Paving the Way to NZEB on two Historical Blocks in Lisbon Pombaline Quarter

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Abstract. The 1758 Lisbon Pombaline Quarter reconstruction plan is made of compact rectangular shaped residential blocks, built with a system that complies solid mass construction elements with a light wooden structure. If we take into consideration both constructive and architectural inherent features of the original Pombaline block, it shows the potential to achieve NZEB level if an energy retrofit strategy at a block scale is implemented, instead of the usual single building or fraction approach. The retrofit of historic buildings has raised questions regarding interventions depth and efficiency, as the impact on the built heritage value has to be residual or null while energy-related improvements must be noticeable. With this in mind, this paper intends to analyse and compare the result on energy demand and primary energy consumption of passive, active and BIST/PV systems packages implementation on two original blocks, with the challenge of minimizing the impact on case studies appearance. A Building Energy Simulation methodology is applied using the whole-of-building dynamic simulation software EnergyPlus. The results show that exterior envelope improvements can reduce up to 50% heating and cooling energy demands increasing thermal comfort at the same time. Finally, a combined VRF/Biomass heating solution display the best results on primary energy consumption while photovoltaic and solar thermal systems proved to have an essential role to achieve NZEB performance.

1. Introduction

Historic and traditional buildings account for about 14% of the building stock in Portugal (Censos2011) [1] and 10% to 40% in developed countries, representing these, around 20% to 40% of total energy consumption. For this reason, any steps taken to increase buildings performance has certainly impact on energy consumption at national scale. However, an energy retrofit in a historic building need to comply with the built heritage conservation principles of reversibility, minimum intervention, authenticity, and compatibility stated on the international charters and conventions of ICOMOS and UNESCO [2]. In this way, any retrofit is bounded a priori due to the impossibility of changing significantly its architectural and constructive features, being unacceptable any kind of action that could threaten the building historic value, increasing the intervention difficulty level [3].

The 1758 Lisbon Reconstruction Plan is the response to the earthquake occurred in 1755 that destroyed Lisbon downtown area, that is known today as “Baixa Pombalina”. The Plan presents itself as an orthogonal matrix, organized and structured by a set of homogeneous rectangular blocks [4]. The
Pombaline Block, an example that illustrates a way of doing architecture and construction whose quality is recognized by several authors [4]–[7], is the fundamental element of an intervention with great historical and cultural relevance at a national and European level.

Figure 1. Original Pombaline block elevation drawing signed by Sebastião José de Carvalho e Melo and Eugénio dos Santos e Carvalho, 1756. [8, pp. 64, 65]

The Pombaline building concept was a mere abstraction, something built progressively to complete or close the block. Proof of this is the absence of author’s floor plans or single buildings designs [4]. Today’s known drawings are elevations intended to illustrate the architectural appearance idealized by plan authors for that area (Figure 1) [8].

In the scope of Portuguese law (REH) [9], mainly in existing residential buildings, any energy improvement must be done considering a single building or fraction scale. This approach limits and disregards the existing energy potential that could be achieved with an integrated block scale strategy.

Therefore, compliant with the plans author conceptual approach, this paper intends to explore the thermal and energy potential of the original Pombaline block to achieve NZEB performance, by designing a passive and active scope retrofit strategy that uses blocks architectural scale to decrease and compensate eventual energy-related weaknesses identified in single buildings.

2. Methodology

2.1. BES and dynamic simulation

A Building Energy Simulation (BES) methodology [2], using dynamic simulation software EnergyPlus [10], is applied on two case studies to test the impact induced by passive and active scope retrofit packages on energy demand and primary energy consumption (C_{ep}), in order to achieve NZEB performance. A similar methodology is described in [2] and applied by other authors [3], [11], [12], with the aim to ascertain and compare improvements caused by several measures in historical buildings in different contexts.

This method is split into several stages. From the work developed by two fundamental authors [5], [6], supported by other relevant sources [7], [8], [13], [14], we carried out an architectural and constructive survey regarding layers, materials, dimensions and compositive elements of Pombaline built features. After that, we built two parametric tridimensional models (BIM) of the original Pombaline blocks and their urban surroundings with IFC Builder 2018 [15], exporting them afterwards to Cypetherm Eplus 2018 [16] which runs the whole-of-building dynamic simulation engine EnergyPlus 8.8 [10]. The Table 1 shows the simulation environment applied to the case studies.
Table 1. Simulation parameters input.

| Simulation period | 1st of January to 31 of December |
|-------------------|----------------------------------|
| Climate data      | .epw file - PRT_Lisboa.085360_INETI, available at https://energyplus.net/weather |
| Temperatures      | Average: coldest month Jan: 10.8ºC / hottest month Aug: 24.2ºC / annual: 17.1ºC |

Zoning and Compartments Loads

| Loads                  | Residential | Commercial |
|------------------------|-------------|------------|
| Ventilation            | 0.8 ACH     | 0.8 ACH    |
| Occupation             | 21m²/person | 5m²/person |
| Activity level         | 100W/person | 130W/person|

Operating Conditions

| Temperature           | Heating and cooling profile: 18ºC – 1st Oct to 31 May / 25ºC – 1st Jun to 30 Sep (Residential 24h, Commercial 9h to 20h) |
| Window Shutters       | Only on upper floors: ON (1 Jun to 30 Sept) 12h to 20h / OFF (1 Oct - 31 May) |
| DHW                   | Only on upper floors: 40 liters/person at 45ºC temperature |

Linear Thermal Bridges

Calculated by Cypether Eplus according to ISO 14683 [17] and ISO 10211 [18]

Planar Thermal Bridges

Exterior envelope openings (header, sil, jams and window nook)

A year-round dynamic simulation is performed in each case study before any retrofit package (scenario_0), in order to determine heating and cooling energy demand and amount of time in thermal discomfort. The energy-related data, for both scenario_0 and retrofit packages, is stated on national and international technical documentation [19]–[23]. Finally, after the retrofit packages employment and simulations we process the results obtained. Parameters related to lighting and internal equipment were not considered.

2.2. Case studies description

The case studies are two rectangular shaped 18th century blocks (Block H and Block T), with five stories each (commercial ground floor and residential upper-levels) located in Lisbon Pombaline quarter. Each block (Figure 2) has facades orientated to every quadrant, a central inner courtyard, and buildings with one or two apartments per floor.

The opaque envelope is made of non-insulated solid stone masonry walls, 100cm to 76cm thick (29cm double hung windows nook), and a ventilated clay shingles sloped roof with dormer windows. The glazed envelope consists of solid wood frames and single transparent glass windows that could be fixed (ground floor), double casement (1st floor) or double hung opening (2nd, 3rd, and 4th floor).

Table 2. Case studies Block H and T features.

| Block H            | Block T            |
|--------------------|--------------------|
| Total net area     | 5570.74 m²         | 6279.13m²         |
| Ground-floor net area | 1165.62 m²      | 1048.43 m²        |
| Floor height       | 3.84m (ground, 1st, 2nd-floor) / 3.62m (3rd-floor) / 3.84m (4th-floor) |
| Block height       | 19m                | 19.38m            |
| Number of buildings| 10                 | 9                 |
| Envelope glazed surface | 964.84 m² (33.13%) | 877.8 m² (31.45%) |

Both blocks have identical architectural elements and construction features. The differences between them relate to proportion, depth, gross area, number of buildings, and longer side orientation - Block H longer side is facing east-west quadrant, while Block T is facing north-south quadrant (Figure 2).
3. Energy retrofit at a block scale concept
It consists of a combination of passive and active scope retrofit measures applied to a block instead of a single building or fraction, in order to exploit its architectural and constructive potential to decrease eventual energy-related weaknesses identified in each building. The energy demand/consumption for heating or DHW in a building with preexisting constraints (e.g. North-orientated, insufficient ventilation, unavailable space for BIST/PV systems) can be compensated by the block overall energy performance. Therefore, if the block achieve NZEB level, every constituent building must be considered NZEB as well.

4. Retrofit packages description
4.1. Scenario_0
The scenario_0 baseline represents an original Pombaline block without any retrofit measures. Regarding active systems was simulated a gas water heater (efficiency = 0.82) for DHW, an electric radiator (2000W) for heating and a portable AC unit (EER = 2.6) for cooling on the residential upper floors, and an air-to-air heat pump multi-split system (COP = 3.4 and EER = 3.0) for heating and cooling on the commercial ground floors. There is no mechanical ventilation.

4.2. Passive measures description
In the hot season, we adopted cooling strategies by increasing the nocturnal ventilation to 3 air changes per hour (ACH) (from 23h to 8h) and to 1 ACH during daytime (from 8h to 23h).

In the cold season, the ACH was set to 0.6 all day and the window shutters closed between 23h to 8h, in order to prevent additional heat losses (pkg_P1). The existing windows were replaced with a class 4, double-glazing (U-value = 2.9 W/m²K and G-value = 0.55), 70mm thickness wood frame (U-value = 2.0 W/m²K) matching the existing one's appearance and function (pkg_P2). On the roof was added insulation to the existing constructive solution by placing a 5cm rigid ICB board and a 10cm MW semi-rigid board, above and between rafters respectively (pkg_P3). At last, regarding the exterior wall insulation, the existing coating was replaced with a visually similar 5cm thermal insulation lime-based plaster (pkg_P4).

The blocks did not have any change on architectural related features. All the previously mentioned packages when combined are named pkg_C.
Table 3. Passive measures thermal features of pkg_C compared with scenario_0.

| Target                  | U-value (scenario_0) (W/m²K) | U-value (pkg_C) (W/m²K) |
|-------------------------|-----------------------------|------------------------|
| pkg_P1 heat and cool demand | n/a                         | n/a                    |
| pkg_P2 Windows          | glass 5.8 / frame 3.0       | glass 2.9 / frame 2.0  |
| pkg_P3 Roof             | 2.69                        | 0.23                   |
| pkg_P4 Exterior wall    | 1.21 to 1.49 a              | 0.51 to 0.56 a         |

* Wall thickness varies according with block height.

4.3. Active systems description

4.3.1. DHW systems

Concerning DHW systems, the proposed solution (pkg_DHW1) intends to respond to the challenge of reducing primary energy consumption with solar generated energy. The proposed package combines a solar thermal system (BIST) with a backup DHW Monobloc heat pump (COP = 2.3) located within each residential fraction. Gathering solar RES is mandatory in Portugal for all new buildings or big scale renovations if all the technical requirements on site are granted. The solar thermal collectors (ST) and the DHW heat pump are compliant with the minimum performance requirements laid down in the Portuguese legislation [24, pp. 6624-(28) to 6624-(29)].

4.3.2. Photovoltaic and Solar Thermal systems

In order to fulfill the NZEB requirement regarding energy produced on site [25] we propose a roof based solar thermal and photovoltaic system (BIST/PV). The ST collectors are grouped, placed on the top of the south and west orientated slopes, near the ridge, in a linear disposition, followed by the photovoltaic panels (PV) in order to maximize their efficiency, following the guidelines stated by [26] related to BIST/PV systems criteria in sensible built environment. The north and east-orientated roof slopes are not occupied (Figure 3).

The photovoltaic system (BIPV) (pkg_PV1) is grid connected, and consists of an assembly of Monocrystalline type PV panels, with a total power of 24.68 kWp and 32.38 kWp, on Block H and T respectively. The energy provided by both systems was calculated using Solterm 5.3 [27].

Table 4. BIST/PV system features and occupied roof area.

| ST collector     | PV panel                  | ST roof occupation (m²) | PV roof occupation (m²) |
|------------------|---------------------------|-------------------------|-------------------------|
| Block H          | REH requirements          | Monocrystalline (174.9W) | 141 (141 panels)         | 183.3 (141 panels) |
| Block T          | REH requirements          | Monocrystalline (174.9W) | 165 (165 panels)         | 240.5 (185 panels) |

Figure 3 – Block H (left) and T (right) PV panels (blue) and ST collectors (yellow) proposal.
4.3.3. HVAC systems
Regarding HVAC systems, we simulated three different solutions. Two of them (pkg_HC1 and HC3) consider the minimum performance requirements stated in Portuguese law [24, pp. 6624-(26) Table I.11, 6624-(29) Table I.19], and the other one is from a commercial manufacturer (pkg_HC2).

The pkg_HC1 and HC2 have an air to air heat pump multi-split system (pkg_HC1: COP = 3.4 / EER = 3.0 and pkg_HC2: variable COP = 4.09-4.71 / EER = 3.36-3.88) for heating and cooling. The pkg_HC3 is a VRF multi-split system (COP = 3.4 and EER = 3.0) for heating and cooling on ground floor levels and a biomass heating system (e.g. ducted air pellet stove) with an efficiency = 0.75 on the upper levels.

With the purpose of minimizing the impact on both blocks architectural appearance, the HVAC systems outdoor units are located on the inner patio, and therefore, not visible from the street level. The indoor units will be at least two per fraction with capacities calculated according to the required indoor spaces BTU’s for heating and cooling. Further, there is no mechanical ventilation system.

5. Results and discussion
The passive scoped retrofit measures (pkg_C), compared with scenario_0, caused a reduction in energy demand for heating (Dheat) of 51.84% and 52.05%, and cooling (Dcool) of 63.49% and 70.48%, in Block H and T respectively. The results show that Block T displays higher Dheat and Dcool reductions due to its existing architectural constraints, whose features, like its surface to volume ratio and longer side south orientation, are in general responsible for a better energy performance when compared with Block H (Figure 4).

![Figure 4. Energy demand monthly comparison after pkg_C implementation in both blocks.](image)

Also, the number of hours exhibiting indoor temperatures above 25°C (T>25°C) dropped 54.16% and 61.76%, and temperatures below 18°C (T<18°C) dropped 7.27% and 6.48%, on Block H and T, respectively. Despite the effectiveness of the passive measures in the hot season, resulting in a T>25°C lower than the Passivhouse standard [28] (< 10%) with 8.63% and 6.74%, Block H and T respectively, in the cold season the case studies behavior were much different. That is to say, that we observe both blocks displaying T<18°C in about 40% of the time, confirming an overcooling problem. This means that it is not possible to increase thermal comfort in winter by simply using passive scoped measures in this kind of buildings, and therefore, it is mandatory an active heating system.

The proposed HVAC packages display reductions on the primary energy consumption for heating (Cheat,ep) and cooling (Ccool,ep) between 73.37% and 86.74% when compared with the scenario_0 (Table 5). The Block T records on average, minus 11% of Cheat,ep and 26% of Ccool,ep than Block H in all the
proposed packages. This performance can be explained by the higher impact that passive scope measures induced in Block T, which leads to lower energy consumption values.

Table 5. HVAC packages primary energy consumption and savings compared with scenario_0

| Block H | Block T |
|---------|---------|
| Heating /Cooling (kW/m²y) | Savings % | Heating /Cooling (kW/m²y) | Savings % |
| pkg_HC1 | 16.60 / 5.20 | 82.56 / 67.09 | 15.00 / 3.70 | 82.36 / 70.63 |
| pkg_HC2 | 13.50 / 4.00 | 85.22 / 74.68 | 11.60 / 2.80 | 86.74 / 77.78 |
| pkg_HC3 | 24.40a / 3.60 | 73.37 / 77.22 | 21.60a / 3.10 | 75.31 / 75.40 |

* 83% of this value is energy consumed by biomass fuel.

The pkg_HC1 and HC2 (both consider and air-to-air heat pump) display the highest impact on C_{heat,ep} reduction due to higher COP versus EER values. Actually, the pkg_HC2 show, at first sight, the lowest primary energy consumption for acclimatization, however, we must consider the pkg_HC3 particularities. In this package, although it presents the highest C_{heat,ep}, we highlight the fact that about 83% of that value refers to biomass fuel (RES - pellets), and therefore, if subtracted from the total energy consumption for heating, as stated in Portuguese legislation [29], Block H and T would consume 4.2 and 3.9 kWh/m²y respectively. This means that pkg_HC3 would have the lowest primary energy consumption for acclimatization in both blocks.

Figure 5. Primary energy consumption for heating and cooling packages versus scenario_0.

Matching the obtained values with other studies, we observed that Block T show C_{heat,ep} values lower than the Passivhouse standard [28] (< 15 kWh/m²y) and [30] research concerning NZEB minimum requirements in Lisbon (< 15.8 kWh/m²y using dynamic simulation), in all the proposed retrofit packages. In the same domain, Block H only miss this target in pkg_HC1. Regarding C_{cool,ep} none of studied retrofit packages are compliant with [30] study (< 2 kWh/m²y using dynamic simulation), however, they are inferior to Passivhouse standard [28] values (< 15 kWh/m²ano).

Concerning thermal comfort, all HVAC packages displayed T_{h>25ºC} values in less than 10% of the time, with the worst one registering 7.38% in this field.

Regarding DHW, the pkg_DHW1 simulation display a primary energy consumption (C_{DHW,ep}) of 7.0 and 4.8 kWh/m²y, meaning these values a reduction of 68.18% and 78.18%, Block H and T respectively, when compared with those obtained in scenario_0. These values were achieved thanks to the proposed BIST system, which contributed with 64.83% and 76.24%, Block H and T respectively, of the required
energy demand for DHW. The solar thermal system superior performance on Block T is explained by the higher collectors covered surface and favorable orientation (south). Expressive results could be obtained by increasing the amount of collectors, as [31] say in their study, 70% of the Baixa Pombalina DHW needs could be fulfilled with a 17% roof occupation with ST collectors.

When it comes to photovoltaic systems, the proposed solution (pkg_PV1) supply 24444 kWh/y and 41686 kWh/y of final energy (E_{sist,pv}) to Block H and T respectively. Table 6 shows the package impact on the reduction of primary energy consumption for heating, cooling and DHW (C_{cp,RES}) considering the previously mentioned HVAC packages.

| pkg package | C_{cp,RES} (kW/m²y) | E_{sist,pv} % | C_{cp,RES} (kW/m²y) | E_{sist,pv} % |
|-------------|---------------------|--------------|---------------------|--------------|
| pkg_C+DHW1+HC1 | 16.5 | 42.71 | 6.90 | 70.64 |
| pkg_C+DHW1+HC2 | 12.2 | 50.20 | 2.60 | 86.46 |
| pkg_C+DHW1+HC3 | 2.50 | 83.11 | -4.80 | 140.68 |

This package generates, in Block T, 41% more energy than Block H, displaying the first one the best performance once more (Fig. 6). This happens due to the south orientation of Block T longer side, and the highest amount of PV panels placed on the roof. The amount of energy provided is enough to meet at least 70.64% (HC1) of the C_{cp}, and can even reach 140.68% (HC3), generating more 4.8 kWh/m²y of primary energy than those necessary to suppress 100% heating, cooling and DHW energy demand. In Block H, the E_{pv} is at least 42.71% (HC1) of C_{cp} and may reach 83.11% if combined with a biomass heating solution for the upper floors (HC3).

![Figure 6. Monthly final energy provided by the photovoltaic system in both blocks.](image)

### 5.1. Optimized measures

In order to mitigate the impact on the blocks appearance, we sought to optimize the BIPV solution by decreasing the amount of PV panels installed on the blocks roof, so that a solar contribution of at least 70% of total primary energy consumption could be achieved. This value is less ambitious than the one stated by [32] (> 80% for a new residential building in Portugal), but we are dealing with sensitive built environment with preexisting constraints, and is in line with the average RES contribution for NZEBs in [33] study.

With a pkg_HC2-type HVAC solution, in Block T, is possible to occupy only the south-oriented slopes with 130 PV panels (9.29% covered surface) and achieve an E_{sist,pv} of 70.53%. By the same token,
with pkg_HC3, the partial occupation of the west-oriented slopes in Block H (120 panels, 9.29% covered surface) and south-oriented slopes in Block T (90 panels, 6.43% covered surface), enable an $E_{\text{ sist, pv}}$ of 71.96% and 72.12%, respectively, of total primary energy consumption.

6. Conclusions
In this paper, an energy retrofit strategy at a block scale, combining passive and active scope measures, was implemented in two historical Pombaline blocks with the purpose to achieve NZEB level. The retrofitted packages were compared with a baseline (scenario_0) to measure the impact on energy performance.

The results show that thermal envelope improvements (insulation addition) can reduce the energy demand for heating (around 50%) and cooling (between 63% and 70%) and increase thermal comfort mainly in hot season (around 54% to 72%). However, both blocks exhibit an overcooling problem (indoor temperatures below 18ºC in more than 40% of the time) that cannot be overcome simply using passive scope measures due to the massive exterior walls and insufficient internal gains.

Therefore, three HVAC solutions were tested. As observed in Table 5 and Figure 5, the pkg_HC3 (VRF commercial ground floor and a biomass heating device for upper residential floors) displayed the lowest primary energy consumption for heating and cooling mainly due to the 83% RES contribution for heating, followed by the pkg_HC2 (commercial brand air-to-air multi-split heat pump). The on-site solar thermal system contributed with 64.83% and 76.24% of DHW primary energy consumption on Block H and T respectively, opening the way to NZEB performance. In a similar way, as seen in Table 6, the energy provided by the photovoltaic system represents a minimum of 42.71% of total primary energy consumption in the worst-case scenario (Block H pkg_HC1), and a surplus of nearly 40% in the best one (Block T pkg_HC3). These results open space to reduce the impact on the blocks appearance, by optimizing the photovoltaic solution decreasing the amount of panels on the blocks roof.

The results comparison with the Passivehouse standard [28] and [30] research prove the effectiveness of the proposed passive scope measures, to the extent that they are responsible for the reduction of heating and cooling energy demands. In addition, it shows that the original Pombaline block presents architectural and constructive potential to hold on-site active and energy generation systems (photovoltaic and solar thermal) that are crucial to achieve NZEB performance, even with the minimum performance requirements stated in Portuguese law.

Finally, it is clear that Block T exhibits superior performance in all packages compared with Block H, whether they are passive or active scope. The main reason for this to happen is related to the original untouched architectural features of the Pombaline block, mainly its longer side orientation (south) and the consequently available roof area for the installation of photovoltaic and solar thermal systems. Therefore, we can say that Block T reaches NZEB level in all the proposed packages and Block H only with the pkg_HC3.

In conclusion, this study contributes for the quantitative definition of NZEB historical buildings, by showing how blocks with a sensibly built fabric could achieve NZEB performance if integrated with active and passive measures designed to take advantage of its main architectural inherent features.

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