Embodied carbon minimisation of retrofit solutions for walls

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Abstract

Energy savings in a building is manly a function of the performance of building insulation and equipment. However, initial embodied carbon (EC) increases as operational carbon decreases and selecting the best energy retrofit solution should take it into account together with building specific needs. Currently there is no regulation of embodied energy/carbon in EU construction. The effectiveness of a low carbon project should be judged by its energy in use together with building specific needs and not the sum total of the energy expended in its retrofit. 3 different buildings, with different occupants' behaviour (a building school from the 80's; a 2sd floor of a multi-family building from the 90's and a dwelling from the 80's) were studied. 5 different retrofit solutions for external rendering of walls were tested. The objective was to establish a relationship between initial EC of a retrofit solution and real operational energy (OE) consumed. A probabilistic approach was developed to predict the number of years that each solution takes to reduce the EC to 0,15kg per kWh of OE produced in each building. The use of cork in mortars represents the most positive measure to reduce EC and increase energy efficiency.

Keywords: Embodied carbon; performance-based design; retrofit solutions; probabilistic approach

1. Introduction:

The building sector contributes up to 30% of global annual greenhouse gas emissions and consumes up to 40% of all energy (Dixit et al, 2010). Thus, mitigation of greenhouse gas emissions from buildings is obviously the cornerstone of every national climate change strategy.

Construction/rehabilitation projects are energy-intensive (Ibn-Mohammed et al, 2013; United Nations Environmental Programme, 2008) which highlight the importance of taking into account embodied emissions in lifecycle emissions analysis of buildings. Currently, the concept of addressing initial embodied energy is not as advanced within the industry and actually, most of the existing studies are focused on improving operational energy efficiency of buildings (Cabeza et al, 2014; Wilde, 2014; Firth et al, 2008; Davies et al, 2015; Iddon and Firth, 2013; Dixit et al, 2010; Davies et al, 2014; Cole, 1999; Brás and Gomes, 2015). However, two another reasons can be pointed out:

- In building construction/rehabilitation projects, savings in embodied CO2 emissions can achieve significant reductions that will take many years to achieve through operational emissions savings alone (H.M. Government, 2010; Dixit et al, 2010).
- Operational emissions reductions depend on the performance of the building. This performance, however, could be lost through sub-optimal management or accelerated refurbishment cycles. Shorter design lives and refurbishment/retrofit cycles increase lifetime emissions. This impact can only be reflected when embodied emissions are considered in lifecycle building emissions analysis (Acuqaye, 2010).

Energy savings in a building is manly a function of the performance of building insulation and equipment. Interventions can be made through passive measures on the building envelope and active measures on building equipment. One of the most significant barriers for achieving the goal of substantially improving energy efficiency of buildings is the lack of knowledge about the factors determining the real energy use.

There is often a significant gap between the designed and the real total energy use in buildings. Factors determining the real energy use are: building envelope, climate conditions, indoor environment conditions, operational activities and occupants' behaviour (Nicolaea and George-Vlad, 2015; Kinnane O, Dyer M., Grey T., 2014; Robinson J., Foxon T., and Taylor P., 2015). Thus, it is necessary to establish a relationship between embodied CO2 emissions and real operational energy consumed in the building, emphasising the importance of energy audits, which take into account the real behaviour of a building. It became obvious the importance of taking into account the embodied carbon in the selection of the best retrofit measures to minimize operational energy of a building.

Here, the development of new facade solutions is a key area for development, since it can respond to the needs of the occupants of both new and refurbished buildings (Kaluarachchi Y., et al, 2005). There are several retrofit strategies. In the field of domestic retrofit it is possible to adopt the following classification (Institute for Sustainability, 2013): whole-house approach (the building acts as an energy system with interdependent parts); the "fabric first" approach (prioritises improvement of the thermal properties of the building fabric); "Passivhaus strategies" (a German-developed standard) and "Insulate then generate" philosophy (very similar to "fabric first" approach since it first aims to reduce energy demand from passive design strategies (building fabric, thermal mass and airtightness, ventilation and heat recovery), and then to meet the remaining demand through the use of microgeneration technologies). It is fairly well accepted that "fabric first" is the most effective strategy for retrofit.

The focus of the EU Building Regulations has been until now on operational energy use to date with embodied energy absent from legislative attention (Directive 2010/31/UE). Currently there is no regulation of embodied energy/carbon in EU construction but in UK a government policy report (HM Government, 2010) has suggested that this should be brought in the regulation framework at some time in the near future once suitable standards for definition and measurement have been established. Attempts to reduce embodied energy of a particular building aspect could lead to material transportation difficulties and changes in the impact of different project life cycle phases.

Building Information Modelling (BIM) will support project stakeholders in the identification of opportunities to improve energy efficiency. It will be made through the creation and use of intelligent databases and 3D models using BIM. However, there are limited comprehensive data available, no coherent method for data capture and little incentive for project stakeholders to reduce initial embodied energy (Davies et al, 2013; BIS, 2010; Ariyaratne and Moncaster, 2014). The results presented by (Bribián et al, 2009) show that cradle-to-gate embodied carbon represents 20–26% (initial embodied carbon) of the total 60 year carbon emissions, with operational carbon representing 74–80% of total emissions. Construction scenarios that reduce operational carbon by improving the thermal envelope led to a 1–13% increase in embodied carbon but a 4–5% decrease in operational carbon compared to the original scenario construction method

The author of this paper propose a performance criteria to help the selection of the best retrofit solution able to minimize embodied carbon and energy and simultaneously to improve the energy efficiency of buildings - with energy retrofit needs.

2. Objectives and motivation

Currently there is no regulation of embodied energy/carbon in EU construction but this should be brought in the regulation framework at some time in the near future. The effectiveness of a low carbon project is judged by its energy in use, not the sum total of the energy expended in its retrofit, nor by the cost of removal and disposal of parts considered to be not sufficiently energy efficient. Such interventions have serious impacts on the fabric of existing buildings where durable elements are replaced with components of shorter life and lower durability.

Therefore, the main objective of the present work is to establish a relationship between embodied CO2 emissions of a retrofit solution and real operational energy consumed in a building, enabling the prescription of effective solutions for building specific needs. The minimum desirable service life of a retrofit solution able to minimise the impact of EC in the building is also take into account. The approach will contribute to the minimization of embodied carbon and energy and simultaneously improve the energy efficiency and minimize condensation effects in existing buildings.

Embodied carbon tends to increases as operational carbon decreases, therefore, a Performance-based design (PBD) using probabilistic approach was develop to predict the number of years that each solution takes to reduce the impact of a certain quantity of embodied carbon as a function of the operational energy in a building. Monte Carlo method was adopted and it took into account the uncertainties of the input parameters, which are explicitly propagated to the uncertainties of the studied performances.

The method for probabilistic analysis and design in this paper is built on some state-of-the-art principles to calculate and analyses the output uncertainty (Macdonald, 2002; Macdonald and Strachan, 2001; De Wit and Augenbroe, 2002 ; Haarhoff and Mathews, 2006; Corrado and Mechri, 2009; Silva and Ghisi, 2014; Vereecken et al, 2015; Faustino et al, 2014a; Faustino et al, 2014b; Faustino et al, 2015).

In order to implement this approach, energy audits were made in three different buildings (situation A, B and C), built in the suburbs of Lisbon:

Situation A: an existing building school from the 80's;
Situation B: the 2sd floor of a multi-family residential building with three floors from the 90's;
Situation C: a dwelling from the 80's.

The development of reference building benchmarks requires some assumptions and data collection, which can prove a difficult task. However, they may be of significant advantage in seeking improvement of energy performance. Detailed energy auditing was done to the buildings including interviews to understand occupants' behaviour during the entire year in terms of equipaments utilisation, construction materials used, energy consumption and lighting (Brás, 2014). The energy consumption of all equipments were recorded individually during 7 days in November and 15 days in February. The results of the predicted energy consumption were then extrapolated for the entire cold season (from October to March) taking into account that data and the information collected during the interviews and the information collected from the energy bills. Energy audits enable the identification of real opportunities to save energy and their objectives are to determine the forms of energy used; to examine how energy is used and their costs; to establish the structure of energy consumption; to determine consumption per division, category, or equipment; to identify opportunities for improving energy performance and analyse technical and economic solutions. Table 1 presents the percentage of power distribution in each situation (A, B and C), according to the energy audit results. Figs 1-3 present a view of each building presented in Situation A, B and C.

Table 1 – Percentage of power distribution in each situation (A, B and C).

	% Power		
	A - School	B - Residential building	C - Dwelling
Lighting	0.7	11.3	13
Climatization - heating season	96.5	24.2	21.2
Electrical appliances for kitchen	0.5	32	39
Office equipments	2.3	7	11
Laundry equipments	0	25.5	15.8
TOTAL	100	100	100

Fig.1: Front side of the school – Situation A.

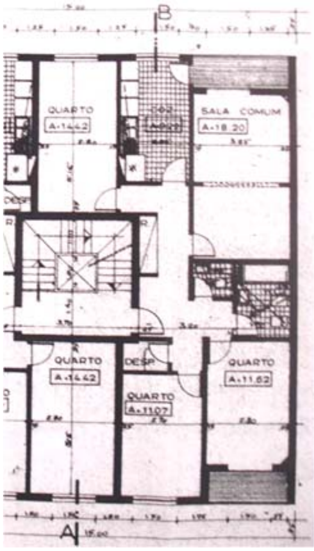

Fig.2: The 2sd floor of a multi-family residential building with three floors from the 90's - Situation B.

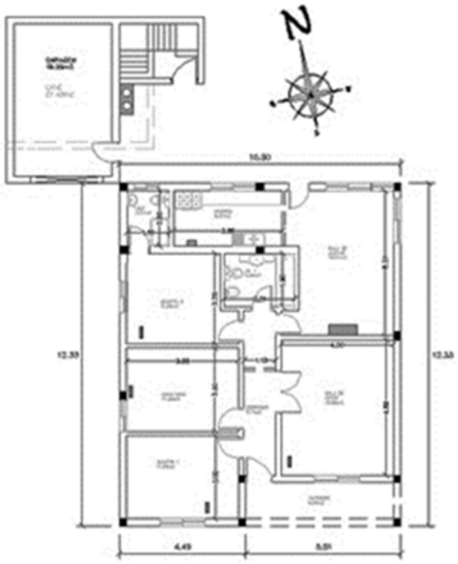

Fig.3: A dwelling from the 80's - Situation C.

The structural details of the 3 buildings are presented in Table 2.

Table 2 – structural details of the 3 buildings.

Structural element	Characteristics	Thermal characteristics
Support frame	Reinforced concrete (RC)	Without thermal insulation in RC wall
Envelope	Brick walls	No thermal insulation
Roof	Small attic covered by asbestos	No thermal insulation
Openings	Extruded aluminium system with single gazing	Extruded aluminium system: simple glazing
Floor construction on ground	Reiforced concrete (RC)	No thermal insulation

None of the three buildings (A, B and C) present thermal insulation in the building envelops at the original state and all of them present condensations problems. In view of this, several mortars for external rendering were developed and optimized from a thermal behaviour point of view, with the intention to be applied in the external walls and improve thermal behaviour. Cement-cork, cement-EPS mortars and hydraulic lime–cork mortars were analysed and compared with traditional solutions (Brás and Gomes, 2015; Brás et al, 2014; Brás et al, 2013).Thus, five different mortars were studied:

Scenario 0 (Original situation – traditional cement cork mortar) – CRef-CEM II
Scenario 1 (traditional hydraulic lime mortar) – Cref-HL5
Scenario 2 (cement-EPS mortar) – CE70
Scenario 3 (hydraulic lime–cork mortar) – CH70
Scenario 4 (cement-cork mortar) – CC70

3. Influence of initial embodied carbon of a retrofit solution in the operational energy of a building

3.1 Life Cycle Assessment of mortars for external rendering

Several mortars were developed and tested, so it was possible to select the best composition to use in buildings retrofit. Those compositions are presented in the following table (Table 3). Detailed properties of those mortars are presented in (Brás et al, 2014; Brás et al, 2013).

Table 3 – Mortar compositions with CEM II/B-L 32,5N – cork, HL5 – cork granulate (CH) and CEM II/B-L 32,5N – EPS (CE) (expanded polystyrene granulate).

Mortars	Identification	Percentage replacement by of sand by cork/EPS (%)	Thermal conductivity (W/mK)
Ordinary cement mortar (Original scenario)	CB	0	1,7
CC=70%	CC70	70	0,48
Ordinary hydraulic lime mortar	CH	0	0,76
CH=70%	CH70	70	0,10
CE =70%	CE70	70	0,80

Notation: CC – cement-cork mortar, CE – cement-EPS mortar, CH – hydraulic lime–cork mortar, =X% - percentage of cork or EPS.

Life Cycle Assessment (LCA) of mortars were performed using the functional unit of 1 kg, in order to enable comparison between different mortars for the same application. The system boundaries adopted characterize a cradle to gate analysis, which covers all stages - from the extraction of raw material for manufacturing to the (cement and concrete) factory's gate - but transportation and use. LCA was developed using the support platform SimaPro 7.3, which accommodates a wide range of research goals and allow database adaptation, ensuring data adherence to the context of interest.

It was intended to simulate the application of 4 cm thickness of the previous mortars in the external walls for Situation A, B and C. Environmental impact was first estimated per square meter of net area. The following figures (Fig. 4-6) presents the results of initial embodied carbon for each mortar when applied in situations A, B and C.

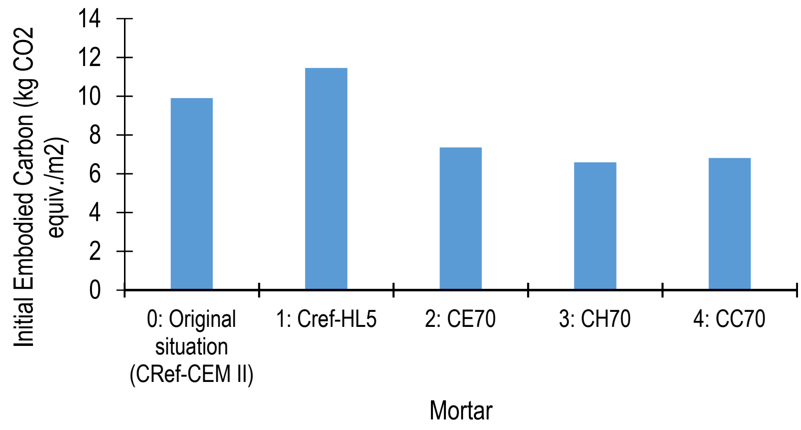

Fig. 4: Initial embodied carbon per m² of net area – Situation A.

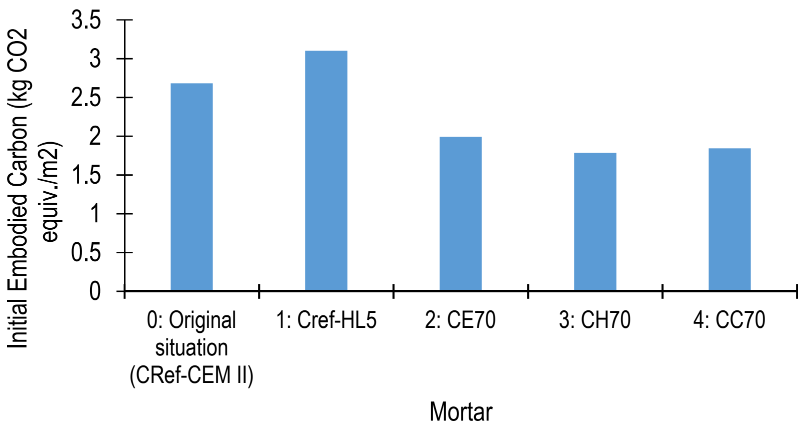

Fig. 5: Initial embodied carbon per m² of net area – Situation B.

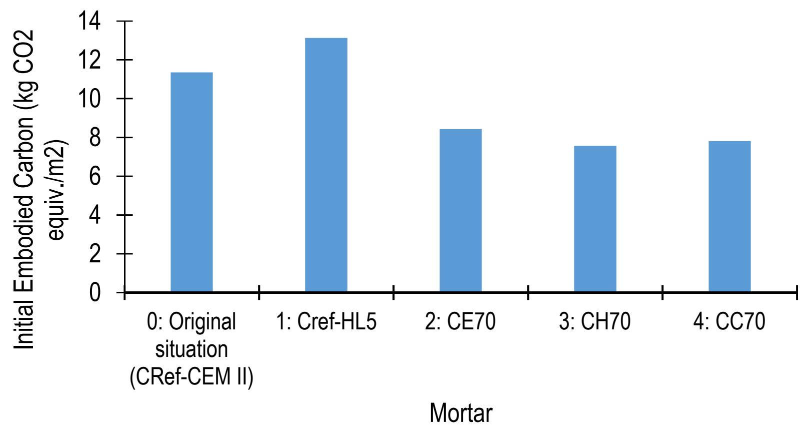

Fig. 6: Initial embodied carbon per m² of net area – Situation C.

Traditional mortars as cement based and hydraulic lime based mortars (CRef-CEMII and Cref-HL5) are the ones that present more initial embodied carbon. The addition of cork granulate represents the most positive measure to reduce embodied carbon.

The use of these retrofitting solutions in Situation A, B or C does not lead to the same embodied carbon. In fact, embodied carbon of Solution A (school) and C (dwelling) are very similar (approximately 8-10kg CO2/m2). On the other hand, Situation B present smaller embodied carbon (approximately 2-2.5kg CO2/m2).

3.2 Economic evaluation of the retrofit solutions

An economic evaluation was carried out concerning the electric energy cost and its annual growing rate in the three buildings, taking into account the previous tested scenarios. Predicted initial investment costs, the maintenance and the predicted energy costs for operational (mainly heating cost) were taken into account and those were divided by the real operational energy cost for heating, according to energy audit data for each building:

$$\frac{C_{g,n}}{C_{real\exp}} = \frac{C_0 + \sum_{x=1}^{n} (C_{manx}(1+\alpha)^x + U \times GD \times 0.024 \times C_{ex} \times (1+\alpha')^x) \times (1+i)}{\sum_{x=1}^{n} C_{real\exp,0} \times x} \quad (1)$$

Where: Cg,n – Global cost in the year n (in €/m²); C_0 – Initial cost in €/m²; $C_{man,n}$ – Maintenance cost adopted (take into account the necessary cleaning work, small repair operations and application of a new wall painting each 7 years: 5.8 €/m2); $C_{real\ exp,0}$ – Real Operational Energy costs for heating in €/m²; GD = degree day (ºC.days); U= is the U-value (Wm^{2}ºC; α = inflation rate (2.77% in 2014); α' = electricity cost rate per year (4%) and *i* = Discount rate (for this private investment, it was used the Euribor rate at 365 days =1.335%).

The initial cost was estimated using the prices data of the construction materials and the necessary manpower to remove the existing external plaster by a new optimized mortar, using the original thickness (Table 4). The prediction of the evolution of the financial costs for the next decades took into account the inflation rate for habitation and maintenance works and the electricity cost rate per year, using the PORDATA data base (Pordata, 2015).

Table 4 - Initial cost of an intervention on field concerning the analysed scenarios (Brás et al, 2014).

Scenario	Situation	Inicial cost (€/m2)
0	Original situation: repair of the existing external plaster	27
1	Cref-HL5	33
2	CE70	37
3	CH70	37
4	CC70	37

Real Operational Energy costs for heating in €/m² presents different values for Situation A, B and C (Table 5).

Table 5 – Operational Energy consumption according to the energy audit made to Situation A, B and C.

	OE_0 (kWh/m2.year)	% of OE_0 for heating
A	50	97
B	67	24
C	25	21

Global Cost of the wall retrofit (€/m2) divided by the real operational energy cost for heating at the original stage was calculated for 30 years after building retrofitting. That behaviour is presented in the following figures (Figs. 7-9).

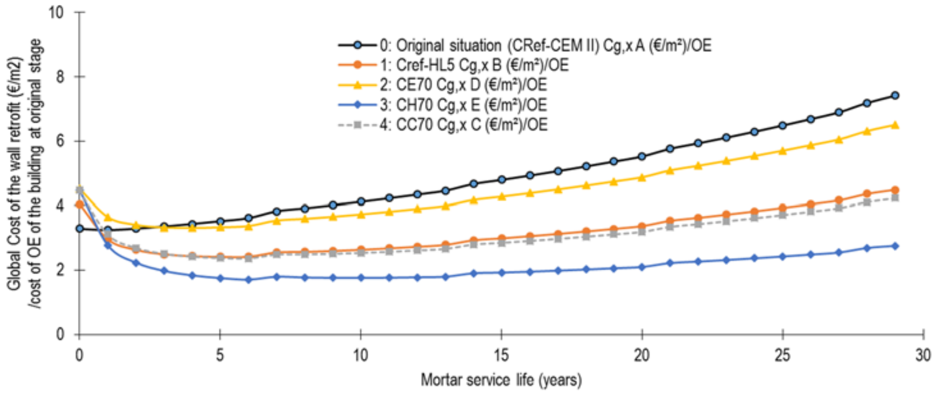

Fig. 7: Global Cost of the wall retrofit (€/m2) divided by the real operational energy cost for heating at the original – Situation A.

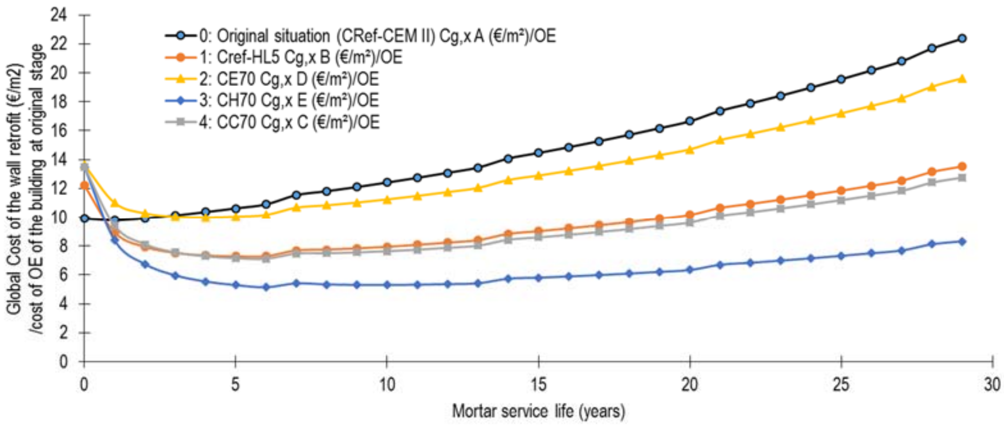

Fig. 8: Global Cost of the wall retrofit (€/m2) divided by the real operational energy cost for heating at the original – Situation B.

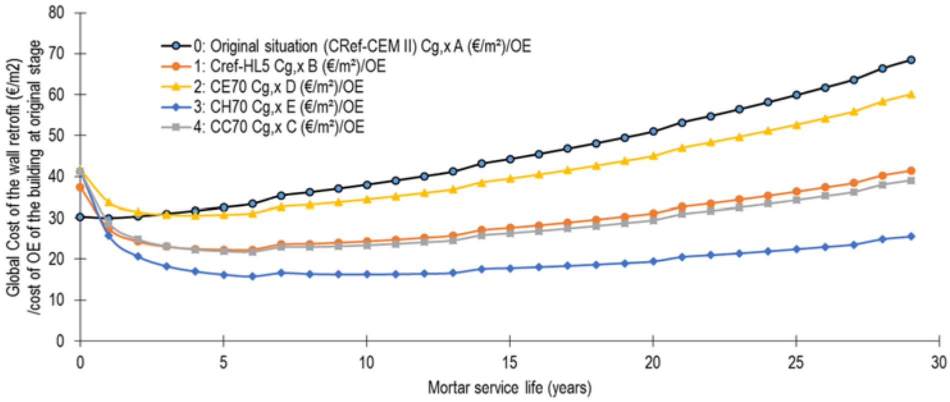

Fig. 9: Global Cost of the wall retrofit (€/m2) divided by the real operational energy cost for heating at the original – Situation C.

Generally, during the first 6 years after intervention, all curves finds their minimum value, which is associated with the relevance of the impact of OE at the original stage. Right after 6 years, those costs are majority affected by economic issues (electricity cost rate per year and the inflation rate).

CRef-CEMII finds its optimum value (the minimum value) 1 year after intervention and right after the costs are majority affected by economic questions, which is non-controlled impact. CRef-HL5 finds the optimum value in 5 years, CE70 in 4 years and the mortar composition with cork (CC70 and CH70) in 6 years. In fact, the previous results show that global cost for CH70 tends to be the smallest one in all situations in only 1 year after building retrofit intervention.

Taking into account the absolute values of global cost of retrofitting divided by the cost of OE of the building at the original stage, it seems that the use of these retrofitting scenarios is more advantage if they are used in the school (Situation A) than in the dwelling or residential building (Situation C and B).

3.3 Influence of mortar service life in the selection of the best solutions for thermal rehabilitation – LCA influence and OE

The effectiveness of a low carbon project is judged by its energy in use and those interventions have serious impacts on the fabric of existing buildings, where durable elements are replaced with components of shorter life and lower durability. Therefore, the goal should start with trying to understand the impact of embodied carbon (ECi_{mp}) of a retrofit solution as a function of OE. The assumption is that the impact of EC decrease with the increasing of a retrofit solution service life. This means:

$$EC_{imp}(x) = \frac{EC \times A_{retrofit}}{xA_p} \tag{2}$$

However, the total OE in a building generally tends to increase for an increasing number of years of the building, which means that:

$$OE(x) = xOE_0 \tag{3}$$

The use of mortars for external envelops causes significant environmental impacts not only due to the fact it is formed by non-renewable raw-materials, but also because the possible reduction of its service life. Mortar service life is directly associated with civil construction environmental liability, which can increase due to the lack of adherence to the substrate, solar exposure, rain and other actions that could affect mortar durability. Thus, in order to understand what could be the influence of a reduction of the mortar service life in choosing the best composition for thermal rehabilitation, the performance criteria should be associated with embodied carbon for all tested mortars as a function of the building operational energy:

$$\frac{EC_{imp}}{OE_0}(x) = \frac{EC \times A_{retrofit}}{x^2 A_p OE_0 H} \tag{4}$$

where EC=initial embodied carbon of each retrofitting solution (kgCO2/m^2); $A_{retrofit}$= retrofit area (m^2); x= solution service life (years); A_p= net area of the building (m^2); OE_0= original operational energy of the building (kWh/m^2); H= ratio of OE used for heating the building (%).

The following figures (Fig. 10-12) present the evolution of Initial Embodied Carbon/ Operation Energy (kg CO2/kWh) for different mortar service life, in Situations A, B and C.

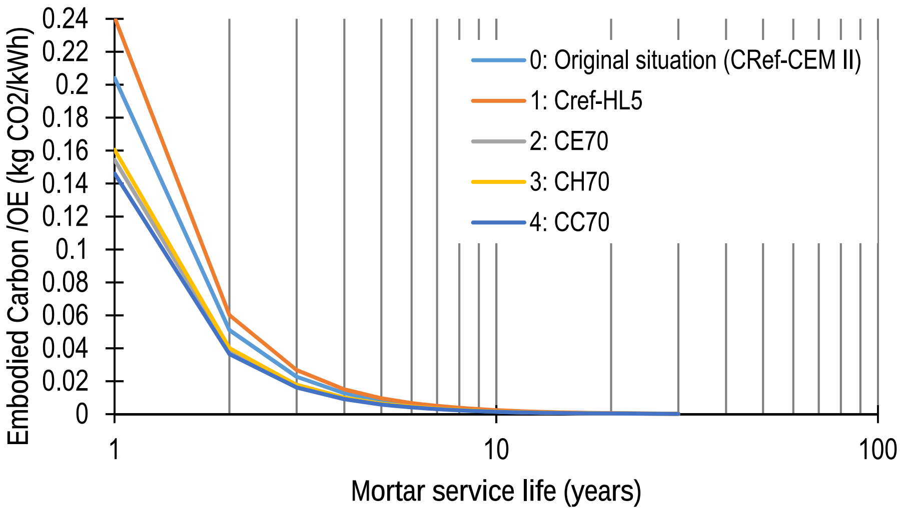

Fig. 10: Embodied Carbon for all tested mortars as a function of the building operational energy, for different mortars service life – Situation A.

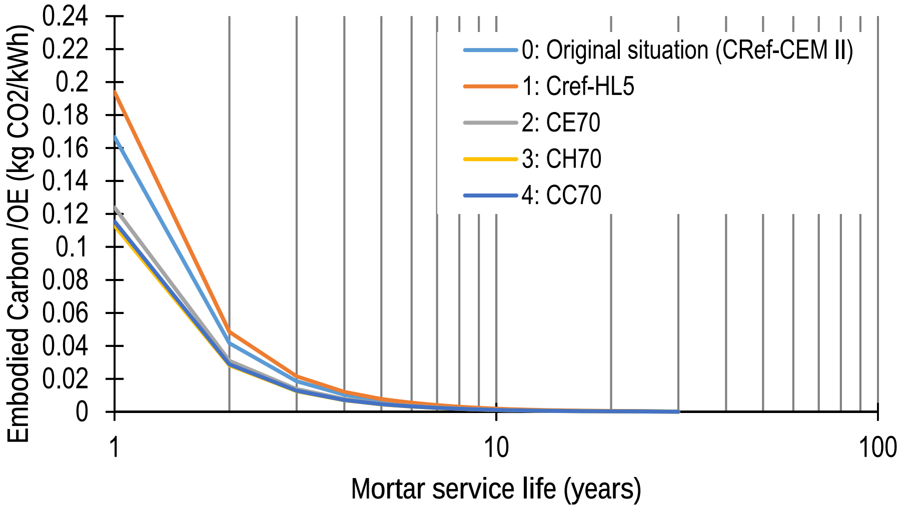

Fig. 11: Embodied Carbon for all tested mortars as a function of the building operational energy, for different mortars service life – Situation B..

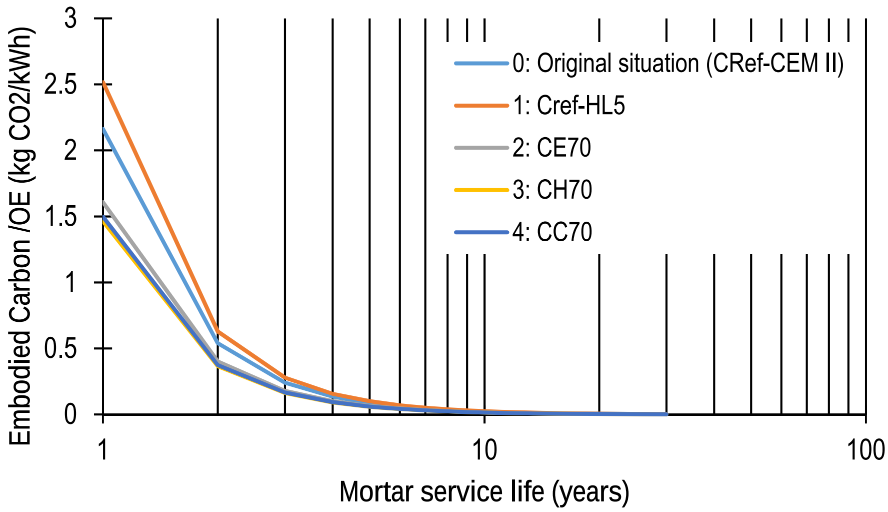

Fig. 12: Embodied Carbon for all tested mortars as a function of the building operational energy, for different mortars service life – Situation C.

The simplified approach proposed allows global comparisons between the embodied carbon and emissions of the building materials used in building rehabilitation and the energy consumption at the use stage. When compared to the traditional solutions, the cement / hydraulic lime- cork mortars are the ones that leads to less heating consumption and simultaneously leads to small impact in terms of embodied carbon. On the other side, hydraulic lime mortar (CH) and cement mortars can represent more embodied carbon.

For different energy consumption at the operational stage (table 5), it was shown that as long as mortar service life increase, the smaller will be the contribution of its embodied carbon. Ten years after retrofitting of Situation A, B or C, the impact of initial embodied carbon of all mortars can be neglected, meaning that this is the minimum desirable service life of a mortar (from a carbon emissions point of view).

The previous methodology enables doing building retrofitting optimization using deterministic studies. However, many influencing parameters are generally fundamentally uncertain, leading to unreliable and inconclusive predictions of design impact. Facilitating effective retrofitting of buildings is a challenge where building performance simulation can be a key role.

3.4 Performance based design - influence of initial embodied carbon

A building retrofit solution should contribute to minimize operational energy, avoiding simultaneously that tendency of embodied carbon to increase beyond a certain limit. However, there is no currently definition of what could be the maximum probability of failure for each building retrofit solution, taking into account the influence of specific solutions for energetic rehabilitation and their relation with current operational energy consumed in a building.

From a building physics engineering point of view, the best retrofitting system corresponds to the best balance between energy savings and hygrothermal risks. Probabilistic approaches are already frequently applied for risk assessment in energy studies [12–16], and can serve as a decision tool (Macdonald and Strachan, 2001; De Wit and Augenbroe, 2002; Haarhoff and Mathews, 2006; Corrado and Mechri, 2009; Silva and Ghisi, 2014).

Statistical uncertainty analysis techniques can be categorized as structured and non-structured methods. Structured methods result from experimental techniques, in which a series of experiments are designed to analyze the outcome for predetermined models. Non-structured methods are stochastic in nature. In the former category, the most popular method for application to building thermal simulation is Differential Sensitivity Analysis (DSA); in the latter category Monte Carlo Analysis (MCA) is the most commonly used non-structured method (Macdonald and Strachan, 2001). DSA is more suitable for practical experiments with relatively few and measured inputs (usually less than a dozen). The MCA technique relies on the central limit theorem to provide an overall assessment of the uncertainty in the predictions being made. This technique generates an estimate of the overall uncertainty in the predictions due to all the uncertainties in the input parameters, regardless of interactions and quantity of parameters.

Based on the previous results presented in Fig. 10-12, for each retrofit solution it was selected the limit of 0,15kg of embodied carbon per kWh of operational energy per year. For this target value, tg, (tg=0,15kgCO2/kWh.year, a probabilistic approach was develop with the following objectives:

- Predict the number of years that each solution takes to reduce the embodied carbon to 0,15kg CO2/ kWh.year, for the 3 analysed situations (A, B and C).
- Analyse the probability of failure (probability of exceed 0,15kg CO2/ kWh.year) for each mortar in Situation A, B and C.
- Analyse the probability of failure for each mortar after 1 year, 5 and 10 years of service life.
- Analyse the probability of failure for each mortar if the energy audit data present a covariance (COV) of 10%, 20%, 30% or 40%.

The objective is to use this methodology in the selection of the best solution for retrofit.

The approach adopted was the Monte Carlo method (Macdonald and Strachan, 2001; Faustino et al, 2014b; Faustino et al, 2015) and it took into account the uncertainties of the input parameters, which are explicitly propagated to the uncertainties of the studied performances.

These performance criteria makes possible to specify and explicitly define desired functions of the building constructive solutions. However, there is the need of having reliable information regarding the data of the involved retrofit solutions – which in this case are the thermal enhanced mortars – and the data of the building to be retrofitted, concerning for example: the mortar service life, mortar global warming contribution, the retrofit area, operational energy consumed in the building, etc. Without reliable data it is not possible to develop performance based models, which enhance also that especial care should be take into account in the realization of a building energy audit to establish the baselines of the intervention.

For all parameters, values from within their probability distribution are randomly selected and a simulation undertaken using Monte Carlo technique. 5000 values were generated for each random variable. The implementation of this method also includes the definition of limits. The following table (table 6) present the values of both deterministic and random variables for each studied scenario.

Table 6 – Calculus variables.

Variable	a	b	Distribution	Source/ Ref.
Global warming contribution for each type of mortar (kg CO2 equiv./m2)				
CRef-CEM II (Original scenario)	13.05	0,20.a	N (a,b)	Ecoinvent v.2.2 database, using Portuguese energy grid, (Brás and Gomes, 2015)
Cref-HL5	15.09	0,20.a	N (a,b)	Ecoinvent v.2.2 database, using Portuguese energy grid, (Brás and Gomes, 2015)
CE70	9.69	0,20.a	N (a,b)	Ecoinvent v.2.2 database, using Portuguese energy grid, (Brás and Gomes, 2015)
CH70	8.68	0,20.a	N (a,b)	Environment Product Declaration (EPD) of the manufacturer, (Brás and Gomes, 2015)
CC70	8.97	0,20.a	N (a,b)	Environment Product Declaration (EPD) of the manufacturer, (Brás and Gomes, 2015)
Retrofit area (m2)				
Situation A	248.7	0,10.a	N (a,b)	(Brás and Gomes, 2015; Brás et al, 2015; Brás et al, 2014)
Situation B	16.5	0,10.a	N (a,b)	(Brás and Gomes, 2015; Brás et al, 2015; Brás et al, 2014)
Situation C	85	0,10.a	N (a,b)	(Brás and Gomes, 2015; Brás et al, 2015; Brás et al, 2014)
Construction area (m2)				
Situation A	327.8	0,10.a	N (a,b)	(Brás and Gomes, 2015; Brás et al, 2015; Brás et al, 2014)
Situation B	80.3	0,10.a	N (a,b)	(Brás and Gomes, 2015; Brás et al, 2015; Brás et al, 2014)
Situation C	97.7	0,10.a	N (a,b)	(Brás and Gomes, 2015; Brás et al, 2015; Brás et al, 2014)
Original Operational Energy (kWh/m2.year)				
Situation A	50	0,30.a	N (a,b)	(Brás and Gomes, 2015; Brás et al, 2015; Brás et al, 2014)
Situation B	67	0,30.a	N (a,b)	(Brás and Gomes, 2015; Brás et al, 2015; Brás et al, 2014)
Situation C	25	0,30.a	N (a,b)	(Brás and Gomes, 2015; Brás et al, 2015; Brás et al, 2014)
Racio of OE used for heating the building (%)				
Situation A	97	0,30.a	N (a,b)	(Brás and Gomes, 2015; Brás et al, 2015; Brás et al, 2014)
Situation B	24	0,30.a	N (a,b)	(Brás and Gomes, 2015; Brás et al, 2015; Brás et al, 2014)
Situation C	21	0,30.a	N (a,b)	(Brás and Gomes, 2015; Brás et al, 2015; Brás et al, 2014)

Notation: N (a,b) = Normal distribution with mean value a and standard deviation b.

3.4.1 Limit state function and variables' distribution laws

The main objective of Monte Carlo method is to obtain the probability of failure for Situation A, B and C and it includes the definition of a limit state function g(x) used for the implementation of the method (Macdonald and Strachan, 2001; Faustino et al, 2014b; Faustino et al, 2015). Generally, the probability of failure Pf, or the probability that the embodied carbon per kWh will exceed the target value of 0,15kgCO2/kWh.year, may be expressed as the probability that the limit state function is positive: Pf=P[g(x)>0].

This design approach allows quantification of the probabilistic distributions of the considered performances for each scenario.

Equation (5) express the limit state function g(x) used for the implementation of the Monte Carlo method.

$$g(x) = \frac{EC \times A_{retrofit}}{x^2 A_p OE_0 H} - t_g \quad (5)$$

The performance of the analysed mortars for retrofitting is expressed in Figs. 13-15, as a result of the implementation of the probabilistic calculus. Probability of exceeding the target value is presented here.

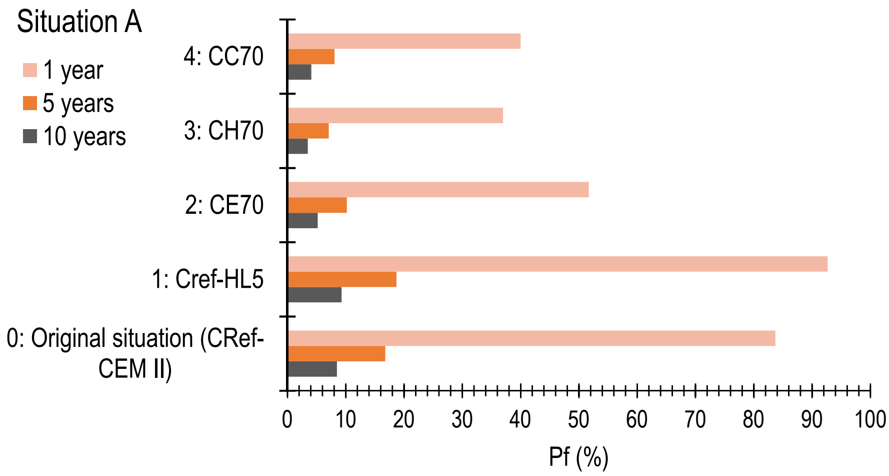

Fig. 13: Probability that the embodied carbon per kWh will exceed the target value for a mortar service life equal to 1, 5 and 10 years – Situation A (existing building school from the 80's).

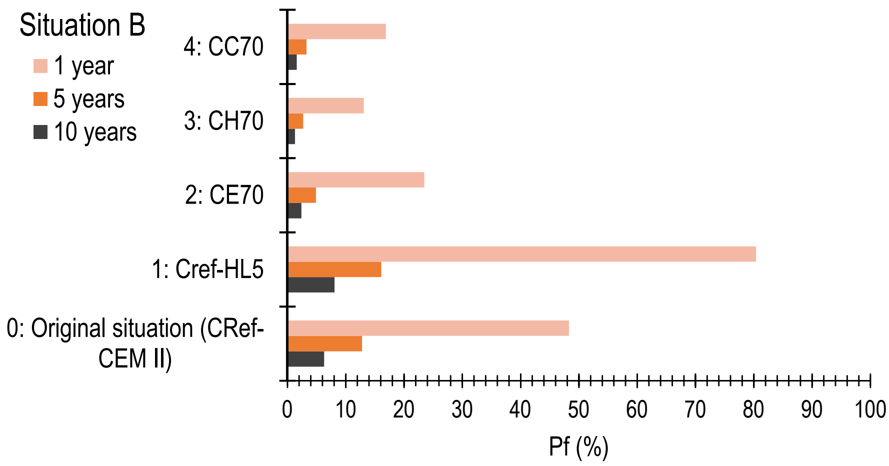

Fig. 14: Probability that the embodied carbon per kWh will exceed the target value for a mortar service life equal to 1, 5 and 10 years – Situation B (2sd floor of a multi-family residential building with three floors from the 90's).

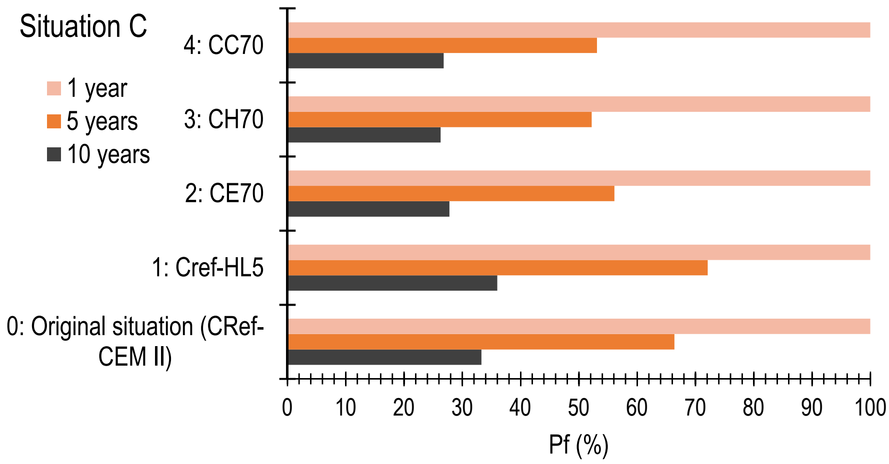

Fig. 15: Probability that the embodied carbon per kWh will exceed the target value for a mortar service life equal to 1, 5 and 10 years – Situation C (a dwelling from the 80's).

It is, nonetheless, worth mentioning that the interpretation of these results should be wary especially because the available data related to the performance in terms of embodied carbon of each mortar is limited. The present study is based on specific available data (Brás and Gomes, 2015). From these figures (Figs. 13-15) it is possible to verify substantial differences for each composition if the effect of embodied carbon in operational energy of each building is took into account.

For Situation A and B, probability of failure is much higher for traditional mortars (CRef-CEM II and Cref-HL5) than for the ones with cork addition. EPS addition leads to intermediate values.
If these retrofitting solutions are used in Solution B (2sd floor of a multi-family residential building with three floors from the 90's) Pf 1 year after intervention is about 15% for the mortars with cork, 25% for the one with EPS, 50% for CRef-CEM II and 80% for Cref-HL5). The same solutions for Situation A leads to Pf values 1.5 to 3 times higher than Situation B and 1.5 to 7.6 times higher for Situation C.

If mortars service life increase to 5 years in Situation A and B, Pf become smaller than 20% for all cases, despite of traditional mortars still present higher values. In situation C, even for an increasing service life until 10 years, Pf is always higher than 30%.

Those results highlight not only the importance of selecting the best materials for retrofitting, but also the need of adapt the solution to the building specific needs in terms of occupants' behaviour and operational energy consumption.

The objective of an energy audit is to study the conditions of energy use in a building and subsequent identification of opportunities for improving energy performance, aiming the reduction of the energy bill and total costs. By using appropriate energy models, economic analysis tools and performance based design methods, the performance of a range of retrofit alternatives can be assessed quantitatively. The objective is to prioritize retrofit solutions based on relevant energy related and non-energy related factors.

The following figures (Figs. 16-21) show Pf evolution for an increasing error that could occur during energy audits works. It was studied the effect of a COV between 10% (acceptable) to 40% (not acceptable), 5 years and 10 years after building retrofit.

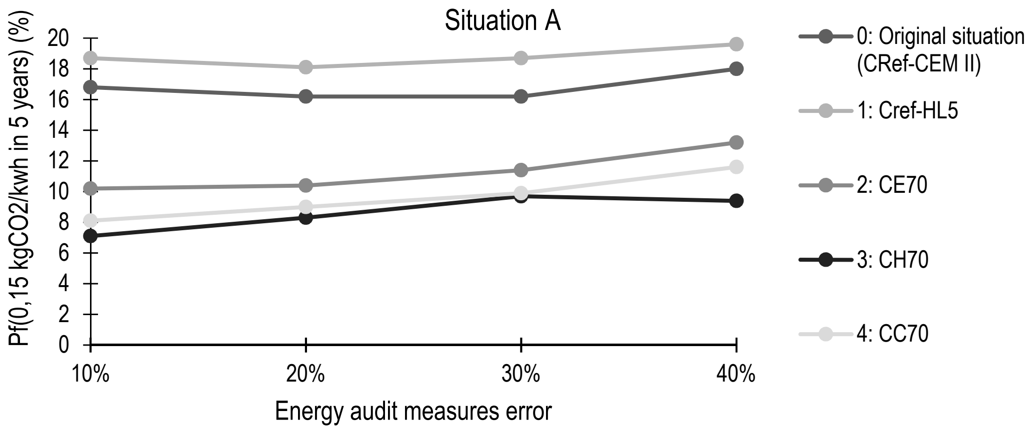

Fig. 16: Probability of failure for each mortar for an increasing energy audit error for service life equal to 5 years – Situation A (existing building school from the 80's).

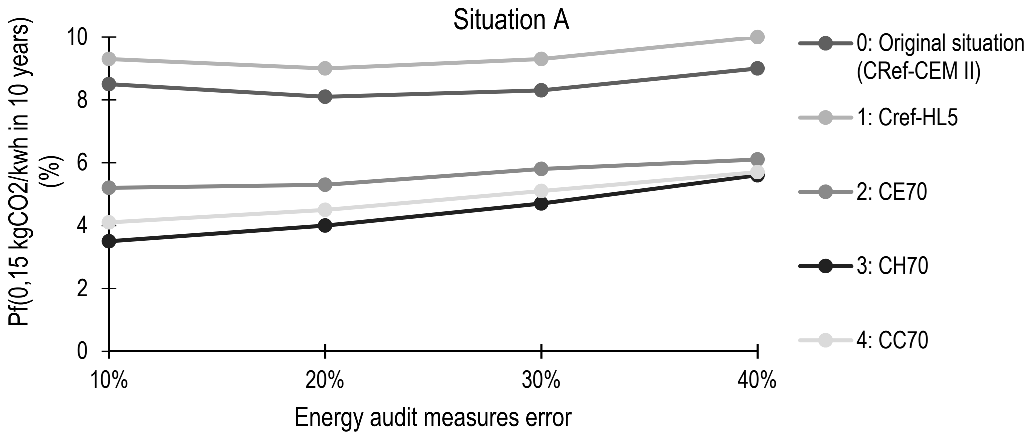

Fig. 17: Probability of failure for each mortar for an increasing energy audit error for service life equal to 10 years – Situation A (existing building school from the 80's).

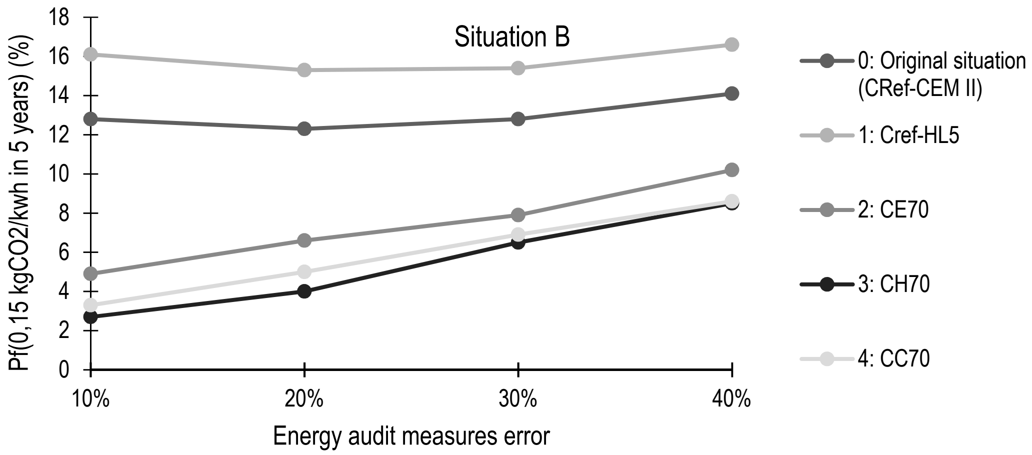

Fig. 18: Probability of failure for each mortar for an increasing energy audit error for service life equal to 5 years – Situation B (2sd floor of a multi-family residential building with three floors from the 90's).

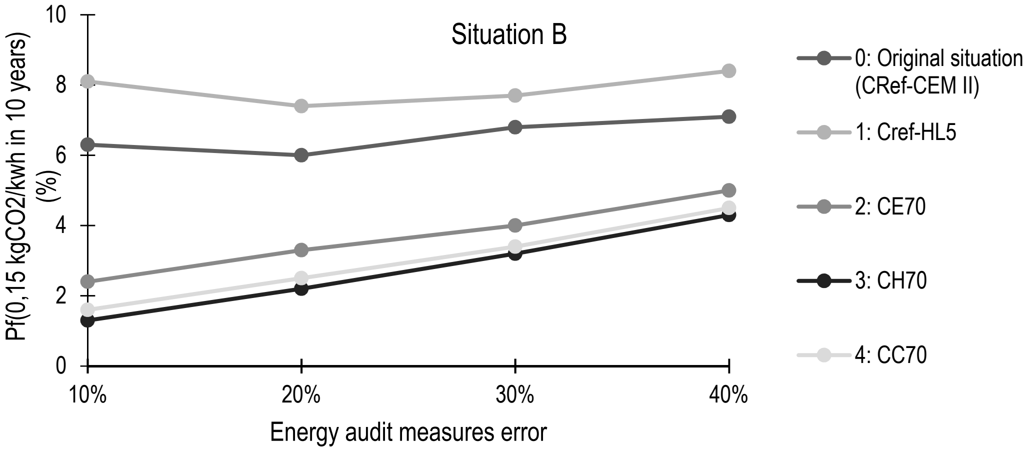

Fig. 19: Probability of failure for each mortar for an increasing energy audit error for service life equal to 10 years – Situation B (2sd floor of a multi-family residential building with three floors from the 90's).

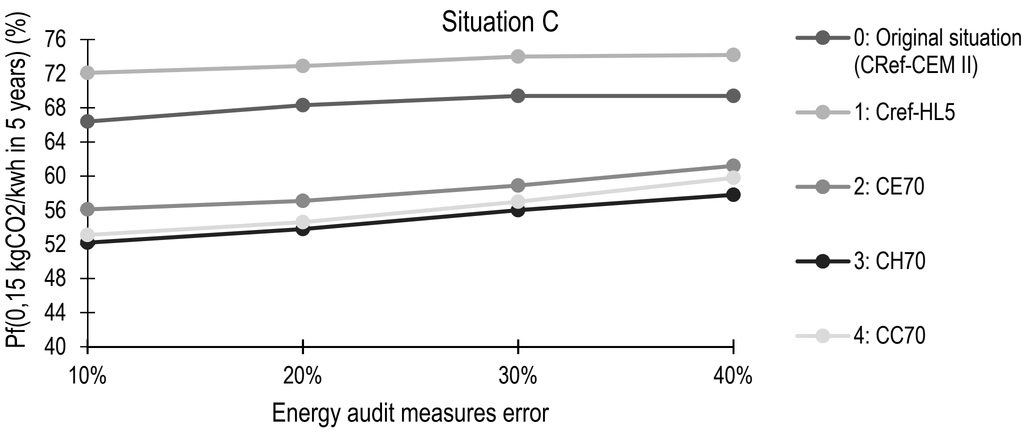

Fig. 20: Probability of failure for each mortar for an increasing energy audit error for service life equal to 5 years – Situation C (a dwelling from the 80's).

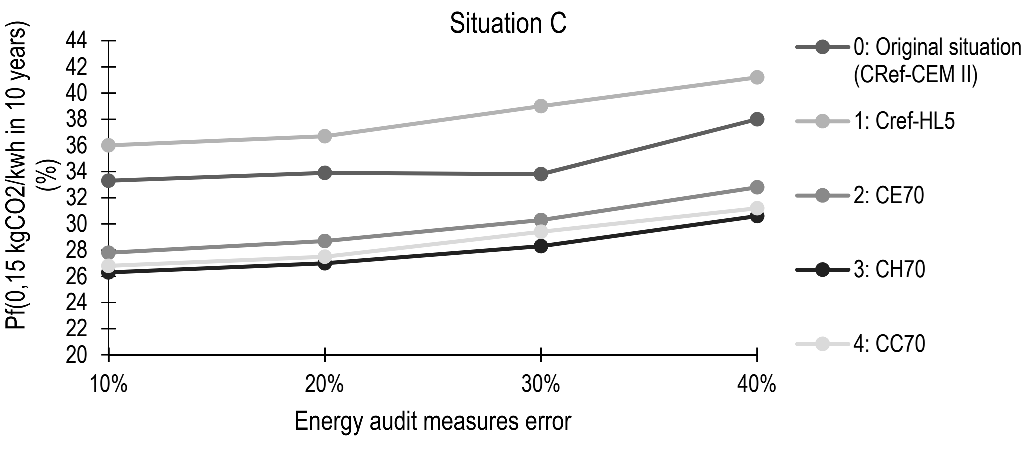

Fig. 21: Probability of failure for each mortar for an increasing energy audit error for service life equal to 10 years – Situation C (a dwelling from the 80's).

Results show that energy audit error can lead to different values of Pf – Situation A and B are clearly examples of that influence (Pf values can easily increase more than 50% if error goes from 10% to 40%).

Besides that, for a service life equal to 5 years, Pf values for CRef-CEMII and CRef-HL5 is much higher than for the thermal enhanced mortars (CE, CH70 and CC70). In Situation A, Pf assumes values between 7-10% for CE, CH70 and CC70 and for traditional mortars Pf is equal to 17-20%.In Situation B, Pf values are smaller for the thermal enhanced mortars (3-8%) and 13-17% for the traditional mortars. Situation C is the one that leads to higher Pf values (for thermal enhanced mortars Pf is approximately 50% and 70% for traditional mortars). If service life is equal to 10 years, Pf reduce about 2 times for all values.

Generally, these mortars for thermal rehabilitation seem to be a good measure in terms of embodied carbon for Situation A and B. For Situation C the probability of failure is extremely high for all mortars, meaning that these type of solution in not suitable for the dwelling from the 80's.

4. Conclusions

Currently there is no regulation of embodied energy/carbon in EU construction. The effectiveness of a low carbon project should be judged by its energy in use and not the sum total of the energy expended in its retrofit. The impact of replacing existing materials by others with different service life (sometimes with shorter life and lower durability) should be take into account. Here, it is proposed a performance criteria to help the selection of the best retrofit solution able to minimize embodied carbon and energy and simultaneously to improve the energy efficiency of buildings - with energy retrofit needs. Three different buildings, with different occupants' behaviour, were analysed. Embodied carbon of each retrofit solution (thermal enhanced mortars with cork or EPS addition and traditional mortars for external rendering) was calculated using LCA and it was made an assessment of the relationship between embodied carbon and operational energy of each building, by performance-based design (PBD), using a probabilistic approach.

The corresponding conclusions are presented as follows:

- The use of cork granulate in mortars represents the most positive measure to reduce embodied carbon and simultaneously increase energy efficiency of a building.
- An intervention using cork gives not only the smallest global costs, but also prevent the increasing of costs mainly due to economic factors such as the electricity cost rate per year and the inflation rate – which are not so dependent on technical issues and those ones we cannot control.
- Traditional mortars are more sensitive to these economic factors.
- The absolute values of global cost of retrofitting divided by the cost of OE of the building at the original stage demonstrate that retrofit using these thermal mortars is more beneficial if they are used in the school (Situation A) than in the dwelling or residential building (Situation C and B).
- It was shown that as long as mortar service life increase, the smaller will be the contribution of its embodied carbon.
- The impact of the EC of a retrofit solution is not the same for all solutions. The probability of exceeding a target value of 0,15kgCO2/kWh.year – probability of failure, Pf - is much higher for traditional mortars (CRef-CEM II and Cref-HL5) than for the ones with cork addition.
- If Pf is limited to 5%, it is only possible to achieve that target in Situation A and B. Besides this, that target is only reached 10 years after building retrofitting, meaning that these solutions are in a first instance not suitable to improve the characteristics of the dwelling - situation C.
- It is shown that energy audit errors can lead to different values of Pf – Situation A and B are clearly examples of that influence (Pf values can easily increase more than 50% if error goes from 10% to 40%) -, enhancing the importance of getting reliable data in a building energy audit.

A PBD approach was develop to predict the number of years that each solution takes to reduce the embodied carbon to 0,15kg per kWh of operational energy produced in each building. The use of cork granulate in mortars represents the most positive measure to reduce EC and simultaneously increase energy efficiency of a building. The results of this study show the importance of future discussion for the improvement of design methodology in the selection of the best solution for retrofit, taking into account the building specific needs in terms of occupants' behaviour and operational energy consumption.
During the first 10 years of service life for each retrofit solution presented here, the impact of embodied carbon in the operational energy consumed in Situation A and B is still relevant (higher than 10%). By using a low carbon solution such as the ones presented here, its impact is equally reduced in the first 5 years. In Situation C the benefits are not so evident. Therefore, it is possible to extrapolate the scale of benefit if a better solution is implemented and/or if this approach is used in the building stock built to the standard of these sample buildings (Situation A and B). School buildings similar to Situation A built in the suburbs of Lisbon are more than 50. Knowing that according to (Pordata, 2015) there are 650 000 buildings from Situation B typology built in Portugal and that at least 30% of them need retrofit works (INE, 2012), 200000 of residential buildings will directly benefit from this approach and easily achieve 30% reduction in embodied carbon and energy in 5 years.

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