Procedia CIRP 90 (2020) 322–327

Contents lists available at ScienceDirect

Procedia CIRP

journal homepage: www.elsevier.com/locate/procir

Investigating eco-efficiency procedure to compare refurbishment scenarios with different insulating materials

Carolina Colli[a,b], Alain Bataille[a,*], Emmanuel Antczak[a]

[a] LGCgE, Université d'Artois, Technoparc Futura, Béthune62400, France
[b] WeLOOP, Pepinière d'éco-entreprises, Bâtiment 1, Rue de Bo urgogne, Base 11/19, France

ARTICLE INFO

Keywords:
Eco-efficiency
Life cycle assessment
Whole life costing
Building
Refurbishment

ABSTRACT

The paper presents a set of situations regarding eco-efficiency. It is built on both environmental and economic performances. Those performances are computed respectively from LCA and from WLC. The present eco-efficiency procedure considers both matrix and ratio methods.

This paper investigates different alternatives for refurbishment insulation of a single-family house located in the North of France. The analyzed refurbishment scenarios consider different insulating materials: standard glass wool, hemp concrete, cellulose fiber, expanded polystyrene (EPS), extruded polystyrene (XPS), and rigid foam polyurethane. The different alternatives are compared using the eco-efficiency procedure.

1. Introduction

The building sector in France represents 20% of the climate change impacts [1]. This sector presents 65% of buildings constructed before 1975 [2]. By that time there was no building thermal standard. The buildings constructed before 1975 have a present average energy consumption of 300 kWh_{PE}/m^2.yr [3]. In order to cut down greenhouse gas emissions, the French Government ratified the law on energetic transition for green development [4]. This law foresees a factor 4 reduction of French greenhouse gas emissions between 1990 and 2050.

Moreover, regulations do evolve constantly, integrating both new and refurbished constructions and a future version of thermal regulation is scheduled for the coming years. Thanks to this new version, the law goals may be achieved followingly. This thermal regulation will include thermal assessments but also environmental analysis, according to the Energy – Carbon reference guide [5].

Decision-makers have an increasing interest in the environmental assessment for their operations, although the primary decision-making criterion remains an economic one. Usually, the investment cost is taken into account. However, this cost is not representative of the whole building life cycle. Indeed, the whole life costing must be assessed and it must integrate the costs of operation as well as the cost of necessary maintenance and replacements along with the life of the building, not forgetting the end of life aspect.

Combining an environmental assessment and an economic one for a building is not straightforward. In this process, the environmental burden of a building can be assessed solely by the carbon footprint, or by the cumulative energy, or again by more than a tenth of other impact categories. Questions are: which one is pertinent to be taken into account? Can we combine the different impact categories? Another problem is how do we display in a handy way the environmental results along with the economic assessment.

This paper addresses these problems by investigating the eco-efficiency method applied to a refurbishment operation. The study focuses on the eco-efficiency of different scenarios of building refurbishment. The scenarios are considering a variety of insulating materials regarding the whole building life cycle. The present eco-efficiency methodology considers LCA as the environmental assessment and WLC as the economic assessment. All environmental indicators are computed into a single score representing the environmental performance. The Net Present Value (NPV) corresponds to economic performance.

The paper is divided into 6 sections: Introduction, Goal and Scope, Life Cycle Assessment, Life Cycle Costing, Eco-efficiency and Conclusions. *Nomenclature*

CC	climate change
PM	particulate matter
FEc	freshwater ecotoxicity

* Corresponding author.
E-mail address: alain.bataille@univ-artois.fr (A. Bataille).

https://doi.org/10.1016/j.procir.2020.02.002

Table 1
Thermal information according to the insulating materials.

Insulating material	Thermal conductivity λ (W/m/K)	Thickness (mm)	Density (kg/m^3)
Glass Wool (GW)	0,032	100	32
Hemp concrete (HC)	0,07	220	250
Cellulose fiber (CF)	0,04	130	40
EPS	0,0345	110	20
XPS	0,0335	110	35
Polyurethane (PU)	0,025	80	35

RD mineral, fossil, and renewable resource depletion
GW glass wool
HC hemp concrete
CF cellulose fiber
EPS expanded polystyrene
XPS extruded polystyrene
PU rigid foam polyurethane

2. Goal and scope

The goal of this work is to propose an eco-efficiency methodology and to implement it. Therefore the work investigates the eco-efficiency of different refurbishment scenarios considering a set of insulating materials: glass wool, hemp concrete, cellulose fiber, rigid foam of polyurethane, expanded polystyrene (EPS) and extruded polystyrene (XPS). Hemp concrete and cellulose fiber are bio-sourced insulating materials. Impacts will be computed according to the whole building life cycle.

2.1. Case study

The assessments consider the refurbishment and the resulting use and end of life of a social single-family house located in the North of France. The dwelling corresponds to a living area of about 60 square meters after refurbishment. A variation of this living area is taken into account according to different insulating materials. The different living areas range from 57.3 m^2 for hemp concrete up to 61.6 m^2 for Polyurethane (PU).

Only inner wall insulation has been varied for the present work, which corresponds to 75 square meters of insulating material. Thickness changes according to thermal conductivity (λ) of each insulating material. Quantities of each material, as well as thicknesses and densities, are reported in Table 1.

The different thicknesses provide the same thermal resistance corresponding to similar energy consumption per square meter and per year. However, as the total living area is different according to the insulating material, the total energy consumption will also vary.

Transport differs between standard insulating materials (530 km) and bio-sourced insulating ones (380 km). These values are averages based on different distances of possible suppliers. The data come from the social landlord [6].

All other refurbishment aspects remained unvaried. Apart from insulation, refurbished parts are the parcel, the windows, the doors (exterior and interior), the roofing, the façade, the sanitary, the electricity and the floor.

Losses of insulating material are described in module A5 (EN 15978 [7]), representing 2% of the total quantity. The transport of these losses is also considered, as well as transport for the end of life and waste treatment.

Replacements are calculated according to the service period of each insulating material. These data were obtained from Inies, a French database [8].

The end of life, after 50 years period, considers deconstruction, transport, and disposal of the total amount of waste.

3. Life cycle assessment

3.1. Methodology

The environmental assessment considered in this work is the LCA. The LCA is a multi-criteria and a multi-phase environmental assessment, standardized by ISO 14040 [9] and ISO 14044 [10]. Its procedure is divided into four steps, which are (i) definition of goal and scope, (ii) inventory, (iii) impact evaluation and (iv) result interpretation. The guidelines are presented in the ISO standards 14040 and 14044, as well as the EN 15978 [7] for building LCA.

The LCA results were calculated considering the six different refurbishment scenarios using different insulating materials. The modeling was performed using Simapro v. 8.3.0.0, with Ecoinvent database v. 3.3 and all 16 ILCD midpoint environmental impact indicators were considered and a single environmental score was computed.

In order to produce data for eco-efficiency analysis, environmental results have been aggregated into a single score ILCD midpoint indicator.

The functional unit considered in this study is as follows: To provide a living space in a semi-detached house for a single family of three persons for a reference service period of 50 years . The reference flow used in this study is the total living area per year.

The total impacts of each construction product is considered, even if its service lifespan is higher than the reference service period.

3.2. Environmental impact evaluation

As mentioned above, 16 indicators were computed. In this section, the results will consider only 4 of them: climate change (CC), particulate matter (PM), freshwater ecotoxicity (FEc) and resource depletion (RD). Those 4 environmental indicators are particularly pertinent for building and construction sector as they represent critical issues such as climate change, and they consider the 3 protection areas. The different indicator results are presented in Fig. 1.

It can be noticed from Fig. 1 some differences in environmental impact between the less impacting refurbishment scenario using hemp concrete and the 5 other scenarios. Disregarding the service period of the hemp concrete, which is 100 years, the total impact of the hemp concrete is allocated to the 50 years of operational life. This means that the environmental impact per year of the refurbishment scenario using hemp concrete should be half of that observed from Fig. 1.

Scenarios using rigid foam of polyurethane or using glass wool have the most important impact considering climate change, particulate matter and freshwater ecotoxicity. Regarding resource depletion, the refurbishment scenario using cellulose fiber is the worst one, followed by the ones using respectively glass wool and rigid foam of polyurethane.

Hill et al. (2018) [11] analyzed insulating materials (glass wool; mineral wool, EPS, XPS, polyurethane, foam glass, and cellulose), considering global warming potential (GWP) and embodied energy.

This is a resupply of March 2023 as the template used in the publication of the original article contained errors. The content of the article has remained unaffected.

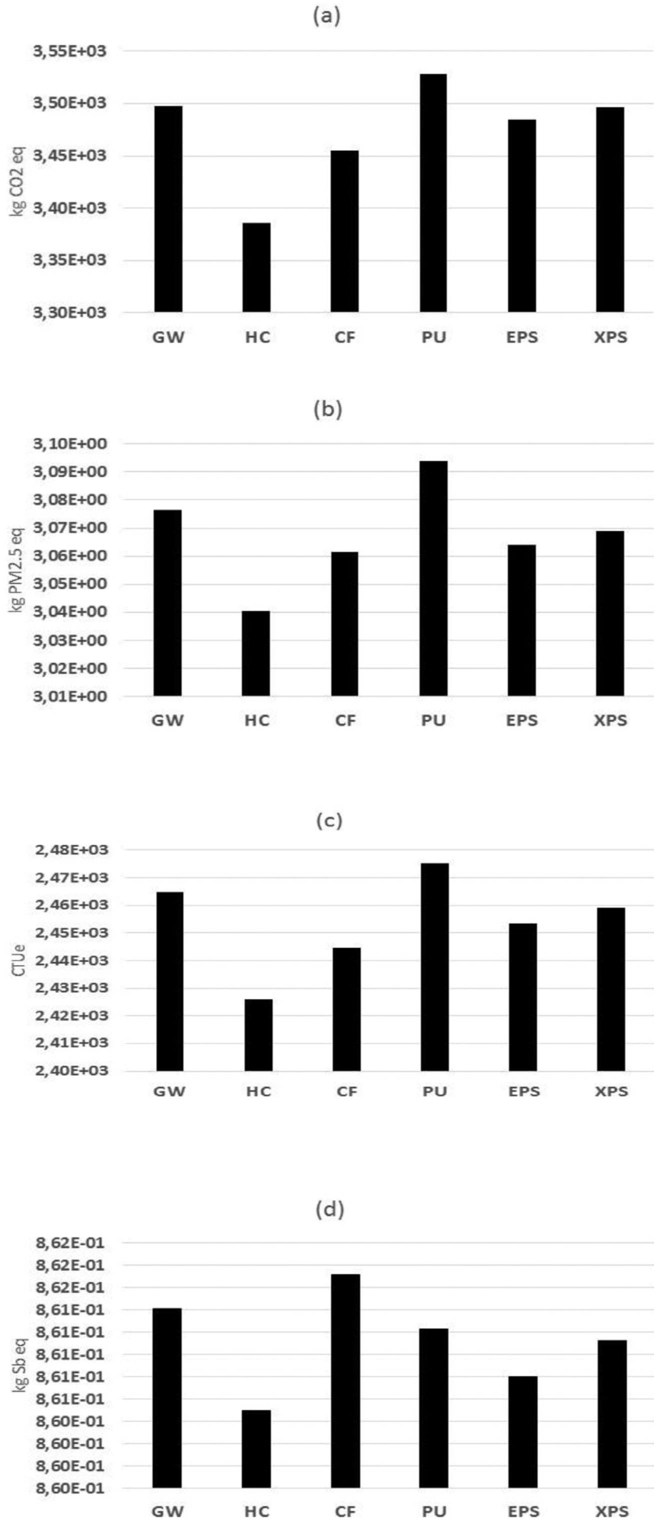

Fig. 1. LCA Results for the social housing refurbishment (total living area and per year) (a) climate change; (b) particulate matter; (c) freshwater ecotoxicity and (d) resource depletion.

According to them, the cellulose presents the lower GWP per kg of insulating material and GWP per functional unit (1 m^2). Considering that they do not include hemp concrete, a similar result is achieved in this work, even if they focus on the life cycle of insulating materials.

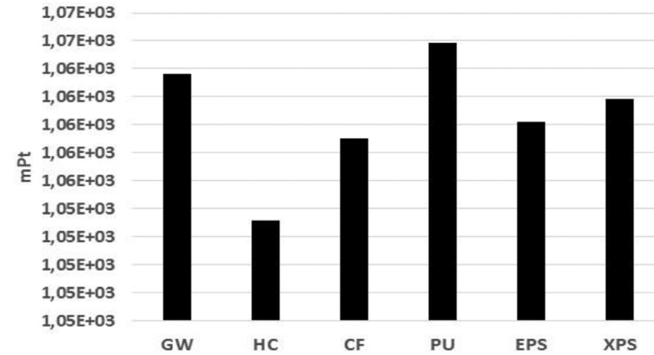

Fig. 2. Single Score ILCD LCA Results for the social housing refurbishment according to the different insulating materials

Pargana et al. (2014) [12] also analyzed the environmental impact of insulating materials (expanded polystyrene, extruded polystyrene, polyurethane, expanded cork agglomerate and expanded clay lightweight aggregates) using a variety of indicators such as abiotic depletion potential, global warming potential, ozone destruction potential. Their results pointed out expanded cork agglomerate as having the best GWP per function unit (1 m^2 with R = 1 m^2 K/W).

Both studies strengthen the present results showing that the most important environmental burden is associated with non-bio-sourced insulating materials.

Su et al. (2016) [13] analyzed the following insulating materials: expanded polystyrene, extruded polystyrene, polystyrene particles, polyurethane, mineral wool, glass wool, foam glass, and phenol-formaldehyde. Foam glass has been identified as corresponding to the most important life cycle primary energy consumption, followed by EPS. Mineral wool has the less important life cycle primary energy consumption. There are difficulties in comparing more precisely their results to the present ones as they use a set of elementary flows instead of midpoint indicators.

Even if those articles have reported studies on the environmental impacts of insulating materials, none of them investigated the difference of impact related to the whole building life cycle, which is the case of this work.

According to single score environmental results showed in Fig. 2, the refurbishment scenario using polyurethane is the worst one whereas the scenario using hemp concrete is the best one. Both bio-sourced materials (hemp concrete and cellulose fiber) are classified as the best environmental insulating materials for this case study.

4. Whole life costing (WLC)

4.1. Methodology

The WLC methodology is standardized by the ISO 15686-5 [14]. It considers the life cycle costing of the building life cycle, as well as the externalities, the non-construction costs, and the income.

The WLC methodology follows the same principle of the LCA methodology, defining goal and scope, inventory (quantifying the values of each contributor), cost evaluation and interpretation.

The economic indicator used in this analysis is the net present value (NPV) as well as the discounted payback time. The first one is proposed by the standard.

4.2. Goal and scope

This economic assessment is performed in order to help decision-makers before refurbishment operation. The economic re-

This is a resupply of March 2023 as the template used in the publication of the original article contained errors. The content of the article has remained unaffected.

Table 2
Insulating material price average.

Insulating material	Price (€/m²)
Glass Wool	48,00
Hemp concrete	57,05
Cellulose fiber	31,70
EPS	23,90
XPS	32,80
Polyurethane	44,83

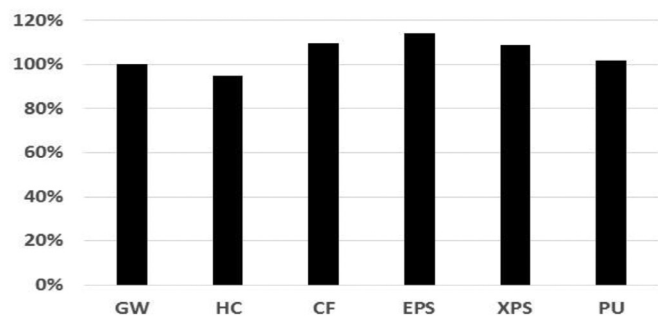

Fig. 3. Net Present Value (NPV) for different insulating material scenarios of refurbishment

sult will be used in the eco-efficiency matrix as economic performance. Thus, all values taken into account in this study are related to the decision-maker, i.e. the social landlord. No costs related to the tenant are considered.

All building life costs have been collected, i.e.: refurbishment costs (initial investment), operational costs (maintenance, replacements, living taxes, and rents), as well as end of life costs (deconstruction, transportation, and disposal of 100% waste).

The externalities taken into account are vacancy rate and unpaid rent rate. Those rates are related to housing attractiveness and tenant capacity to pay the rent.

The non-construction costs are related to the cost of the study as well as the financing cost. No income as defined in the ISO 15686-5 is considered in this analysis. Also, no environmental cost is computed, in order to avoid double-counting of the environmental impacts.

4.3. Economic impact evaluation

The insulating material prices have been sourced from the market and they have been averaged, based on the different prices. Only two prices were collected for the hemp concrete. The price of glass wool has been obtained from the social landlord. This price usually includes material installation.

The other costs have been drawn from the social landlord database. Table 2 shows the average prices considered here.

Those prices were computed with all other costs to calculate the economic performance, which is the NPV.

The results presented in Fig. 3 shows a variation related to the reference scenario (building refurbishment scenario with glass wool insulating material). The relative results vary from −6 % up to +16%. These results are given for a period of analysis of 50 years and for the living area of the refurbished house. It can be observed that the best economic refurbishment scenario according to this analysis is the one using expanded polystyrene, and the worst economic scenario is the one using hemp concrete. However, as already commented in this paper, hemp concrete has a service life of 100 years instead of 50 years, which is the service life for all the other insulating materials..

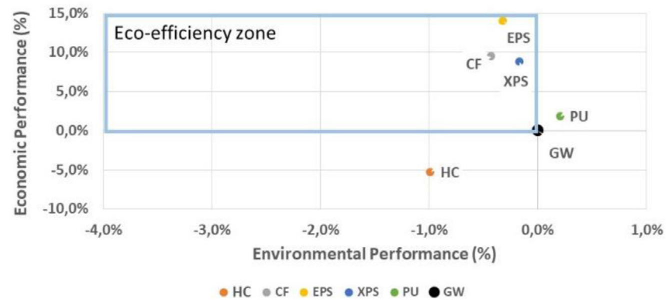

Fig. 4. Eco-efficiency matrix for different insulating material scenarios of refurbishment (ILCD single score – 50 years RSP)

5. Eco-efficiency analysis

5.1. Methodology

The principles of eco-efficiency are defined in ISO 14045 [15]. The eco-efficiency methodology was first developed by BASF in 2002 [16] and it considers two different scores: an environmental one and an economic one. These scores are represented in a matrix where a win-win zone can be located. The methodology can be used in comparing different scenarios, in order to define the best eco-efficient scenario between the analyzed ones. Thus, the eco-efficiency is a relative concept, where a scenario can be more or less eco-efficient according to another scenario.

Huguet et al. (2018) [17] present three different methods in order to combine economic and environmental scores: vector optimization, ratio, and weighting. The first method is similar to the BASF one. The second one uses a ratio of the same scores, defining the performance in euros spent per generated impact. This ratio method will be also used in this work, but only in association with the first method mentioned. Indeed, this method can be tricky as the more money is spent, the smaller the ratio. Thus, the ratio method will be used only for scenarios without any win-win or lose-lose situation.

5.2. Eco-efficiency evaluation

Both axes of the eco-efficiency matrix are presented in percentages. Each axis expresses the relative difference to the reference scenario, which corresponds to the refurbishment scenario using glass wool as insulating material.

The x-axis represents the relative variation of environmental performance expressed in percentage. The reference scenario (glass wool material) has been allocated to 0% . Any negative variation of environmental performance means a lower environmental burden for the corresponding insulating product.

The y-axis represents the relative variation of economic performance. It is expressed in relative NPV variation for each scenario. The values are also in percentage in this axis, taking the glass wool scenario as a reference, with a percentage of 0%.

Fig. 4 shows the eco-efficiency matrix for the different refurbishment scenarios with different insulating materials analyzed in this work.

The eco-efficiency zone is illustrated in Fig. 4. This zone locates the scenarios combining both best economic and environmental performances. Three different refurbishment scenarios are located in this zone, the ones using the following insulating materials: cellulose fiber, expanded polystyrene, and extruded polystyrene.

The best environmental performance, considering all the different refurbishment scenarios, is the one using the hemp concrete as insulating material. However, the high price of hemp concrete

Table 3
Eco-efficiency ratio results for the EPS and CF.

Insulating material	NPC(€)	EP*(mPt)	Ratio (€/mPt)
CF	119 308	1059,06	112,65
EPS	118 590	1060,22	111,85

*EP: Environmental Performance.

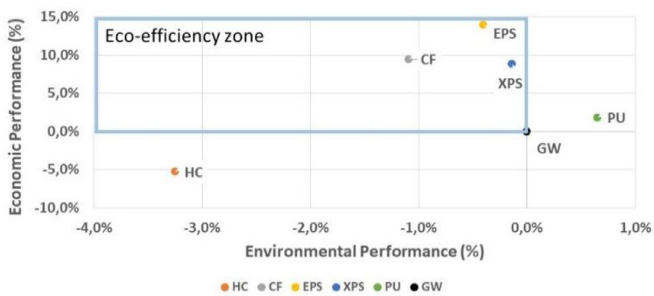

Fig. 5. Eco-efficiency matrix for different insulating material scenarios of refurbishment (ReCipe single score – 50 years RSP)

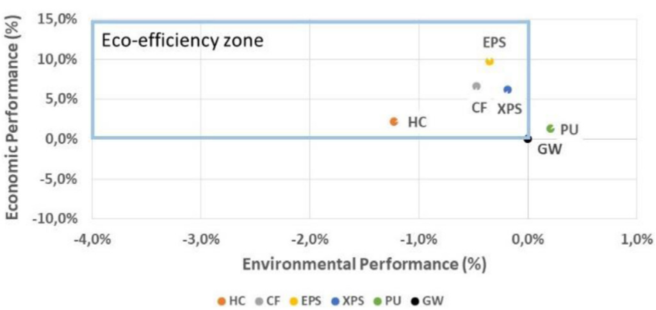

Fig. 6. Eco-efficiency matrix for different insulating material scenarios of refurbishment (ILCD single score – 100 years RSP)

does not favor its economic performance. Thus, it is not located in the eco-efficient zone, but in a so-called eco-friendly zone.

The refurbishment scenario using polyurethane as an insulating material has good economic performance. However, it presents the worst environmental performance.

Among the three refurbishment scenarios located in the eco-efficiency zone, two of them (EPS and CF) present results that do not allow to select the best eco-efficient refurbishment operation and thus the best eco-efficient insulating material for this case study. A ratio methodology was used complementarily for both of them in order to identify the one presenting the smallest amount of euros spent per generated impact.

In order to obtain these values, the net present cost (NPC) is used instead of the net present value, as no benefit is taken into account. The results are given in Table 3.

The difference between both ratios is tiny. This difference could be balanced by result uncertainty. Hence it is difficult to have a definitive conclusion on this matter

5.3. *Eco-efficiency sensitivity analysis*

A sensitivity analysis has been performed for the eco-efficiency results, assessing influence of: (i) RSP variation and (ii) impact evaluation methodology change .

The results are given in Figs. 5 and 6.

The eco-efficiency matrix does not give a unique result about the best eco-efficient refurbishment scenario. Thus, the eco-efficiency ratio is used in those three cases. Table 4 shows the ratio results accordingly to RSP and impact evaluation methodology.

The scenario using EPS as insulating material remains the best eco-efficient scenario according to the different impact evaluation methodologies and RSP. The sensitivity results on eco-efficiency show the importance of RSP when considering refurbishment scenarios with insulating materials with different service lives. The refurbishment scenario using hemp concrete as an insulating material is considered eco-efficient only for a 100-years period.

Hemp concrete scenario is disadvantaged due to a higher price. Hence, hemp concrete is less favorable economically. One can expect that its price will decrease in the coming years, as it is a developing alternative in building insulation in France

The other three eco-efficient refurbishment scenarios, using EPS, CF and XPS, remain in the eco-efficiency zone, no matter which RSP or impact evaluation methodology.

6. Conclusions

This work investigates the eco-efficiency methodology applied to refurbishment scenarios over the whole building life cycle, using different insulating materials.

According to environmental performance, the best refurbishment scenario is the one using hemp concrete. Polyurethane has the worst environmental performance.

The economic performance is the best for expanded polystyrene (114% of reference NPV), while hemp concrete showed the worst economic performance (95% of reference NPV) due to its higher price.

The eco-efficiency matrix gave a group of three eco-efficient refurbishment scenarios using different insulating materials (expanded polystyrene, extruded polystyrene, and cellulose fiber). In order to point out the best of those insulating materials, the eco-efficiency ratio was calculated, but the ratio difference was not enough to be conclusive..

A sensitivity analysis has been performed for the eco-efficiency results according to RSP and impact evaluation methodology. The results show that the refurbishment scenario using hemp concrete can be located in the eco-efficiency zone when the RSP is changed to a 100-years period of analysis (which is the service life for this insulating material).

A future sensitivity analysis should be carried out in order to consider the influence of hemp concrete market price on the eco-efficiency results. Indeed, this insulating material is new in the market and its price is not yet stabilized. The quantities used of this insulating material can increase in the coming years. Consequently, its price can lower, allowing it to become one of the best eco-efficient refurbishment scenarios.

The eco-efficiency procedure allowed us to present both environmental and economic performances and to compare differ-

Table 4
Eco-efficiency ratio for the EPS, CF and HC.

Insulating material	ILCD 100 yrs(€/mPt)	ReCipe E 50 yrs(€/Pt)	ReCipE E 100 yrs(€/Pt)
CF	159,61	232,99	334,40
EPS	158,42	229,98	329,77
HC	162,23	242,85	346,73

ent scenarios in a practical and straightforward way. Hence, eco-efficiency can be a very interesting tool to help decision-making for refurbishment choices. This implementation of eco-efficiency can solve the problems mentioned in the Introduction and it gives also some answers to the raised questions.

Moreover, the implemented procedure does not need any user aggregation of the two performances, rendering the comparison more reliable and less user-dependent.

CRediT authorship contribution statement

Carolina Colli: Methodology, Software, Formal analysis, Writing - original draft. **Alain Bataille:** Writing - review & editing, Project administration. **Emmanuel Antczak:** Supervision, Project administration.

Acknowledgements

This work was carried out in the framework of the Bat-Eco2 research project, co-financed by the French Region of Hauts de France through the European Union ERDF program. and by Maisons &Cités.

References

Bâtiments et biens immobiliers construits - Prévision de la durée de vie – Partie 5: approche en coût global, (2017).
Consommations énergétiques des ménages en 2012, (2015) 10.
Contribution des ouvrages de construction au développement durable - Evaluation de la performance environnementale des bâtiments - Méthode de calcul, (2012).
Evaluation de l'éco-efficacité des systèmes de produits – principes, exigences et lignes directrices, (2012).
France Analyse du Statu Quo National, (2013).
Hill, C., Norton, A., Dibdiakova, J., 2018. A comparison of the environmental impacts of different categories of insulation materials. Energy Build. 162, 12–20. doi:10.1016/j.enbuild.2017.12.009.
Huguet Ferran, P., Heijungs, R., Vogtländer, J.G., 2018. Critical analysis of methods for integrating economic and environmental indicators. Ecol. Econ. 146, 549–559. doi:10.1016/j.ecolecon.2017.11.030.
Inies database website, (n.d.). http://www.inies.fr/accueil/.
LOI n° 2015-992 du 17 août 2015 relative à la transition énergétique pour la croissance verte (1), (1).
Management environnemental – analyse du Cycle de vie - Principes et cadre, (2006).
Management environnemental – analyse du cycle de vie - Exigences et lignes directrices, (2006).
Pargana, N., Pinheiro, M.D., Silvestre, J.D., de Brito, J., 2014. Comparative environmental life cycle assessment of thermal insulation materials of buildings. Energy Build. 82, 466–481. doi:10.1016/j.enbuild.2014.05.057.
Référentiel "Energie-Carbone" pour les bâtiments neufs - Méthode d'évaluation de la performance énergétique et environnementale des bâtiments neufs - Juillet 2017, (n.d.).
Référencement Groupe Maisons & Cités 2012, (n.d.). http://www.maisonsetcites.fr/outils_transversaux/blocs_bas_de_page/toutes_rubriques/marches/cahier_des_charges_produits_et_materiaux(Accessed 15 January 2017).
Saling, P., Kicherer, A., Dittrich-Krämer, B., Wittlinger, R., Zombik, W., Schmidt, I., Schrott, W., Schmidt, S., 2002. Eco-efficiency analysis by basf: the method. Int. J. Life Cycle Assess. 7, 203–218. doi:10.1007/BF02978875.
Soust-Verdaguer, B., Llatas, C., García-Martínez, A., 2016. Simplification in life cycle assessment of single-family houses: a review of recent developments. Build. Environ. 103, 215–227. doi:10.1016/j.buildenv.2016.04.014.
Su, X., Luo, Z., Li, Y., Huang, C., 2016. Life cycle inventory comparison of different building insulation materials and uncertainty analysis. J. Clean. Prod. 112, 275–281. doi:10.1016/j.jclepro.2015.08.113.