Combining embodied and operational energy in buildings refurbishment assessment

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ABSTRACT

Buildings' refurbishment is becoming a major trend in civil construction in Europe. At the same time European environmental and cultural commitments are being transposed to building and urban regulations. Energy efficiency and heritage safeguarding are two objectives of buildings' refurbishment policies which do not always lead to the same refurbishment options. Energy efficiency assessment is not always suitable to existing buildings in different local contexts and, while focusing on operational energy, it does not include embodied energy in buildings.

This article calculates and combines embodied energy and operational energy, proposing a methodology for the assessment of building components life-cycle energy, suitable for the assessment of repairing and replacing scenarios. The methodology is applied to a case study, comparing walls repair or replacement and considering different scenarios of users' requirements of thermal comfort. Results show the advantages of preserving building components and materials in terms of whole life cycle energy demand.

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1. Introduction

Refurbishment of urban buildings is important in the context of the densification of existing cities. In European and Portuguese cities, refurbishment of single buildings is a growing activity [26] but part of the urban building stock is being refurbished without evidence of concern for cultural or environmental values.

Regarding environmental values, the main concern of the promoters is energy, because of the legal framework for the energy performance of buildings [15]. However, this legal framework considers only operational energy and has some limitations, making it not always suitable to older buildings and to the southern European socioeconomic context and climate [29,38]. Additionally, environmental performance of refurbished buildings can also be regulated through voluntary environmental schemes (as BREEAM or LEED) which are not specific for refurbishment works.

In terms of cultural values, there is no legal framework, except for the listed heritage buildings and sites [22]. Hence, the evaluation of not listed urban heritage legacy is affected by public perceptions of urban space, and this perception often concerns only

the exterior of buildings [5]. However, buildings may contain relevant cultural values and environmental resources that go beyond the building envelope and influence energy demand [8,22].

With the aim of providing scientific support to decision in urban buildings refurbishment, the specific objectives of this study are: to increase knowledge on the energy value of construction elements, demonstrating the advantages of repairing buildings; and, to highlight the potential rebound effects of energy refurbishment actions which replace construction components that may have an important role in the buildings thermal performance [35].

Energy efficiency and heritage safeguarding are two objectives of buildings refurbishment policies which do not always lead to the same refurbishment options [8,34]. Energy refurbishment of buildings concerns energy-efficiency and primary energy demand savings [24]. Measures for the building envelope have been widespread in Europe in the context of climate change mitigation and "decarbonisation" initiatives [1]. However, in general building archetypes used to estimate the cost-efficiency of energy measures do not cover older buildings types [51]. Additionally, certification methodologies are not always suitable [29] and the environmental or economic effects of energy refurbishment are not always as expected [17,45]. Building refurbishment works include repairing and replacing components [6] but usually are not submitted to any specific environmental regulation.

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This article gathers information and produces knowledge about the energy impacts of different refurbishment options aiming to support decision makers and technicians.

2. Framework

2.1. Life-cycle energy in buildings refurbishment

In an ecological perspective, energy assessment in buildings should consider the whole life-cycle of the building to avoid contradictory conclusions from the isolated evaluation of embodied or operational energy [11].

There is an already established physical life-cycle model for buildings in Europe, presented in EN 15804:2012 [7] and EN 15978:2011 [6]. According to this model, a building's life cycle consists of four main stages: product stage (A1-3), construction process stage (A4-5), use stage (B) and end-of life stage (C). The use stage includes the modules of repair (B4), replacement (B4) and refurbishment (B5). The refurbishment module covers the combination of all actions taken during the service life of a product associated to the return of a building or their parts to a condition in which it can perform its required functions. These actions cover maintenance, repair and/or replacement works.

In Portugal, buildings' refurbishment has recently assumed a higher importance in the construction sector [26] increasing the possibilities of reusing buildings (and its components and materials) rather than replacing them and building new ones. Many of the existing buildings (built until 1940) contain heavy construction systems, with embodied energy related to traditional processes of construction [40]. These are passive buildings with low operational energy needs and with high embodied energy from long lasting materials.

It is important to notice that European pre-industrial buildings can last hundreds of years [40]. During this long life, buildings are submitted to maintenance, refurbishment and transformation processes, as well as to new comfort requirements, which add embodied energy and change the operational energy of the building [2]. Therefore, building refurbishment research studies comprising embodied and operational energy often give a high importance to building integrated technical systems (BITS) [24].

Since the diversity and extension of data involved in the life cycle energy of a building is significant, it is important to consider the main types of energy in the main stages of the building life cycle: embodied energy (materials extraction and manufacturing, construction, maintenance and repairing, replacement and refurbishment works); operational energy (related to occupancy patterns, comfort requirements and types of use; and, end of life (demolition, transport, disposal and eventual recycling or reuse of materials).

Operational energy was for a long time taken as a key issue for energy efficiency and primary energy savings for new construction in Central and Northern Europe (where energy needs for thermal comfort is very high) [11]. More recently, literature on sustainable buildings shows that the proportion between embodied energy and operational energy is variable in different types of construction of dwellings [28]. Additionally, in southern Europe several factors constrain operational energy-efficiency achievements and cost-efficiency of energy refurbishment measures, like the mild climate and the higher energy prices in relation to the population's income [18,31].

It may be assumed that where energy needs for thermal comfort are relatively lower, embodied energy increases its relative importance in life-cycle primary energy savings.

Additionally, there are variations on the service life of each building component which may influence the life cycle energy accounting [12]. The service life of materials depends on the type of construction element, the situation of the construction element and the position of the material layer within the construction element [24]. The approaches for aggregating the different forms of primary energy resources also have a great influence on the life cycle energy results [23].

2.2. Embodied energy

2.2.1. Product embodied energy

According to [11] "*The fact that each building is unique with a long dynamic life-cycle makes embodied impact comparisons across studies difficult*". Dixit also refers that key methodological parameters for measuring embodied energy in buildings include system boundary definitions, methods of embodied energy measurement, and type and form of energy included in calculations (Table 2).

The common system boundaries for buildings and building components are "cradle-to-gate", "cradle-to-site", "cradle-to-handover", "cradle-to-end-of-use", "cradle-to-grave". For environmental products declarations (EPD) only the embodied energy in initial product stage (A1-3 in EN 15804 and EN 15978) is mandatory and accounted "cradle to gate" in data bases of embodied energy in construction materials (ICE [27]). Beside the selection of system boundaries, also the estimated service life of components and the reference study period are important parameters that influence the results [23]

Moreover, buildings comprise materials in different quantities and therefore it is not enough to know the embodied energy of each product by weight or volume, as presented in data bases. Because few studies concern embodied energy in refurbishment and demolition [53], specific measurements of volumes and weights in the assessed building must be developed based on technical data [16].

Essential steps to measure embodied energy in existing buildings concern the inventory of materials quantities and allocation the embodied energy to those quantities. In these steps, different sources of data and levels of uncertainty are involved (Section 2.2, Table 2). The inventory of building materials in a functional unit requires data from the building plans, specifications and construction technical tables. It includes the tasks of: identifying components; measuring surfaces and volumes of components; disaggregating components in materials; calculating quantities of materials in each component; and finally, converting material volumes into weight (Table 3, Table 4).

Further on, the allocation of embodied energy to the materials inventory requires the selection and combination of reference values from data bases and literature (Table 1) or the gathering of primary data (inquiring manufacturers). These values can present variations and can comprise different fractions of energy [3,11,43]. The sources used in Table 1 consider feedstock energy and renewable energy [27].

Reference values of embodied energy are often obtained in environmental products declarations [7] but are rarely available in historical sources or for pre-industrial building components. Thus, the embodied energy of the older buildings' materials must be accounted based on current production processes. The embodied energy assessment of pre-industrial materials and components in the case study of this article was developed using the reference values of the energy used to produce those materials nowadays.

Either for calculating initial, or refurbishment embodied energy in buildings' components, there is the need of measuring materials specific volumes and weight before using general embodied energy reference values. Data sources for measurements are technical plans or BIM, detailing plans, architecture project specifications or technical descriptions of products. Data sources for reference values are technical tables or specific literature, data bases and liter-

Table 1
Reference values for embodied energy in construction materials.

Material	Density	Embodied energy GJ/ton								
	kg/m³ [43]	Pinto,2008		Average 1	Azpillicueta, 2018 [4]		Average 2	ICE, 2017		Mean Average
		min	max		min	max			calc.	
Sand	1500	0,03	0,93	0,48		0,10	0,10	0,15		0,24
Aggregate	1700					0,10	0,10	0,11		0,11
Lime	1700		5,27	5,27		5,60	5,60	4,24		5,04
Lime mortar	1600					1,78	1,78	–	1,50	1,64
Stone (compact)	2200		0,80	0,80		3,58	3,58	1,00		1,79
Stone (Limestone)	1500		0,80	0,80		1,64	1,64	0,37		0,94
Wood/Timber	600	0,52	2,50	1,51	3,00	7,10	5,05	9,43		5,33
Cement	1800		4,30	4,30		7,00	7,00	5,32		5,54
Cement mortar	2000				1,00	1,34	1,17	1,54		1,36
Concrete	2400				0,99	1,10	1,05	–	1,33	1,19
Reinforced concrete	2500		2,80	2,80		1,64	1,64	–	2,56	2,33
Clay Bricks	1700	1,00	9,40	5,20		4,50	4,50	3,00		4,23
Bricks masonry	1200				2,85	2,96	2,91	–	2,27	2,59
Wood/ OSB	650		11,00	11,00		8,88	8,88	14,95		11,61
Steel	7800	24,00	59,00	41,50	35,00	54,00	44,50	31,25		39,08
Glass	2500	13,00	31,00	22		19,00	19,00	20,08		20,36
Gypsum board	900					3,15	3,15			3,15
Polystyrene	18		50,00	50,00		100,00	100,00	104,03		84,68

ature (Table 1), products specifications, and inquiries to manufacturers and historical sources.

The Building Integrated Model (BIM) can simplify these measurements through the 3D modelling of buildings and data assignment and can help supporting Buildings' Life Cycle Management [48]. However, in general, it is easier to apply BIM to new buildings than to pre-existing ones, since the modelling and data inputs are made according to the project development and its specifications. In case of refurbishment of pre-existing buildings, built prior to the BIM use, the modelling and data allocation must be developed from scratch, over previous plans and specifications, collected for the purpose.

2.2.2. End of life energy

End of life energy comprises energy spent on demolition, transport, waste processing, disposal or eventual recycling of construction materials [6]. End of life energy of materials which are removed in refurbishment works can be accounted as recurrent embodied energy, if repeated along the components life-service [12].

Regarding transport, research and data bases provide reference values of energy spent by trucks (e.g. EcoTransIT World Initiative (EWI) [25]), per volume transported (in this case waste). Waste treatment and disposal energy refers to selective demolition and treatment processes for mixed materials, mostly to avoid contamination. These processes occur only in very specific materials and are rarely accounted [52].

Recycling energy corresponds to the energy used for recycling materials, when there is selective demolition or removal. It depends on the types of materials, technologies and practices used ([37], 60), [30]. Heavy construction materials, as stone, are turned into aggregates but the rate of its effective reutilization in Portugal is still low, corresponding to less than 10% [10]. In order to avoid double counting of embodied energy it is assumed that the energy related to the recycling of a material (e.g. stone crushed for aggregates) is accounted as embodied energy of the recycled material itself, meaning it will be part of the embodied energy of the new construction.

2.3. Operational energy

Operational energy corresponds to the energy demand for achieving comfort and well-being in a building during its use. The main functions in a building considered in the use of a building are: heating, cooling, ventilation and lighting. In some buildings in mild climates operational energy demand can be reduced only through passive measures, without relying on building integrated technical systems (BITS) [35].

Briefly, it can be considered that there are three main ways to diagnose and assess operational energy performance in already existing buildings [33]: through direct audits and monitoring; through building energy simulation software and, basing on energy certification schemes and statistic calculations. Some authors consider that building simulation should always be complemented by direct measuring, energy consumption data analysis and comfort inquires [32] and that often traditional buildings perform better than expected in terms of operational energy simulation [17].

Operational energy demand depends, beside other factors, on users' requirements, behaviour and expectations. In southern Europe climate, construction traditions, social and economic factors, can explain a low operational energy demand for comfort. Conflicts between winter and summer, as well as between cold and mild climates, are a barrier to the definition of universal optimal operational energy reduction measures [36].

While the initial focus of building operational energy simulation tools was primarily applied on the design phase, nowadays it is becoming increasingly more relevant in post-construction phases of the building life-cycle, such as commissioning and operational management and control, and also to perform refurbishment analysis and assessment [9]. One of the primary benefits of detailed simulation models is their ability to predict system behaviour given previously unobserved conditions. This allows analysts to change the building design or operation while simultaneously monitoring the impact on system behaviour and performance.

3. Methodology

3.1. Buildings refurbishment life-cycle energy

This article proposes and tests a methodology for the calculation of buildings refurbishment life-cycle energy, focusing on certain life cycle stages modules, as defined in EN 15804 and EN 15978: products embodied energy (modules A1-3 and B3-5); end-of-life energy (modules C1-C2); and space heating and cooling operational energy (module B6) (Fig. 1).

On the one hand this methodology excludes the energy related to construction processes (modules A4-5), since pre-industrial
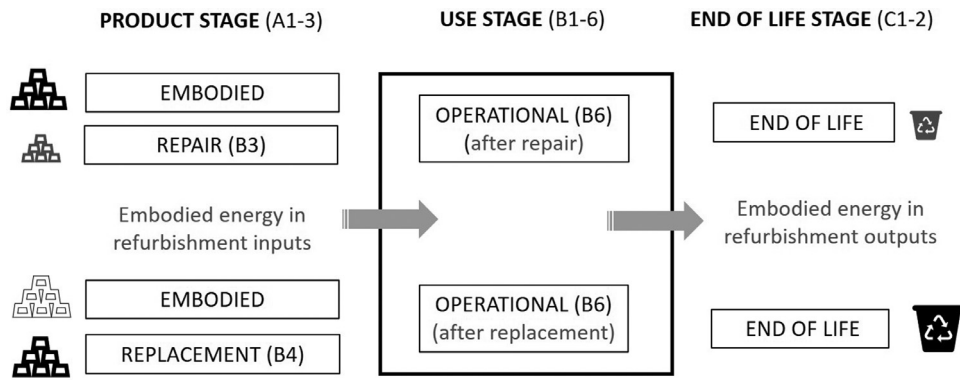
PRODUCT STAGE (A1-3)   **USE STAGE** (B1-6)   **END OF LIFE STAGE** (C1-2)

Fig. 1. Energy stages considered in the methodology and EN 15804 modules included.

Table 2
Identifying uncertainty fields and response.

	Uncertainty field	Key issues	Guidelines for the case study
System boundary	Method used	cradle to gate, cradle to site, cradle to grave; construction energy, recurrent energy, demolition energy	Only cradle-to-gate embodied energy in walls materials is accounted
	Building description	ways to calculate volumes and weights; geometrical disaggregation of components	Walls are drawn and disaggregated in CAD and volumes are estimated
	Service life	Building and components life service; level of maintenance and replacement; owners refurbishment options	100 years for heavy construction before refurbishment; 50 years for its repairing or replacing elements
Embodied energy reference values	Method used	Input-output model; process-based; hybrid; statistical analysis.	
	Energy inputs	primary and delivered energy; renewable and non-renewable energy feedstock energy, labour, human energy and capital energy; recovery of energy	Depending on data sources of reference values of embodied energy
	Data representativeness	Change in energy intensities of transportation, power, manufacturing, and construction industry over time	Industrial reference values used for pre-industrial materials

buildings construction processes were mainly based on human and animal labour. On the other hand, it excludes waste processing and disposal (modules C3-4), since demolition waste in Portugal is mainly disposed in landfill [10] and the energy associated to waste processing in landfilling is residual.

On chapter 4 this methodology is applied to building components in a case study, calculating and summing embodied energy, end-of-life energy and operational energy. Cumulative life-cycle energy demand is obtained in two refurbishment options combined with three thermal comfort users' requirements (Eq. 1, Fig. 4).

Proposed calculation of building refurbishment cumulative life-cycle energy demand

$$BRLCE = \left(\sum \text{Products Embodied Energy} \right.$$
$$\left. + \sum \text{End of Life Energy} + \sum \text{Operational Energy} \right) \quad (1)$$

3.2. Specifications for buildings refurbishment life-cycle energy calculation

3.2.1. Embodied energy: production and end-of-life

Materials embodied energy calculation: Selecting and combining embodied energy reference values comprises several uncertainty fields, related to: subsystem boundaries (products and processes embodied in buildings components); method of embodied energy calculation used (in the sources); and, types and forms of energy inputs considered [11] (Table 2).

This section explains the options taken for the methodology application to the case study. Calculations developed in this article

focus on the inner and outer walls of the building, delimiting a subsystem and highlighting its role in the energy and environmental performance of the building. Concerning the system boundary a three step approach was followed: selecting key products and processes (inner and outer walls materials production); developing a vectorial geometrical inventory of components (with CAD software); and, identifying all the materials contained in the component, using specific density values from technical tables [16] also for traditional materials and pre-industrial construction systems [16,41,42,44].

Concerning materials' embodied energy, an average of reference values was produced (Table 1). Data representativeness problems, related to change in energy intensities of the construction industry over time, are significant since construction systems had discontinuities of more than 100 years. Since it was not possible to collect reliable data about energy spent in the 19th century construction industry, industrial reference values were used for pre-industrial walls.

End-of-life materials energy calculation: In this study, end-of-life energy assessment includes demolition and transport energy (modules C1 and C2 from EN). Demolition energy includes the energy spent to dismantle the building or the components of the building to refurbish. Transport energy refers to the energy spent to transport the waste materials to disposal or recycling.

Though the data about the energy spent to dismantle buildings is critically scarce in literature, a source was found that assessed the demolition energy of residential building [50]. That energy ratios (kWh/m3) for the demolition was used for the case study presented in this paper, after converting to primary energy using the efficiency of diesel refining estimated in [20].

For the waste transportation it was used the Eco Transit on-line tool [25]. This tool allowed the estimation of the fuel spent by trucks to move waste until the nearest existing disposal site in Lisbon (15 km), considering the well to wheel (WTW) analysis. WTW refers to specific lifecycle analysis applied to transportation fuels and their use in vehicles and it includes resource extraction, fuel production, delivery of the fuel to vehicle, and end use of fuel in vehicle operations.

3.2.2. Operational energy simulation: space heating and cooling needs

Building energy simulation (BES) models using forward approach, involves the prediction of the output variables using detailed structure and parameters of the model subject to a specific set of input variables. Such models are highly accurate as most of the energy transfer processes are mapped while developing the BES modelling structure. Also, with increased trends of sophistication in computing techniques, BES models with high accuracy have been possible. Forward modelling of BES is practiced in the stages of preliminary design and analysis during energy audit process. The step-wise procedure example for forward approach modelling is given below (adapted from [21]) and was followed in this paper.

- Step 1: Acquire Climate data as per location of the building under study.
- Step 2: Acquire building design data.
- Step 2.1: Acquire building geographical characteristics: location, orientation, etc.
- Step 2.2: Acquire building construction data: Thermo-physical properties of the building materials, etc.
- Step 3: Heat plant characteristics
- Step 3.1: Type of HVAC system
- Step 3.2: Type and characteristics of the HVAC subsystems: Air Handling units, Coil units, etc.
- Step 4: Building operating schedules
- Step 5: Simulate the model as per the desired simulation periods
- Step 6: Predict the net energy (peak or average values) consumption patterns.

To analyse the effect of different envelope solutions, BES models constitute a very useful tool since they can predict the thermal behaviour and the thermal needs for heating and cooling in small time frames (e.g. one hour). It is then possible to assess the space at a different outdoor environmental condition along the year.

Table 3
Material volumes and weight in walls in the case study: Original pre-industrial heavy construction.

	Material	m³	ton/m³	Ton
External walls	Stone - compact	0,66	2,20	1,45
	Stone - masonry	49,44	1,50	84,05
	Brick (openings)	3,60	1,32	4,75
	Lime mortar	13,50	1,73	23,35
Inner walls (F)	Wood	2,15	0,60	1,29
	Stone - small parts	0,72	1,79	1,28
	Bricks - small parts	0,72	1,32	0,95
	Lime mortar	0,72	1,73	1,24
Inner walls (T)	Wood	4,03	0,70	2,82
	Lime mortar	1,34	1,73	2,32
TOTAL		**76,87**	**1,61**	**123,51**

3.2.3. Constraints of the methodology

This is an inclusive methodology in what concerns to energy types and to building life-cycle energy stages. It is possible to apply this methodology to the assessment of the repair or replacement of several components of the building. The application of this methodology to the case study is selective and focus on elements of pre-industrial construction that may be important for the thermal performance of the building and that are often being removed in refurbishment works without enough assessment.

4. Case study

4.1. Original building context

The studied building was constructed in the pre-industrial Lisbon (at the location in Fig. 2). Its construction is characterized by external walls of stone and lime masonry and inner walls of wooden structure, filled with smaller stones, bricks and lime mortar. Inner walls are constructed in a crossed compact wood structure (*frontais de cruzes de santo André* - F inner walls, Table 3) or in boards (*tabiques* - T inner walls, Table 3) constructed with remaining wood from the primary inner walls. This construction system was current in Lisbon during all the 18th and mid 19th centuries and it is the antecedent of a sophisticated anti-seismic system conceived for the city's reconstruction after the Earthquake of 1755 (*gaiola pombalina*) [44].

The studied building was constructed around the beginning of the 19th century and enlarged in 2016 (Fig. 3, left). It has two original floors constructed with heavy pre-industrial components, based on stone and wood, and a third added floor constructed with industrial components, based on concrete and light weight wood strand panels. The coincidence of these two types of construction

Fig. 2. Case study location in Lisbon.

| Circa 1900-2015 | 2016 | Circa 1800 | 2016 |

Fig. 3. Building for case study (left) and second building for additional comparisons (right).

Heavy pre-industrial construction
Repair Option

Light weight industrial construction
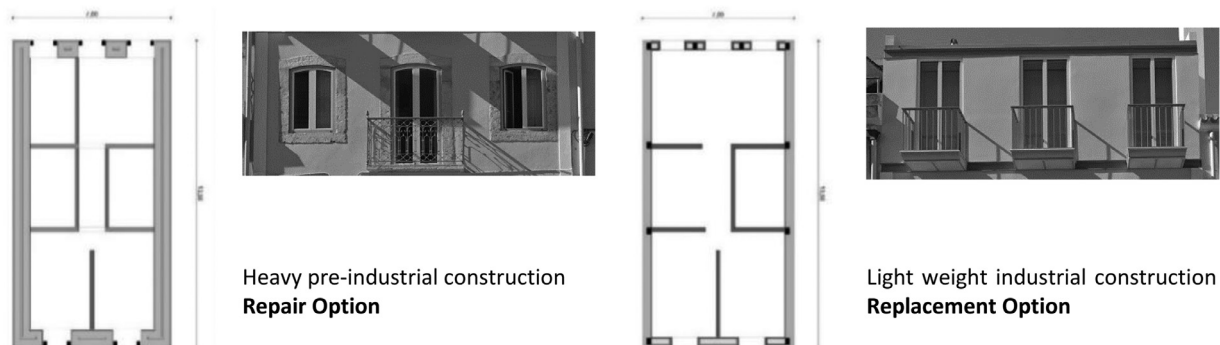**Replacement Option**

Fig. 4. Simplified plans of the functional unit in the two refurbishment options.

in the same building motivated the comparison of the refurbishment options, as presented in this paper (4.2.1). This comparison was also motivated by the temperature measurements taken in a similar neighbouring building, showing a very low operational energy, which justified assessing a free float scenario (without building integrated systems) in the case study (Fig. 3, on the right).

4.2. Building refurbishment case study

4.2.1. Refurbishment options: repair or replacement

As case study a functional unit of 94,5 m^2 gross floor area was defined, corresponding to one floor of a dwelling. This functional unit was compared in two hypothetical refurbishment options: 1) the conservation of pre-industrial heavy walls (inner and external), repairing mortars and wood elements in inner walls; and, 2) the full replacement of walls by lighter and insulated walls, based on wood fibre panels (OSB) with reinforced concrete structure (Fig. 4). Walls in the two different refurbishment options have different life-cycle energy (Eq. 3, Eq. 4) and a different life-service (4.2.3). It was assumed that the rest of the climate shell (roofs and floors) is not changing in the two refurbishment options, and therefore is not accounted in this energy assessment.

4.2.2. Scenarios of users' thermal comfort requirements

The functional unit was also analysed and compared in three thermal comfort conditions, which represent different users´thermal comfort requirements that potentially influence the building's energy consumption. Therefore, two indoor temperature setpoints ranges were defined, and, on one third situation, the indoor temperature was not limited by any system (*free-float*) (Fig. 3).

This approach results in three operational energy options: A, representing a more adaptive comfort approach, with the bedroom

indoor temperature setpoint set between 18 and 27 ºC; B, representing a more demanding comfort situation, based in reference temperature indicated in national regulation, in which the considered bedroom indoor temperature setpoint range is 20–25 ºC; and, C, the *free-float* case, where there is no use of heating or cooling systems, and the indoor temperature fluctuates without restriction.

The thermal comfort analysis (applied just for case C) was performed using the adaptive model developed by Matias [32], in which the limits of thermal comfort for Portuguese buildings were estimated by analysing a large number of buildings and occupant's thermal sensations and establishing the relation between the outdoor and the indoor temperatures. This adaptive model adjusted for the Portuguese reality, proposes the indoor temperature limits of comfort (*Tcomf*) for the daily running mean outdoor temperature (*Trm*) (Eq. 2) [31].

For the weather file considered in this simulation, the thermal comfort limits are presented in Fig. 5. The thermal comfort results for the refurbishment options' comparison was defined assessing the hours of thermal discomfort.

Indoor temperature limits of comfort

$$Tcomf \, [°C] = 0,43.Trm + 15,6 - (+/-3°C) \qquad (2)$$

The functional unit comprises only bedrooms and energy needs for options A and B were only calculated when these bedrooms were occupied. Combining the repair (RPR) and replacement (RPL) refurbishment options with thermal comfort users´requirements scenarios (A, B, C) six situations were assessed (LCEA): RPR A; RPR B; RPR C; RPL A; RPL B; RPL C (Fig. 6).

4.2.3. Building components life service and reference study period

Considering the type of building studied, it was assumed that the original walls had lasted previously 100 years and could last

Equation 2 – Indoor temperature limits of comfort
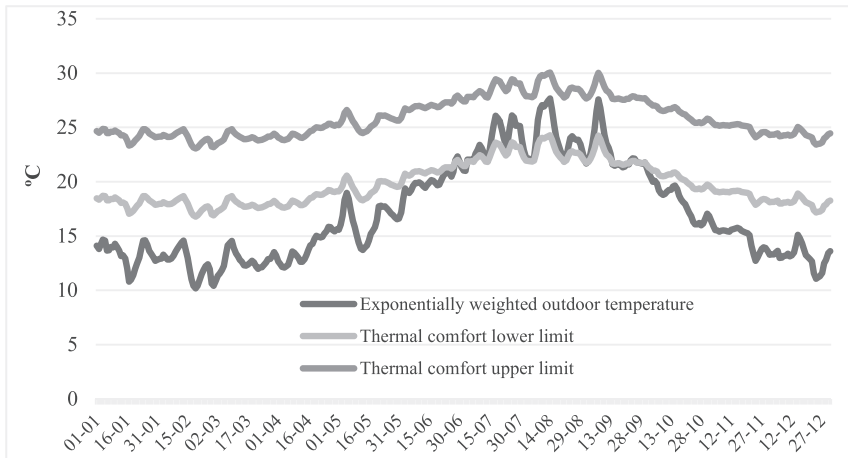
Tcomf [ºC] =0,43.Trm+15,6- (+/- 3ºC)

Fig. 5. Thermal comfort indoor temperature limits for the outdoor exponentially weighted temperature.
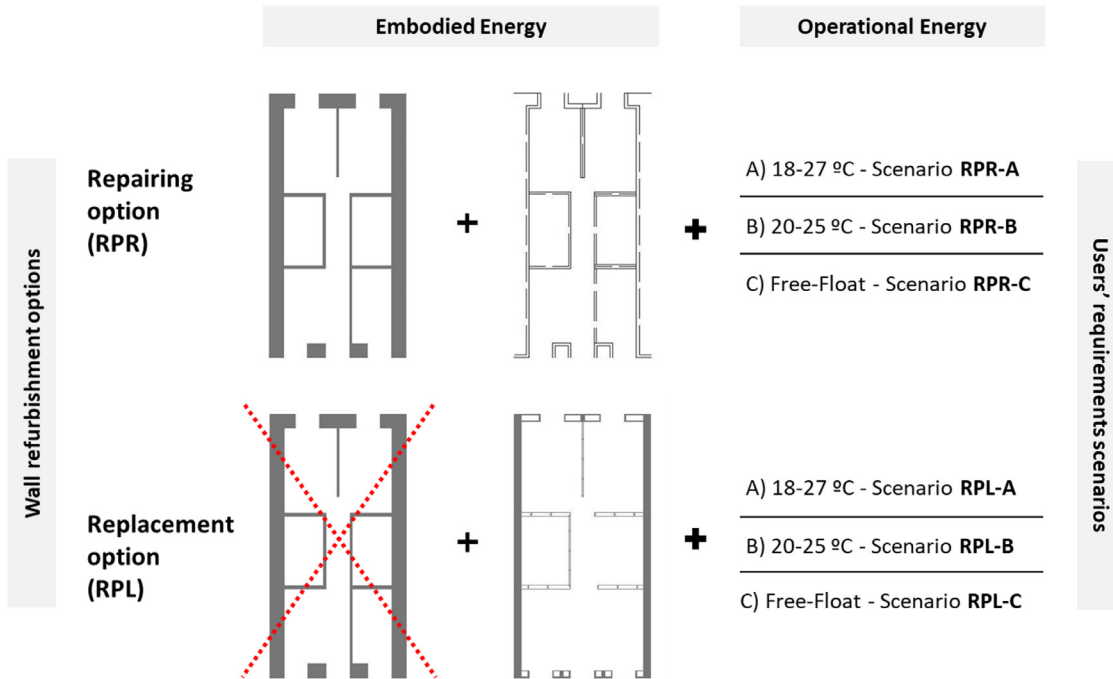

Fig. 6. Case study refurbishment options and scenarios.

100 years more after being repaired. The defined life service of masonry walls was then of 200 years, in the repair option (Eq. 3), as confirmed by the literature [42]. For the replacement option, since the components are removed it was considered a life service of only 100 years (Eq. 4).

For the calculation of the repair embodied energy, materials used in repairing the stone-wood heavy construction were defined as lasting 50 years, according to inspections and works in the building, and considering the longevity of the materials [42]. For the replacement embodied energy calculation, materials used in lightweight construction were considered as lasting also 50 years, according to the literature [12,24]. Thus, walls refurbishment life cycle primary energy demand is calculated for a 50 years reference study period, corresponding to the defined life-service of the refurbishing materials for repair or replacement.

Calculation of LC primary energy demand per year in walls repair option

$$\text{RPR LCE} = \Big(\sum \text{Initial Embodied Energy}/200$$
$$+ \sum \text{Repair Embodied Energy}/50$$
$$+ \sum \text{Yearly Operational Energy}\Big) \qquad (3)$$

Calculation of LC primary energy demand per year in walls replacement option

Table 4
Material volumes and weight in walls in the case study: New lightweight construction.

	Material	m³	ton/m³	Ton
External walls	Reinforced concrete	1,98	2,55	5,05
	Brick masonry	32,40	1,47	47,63
	Cement mortar	1,47	2,14	3,15
	Oriented Str Board	0,78	0,65	0,51
	Cement mortar	1,23	2,14	2,63
	Insulation	1,29	0,02	0,03
Inner walls	Wood structure	1,40	0,6	0,84
	Gypsum boards	1,23	0,9	1,11
TOTAL		**41,79**	**1,46**	**60,94**

Table 5
Initial embodied energy on heavy construction (for Repair).

Components	Material	Ton	GJ/Ton	GJ
External walls	Stone - compact	1,45	1,79	2,60
	Stone - masonry	84,05	0,94	79,01
	Bricks	4,75	4,23	20,10
	Lime mortar	23,35	1,64	38,29
Inner walls (F)	Wood	1,29	5,33	6,88
	Stone	1,28	0,94	1,21
	Bricks (broken)	0,95	2,12	2,00
	Lime mortar	1,24	1,64	2,03
Inner walls (T)	Wood	2,82	5,33	15,04
	Lime mortar	2,32	1,64	3,81
TOTAL		**76,87**	**1,38**	**170,966**

Table 6
Initial Embodied Energy on Light Construction (for Replacement).

Components	Material	Ton	GJ/Ton	GJ
External walls	Reinforced concrete	5,05	2,33	11,764
	Brick masonry	47,63	2,59	123,357
	Cement mortar	3,15	1,36	4278
	OSB	0,51	11,61	5916
	Cement mortar	2,63	1,36	3580
	Insulation	0,03	84,68	2193
Inner walls	Wood structure	0,84	5,33	4477
	Gypsum boards	1,11	3,15	3493
TOTAL		**41,79**	**2,61**	**159,058**

$$\textbf{RPR LCE} = \left(\sum \text{Initial Embodied Energy}/100 \right.$$
$$+ \sum \text{Replacement Embodied Energy}/50$$
$$\left. + \sum \text{Yearly Operational Energy} \right) \qquad (4)$$

4.3. Embodied energy results

4.3.1. Materials quantification

Using the plans of the functional unit (Fig. 4) building materials contained in walls were measured, providing the geometric support for volumes and weights calculation, both in the original pre-industrial heavy construction and in new lightweight construction. The quantification in Table 3 provides weights for the calculation of the embodied energy in the original pre-industrial building components, which will be repaired, while the quantification in Table 4 provides weights for the calculation of embodied energy in the new industrial components for replacement of the previous.

4.3.2. Initial embodied energy

After the measurement of materials, initial embodied energy in the two construction types, associated to the two refurbishment options, was accounted. As Table 5 and Table 6 show, new industrial lightweight construction requires less embodied energy in materials than original pre-industrial heavy construction in absolute values, however in values by weight it requires more energy.

Table 7
Repair and replacement additional embodied energy.

	GJ	GJ/ton
Initial Embodied Energy	170,96	1,38
+ Repair Embodied Energy (RPR)	30,05	2,51
+ Replacement Embodied Energy (RPL)	159,05	2,61

Table 8
End of Life Energy.

	Repair	Replacement
Volume of waste materials (m3)	14	75,3
Demolition energy (GJ)	1,20	6,50
Waste transport energy (GJ)	1,07	5,11
Total (GJ)	**2,27**	**11,61**

4.3.3. Repair and replacement embodied energy assessment

Products embodied energy: For assessing the refurbishment options, first repair embodied energy was accounted (RPR in Table 7) in relation to the initial embodied energy. This parcel represents the embodied energy in mortars and wood repairments and it can be recurrent, however, in the case study it was counted only once, to compare momentaneous refurbishment options. Considering the volumes of the repaired materials, the walls repair embodied energy corresponds to 14% of the initial embodied energy of these components.

After, for assessing the second option, replacement embodied energy was accounted considering the initial embodied energy in new components (RPL in Table 7), considering that the existing walls were fully removed and new walls were added. As Table 7 shows, in the repairing option, a small amount of embodied energy is added, while in the replacement option more than 90% of the initial embodied energy is added.

End of life energy: For assessing the wall refurbishment option, the amount of end-of life energy was also counted - corresponding to demolition and waste transport until disposal site (Table 8). In the repairing option the volume of materials removed corresponds to the volume of materials added (14%). In the replacement option, all the initial embodied energy is disposed as waste, requiring higher end-of life energy.

Total embodied energy: Considering the 50 years life-service established, embodied energy demand per year was summed including initial, repair and replacement product energy and demolition and transport end-of-life energy.

4.4. Operational energy results

In order to evaluate the operational energy regarding different walls refurbishment options, a building energy simulation tool was used, allowing to evaluate the heating and cooling needs for the different scenarios proposed. The inputs for the simulation were defined to be as close to reality as possible. A monitoring campaign (air temperature and humidity measurements) was performed and questionnaires to the house occupants were made to infer information about internal gains such as occupation, lighting and equipment as well as their usage schedules. Other relevant aspects that influence the thermal behaviour of the buildings, such as surrounding shading from neighbourhood buildings and window shading materials and use were also assessed and considered.

The energy simulation software considered in this paper was the EnergyPlus® version 6 [13] and the geometry was defined using Google Sketchup 7® [19].

To analyse the operational stage two perspectives were taken. One focused on the heating and cooling needs and the other relying on the thermal comfort assessment. Although the evaluation of the thermal comfort is not part of a typical life-cycle analysis
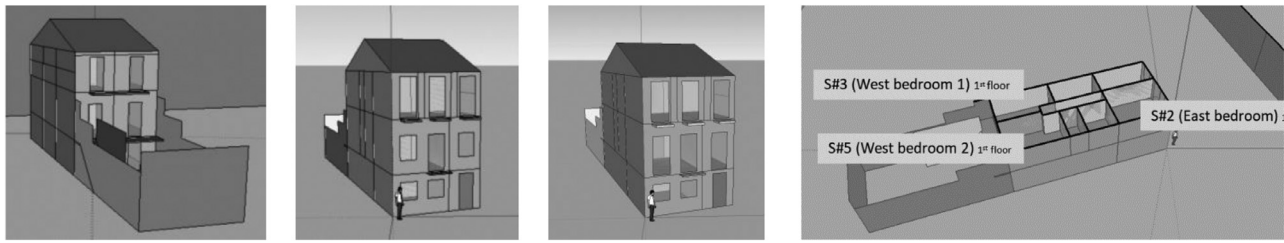
Fig. 7. Southeast view of both scenarios, Northwest view of each scenario and thermal zones of the functional unit (1st floor).

it is relevant to show the influence of the building occupants' behaviour and expectations on the operational energy and to allow the consideration of low (or zero) energy consumptions for heating and cooling.

To evaluate the performance of the two refurbishment options in the different indoor temperature scenarios, an "*Ideal*" air load system was considered in the simulation models to maintain the room indoor temperature within the defined range. The energy necessary to maintain the indoor temperature within the defined range is referred as energy needs (for heating and cooling).

The reference values used for converting the energy needs calculated by the EnergyPlus to primary energy consumption values are presented in Table 11. The efficiency values were defined considering the theoretical performance of a heat-pump for the HVAC. As it was considered a theoretical HVAC equipment for both scenarios the life-cycle analysis for the equipment was not performed. Nevertheless, the embodied energy for the different stages of the life-cycle assessment regarding the HVAC system would be the same for both scenarios.

The following equations were used for the final and primary energy calculations:

Final energy calculation from heating and cooling needs

Final Heating Energy Consumption

= Heating Energy needs/COP;

Final Cooling Energy Consumption

= Cooling Energy needs/EER (5)

Primary Energy calculation from final energy

Primary Heating Energy Consumption

= Final Energy Consumption * PEF;

Primary Cooling Energy Consumption

= Final Energy Consumption * PEF (6)

4.4.1. Building model geometry

The building model geometry differs slightly between the two scenarios to follow their different architectural solutions. The thermal zones areas are presented in Table 12. The building simulation model perspectives, and the main thermal zones, are presented in Fig. 7.

4.4.2. Building simulation inputs

The internal heat gains considered for this simulation are related to people and lighting. There was no equipment in the thermal zones analysed (or their use was negligible), so the internal gains for equipment were considered zero. The internal gains schedules and values were defined to be the closest to the real patterns, being the occupation of the thermal zones (bedrooms) between 21h00 and 8h00. Table 13 presents the values for the internal gains considered in the simulation.

The walls are the key element of this study, representing the main difference between the two refurbishment options: for the replacement option (lightweight exterior walls and higher window-wall ratio) the definition of the wall materials is simple, since the new materials are homogenous and displayed on well-defined layers (the thermal properties were taken from the national guidance document for the thermal characteristics of industrial constructive solutions including thermal insulation materials [39]); for the repair option, since the stone masonry wall is not homogenous, an equivalent thermal conductivity value was calculated accordingly to the thermal conductivity value of each material, weighted by the material volume. The average value for the thermal conductivity of the traditional exterior wall was of 0,86 W/(m °C). The U-value for the two options are presented in Table 14.

The air infiltration rates were calculated using the method [49] from the national regulation for building energy certification [47]. The values are presented in Table 15. The weather file used for the building simulation was the PRT_Lisboa.085360_INETI.epw, for Lisbon, selected from the EnergyPlus® weather site [13,14].

4.4.3. Operational energy assessment for three thermal comfort requirements

Heating and cooling needs: Fig. 8 presents the heating, cooling and total primary energy consumption for the two refurbishment scenarios, considering the case A (18–27 °C) and B (20–25 °C). When comparing the two scenarios for the same setpoint reference, it is possible to conclude that the total energy consumption is very similar for both scenarios, being slightly higher for the RPR scenario. The RPL scenario (lightweight construction) presents lower consumptions for the winter period and higher consumptions for the summer period.

The bedrooms present, during the winter, higher indoor temperatures for the RPL refurbishment. This fact is related to the much higher insulation and therefore lower U-value when compared with the RPR scenario. This results in lower heat losses through the envelope, benefiting from the solar heat gains in the room to achieve higher temperatures. As the indoor temperature is higher when the room is not occupied (and not temperature conditioned), the energy necessary to achieve the temperature setpoint (in this case 20 °C) is lower than compared to the RPR refurbishment option.

The thermal behaviour for the summer period follows the same trend of the winter period, but in this case, benefiting the RPR refurbishment since it results in lower indoor temperatures. The bedrooms present, during the summer, higher indoor temperatures for the RPL refurbishment especially for the east orientation bedroom. This fact is related with the much higher insulation (lower U-value) when compared with the RPR refurbishment scenario and the non-desirable solar heat gains, higher in lightweight construction due to the slightly higher windows/wall ratio. As the indoor temperature is higher when the room is not occupied (and not conditioned) the energy necessary to achieve the temperature setpoint (in this case 25 °C) is higher than compared to the RPR refurbishment scenario.
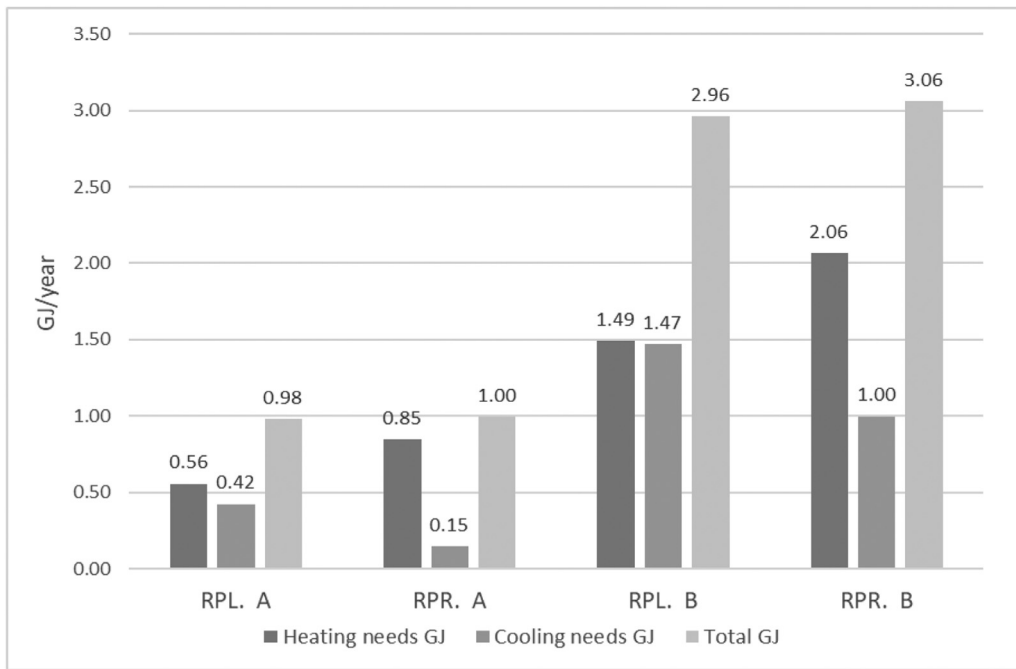
Fig. 8. Heating, cooling and total cooling needs for the two refurbishment options studied.
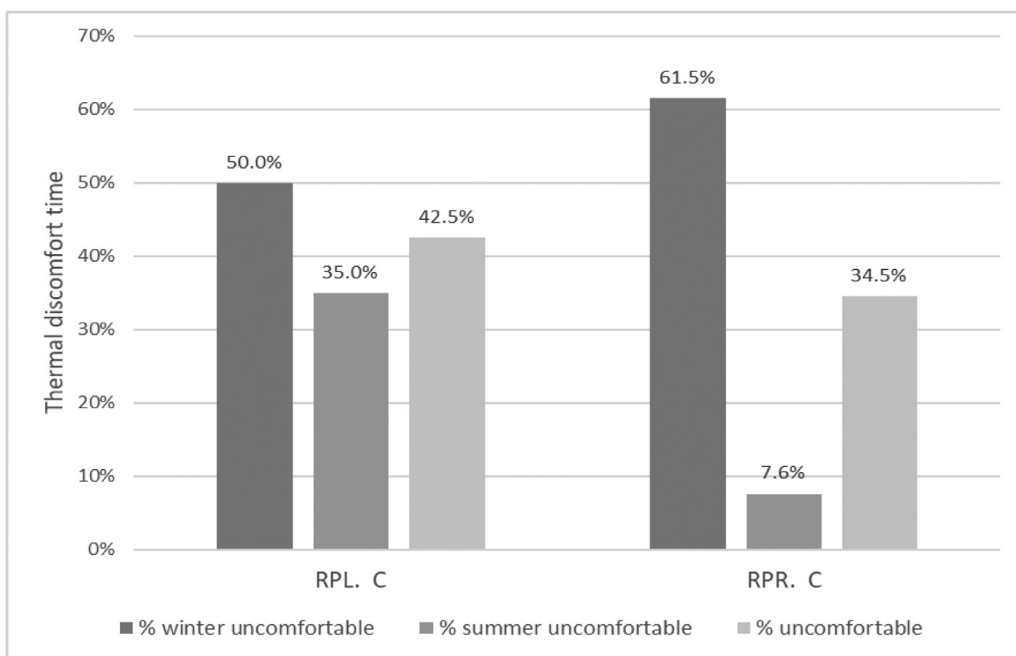

Fig. 9. Thermal comfort analysis when in free-float mode for the two refurbishment options.

Thermal comfort evaluation: When considering that the building is on free-float mode, the energy consumption concerning heating and cooling is obviously zero. The evaluation relied on the thermal comfort analysis between the different refurbishment options. Fig. 9 presents the percentage of discomfort time in one year, for the two refurbishment options, considering the adaptive model.

The following conclusions sum up the results of the case study scenarios operational energy simulation:

- winter: RPL refurbishment option presents less thermal discomfort time when comparing to RPR refurbishment option;
- summer: RPL refurbishment option has a considerable higher thermal discomfort than the RPR refurbishment option;
- overall, the RPL refurbishment option presents a higher thermal discomfort than the RPR refurbishment option.

Table 9
Total Embodied Energy in walls repair options.

	EE (GJ)	EE (GJ/year)
Initial Embodied Energy (200 years)	170,96	0,855
Embodied (50 years)	30,05	0,601
End of Life (50 years)	2,27	0,045
TOTAL		**1501**

Table 10
Total Embodied Energy in walls replacement options.

	EE (GJ)	EE(GJ/year)
Initial Embodied Energy (100 years)	170,96	1710
Embodied (50 years)	159,05	3181
End of Life (50 years)	11,61	0,232
TOTAL		**5123**

Table 11
HVAC equipment efficiency and Final to Primary energy factor.

COP (coefficient of performance for heating)*	3
EER (energy efficiency ratio for cooling)*	3
PEF (primary energy factor)*	2.5

* From [46].

Table 12
Thermal zone areas.

Thermal zones	Area (m²)
(East bedroom)1st floor	15
(West bedroom 1)1st floor	11
(West bedroom 2) 1st floor	13

5. Combined results and conclusions

5.1. Life-cycle energy assessment

5.1.1. Results

As explained in Section 4.2.3, the life cycle energy assessment was developed considering that original components have a life-service of 200 years if repaired and of 100 years if replaced. The life-service of added materials was established of 50 years and the reference study period assessed was also of 50 years. Hence, summing the total embodied (Table 9, Table 10) and operational primary energy demand per year (Fig. 8) the cumulative life-cycle primary energy per year it is obtained, and the different com-

Table 13
Internal gains considered in the simulation.

	Occupation (Number of people)	Lights in occupied area (W)
(East bedroom)1st floor	1	60
(West bedroom 1)1st floor	1	36
(West bedroom 2) 1st floor	2	24

Table 14
Exterior wall thermal properties for the two scenarios.

Exterior wall	Reflectance	U-Factor [W/(m².ºC)]
Repair option	0,6	1,10
Replacement option	0,6	0,35

Table 15
Air infiltration values for the Winter and Summer.

Rph, winter (h⁻¹) Heating*	0,40
Rph, summer (h⁻¹) Cooling**	0,60

Rph, winter (h^{-1}) Heating*	0,40
Rph, summer (h^{-1}) Cooling**	0,60

* from 01/01 until 03/31; from 09/30 until 12/31.
** from 03/31 until 09/30.

binations of refurbishment options with thermal comfort users' requirements scenarios can be compared (Table 16).

5.1.2. Discussion

Combining embodied and operational results lead to the identification of the lower energy scenario: the repair option in a free-float thermal comfort scenario (RPR C), showing that it does not correspond to higher discomfort rates. The more intensive energy scenario is the replacement option with the higher thermal comfort requirements (RPL B). Thus, the lower energy scenario, in terms of combined life cycle energy, is the combination of conserving and repairing building components with the passive use (possible in lower requirements).

Observing the proportion of embodied energy to cumulative life-cycle energy (LCE) (Fig. 10) in each situation, embodied energy presents a high percentage of LCE (83%) in the replacement option combined with the medium thermal comfort requirements (RPL A) but when those requirements are higher this percentage is lower (63%). These results go along the empirical observation of refurbishment trends, where major replacements of buildings are aimed at very high standard housing and where users' behaviours and expectations correspond to high thermal comfort requirements, resulting in intensive life-cycle energy scenarios. Therefore, main
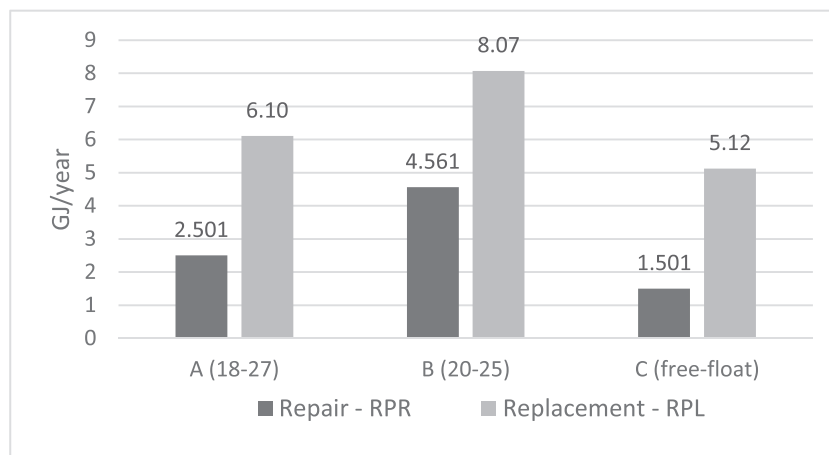

Fig. 10. Cumulative life cycle energy demand in the assessed situations.

Table 16
Life cycle energy per year in the six scenarios.

Scenarios	Embodied energy (GJ/year)	Operational energy (GJ/year)	Life-cycle energy (GJ/year)	% (EE/LCE)
RPR A (18–27)	1501	1,00	**2501**	60
RPR B (20–25)		3,06	**4561**	33
RPR C (FF)		0	**1501**	100
RPL A (18–27)	5123	0,98	**6103**	83
RPL B (20–25)		2,96	**8083**	63
RPL C (FF)		0	**5123**	100

conclusion of this study is that the repair of buildings' components reduces cumulative life-cycle primary energy demand and can also reduce operational energy.

5.2. Conclusions

This article presented an overview of the challenges associated to buildings refurbishment life cycle energy assessment, contributing to the discussion about the energy impacts of conserving and repairing versus removing and replacing building components. We established a framework involving the main stages of energy in buildings (product stage, operational stage and end of life stage) proposing a methodology and testing it in a case study. The methodology was used to develop a comparative assessment of buildings refurbishment options combined with different thermal comfort users' requirements scenarios.

The embodied energy in inner and outer walls in pre-industrial heavy construction and industrial lightweight construction was calculated. The application to the case study using primary sources showed that the case specific quantification of materials contained into buildings components is an important methodological issue.

We also calculated end-of-life energy, focusing on waste material transport and demolition. Moreover, a process to simulate operational energy assessing three different thermal comfort requirements was presented, considering the variations of the users' behaviour and expectations concerning thermal comfort.

With the proposed methodology it was possible to quantify cumulative primary energy demand in the refurbishment process of the selected building components, providing the same detail to operational energy than to embodied energy.

Total results for embodied energy show that there is a significant material and energy loss in replacement scenarios and this loss is not always compensated by lower operational energy results. Operational energy results reveal that adaptive thermal comfort models (18–27 ºC) are compatible with the option of repairing passive traditional buildings.

Thus, pre-industrial heavy construction may provide thermal comfort to their occupants, if adaptive strategies are considered. This is relevant in a country like Portugal where the thermal comfort expectations due to social, cultural and climatic reasons, are not as high as in other European countries. On the other hand, the adaptive thermal comfort models showed that high thermal insulation refurbishment, e.g. for the exterior walls, as in new industrial replacement options, may cause discomfort situations (overheating) during the cooling season.

In this article it was possible to compare refurbishment options considering also the role of social expectations on comfort, covering both the situation of high availability and will to spend energy in comfort, and the opposite situations where users prefer not to spend energy for those purposes. The results show that such different occupants' expectations are reflected in the building energy needs and may suggest different refurbishment solutions.

This study and the associated methodology are of high importance for supporting a more informed and detailed assessment of urban buildings and components refurbishment options, as it can help to prescribe better options for specific urban contexts, weighing life-cycle energy saving goals against heritage safeguarding purposes.

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