studied could be analyzed, individually or combined, considering their impact on indoor conditions, alongside key information such as climate and social housing occupancy. It is advised that this type of analysis is carried out for both actual and future climate scenarios, as studied by Barbosa et al. [2], to evaluate summer overheating potential using actual and future weather data, as well as studying this measure in its relation to ventilation possibilities.

A thermography survey of the entire building envelope is also proposed as future work to confirm the repetition of the identified anomalies. The fact that the dwelling was not occupied, and no electricity was available limited the analysis performed, especially in northern elevations where potential problems are yet to be confirmed. Therefore, combining internal and external surveys recurring to active thermography where dwellings could be heated can contribute to verifying both identified and new anomalies in the building façades. Moreover, combining walk-through thermography with other analysis procedures such as air-tightness testing and computer simulation [31] can provide data with the potential to be subject to specific statistical analysis.

Author Contributions: Writing—original draft preparation and review, P.I.B.; supervision and writing review, J.C.G.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Acknowledgments: Covilhã and Fundão Municipalities, LABSED—Housing Health Lab—UBIMedical.

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

References

1. Santamouris, M. Innovating to zero the building sector in Europe: Minimising the energy consumption, eradication of the energy poverty and mitigating the local climate change. *Solar Energy* **2016**, *128*, 61–94. [CrossRef]
2. Barbosa, R.; Vicente, R.; Santos, R. Climate change and thermal comfort in Southern Europe housing: A case study from Lisbon. *Build. Environ.* **2015**, *92*, 440–451. [CrossRef]
3. Magalhães, S.; Freitas, V. A complementary approach for energy efficiency and comfort evaluation of renovated dwellings in Southern Europe. *Energy Procedia* **2017**, *132*, 909–914. [CrossRef]
4. European Environment Agency. *Climate Change, Impacts and Vulnerability in Europe 2016 (Report No. 1/2017)*; Publications Office of the European Union: Luxembourg, 2017.
5. IPCC. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Core Writing Team, Pachauri, R.K., Meyer, L.A., Eds.; IPCC: Geneva, Switzerland, 2014.
6. EUR-LEX—Directive (EU) 2018/844. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2018.156.01.0075.01.ENG (accessed on 19 February 2021).
7. EUR-LEX—COM (2020) 662. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1603122220757&uri=CELEX:52020DC0662 (accessed on 19 February 2021).

8. Ortiz, J.; Fonseca, A.; Salom, J.; Garrido, N.; Fonseca, P.; Russo, V. Comfort and economic criteria for selecting passive measures for the energy refurbishment of residential buildings in Catalonia. *Energy Build.* **2016**, *110*, 195–210. [CrossRef]
9. Flores, J. The Investigation of Energy Efficiency Measures in the Traditional Buildings in Oporto World Heritage Site. Ph.D. Thesis, Oxford Brookes University, Oxford, UK, 2013.
10. Dall'Ó, G.; Galante, A.; Pasetti, G. A methodology for evaluating the potential energy savings of retrofitting residential building stocks. *Sustain. Cities Soc.* **2012**, *4*, 12–21. [CrossRef]
11. Sarihi, S.; Saradj, F.M.; Faizi, M. A Critical Review of Façade Retrofit Measures for Minimizing Heating and Cooling Demand in Existing Buildings. *Sustain. Cities Soc.* **2021**, *64*, 102525. [CrossRef]
12. Ariosto, T.; Memari, A.; Solnosky, R. Development of designer aids for energy efficient residential window retrofit solutions. *Sustain. Energy Technol.* **2019**, *33*, 1–13. [CrossRef]
13. EU Mies Award 2019. Available online: https://miesarch.com/work/3889 (accessed on 19 February 2021).
14. Oteiza, I.; Alonso, C.; Martín-Consuegra, F.; Monjo, J.; González-Moya, M. Energy Retrofitting for Social Housing by Improving the Building Envelope: Madrid, 1939–1979. In *The Sustainable Renovation of Buildings and Neighbourhoods*; Mercader-Moyano, P., Ed.; Bentham Science Publishers: Sharjah, United Arab Emirates, 2018; pp. 3–32.
15. Suárez, R.; Fragoso, J. Estrategias pasivas de optimización energética de la vivienda social en clima mediterráneo. *Informes de la Construcción* **2016**, *68*, e136.
16. Alonso, C.; Oteiza, I.; Martín-Consuegra, F.; Frutos, B. Methodological proposal for monitoring energy refurbishment. Indoor environmental quality in two case studies of social housing in Madrid, Spain. *Energy Build.* **2017**, *155*, 492–502. [CrossRef]
17. Curado, A.; Freitas, V.P. Influence of thermal insulation of facades on the performance of retrofitted social housing buildings in Southern European countries. *Sustain. Cities Soc.* **2019**, *48*, 101534. [CrossRef]
18. Boeri, A.; Gabrielli, L.; Longo, D. Evaluation and feasibility study of retrofitting interventions on social housing in Italy. *Procedia Eng.* **2011**, *21*, 1161–1168. [CrossRef]
19. Instituto da Habitação e da Reabilitação Urbana. *Cem Anos de Políticas Públicas em Portugal: 1918–2018*; IHRU: Lisbon, Portugal, 2018.
20. Instituto Nacional de Estatística—Base de Dados. Available online: https://www.ine.pt/xportal/xmain?xpid=INE&xpgid=ine_main (accessed on 15 January 2021).
21. Matic, D.; Calzada, J.R.; Eric, M.; Babin, M. Economically feasible energy refurbishment of prefabricated building in Belgrade, Serbia. *Energy Build.* **2015**, *98*, 74–81. [CrossRef]
22. Nikolic, J. Building "with the Systems" vs. Building "in the System" of IMS Open Technology of Prefabricated Construction: Challenges for New "Infill" Industry for Massive Housing Retrofitting. *Energies* **2018**, *11*, 1128. [CrossRef]
23. Portal do Clima. Available online: http://portaldoclima.pt/pt/ (accessed on 15 January 2021).
24. Gouveia, J.; Seixas, J.; Palma, P.; Simões, S. *LIGAR—Eficiência Energética para Todos!—Mapeamento da Pobreza Energética em Portugal*; Universidade Nova de Lisboa: Lisbon, Portugal, 2018.
25. Presidência do Conselho de Ministros. *Resolução do Conselho de Ministros n.° 48/2015*; n.° 136/2015, Série I de 2015-07-15; Diário da República: Lisbon, Portugal, 2015.
26. Douglas, J. *Building Adaptation*; Butterworth-Heinemann: Edinburgh, Scotland, 2002.
27. ADENE—Agência para a Energia. *Isolamento de Paredes*; ADENE—Agência para a Energia: Lisbon, Portugal, 2016.
28. Ministério do Ambiente, Ordenamento do Território e Energia—Direção-Geral de Energia e Geologia. *Despacho (Extrato) n.º 15793-F/2013*; Diário da República n.° 234/2013, 3 ° Suplemento, Série II de 2013-12-03; Diário da República: Lisbon, Portugal, 2013.
29. SCE.CLIMA. Available online: https://www.dgeg.gov.pt/pt/areas-setoriais/energia/energias-renovaveis-e-sustentabilidade/sce-er/ (accessed on 15 January 2021).
30. Diz-Mellado, E.; Mascort-Albea, E.J.; Romero-Hernández, R.; Galán-Marín, C.; Rivera-Gómez, C.; Ruiz-Jaramillo, J.; Jaramillo-Morilla, A. Non-destructive testing and Finite Element Method integrated procedure for heritage diagnosis: The Seville Cathedral case study. *J. Build. Eng.* **2021**, *37*, 102134. [CrossRef]
31. Fox, M.; Goodhew, S.; De Wilde, P. Building defect detection: External versus internal thermography. *Build. Environ.* **2016**, *105*, 317–331. [CrossRef]
32. Fox, M.; Coley, D.; Goodhew, S.; De Wilde, P. Thermography methodologies for detecting energy related building defects. *Renew. Sustain. Energy Rev.* **2014**, *40*, 296–310. [CrossRef]
33. Google Earth. Available online: https://www.google.com/earth/ (accessed on 15 January 2021).
34. Serrano-Jiménez, A.; Lizana, J.; Molina-Huelva, M.; Barrios-Padura, Á. Indoor environmental quality in social housing with elderly occupants in Spain: Measurement results and retrofit opportunities. *J. Build. Eng.* **2020**, *30*, 101–264. [CrossRef]
35. Sadineni, S.; Madala, S.; Boehm, R. Passive building energy savings: A review of building envelope components. *Renew. Sustain. Energy Rev.* **2011**, *15*, 3617–3631. [CrossRef]
36. Fisk, W.; Singer, B.; Chan, W. Association of residential energy efficiency retrofits with indoor environmental quality, comfort, and health: A review of empirical data. *Build. Environ.* **2020**, *180*, 107067. [CrossRef]
37. Ministério do Ambiente, Ordenamento do Território e Energia. *Portaria n.° 379-A/2015*; n.° 207/2015, 2° Suplemento, Série I de 2015-10-22; Diário da República: Lisbon, Portugal, 2015.
38. Ambiente e Transição Energética. *Portaria n.° 297/2019*; n.° 172/2019, Série I de 2019-09-09; Diário da República: Lisbon, Portugal, 2019.

39. Holt, G. *Common Sense Approach to Thermal Imaging*; SPIE—The International Society for Optical Engineering: Washington, DC, USA, 2000.
40. Pearson, C. *Thermal Imaging of Building Fabric*; BSRIA—Building Services Research and Information Association: Bracknell, UK, 2011.
41. Testo 885 Thermal Imager—Instructions Manual. Available online: https://www.testo.com/en-ID/testo-885-kit/p/0563-0885-X2 (accessed on 15 January 2021).
42. BSi. *BS EN 13,187:1999—Thermal Performance of Buildings: Qualitative Detection of Thermal Irregularities in Building Envelopes: Infrared Method*; Bsi: London, UK, 1999.
43. Testo IRSoft. Available online: https://www.testo.com/en/software-testo-irsoft/p/0501-8809 (accessed on 15 January 2021).
44. Matias, L.; Pina dos Santos, C. *ITE50—Coeficientes de Transmissão Térmica de Elementos da Envolvente Dos Edifícios*, 1st ed.; Laboratório Nacional de Engenharia Civil: Lisbon, Portugal, 2006.
45. Ministério do Ambiente, Ordenamento do Território e Energia—Direção-Geral de Energia e Geologia. *Despacho (Extrato) n.º 15793-K/2013*; Diário da República n.° 234/2013, 3° Suplemento, Série II de 2013-12-03; Diário da República: Lisbon, Portugal, 2013.
46. Alonso, C.; Oteiza, I.; García-Navarro, J.; Martín-Consuegra, F. Energy consumption to cool and heat experimental modules for the energy refurbishment of facades. Three case studies in Madrid. *Energy Build.* **2016**, *126*, 252–262. [CrossRef]
47. Gonçalves, H.; Graça, J.M. *Conceitos Bioclimáticos Para Os Edifícios em Portugal*; INETI: Lisbon, Portugal, 2004.
48. Stazi, F.; Bonfigli, C.; Tomassoni, E.; DiPerna, C.; Munafò, P. The effect of high thermal insulation on high thermal mass: Is the dynamic behaviour of traditional envelopes in Mediterranean climates still possible? *Energy Build.* **2015**, *88*, 367–383. [CrossRef]
49. Tribuiani, C.; Tarabelli, L.; Summa, S.; Di Perna, C. Thermal Performance of a Massive Wall in the Mediterranean Climate: Experimental and Analytical Research. *Appl. Sci.* **2020**, *10*, 4611. [CrossRef]
50. Suárez, R.; Fernández-Agüera, J. Passive energy strategies in the retrofitting of the residential sector: A practical case study in dry hot climate. *Build. Simul.* **2015**, *8*, 593–602. [CrossRef]
51. Blecich, P.; Frankovic, M.; Kristl, Z. Energy retrofit of the Krsan Castle: From sustainable to responsible design—A case study. *Energy Build.* **2016**, *122*, 23–33. [CrossRef]
52. Ascione, F.; Bianco, N.; DeMasi, R.F.; Perone, T.; Ruggiero, S.; Strangio, P.; Vanoli, G.P. Light and Heavy Energy Refurbishments of Mediterranean Offices. Part II: Cost-optimal Energy Renovation of an Institutional Building. *Procedia Eng.* **2017**, *180*, 1518–1530. [CrossRef]
53. Canha, N.; Lage, J.; Candeias, S.; Alves, C.; Almeida, S. Indoor air quality during sleep under different ventilation patterns. *Atmos. Pollut. Res.* **2017**, *8*, 1132–1142. [CrossRef]
54. Alfano, F.; Dell'Isola, M.; Ficco, G.; Pallela, B.; Riccio, G. Experimental Air-Tightness Analysis in Mediterranean Buildings after Windows Retrofit. *Sustainability* **2016**, *8*, 991. [CrossRef]
55. Ghoreishi, K.; Fernández-Gutiérrez, A.; Fernández-Hernández, F.; Parras, L. Retrofit planning and execution of a mediterranean villa using on-site measurements and simulations. *J. Build. Eng.* **2021**, *35*, 102083. [CrossRef]