IOP Conf. Series: Materials Science and Engineering **415** (2018) 012021 doi:10.1088/1757-899X/415/1/012021

Energy Certification Label vs. Passive Discomfort Index for existing dwellings

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Abstract. Several studies highlight the significant differences between theoretical energy consumptions, - considered in the Energy Certification Schemes (ECS), following the Energy Performance of Buildings Directive (EPBD) -, and the actual energy household consumptions, obtained from extended surveys and monitoring campaigns, especially in Southern European countries. These differences are referred in the literature as *"heating gaps"*. Actual consumptions are significantly unpredictable (depending on outdoor climate, income, energy prices, cultural habits, etc.), but, in most cases, lower than permanent heating/cooling assumptions, present on regulations. This inaccuracy may lead to the suggestion of inappropriate measures on ECS, for low energy-consumption dwellings. Inappropriate because the impact of the same measure on energy consumptions and thermal comfort is different for cases with a permanent heating behavior and cases without it, and because it may lead to hygrothermal pathologies and, finally, an economic mistake, as the real payback time of that measure will be higher than the one suggested, misleading economically more vulnerable households. A complementary approach for the evaluation of thermal performance in existing dwellings, considering intermittent heating scenarios is proposed, by the definition of the "Passive Discomfort Index" (PDI), complementary to the energy label. This index is quantified by the calculation of the temperatures outside the comfort range within the building, in realistic use conditions. A 19th century building, located in Porto, was used to perform a monitoring campaign of temperature and HR to calibrate a numerical model, developed using an advanced simulation tool. It was then performed a sensivity analysis, comparing the energy label with the PDI value, for different retrofitting scenarios, mainly with different insulation thicknesses. The results show that there is no obvious relation between the energy label and the comfort conditions, for intermittent heating scenarios, among others, reinforcing the need of a complementary approach. This is especially important for existent buildings and for Southern European countries, where the "*heating gap*" is higher.

1. Introduction

Reducing household energy consumption is a fundamental European goal, since 40% of the total energy consumption is spent inside buildings [1]. It is very important, although, to identify where and how it is spent, so that policies are drawn right to the target.

Energy Performance of Buildings Directive (EPBD)[1] was designed assuming that there is a permanent (24h/7d) heating/cooling practice inside buildings, to achieve permanent comfort conditions, being space heating the higher end-use consumption. The evolution of the Directives, from 2002 to its recast at 2010, and of the National Regulations following it, presents ever-decreasing U impositions, only achievable with large thicknesses of insulation. However, several studies focusing on actual consumptions, provided by energy suppliers databases and household surveys, point to the fact that actual household heating consumption are lower (intermittent and not in 100% of the floor area) than theoretical assumptions from regulations, especially in the less efficient buildings, what is referred on literature review as "*rebound effect*" [2-4]. The "rebound effect" means people tend to spend more energy on heating, as more efficient the house is and vice versa, as mentioned by Hens [2] and Sorrel [5], among others .

Laurent et al. [4] compared theoretical with actual heating consumptions, in four european countries (United Kingdom, France, The Netherlands and Germany) with the higher differences marked with a dashed array (Figure 1.a). The variability and unpredictability of occupant's behavior is also often referred to as a major factor to explain these differences. Guerra Santin [3] concluded the same for a Dutch Residential Stock sample (Figure 1.b)). b)

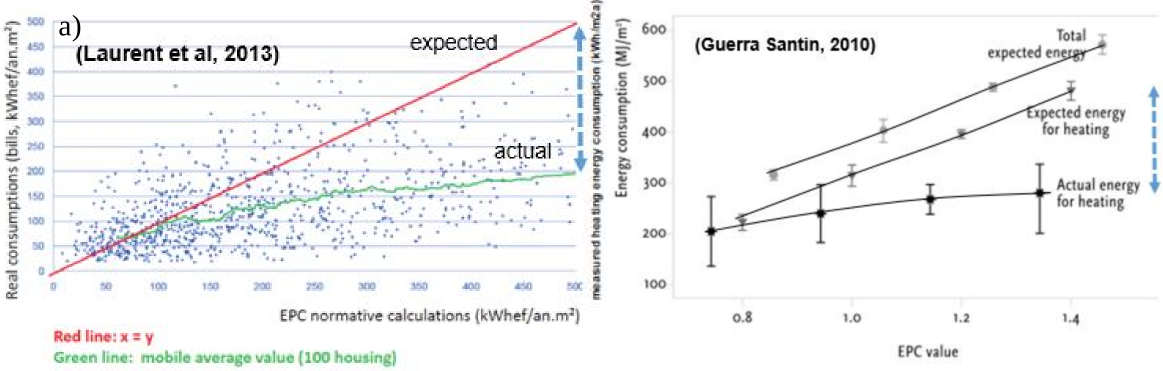

Figure 1. Heating energy consumptions (theoretical vs. actual) for European samples

This discrepancy is even higher in southern/ Mediterranean Europe, which present a moderate climate, compared to the central/northern countries. In fact, and observing the Portuguese example, only 21% [6] of the annual household energy bill is spent with space heating (kitchen represents 39%, water heating 23%, beside other end-uses), what is a much lower value than 67%, for the European average (for space heating weight) [7]. Magalhães [8] found an "*heating gap*" of 95% in Portugal, which means only 5% of the regulation assumption heating needs are actually consumed (considering all dwelling at 20ºC all winter period) .

Though, despite the lower energy consumptions, these southern/Mediterranean countries still present conditions of discomfort in the winter for most of the time [9]. This means that these countries don't need to heat so tightly, as the central and northern countries, but, when they need to do it, they just can't afford it, most of the time [8, 10]. This is explained by the phenomenon of "fuel" or "energy poverty" and in a simple way, results from the reunion of two main conditions: low incomes and high energy costs [11].

The improvement measures suggested by the Portuguese Regulation methodology [12], following EPBD, point mainly to the introduction of strong insulation thicknesses in the opaque envelope. There are several studies with Life Cycle Cost analysis to evaluate the impact of implementing these measures, but always with the assumption of permanent heating. However, there are very few studies evaluating the impact of these same measures, but with intermittent heating profiles, which is the realistic scenario for Portugal and other vulnerable countries. And these few studies point to some interesting conclusions. If, on the one hand, the introduction of insulation does not have a significant impact for comfort conditions improvement in winter, when there is an intermittent heating behaviour [10, 13], in summer it can even lead to an overheating risk, when inappropriately placed (on the internal side, reducing building inertia) [14]. Moreover, other disadvantages are identified, like increasing pathology risks (interstitial condensations), air quality prejudice, effects that can be worsened with the wrong using behaviours. Some of these buildings, were built in a totally different perspective, considering natural ventilation most of the times, and the increasing tightness demanded on the regulations distorts its thermal performance. Adding to the previous aspects, it is also important to mention the strong investment that some measures imply for the owners, not having the expected payback, presented in the Energy Certificates, that are based on theoretical savings. It's impossible to save what is not spent. Finally, the architectural value of some existing buildings that are often incompatible with the introduction of insulation.

In a macro perspective view, national and European policy targets for reducing energy consumption, based on the theoretical consumptions, can be also misleading, with all the economic consequences.

It is, therefore, clear that EPBD is a very useful tool for new buildings and when there is permanent heating, but it may reveal inappropriate for countries where there is no such practice and for existing buildings, where improvement measures have different impacts and implications compared to new ones.

The present work proposes an alternative methodology for evaluating the thermal performance of existing buildings, based on the quantification of the discomfort, which exists and it is a problem, not the heating consumptions, which are already low many times, especially in Portugal.

2. Energy poverty and heating consumptions in Portugal and southern Europe

Portugal is one of the European countries that most suffers from “fuel poverty” or “energy poverty” [15], defined in literature as the ‘*lack of affordability of energy for heating*’ [11]. Another Mediterranean or East countries, are also the most energy poverty vulnerable. This incurs in low heating habits for these countries.

2.1. Energy poverty – Portugal vs. Europe

Portuguese median disposable income[1][16] was, in 2016, 9916€, a 39% lower value than EU-27 European average of 16351€. On the other hand, electricity price was, in 2015, 9% more expensive (0.23€/kwh) than EU-27 average (0.21€/kwh) and gas price, 38% more expensive than EU-27 average (0.098 and 0.071€/kwh, respectively), as shown in Figure 2 (a). Both conditions: - income and energy costs - lead to an energy poverty vulnerability context and low heating consumptions. This phenomenon is not exclusive from Portugal, despite this is a paradigmatic case.

Hills [17] proposed in his research concerning Fuel Poverty in Europe, the index “Low income – high cost” (LIHC). This index was applied at a cross-national level, in the present study, using the same statistic data from Figure 2 (a). Results are presented on Figure 2 (b), highlighting the fuel poverty vulnerable area, where four countries stand out: Portugal, Spain, Greece and Cyprus.

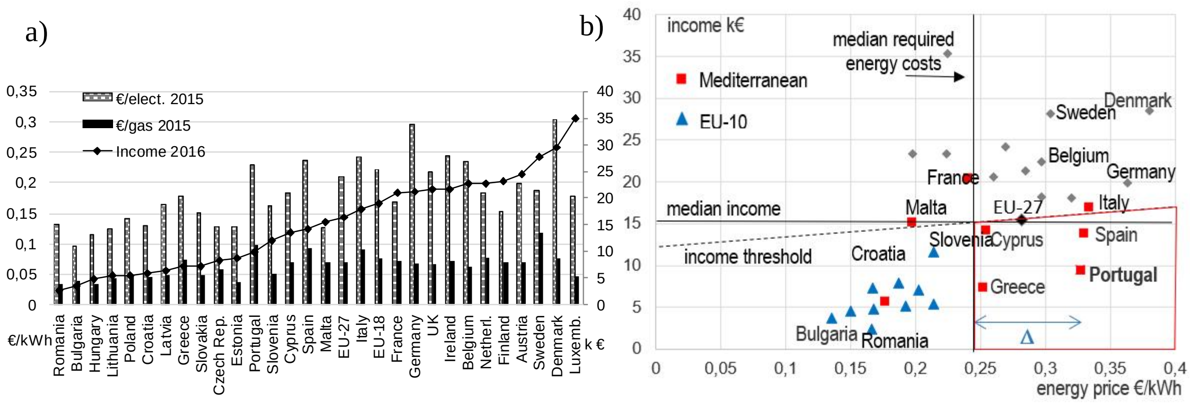

Figure 2. Median disposable income, electricity and gas prices in EU-28 (a) and Hills LIHC index adaptation

It's interesting to notice, moreover, that it is in the Mediterranean area that there are more winter deaths. A study from Oxford University [18], calculated the EWDI (Excess Winter Deaths Index), defined by the ratio of winter deaths for total deaths, from 2005 to 2014, for 31 European countries. Malta presented the highest value (28.3%) followed by Portugal (25.9%), Spain and Cyprus, confirming the previous findings from Figure 2 (b).

2.2. Household heating consumptions – Portugal vs. Europe

[1] For upper secondary and post-secondary non-tertiary education (levels 3 and 4), from 18 to 64 years old.

Previous findings regarding energy poverty phenomenon - namely high energy costs and low-income levels – are present all across Europe, but with more expression in Mediterranean area and some East countries, being Portugal one of the most evident case. These aspects, justify, itself, the low heating habits for these countries, but there is one more obvious for Mediterranean area, that is climate. Portugal has 1155ºCd, 63% less “heating degrees days” (HDD) than EU-28 average of 2817ºCd and only 19% of the Finland value [19]. So, it’s not surprising that Portugal, as other southern/Mediterranean countries, heat much less than EU average and, especially, northern countries.

Indeed, space heating weight in Portuguese average household energy bill is 21% of the total consumption and 11% of the total cost [6]. In contrast, this end-use weigh rises considerably for EU average being the main energy end-use with 67% of total consumption [7].

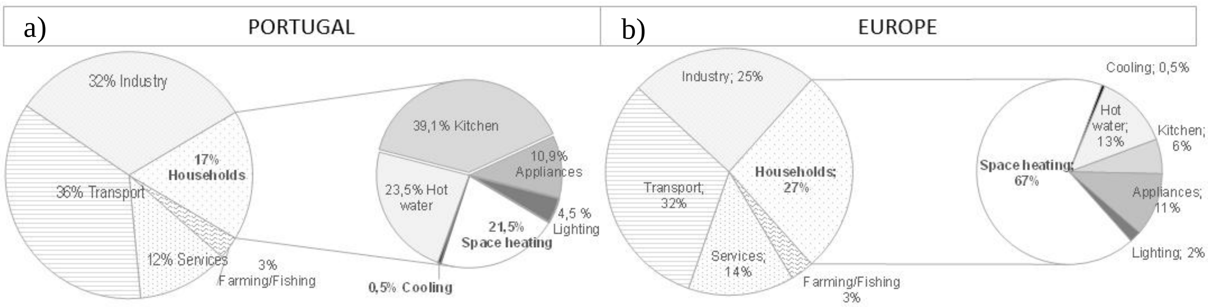

Figure 3. Energy total consumptions by end-use and household detail, for Portugal (a) and EU (b)

This way, being heating consumptions already low (and cooling, negligible), discomfort minimization should the target for these countries, more than energy efficiency for heating or cooling. That is the motivation and main purpose for this study.

3. Methodology

3.1. Experimental campaign and numerical model

A century building located in Porto, northern Portugal (Figure 4 a)), was used to validate the numerical model. The building presents a typical construction from the 19th century, with stone heavy external walls, wooden floors and roof, naturally ventilated, which was refurbished maintaining the main characteristics. Both apartments, north (N) and south (S) oriented, are located on the 1st floor and were monitored (temperature and relative humidity) during 2016. A geometric model for both apartments was built on ©WUFIPlus software (Figure 4 b)). This has been calibrated by experimental data (Figure 4c)), with 0.5ºC maximum temperature difference and 3.5% relative maximum humidity difference in the 5 rooms/2 dwellings.

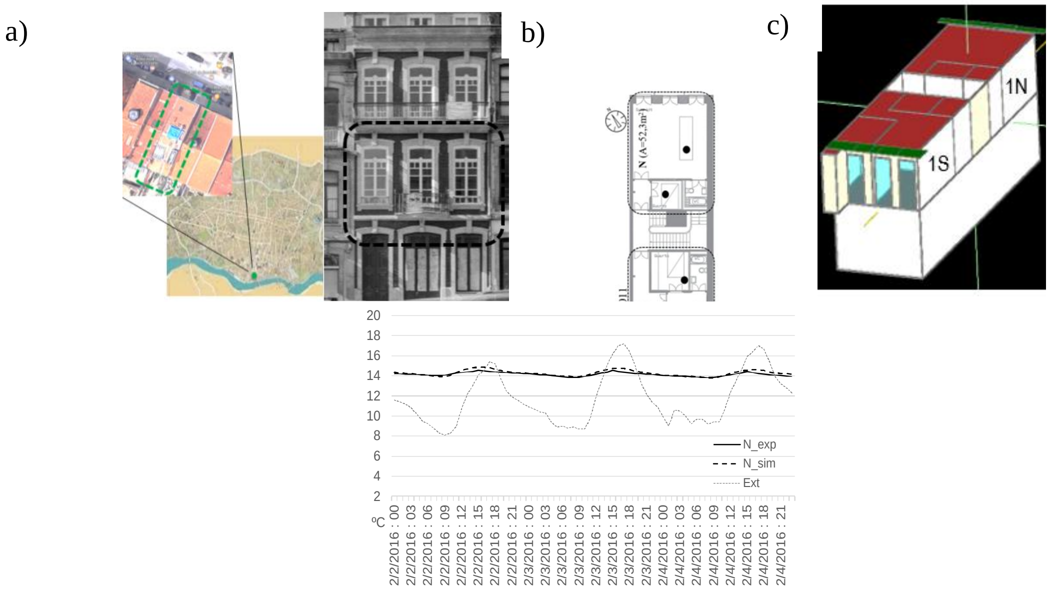

Figure 4. Case study building and experimental campaign (a), numerical model (b) and temperature validation (num. vs. exp.) (c)

3.2. *"Passive Discomfort Index" (PDI) definition*

The present study main purpose is to develop a new approach for evaluating the thermal performance of existing dwellings in low heating countries. This new approach consists in quantifying the discomfort outside a defined comfort range, that is, for the present study, [20-25] ºC or [18-25] ºC, this last case the Portuguese regulation "definition" of comfort (steady state assumption). This "discomfort" is quantified by the PDI that is numerical defined by formula (1) and in a graphic way by Figure 5.

$$PDI = PDI_{win} + PDI_{sum} = \int_{year} {}^{o}\mathrm{C}*\mathrm{h}_{\ win} + \int_{year} {}^{o}\mathrm{C}*\mathrm{h}_{\ sum} = \sum_{h=1}^{8760}(20 - Ti) + \sum_{h=1}^{8760}(Ti - 25) \qquad (1)$$

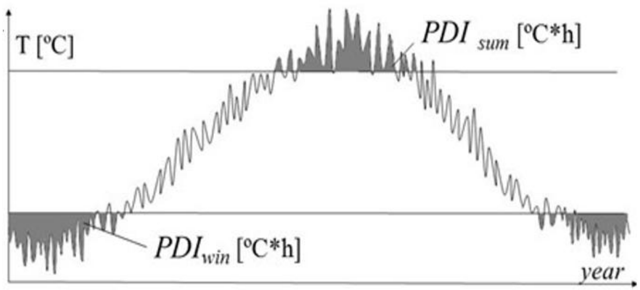

Figure 5. Free-floating temperature along the year and PDI definition (winter and summer)

3.3. *Energy Label – Portuguese Regulation (REH)*

REH [12] is the Portuguese thermal regulation for residential buildings, being the current transposition of the recast EPBD. It is based on the comparison of the nominal primary energy needs (N_{tc}) and the same needs for a reference building (N_t), summing different components as the heating needs, the cooling needs, the ventilation losses, solar gains, among others.

The Certification Scheme assigns an energy label to the dwelling, depending on the value of $R_{NT} = N_{tc} * N_t^{-1}$, from **A** (when $\mathbf{R_{NT} \leq 0,25}$) to **F** (when $\mathbf{R_{NT}}$ > 2,5). It's important to notice that REH´s building energy calculation models consider a permanent, in space and time, heating behavior inside dwelling (if the temperature is above 18ºC, in the current version).

3.4. Sensitivity analysis – scenarios definition

Variables considered to perform a sensitivity analysis include: three insulation thicknesses ("I" 4/6/8cm, with U=0.63/0.48/0.39 W/m2ºC, respectively) by the interior side of the wall, and a non-insulated or "base" scenario ("B", U=2 W/m2ºC), reflecting the real building; five heating profiles (0/4/6/8/24h) and three technical heating systems, to evaluate its influence on discomfort hours and energy label assigned to the building. Table 1 presents the several options.

Table 1. Scenarios definition [d]

[Comfort range]	A - PDI_{win} vs. Heating Energy [20-25] ºC												
	B - PDI vs. Energy Label [18-25] ºC [a]												
Scenario Code [b]	**B0h_N/S**	**B4h_N/S**	**B6h_N/S**	**B8h_N/S**	**B24h_N/S**	**I#_0h_N/S**	**I#_4h_N/S**	**I#_6h_N/S**	**I#_8h_N/S**	**I#_24h_N/S**	**BS2_0h_N/S**	**BS3_0h_N/S**	**I4S3_0h_N/S**
Envelope	"B" (non insulated)					"I#" (insulated with #4/6/8 cm)					"B"		I4
Heating (h)	0h	Intermittent			24h	0h	Intermittent			24h	0h		
Cooling (h)	0h				24h	0h				24h	0h		
Systems [c]	S1 ("Default system")										S2	S3	

a [18-25] ºC is the Comfort range considered on Portuguese Regulation, REH
b Scenario code means: Insulation option_Hours of heating_North/South orientated; In the case of B evaluation, after Insulation option, it's mentioned also the alternative technical system considered.
c S1 means Electrical appliances (default system, with efficiency factor η = 1); S2 means Gas Boiler for heating (η = 0,85); S3 means Heat pump+Solar Panels (COP = 3,5 / EER=2,5)
d Other parameters: Ventilation = $0.5h^{-1}$; no occupation; A_{win}/A_{floor} = 20%; Openings: U_w=2.71/Solar factor=0.65; adjacent buildings and dwellings with the same inner climate.

Two approaches are considered. First, in "A" evaluation, it's compared the "passive discomfort index" (PDI), considering the comfort range [20-25] ºC and the total energy consumption, obtained from the numerical advanced model in a dynamic state. In "B" evaluation, on the other hand, it's compared the PDI with the energy label, obtained from the Portuguese Regulation REH calculation model (where it's assumed the comfort range [18-25] ºC in a steady state approach). So that there is a common basis, for B evaluation, PDI is calculated considering also the comfort range [18-25] ºC.

4. Results and discussion

In the present chapter, the results for the two separated approaches mentioned on §3, are presented. Results for A are presented in Figure 6, in an energy consumption ranking, for all scenarios. Still for A approach, it's compared, in Figure 7, the PDI values with the heating consumptions, both only for winter, comparing the non-insulated scenario with the 8cm insulated scenario, and north and south orientated, for different intermittent profiles. Figure 8 presents, on the other hand, the annual energy consumptions, obtained from the dynamic model, with the energy label obtained from the ECS, for all scenarios.

4.1. A: PDI vs. Actual heating consumption

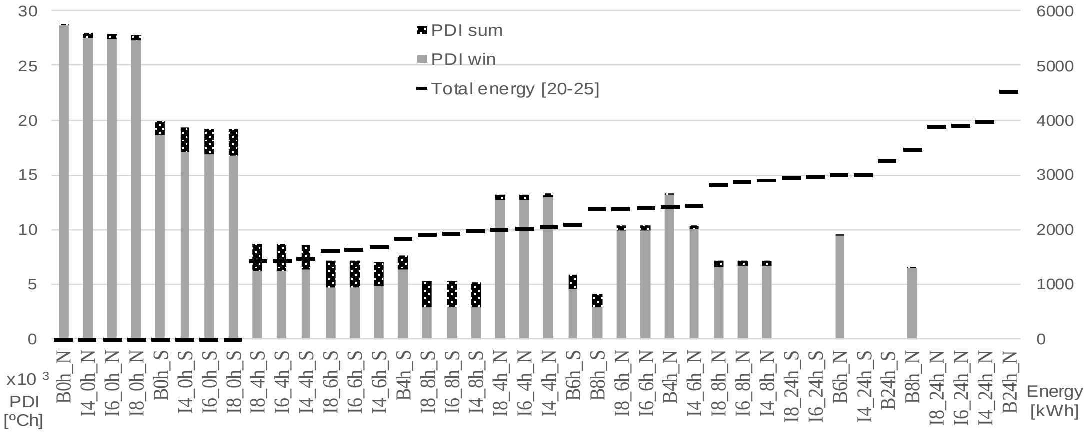

Figure 6. Ranking of the total energy consumption (dynamic) and relative PDI_{win} and PDI_{sum}

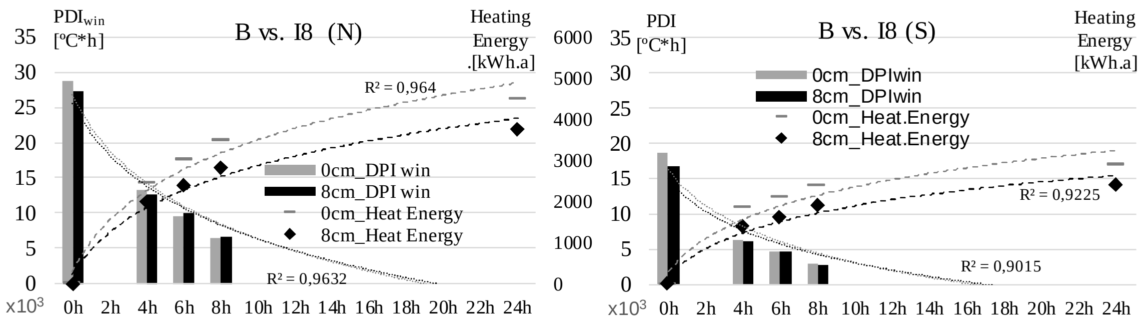

Figure 7. PDI_{win} vs. Heating energy consumption for different heating scenarios, without or with 8cm insulation, for North (a) and South (S) orientated dwellings

It's possible to observe, in Figure 6, that there isn't a clear inversely proportional relation between discomfort and energy consumption, considering all variables. There are scenarios with more energy consumptions and more discomfort than others, even for the same orientation. Also, the insulation thickness has a very small impact on the annual discomfort, as the total discomfort is very similar, for scenarios I8/6/4, regardless the heating profile or orientation. The summer discomfort for north orientated dwelling is negligible, but for south orientated it can have a significant impact. From Figure 7 a) and b) it's possible to observe, only for winter, the important role of orientation on total heating energy/PDI_{win}. Also, it's clear, once again, the low influence of insulation, considering the extreme cases: without insulation or with 8cm, on total heating energy/$PDI_{win.}$ Finally, it is possible to see that the major decrease of discomfort happens with the first hours heating and this decrease is increasingly lower with the number of heating hours. It is evident, in Figure 7, the non-linear (logarithm) relation between energy/discomfort and the heating profile.

4.2. B: PDI vs. Energy Label

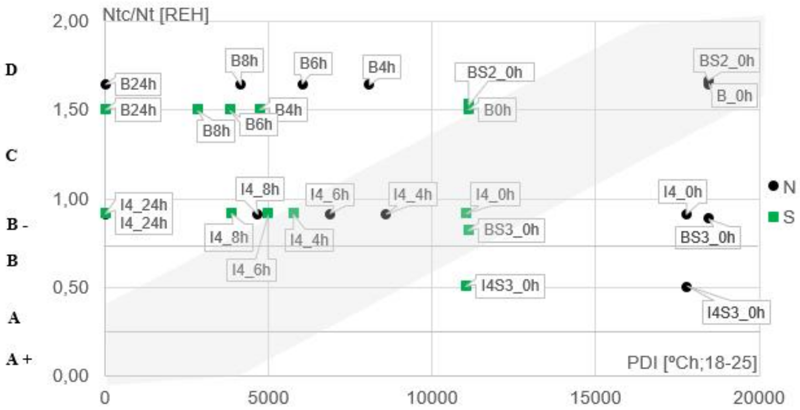

Figure 8. PDI vs. Energy Label (REH)

In B approach, it's possible to observe, in Figure 8 now considering all scenarios, there isn't any visible relation between the energy label and the annual discomfort (the expected relation should be in the grey area). Also, the technical system plays an important role on the label assigned, regardless the discomfort of that scenario. And a better energy label does not always mean a lower discomfort. For instance, I4S3_0h (north) is an A label, but presents a higher discomfort than I4_0h (south), that is a B, both non- heated. Considering extreme cases, the same north orientated dwelling, can present totally different discomfort levels, from 0 to almost 20000ºCh (B24h and BS2_0h), despite always being a D label. If 4cm of insulation are introduced, the label is improved for an A, but the discomfort remains the same if it is not heated.

5. Conclusions

From the results presented on the previous chapter, it is possible to conclude:

- In intermittent heating scenarios - the most common on southern Europe -, insulation thickness (when placed by the interior side) has a negligible impact on winter discomfort hours, for Porto climate; for free-floating scenarios, it is irrelevant to place insulation at all; this raises the issue of the real interest of the ever-increasing insulation thicknesses imposed by the regulations, for these climates and for existing buildings;
- There are multiple variables that have a much higher impact on annual/winter discomfort hours, than insulation thickness, such as orientation and the heating profile;
- There is a logarithm relation between discomfort/energy and the heating profile; this means the number of heating hours have an ever-decreasing impact on winter discomfort reduction (or energy increase);
- There is no evident relationship between the energy label, obtained from the national regulation transposed by EPBD, and the annual discomfort level, considering intermittent heating scenarios on winter;
- For this reason, a complementary approach to energy is needed to evaluate the thermal performance of existent residential buildings, especially when located in temperate climates, where intermittent heating habits prevail.

Acknowledgements
This work was financially supported by: Project POCI-01-0145-FEDER-007457 - CONSTRUCT - Institute of R&D In Structures and Construction funded by FEDER funds through COMPETE2020 - Programa Operacional Competitividade e Internacionalização (POCI) – and by national funds through FCT - Fundação para a Ciência e a Tecnologia; SFRH/BD/96068/2013.

COMPETE 2020 PORTUGAL 2020 UNIÃO EUROPEIA Fundo Europeu de Desenvolvimento Regional FCT Fundação para a Ciência e a Tecnologia

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