Energy Performance of Two 18th Century Blocks in Lisbon Pombaline Quarter

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Abstract. The 1758 Lisbon Pombaline quarter Reconstruction Plan consists of a homogeneous urban fabric, structured by rectangular shaped residential blocks, built with a system that matches heavy mass construction elements with a light timber structure, called "Gaiola". Although Pombaline architecture and construction generate consensus among authors about its importance as a historical fact and exceptional construction quality, this kind of buildings experienced several modifications over time with severe consequences to their built fabric properties and architectural elements. However, if we take into consideration both constructive and architectural inherent features of the 18th century Pombaline block, it has the potential to hold and achieve high-energy performances if considered as a “single” unit. In this way, this paper intends to analyse and compare the energy performance of two block units replicating the "original" 18th century Pombaline design and constructive features. The method involves the conception of a Building Energy Model of two case studies with different volumes, form and orientation, loaded with energy parameters related to Pombaline construction, and subsequently simulated with the EnergyPlus dynamic analysis software. In order to calculate the energy demands for heating and cooling, we set the indoor temperature value between 18ºC and 25ºC. The results show that due to its architectural features, Block T presents a better overall performance compared with Block H, demanding 8% less energy and displaying less time in thermal discomfort. Finally, the blocks east side and the highest story registered the worst energy performance in both case studies.

1. Introduction

The 1758 Lisbon Reconstruction Plan is the response to the earthquake occurred in 1755 that destroyed Lisbon downtown area known today as “Baixa Pombalina”. The Plan presents itself as an orthogonal matrix, organized and structured by a set of homogeneous rectangular residential blocks [1]. The Pombaline Block (Figure 1), an example that illustrates a forgotten way of doing architecture and construction whose quality is recognized by several authors [1-5], is the key element of a wider intervention acknowledged today with historical and cultural importance at a national and European level.

The best example of the block conceptual value is the irrelevance given by the plan authors to the building perceived as a single unit. The Pombaline building concept was abstract, something built progressively to complete or close the entire block. Proof of this, is the absence of floor plans or single buildings drawings, unknown to us so far, which would have allowed us to consider this possibility
1. Today’s known drawings are elevations intended to illustrate the architectural image idealized by the plan authors for that area [6].

Over time, the original blocks had a wide range of interventions that contributed progressively to its architectural, constructive and functional identity loss (Figure 1). The interventions go from the undifferentiated stories addition and roofs geometry modification, changes in uses and functions, facade remodelling, structural walls removal and/or insertion of non-compatible elements with the existing constructive system [7].

![Figure 1](image1.png)

**Figure 1.** Extra floor-levels additions and enlarged showcase windows on the ground floor are some of the most common changes in Pombaline buildings. (Photographs by the author, May 2019)

However, we observed that the original Pombaline blocks present both architectural and constructive features that suggest a favourable thermal and energy performance. Some of these attributes are the compact rectangular shape without recesses or protrusions, five-floor levels, windows on both facades with an inner patio “alfugere” for ventilation purposes, sloped coplanar roofs with dormer windows and a thermal envelope built of thick mass elements articulated with a timber flexible structure [2].

Given that, this paper intends to show the original Pombaline blocks energy demand values regarding heating (D$_\text{heat}$), cooling (D$_\text{cool}$), and domestic hot water (D$_\text{DHW}$) using EnergyPlus [9] dynamic simulation software in two case studies with distinct formal features: Block H and Block T (Figure 2).

Since the conditions that distinguish both blocks relates to volumetric and orientation matters, this study foresees the impact that architectural features have in energy demand on this sensible built fabric, and identify which block have the lower energy demand to maintain its interior comfort. The study presented here implies a new perspective on thermal and energy performance analysis and simulation in these type of structures, which has been done at a single fraction or single building scale so far$^1$.

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$^1$ On the December 30th, 2017 the authors inquired Portuguese Agency for Energy – ADENE [8], about the existence of conducted energy analyses concerning Pombaline residential buildings. On the February 26th, 2018, ADENE replied energy certificates issuance occurs at a single fraction level, according to Article 2 of National Decree nº28/2016 [9].
1.1. Case Studies Description

The case studies are located in Lisbon Pombaline Quarter and possess the following features (Table 1 and Figure 3).

| Table 1. Case studies Block H and T features |
|---------------------------------------------|
|                | Block H       | Block T       |
| Total net area | 5570.74 m²    | 6279.13 m²    |
| Ground-floor net area | 1165.62 m² | 1048.43 m²    |
| Floor height   | 3.84m (ground, 1<sup>st</sup>, 2<sup>nd</sup>-floor) / 3.62m (3<sup>rd</sup>-floor) / 3.84m (4<sup>th</sup>-floor) | 3.84m (4<sup>th</sup>-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 single-buildings, and longer side orientation. Regarding this last item, Block H has a longer side and is facing east-west quadrant, while Block T is facing north-south (Figure 3 and Figure 4).
2. Methodology

We used a Building Energy Simulation (BES) methodology [10, p. 753] in both case studies. First, we did an architectural and constructive synthesis by consulting the work of two fundamental authors [2], [3], [5], supported by other relevant sources [4], [7], [11]. This allowed us to define each constructive component regarding its energy and thermal performance: ground and intermediate floors, exterior and interior walls, roofs, and opaque and glazed openings. The energy-related data used to delineate the constructive solutions is stated on national and international technical documentation and bibliography [12-16], among other authors [17].

Then, using the IFC Builder 2018 [18] software, we designed a Building Information Model (BIM) of each case study. Each thermal zone matches to a building floor and each indoor space to an apartment. With this method, we can extract disaggregated data per floor-level, single building, and the whole block.

Afterwards, we export BIM in .ifc format and imported it to Cypetherm Eplus [19], a software interface used to boot the EnergyPlus dynamic simulation engine [20]. In Cypetherm Eplus, we loaded the previously consulted energy-related data regarding building components thermal performance and simulation parameters input (Table 2). After the simulations stage, we obtained single reports of each case study with disaggregated data per block, floor-level, and single building.

| 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 |
|-------------------------------|
| **Residential**               | **Occupation** | **Activity Level** |
| 0.8 ACH                       | 21 m²/person   | 100 W/person       |
| **Commercial**                | 0.8 ACH        | 5 m²/person         | 130 W/person |

| Operating Conditions          |
|-------------------------------|
| **Temperature**               | heating and cooling profile: 18°C – 1st Oct to 31 May / 25°C – 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 litres/person at 45ºC temperature |

| Linear Thermal Bridges        | Calculated by Cypetherm Eplus according to ISO 14683 [21] and ISO 10211 [22] |
| Planar Thermal Bridges        | Exterior envelope openings (header, sill, jambs and window nook) |
3. Results and Discussions

3.1. Blocks Energy Performance

After data processing, we found that both Block H and T have similar behaviours regarding their energy demand patterns. Both require energy to acclimatize indoor spaces throughout the year, however, Block T have a lower energy demand (65.7 vs 71.4 kWh/m²/year), requiring less 9% of energy for heating and 8.3% for cooling compared with Block H. This means that Block T displays a higher performance, demanding, on average, 8% less energy to maintain comfortable indoor temperatures (Table 3 and Chart 1). Therefore, we can observe the impact that architectural features like shape, proportion, longer side orientation, and urban context have in blocks built with old constructive systems.

### Table 3. Block H and T annual energy demand for heating, cooling and DWH

|          | $S_u$ | $D_{heat}$ | $D_{cool}$  | $D_{DHW}$ | Total     |
|----------|-------|------------|-------------|-----------|-----------|
|          | m²    | kWh/year   | kWh/m²/year | kWh/year  | kWh/m²/year |
| Block H  | 5570.74 | 226891.50  | 40.73       | 70465.20  | 100337.40  |
| Block T  | 6279.13 | 229494.10  | 36.55       | 66005.70  | 117213.60  |

Concerning $D_{DHW}$, it is relevant to mention that it requires 30% more energy than $D_{cool}$ in Block H and 44% in Block T, reaching its maximum throughout the wintertime, due to lower water temperatures in Lisbon network. During this period is required, on average, 13% more energy for DHW than summertime for both case studies.

3.2. Floor-levels Energy Performance

With regard to stories (Table 4 and Chart 2), both blocks registered higher $D_{heat}$ than $D_{cool}$ except the ground floor, where there is a behavioural inversion, due to a heavier occupation profile pattern and its position that leads to an inadequate sun exposition.

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2 The average annual percentage of hours registering temperatures <18°C is 44.02% on Block H and 42.98% on Block T (almost half a year). Otherwise, temperatures >25°C, are exhibit in 18.82% and 17.63% of the time in Block H and T respectively.
Table 4. Block H and T annual energy demand for heating and cooling per floor-level.

|           | Su (m²) | Dheat kWh/year | Dcool kWh/m²year | Total kWh/m²year |
|-----------|---------|----------------|------------------|-----------------|
| Block H   |         |                |                  |                 |
| Ground floor | 1048.43 | 14603.80       | 13.93            | 20677.20        |
| 1st floor  | 1104.39 | 52647.20       | 47.67            | 9140.60         |
| 2nd floor  | 1126.00 | 46851.00       | 41.61            | 9451.50         |
| 3rd floor  | 1147.62 | 44397.60       | 38.69            | 8933.50         |
| 4th floor  | 1144.30 | 68391.90       | 59.77            | 22262.40        |
| Block T   |         |                |                  |                 |
| Ground floor | 1165.62 | 14238.80       | 12.22            | 20390.40        |
| 1st floor  | 1244.90 | 49999.50       | 40.16            | 8056.90         |
| 2nd floor  | 1263.88 | 42919.30       | 33.96            | 7512.80         |
| 3rd floor  | 1282.94 | 44278.50       | 34.51            | 6490.50         |
| 4th floor  | 1321.79 | 78058.00       | 59.05            | 23555.10        |

As shown in Chart 2, the levels displaying the highest energy demand for acclimatization are the 4th, followed by 1st, 2nd, 3rd, and ground-floor. The 4th floor has the highest Dheat on both blocks, and the highest and second highest Dcool on Block T and H respectively, requiring on average 2.5 times more energy than the ground floor to maintain temperatures within a comfortable range. The 4th floor level exposition to natural elements and the high transmittance values displayed the roof constructive solution, can explain its poor performance. These values label the top floor as the "coldest" and the "hottest" on both blocks, assuming itself as the one to prioritize in a shortcoming energy retrofit.

On the intermediate levels, energy demand decrease as you go up in height, mainly Dheat, while Dcool is similar in all of them, with values ranges between 7.78 and 8.39 on Block H, and 5.06 and 6.47 kWh/m²/year on Block T (Chart 2). In this Block, we observe a better performance in Dheat and Dcool values, demanding, in average, less 17% compared with Block H intermediate levels. It is also relevant to state that the Dheat is, on average, 83% higher than Dcool on Block H, and 84% on Block T, which confirms the overcooling issue observed in the previous section.

Chart 2. Block H and T annual energy demand for heating and cooling per floor-level, kWh/m²/year

3.3. Block Sides Energy Performance

Since we are dealing with rectangular shaped blocks, each side has a different orientation and subsequent performance. As shown in Chart 3, Block T displays similar energy demand values between its sides when compared with Block H, that present relevant differences (mainly the east-side). Regarding this matter, on Block H, the south and west-orientated sides have the best energy performance, while on Block T, the south-side is the one that displays the lower values for
acclimatization (Table 5). On the other hand, the east-side has the worst performance in both blocks, demanding 23% more energy than the west-side in Block H, and 12% more than the south-side of Block T.

### Table 5. Block H and T annual energy demand for heating and cooling per side

| Orientation | S_{m²} | D_{heat} kWh/year | D_{heat} kWh/m²/year | D_{cool} kWh/year | D_{cool} kWh/m²/year | Total kWh/m²/year |
|-------------|--------|-------------------|----------------------|------------------|----------------------|-------------------|
| Block H     |        |                   |                      |                  |                      |                   |
| East        | 2363.61| 114960.80         | 48.64                | 39566.7          | 16.74                | 65.38             |
| West        | 2843.40| 111930.70         | 39.37                | 30898.5          | 10.87                | 50.23             |
| North       | 1414.92| 61196.90          | 43.25                | 16305.8          | 11.52                | 54.78             |
| South       | 1162.36| 39383.10          | 33.88                | 19994.4          | 17.20                | 51.08             |
| Block T     |        |                   |                      |                  |                      |                   |
| East        | 1641.83| 60840.80          | 37.06                | 22928.60         | 13.97                | 51.02             |
| West        | 1404.36| 51543.30          | 36.70                | 17745.10         | 12.64                | 49.34             |
| North       | 3217.32| 132854.10         | 41.29                | 26772.90         | 8.32                 | 49.61             |
| South       | 2437.84| 76869.30          | 31.53                | 33148.10         | 13.60                | 45.13             |

When it comes to D_{heat}, the south-side presents the best performance in both blocks, followed by the west-side, with a 14% difference between them. The worst performance goes to the east-side on Block H and north-side on Block T, demanding 30% more energy than the south-side on the first one and 23.5% on the second, to keep indoor temperatures >18ºC. Concerning D_{cool}, the best behaviour goes to the west-side on Block H and north-side on Block T. In opposition, on Block H, the south-side displays the higher value, demanding 37% more energy than the west side, while on Block T the east side requires 40% more energy than the north side to keep indoor temperatures under 25ºC (Chart 3).

![Chart 3. Block H and T annual energy demand for heating and cooling per side, kWh/m²/year](image)

We found relevant to state that despite displaying the blocks best and second best performance regarding total energy demand, the south-side has the lower D_{heat} and the highest D_{cool} values due to its orientation and incapacity to control extreme temperatures, while the east-side appears to be the most problematic, displaying the highest values in both fields.

### 3.4. Single-building Energy Performance

When it comes to single-building analyses (Chart 4), the ones displaying the highest values regarding energy demand are Assunção B, Santa Justa A and Prata A on Block H, and Augusta A, Julião A and Prata A on Block T (Figure 4). On the other hand, Assunção A and Correeiros B exhibit the best performance, demanding in average 18% less energy than the previously stated ones on Block H, and
on Block T, Augusta B and Julião C require an average value of 24% less energy than the previously stated ones.

As shown in Chart 4, in Block H, Assunção B (south-side) have the $D_{cool}$ highest values while the Correeiros Street buildings (west-side) the lowest ones, demanding in average 61% less energy. Respecting $D_{heat}$, there is a similar behaviour between all buildings except Assunção A and B, which register the lowest values, needing in average 20% less energy than the remaining buildings.

When it comes to Block T, Julião A and Prata A (south and east) have the highest $D_{cool}$ values, while the Conceição Street buildings (north) the lowest ones, demanding in average less 40% energy than the previously stated ones. Concerning $D_{heat}$, Augusta A stands out, followed by Prata A, Conceição A, and Conceição B, while Julião A building (south), displays the lowest values in this field, with 35% less energy demand than Augusta A.

It is perceptible that in Block H, the south-facing orientation and corner position of Assunção A and B have a noticeable impact regarding their $D_{heat}$ and $D_{cool}$ values. In a similar way, in Block T, the north-facing orientation of Conceição Street buildings and the cornered positioned buildings, like Prata A and Augusta A, have a negative impact regarding $D_{heat}$ and positive concerning $D_{cool}$ values. Therefore, it is clear that the building position in the block context has consequences in their heating

\[ Chart 4. \] Block H and T annual energy demand for heating and cooling per building, kWh/m²/year

As shown in Chart 4, in Block H, Assunção B (south-side) have the $D_{cool}$ highest values while the Correeiros Street buildings (west-side) the lowest ones, demanding in average 61% less energy. Respecting $D_{heat}$, there is a similar behaviour between all buildings except Assunção A and B, which register the lowest values, needing in average 20% less energy than the remaining buildings.

When it comes to Block T, Julião A and Prata A (south and east) have the highest $D_{cool}$ values, while the Conceição Street buildings (north) the lowest ones, demanding in average less 40% energy than the previously stated ones. Concerning $D_{heat}$, Augusta A stands out, followed by Prata A, Conceição A, and Conceição B, while Julião A building (south), displays the lowest values in this field, with 35% less energy demand than Augusta A.

It is perceptible that in Block H, the south-facing orientation and corner position of Assunção A and B have a noticeable impact regarding their $D_{heat}$ and $D_{cool}$ values. In a similar way, in Block T, the north-facing orientation of Conceição Street buildings and the cornered positioned buildings, like Prata A and Augusta A, have a negative impact regarding $D_{heat}$ and positive concerning $D_{cool}$ values. Therefore, it is clear that the building position in the block context has consequences in their heating
and cooling energy demand, particularly those located at the “corners”, possessing two facades facing different orientations.

4. Conclusions
This paper aims to show the performance of two original 18th century Pombaline blocks with distinct formal features, regarding its heating, cooling, and DHW energy demands using EnergyPlus dynamic simulation engine.

Architectural features, such as shape, proportion, building depth, and longer side orientation, have a direct impact on energy demands to keep indoor temperatures under control. Regarding this matter, the compactness and south facing Block T display a superior overall performance compared with Block H, with a total energy demand value 8% lower, and requiring, respectively, 9% and 8.3% less energy for heating and cooling. Concerning DWH energy demand, the values are similar in both case studies and superior to the cooling demands (Chart 1). The higher efficiency observed in Block T can be partially explained due to buildings lower energy demand levels located at the north and south-sides, which counterbalance the requirements of north-orientated corner buildings. Regarding side behaviour, the east-side has the worst energy performance in both blocks, while those revealing the lowest energy demand are the west and south-side, in Block H and T respectively, requiring 23% and 12% less energy.

Pombaline blocks have a better performance dealing with hot temperatures, due to the thermal inertia effect generated by its mass envelope. Both blocks display, on average, temperatures >25°C in 18.22% of the time, versus the 43.5% <18°C. This clearly states that both blocks have an overcooling issue that leads to high heating demands. Despite the energy required to control indoor temperatures during the year, there is a clear upward demand for heating overcooling (approximately 3 times higher on Block H and 3.5 times on Block T) reaching its maximum in January/December and July/August respectively (Chart 1). The floor-level pattern follows this tendency except for the ground floor. In this level, there is a behavioural inversion resulting in overheating due to its position and occupation profile pattern (Chart 2). On the intermediate floor levels (1st to 3rd), the heating demands decrease as you go up in height while cooling needs display similar values between them, with the first floor showing the highest total energy requirements. At last, the 4th floor (top floor) reveals itself as the most problematic and unbalanced, due to its non-insulated roof constructive solution, demanding in average 41% to 49% more energy than the remaining floors.

Acknowledgments
The authors gratefully acknowledge Top-Informática, LDA (www.topinformatica.pt/) for providing an educational version of the Cypetherm Eplus software without which it would be impossible to carry out this study. This research received financial support from Research Centre for Architecture, Urbanism and Design (CIAUD) and Fundação para a Ciência e Tecnologia (FCT).

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