Building and Environment 228 (2023) 109813

Contents lists available at ScienceDirect

Building and Environment

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

Environmental and economic optimization and prioritization tool-kit for residential building renovation strategies with life cycle approach

Markel Arbulu [a,*], Xabat Oregi [a], Lauren Etxepare [b]

[a] CAVIAR Research Group, Department of Architecture, University of the Basque Country UPV/EHU, Plaza Oñati, 2, 20018, Donostia - San Sebastián, Spain
[b] Department of Architecture, University of the Basque Country UPV/EHU, Plaza Oñati, 2, 20018, Donostia-San Sebastián, Spain

ARTICLE INFO

Keywords:
Building energy renovation
Life cycle analysis (LCA)
Decarbonising
Cost-effectiveness
Script
Methodology

ABSTRACT

The most recent regulations, as well as the scientific studies, remark the importance of the evaluation of the entire life cycle on building renovations, relative to the environmental impact and economic feasibility, making the Life Cycle Assessment (LCA) the prioritizing analysis. The objective of the study is to develop a simplified methodology for the environmental and economic assessment of residential building renovations with life cycle approach. For this, a script-based tool-kit is developed: the first tool optimizes the thickness of envelope insulation based strategies; the second tool is for the prioritization of strategies by assessing their environmental performance and economic feasibility. In order to follow the objective, the development of the two tools is presented: both tools follow a parallel scheme where the input parameters are required by an excel file and the calculation script provides the results automatically by exporting the results excel file. The evaluation provides the quantification of the relative environmental improvement with the net energy ratio (NER), and the economic feasibility by the financial indicator of internal rate of return (IRR). The tool-kit is applied in a case study of a multifamily residential building. The results show, on the one hand, that the usability of the tool-kit can be determinant in the decision-making of stakeholders; and in the other hand, the importance of carrying out a dynamic assessment, taking into account the variation of the results caused by the uncertain parameters that differ in time. Moreover, the tool-kit can assist the development of cost-effective decarbonisation strategies.

1. Introduction

1.1. Context

The energy consumption of the buildings covers about the 40% of energy consumption in the European Union (EU), taking into account all the stages of the buildings' life [1]. Moreover, the EU reclaims a mayor energy saving because of the nowadays energetic political and economic situation together with the war in Ukraine, being the buildings one of the keys to achieve the savings and reduce the energy dependency, accelerating and strengthening mid and long term energetic objectives of the UE [2]. Among all the buildings, the households are responsible of the biggest part, being responsible of over the 25% of the total energy consumption in the EU [3].

The renovation of the building stock can bring energy achievements, as around the 75% of the buildings of the EU are inefficient. However, the yearly renovation rate is only around the 0,4% - 1,2%, and these rates should be at least doubled to achieve the energy objectives of the EU [1]. The main objectives relative to the renovation of buildings are included in the energy performance of buildings directive (EPBD) (Directive 2018/844 [4]) together with economic objectives and the cost-effectivity. The complementary document "Commission Recommendation (EU) 2019/786 of May 8, 2019 on building renovation" [5] included an evaluation scope to be followed by the member states (MS) to assess the renovation of the building stock. The document shows the lack of an accurate and standardized methodology for the evaluation of building renovation [6] and also mentions the need to evaluate the "identification of cost-effective approaches to renovation (…) where applicable, in the life-cycle of the building" and the "reduction of whole life carbon" [5]; this way the it reclaims the environmental and economic evaluation of the whole life cycle of the buildings as it does the life cycle assessment (LCA). However, as a previous study the life cycle thinking is implemented in a minor way, being unable to quantify the whole impact of the renovated buildings [7].

The integration of the life cycle perspective is also remarked as the main methodological approach to assess and quantify the

---

* Corresponding author.
E-mail address: markel.arbulu@ehu.eus (M. Arbulu).

https://doi.org/10.1016/j.buildenv.2022.109813
Received 19 September 2022; Received in revised form 20 October 2022; Accepted 13 November 2022

decarbonisation of the building stock in many other reports such as Level(s) [8], the European framework for sustainable buildings, and the recent published report "Roadmap for the decarbonisation of buildings throughout their life cycle" by GBCe in 2022 [9]. Moreover, studies found the high influence of non-operational stages of the buildings' life on the environmental and economic sustainability of refurbishment [10], and according to the literature the LCA is the prioritizing analysis on building renovation studies [11,12].

As a response of these needs, many methodologies have been published together with a European standard, the EN 15978:2012 [13], assessing the environmental aspects of the renovation of buildings with life cycle perspective, even European research projects like ENSLIC Building Project investigated the new methods and guidelines to carry out the LCA in buildings [14]. In terms of environmental evaluation, Van Gulck et al. [15] developed a methodology to assess façade renovations to "compare environmental-financial optimal façade renovation solution", using the SimaPro software to quantify the environmental impact; the study used a single score in points to evaluate the environmental impact. As another measurement method, the investigation to identify "cost-effective and climate-friendly renovation solutions" developed by Galimshina et al. [16] assessed the environmental impact at the midpoint level by the indicator if greenhouse gas (GHG) emissions. The financial evaluation with life cycle perspective, known also as life cycle cost (LCC) according to the standard EN-16627:2016 [17], has been also carried out by many studies. The previously mentioned recent study by Van Gulck et al. [15] used the net present value (NPV) to evaluate the economic feasibility of renovation solutions, and the study by Galimshina et al. [16] applied the LCC method including an uncertainty analysis. Moreover, the economic evaluation with life cycle approach is applied in more specific and detailed techno-economic evaluations like in complex heating, ventilation and air conditioning (HVAC) systems, assessing by the indicators of annual life cycle cost (ALCC) and the capital recovery factor (CRF) [18,19] and also calculating the financial interest rate as it was done by M. Esen & T. Yuksel [20] using the David Cantrell method [21].

In terms of evaluation techniques, programming and machine learning (ML) are commonly used in processes and strategies to improve the energetic behaviour of buildings. The literature shows that many methodologies like prediction models have been studied, which can predict the heating and cooling loads or a day ahead prediction of the electricity consumption, studied deeply different methods comparing their accuracy [22,23]. Moreover, ML is a good tool for the control of HVAC systems by the model predictive control (MPC), showing great improvements in systems' efficiency and using from simple linear models with on-off control to advanced neural networks [24]. In this field, P. Hosseini et al. [25] developed a ML methodology for the optimization of the systems of a smart educational building answering evaluated from the point of view of exergy, economics, and environment. Advanced algorithms like the deep-learning neural network prediction have been also applied to innovative solutions like solar-based absorption chiller cooling systems [26]. Nevertheless, there is no a significant ML based methodology for the assessment of renovation of buildings with life cycle perspective, which could be directly applied for decision making of stakeholders and further studies.

1.2. Objectives

The objective of the study is to develop a simplified and automatized methodology based in programming and ML for the environmental and economic assessment of residential building renovations with life cycle approach; for that, a script-based tool-kit is expounded, composed by two assessment tools. On the one hand, the first tool makes possible the optimization of insulation based passive renovation strategies by identifying the optimal thickness of the insulation, according to the environmental impact and economic cost-effectiveness in their life cycle. On the other hand, the second tool carries out the prioritization of passive, active and renewable energy source (RES) integration based strategies by assessing their environmental improvement and economic feasibility of the investment of the strategy. This ways is possible to attend to the need of an evaluation methodology with life cycle approach completely developed by programming language and ML, and each of the tools can be run in one single step with a data input and output functionality. section 2 explains the tool-kit based methodology development, section 3 applies the tool-kit in a case study, including a sensitivity and uncertainty assessment, and section 4 discusses the results obtained.

2. Methodology

In order to follow the objective, the study develops and provides the tool-kit covered by a common LCA goal and scope, assessing the environmental LCA and the economic LCA, also known as LCC. The goal of the methodology is to evaluate the environmental impact and the economic feasibility of residential building renovation strategies with life cycle approach. The evolution is focused exclusively in the improvement of the efficiency of heating and DHW; this means that the impact and costs of the energy use of the building to be taken into account are the ones attributed to the heating and DHW. To set the bases, the common LCA goal and scope are defined, and then the two tools' methodological developments are presented following the scheme of Fig. 1: first, the optimization tool to optimize each insulation based passive strategy, and second, the prioritization tool evaluates the renovation strategies to prioritize the best performing strategies. Each tool is based in a script written in Python 3, in format *. py*, and a data input excel file in format *. xlsx*. The tool-kit is available in open source in the GitHub repository (https://github.com/markelarbulu/LCA_residential_building_renovation.git).

The common LCA goal and scope definition is composed by five parameters: the functional unit (FU), the reference study period (RSP), system boundary conditions, the impact indicators and the prioritization indicators (see Table 1). The first parameter to be established is the FU, defined as the "quantified performance of a product system for use as a reference unit" by the ISO-14040:2006 [27], with the purpose of providing a reference to relate the input and output data, and allows the comparison between different scenarios and situations. The present methodology uses the $m^2/year$ of the heated net area as the FU, aligned with the goal of the study focused in the improvement of the energy efficiency of the heating and DHW.

The RSP is understood as the time period for which characteristics of the element under assessment are analysed, defined in the standard EN-15978:2012 [13], in the unit of years (following the FU). There is not any standardized value, so it can be defined by the estimated service (ESL) of the building according to the standard EN-15978:2012 [13], defined in the tool as the reference service life of the building (RSL_B). The present methodology uses 50 years as a default value.

The boundary conditions are defined following the standard EN-15978:2012 [13], selecting the most influential life stages and avoiding the life stages with less than 1% of influence in the total final life cycle impacts following the previous studies by Oregi et al. [10]. The determination of the cut-off rules is in accordance with the rest of the methodological assumptions made, following the accuracy that a theoretical methodology for the prediction of the impact and costs of a building renovation; moreover, many uncertain parameters are assessed (see section 3.3, Sensitivity assessment) with a differing effect beyond the error of 1%. The selected life stages to be taken into account are shown in Table 1, the ones for the environmental assessment and the economic assessment.

The impact indicators to assess the environmental and economic influence of each scenario and renovation strategy are the "Global warming potential" (GWP) and the total use of "Non-renewable primary energy resources" (NRPE) for the environmental assessment, with the corresponding units of the EN-15978:2012 [13] ($kg{\cdot}CO_2eq$ for GWP; *MJ* for NRPE). For the economic assessment the impact indicator of full-cost

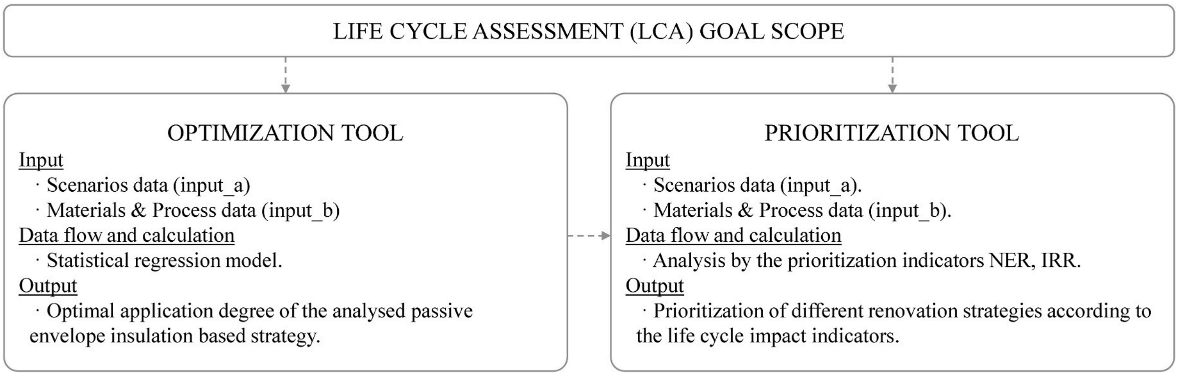

Fig. 1. Methodology scheme for the environmental and economic optimization and prioritization tool-kit.

Table 1
Life Cycle Assessment (LCA) goal and scope definition.

Functional unit (FU)		
m^2/year		
Reference study period (RSP)		
50 years		
Boundary Conditions		
Life cycle stage	*Environmental assessment*	*Economic assessment*
A 1–3 Product stage	X	X
A5 Construction process		X
B2 Maintenance		X
B4 Replacement – A 1–3 Product stage	X	X
B4 Replacement – A5 Construction process		X
B6 Operational Energy use	X	X
Impact indicators		
Assessment LCA field	*Indicator*	*Unit*
Environmental	Global warming potential (GWP)	kg CO2eq./FU
	Total use of non-renewable primary energy resources (NRPE)	MJ/FU
Economic	Full-cost (FC)	€/FU
Prioritization indicators		
Assessment LCA field	*Indicator*	*Unit*
Environmental	Net energy ratio (NER)	–
Economic	Internal rate of return (IRR)	%

(FC) is used, with the € unit as the EU's currency (see Table 1). These indicators will provide the information of each analysed scenario of the renovation strategies individually without any comparison with the baseline scenario.

Furthermore, the prioritizing indicators assess each scenario indicating the relative environmental and economic sustainability, ergo, the reached improvement of the renovation strategies comparing to the baseline scenario in the environmental and economic field (see Table 1). On the one hand, for the environmental assessment, the prioritization indicator "Net energy ratio" (NER) is used, developed by Hernandez & Kenny [28] to evaluate the environmental impact of the building renovation with life cycle approach. The NER is a unitless parameter that quantifies how many time is the embodied energy (relative to the stages A1-3 and B4 A1-3) saved by the energy reduction provided by the renovation. On the other hand, for the economic assessment, the prioritization indicator "Internal rate of return" (IRR) is used, indicating the percentage value that equals the initial difference (net present value) between the initial payment and the income relative to the energy consumption saving attributed to the renovation strategy.

2.1. *Optimization tool*

The optimization tool evaluates the environmental and economic optimal application degree of passive envelope insulation based strategies, calculating the optimal thickness of the insulation of each. The calculation is based on the statistical regression model of scenarios' data introduced with different application degrees for each strategy. As a result, the tool calculates the optimal thickness of the insulation, on the one hand, according to the environmental prioritization indicator (NER), and on the other hand according to the economic prioritization indicator (IRR). The calculation is made only taking into account the energy demand of heating and it is divided in three blocks: the input data (entry); the data flow and mathematical calculation (process); and the output data (results). The input data is introduced in the . *xlsx* file and organized following section 2.1.1; the data flow and mathematical calculation is done by script; finally, the output data is given in a new . *xlsx* file exported by the script.

2.1.1. *Input data*

The input data is organized in the categories of the scenarios data parameters (input_a) and the materials & processes data parameters (input_b), shown in Table 2 The data is introduced in the excel file with a sheet for each input chapter (input_a, input_b).

The first data category, the scenarios data (input_a), demands the data from scenarios with different thicknesses of the insulation to be added. The more scenarios with different application degrees are analysed the higher is the accuracy of the optimization, but the study suggests using four thicknesses and three at least (e.a. 20, 40, 100, 180 mm), plus the baseline scenario. The data to be introduced includes general data of the case study and specific data for each application degree. The general data of the case study is composed by three parameters: the reference service life of the building (RSL_B), the heated surface (S) and the economic inflation rate (IR). Firstly, the RSL_B is considered the RSP defined as 50 years, but it can be modified; secondly, the heated surface is the net habitable surface related to the energetic use of the building in the unit of m^2 (following the FU); thirdly, the inflation rate (IR) can be determinated by the last trends of the economic growth or set as a standard expected of 1,5% [29]. For the specific data, the input data sheet demands the energetic data of each application degree, including the operational energetic data (annual heating energy demand (Ed_H), energy efficiency (Ee_H) of the heating installation and distribution losses (El_H)), the operational processes (energetic processes for heating installations) and data about the materials and processes of the renovation strategy (the used materials and processes, and the measurement or quantity). For the calculation of the Ed_H of each scenario, several techniques can be applied, but this study suggests the use of "complete level" calculation scheme using a dynamic energy simulation tool, such as Design Builder [30] software (interface for Energy Plus calculation engine [31]) with the climatic data from the International Weather for Energy Calculation [32] (from ASHRAE). The energy efficiency could be with on-site tested values or could be estimated according to the installations and its conditions, and the same for the energy losses

Table 2
Input parameters for the Optimization tool.

Data category	Input	Tool code	Unit
Scenarios data *(input_a)*	Reference service life of the building (RSL_B)	rslb	yr
	Heating surface (S)	s	m^2
	Inflation rate (IR)	inf	%
	Annual heating demand (Ed_H)	ed_h	KWh/ $m^2 \cdot yr$
	Energy efficiency of the heating system (Ee_H)	eef_h	%
	Energy distribution losses (El_H)	el_h	%
	Heating operational energetic processes	process_h	–
	Material of renovation strategies	mat_n	–
	Material measurement/ quantity	mat_n_med	(unit)
Materials & Processes data (LCI) *(input_a)*	Conversion factor of operational energy processes as GWP	gw_b6	Kg CO_2 eq./MJ
	Conversion factor of operational energy processes as NRPE	pe_b6	MJ/MJ
	Economic cost of the operational energy processes (EP)	fc_b6	€/MJ
	Energy price increment (EPI)	fc_in_b6	–
	Reference service life of the material	rslm	yr
	Production impact of the materials as GWP	gw_a13	Kg CO_2 eq./(unit)
	Production impact of the materials as NRPE	pe_a13	MJ/(unit);
	Production economic cost of the materials	fc_a13	€/(unit)
	Construction/installation cost of the materials	fc_a5	€/(unit)
	Maintenance annual economic cost of the materials	fc_b2	€/(unit)·yr
	Conversion factor from material measuring unit to FU	conv	$m^2 \cdot yr$/ (unit)

according to the distribution of the heating system.

The second category of the materials and processes data (input_b) demands the life cycle inventory (LCI) analysis, including all the environmental impacts and economic costs of processes and renovation strategy's materials in the midpoint level. The operational processes are linked to the primary energy source for heating systems, and the needed parameters are the ones linked to the operational energy (B6 stage): the conversion factors of the operational energy processes, for both environmental impact indicators (GWP, NRPE); the economic cost of the energetic processes (EC); and the energy price increment (EPI) coefficient. According to the materials linked to the renovation strategy, the needed parameters are the ones related to the embodied impact and cost: the reference service life of the material (RSL_M) (to quantify the needed replacements during the building's service life); production impact of the materials and the economic cost (for the A1-3 life stage); construction and installation costs (for the A5 life stage); and maintenance annual cost (for the B2 life stage). To carry on the LCI analysis the study suggests the use of specific environmental product declarations (EPD) for the embodied impacts of the materials and systems as long as possible, otherwise, the Ecoinvent database [33] can be used; for the impact processes (for conversion factors) the study suggest the Ecoinvent database [33].

2.1.2. Data flow and mathematical calculation

In order to process the calculation, the script makes the calculations and the exportation of the *.xlsx* file with the output data. The calculation is based on the definition of the prioritization indicators (NER and IRR) in function of the thickness of the insulation layer to be added, identifying the maximum NER and IRR and accordingly the optimal thicknesses (the optimal thickness for the maximum NER and the optimal for the maximum IRR). The two results are calculated independently but they both use the prediction by the mathematical regression model using the machine-learning module Scikit-learn [34].

On the one hand, for environmental optimization, the NER function is defined by the ratio between the embodied impact of the refurbishment strategy and the operational impact saving achieved. The embodied impact is the sum of the non-operational life stages (A1-3 and B4 A1-3), calculated following the equations of the Annex 1; the operational reduction is calculated by subtracting the NRPE of the stage B6 (operational energy use) of the renovated scenario and the baseline scenario (equations on the Annex 1). The calculated impact indicators data points will allow creating the regression model of both indicators (embodied and reduction of operational), creating the mathematical definition of the impacts in function of the thickness. The resulting regression mathematical models define the impact (both embodied and operational reduction) in function of x as the thickness. In the case of the reduction of the operational impact, the mathematical relation with the thickness is logarithmic, it means that the reduction slope of the operational impact decreases while the insulation increases, and can be defined as $f(x) = a \cdot \ln(x) + b$. Besides, relation between the thickness and the embodied impact is linear, it means that the increasing of the thickness and the embodied impact are proportional, and is defined by as $g(x) = m \cdot x + c$. The script calculates the constants a, b for the logarithmic function and m, c for the linear function fitting with the functions in the calculated impact points by introduced data (see Fig. 2a). By this, the NER definition can be calculated in function of the thickness as $h(x) = f(x)/g(x)$ function, and the null derivation, $h'(x) = 0$, gives the optimal thickness for the environmental assessment.

On the other hand, the economic optimization departs from the mathematical definition of the energy demand and calculates all the economic costs of all the life stages and then the IRR for each unit of thickness; finally, the optimal thickness is calculated by identifying the maximum IRR. The direct calculation cannot be done as in the environmental assessment due to the calculation method of the IRR, as the yearly cash flow needs to be defined for each unit of thickness. For the calculation, the mathematical definition of the heating energy demand is calculated applying the logarithmic relation between the energy demand and the insulation thickness, defining the energy demand in function of the thickness as $f(x) = a \cdot \ln(x) + b$. With the obtained function, the costs for the scenarios of each unit of thickness are calculated getting as resultant the IRR (following the equations of the Annex 1); this allows the identification of the maximum IRR value and consequently the optimal thickness for the economic assessment.

As a result, Fig. 2 shows the mathematical expressions to determinate the optimal values of the thickness according to the NER (Fig. 2a) and IRR (Fig. 2b); moreover, it shows the tendencies of the predicted operational reduction environmental impact and economic cost as a logarithmic function, and the predicted embodied environmental impact and economic cost as a linear relation with the thickness, both with the calculated scenarios. Even if both calculations methods are different, Fig. 2 shows the similarity of the environmental and economic situations, with the relations between the logarithmic operational cost and impact reduction, the linear embodied cost and impact, and the prioritization indicators. Finally, the script exports the result of two optimal application degrees of the analysed passive envelope together with the energy demand for each of the thicknesses, as an *.xlsx* file.

2.1.3. Output data

The results are given in the *.xlsx* file exported by the script providing all the input data, as well as an additional sheet with the results: firstly, the optimal insulation thickness according to the environmental impact,

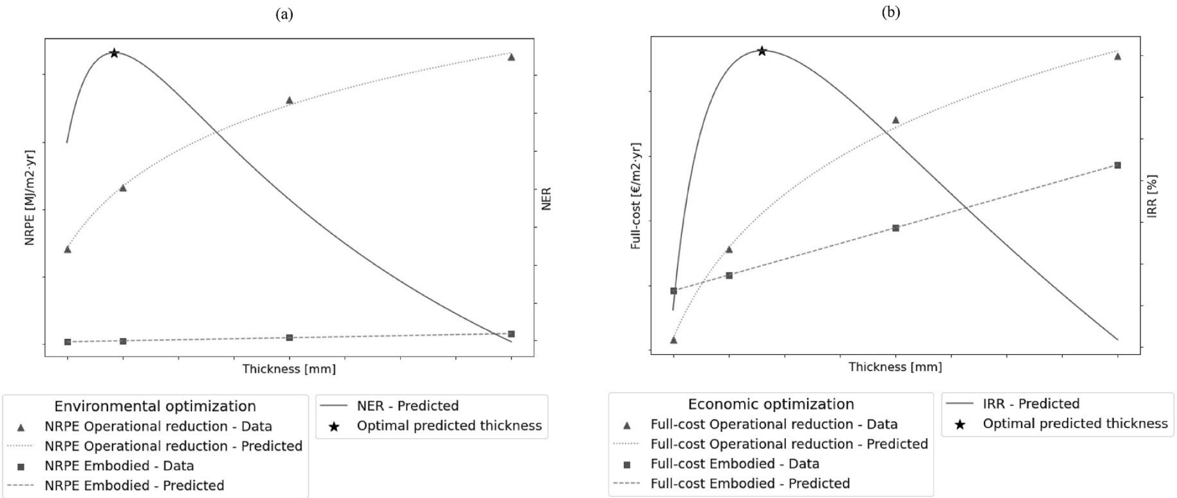

Fig. 2. Calculation of the optimal insulation thickness by the regression mathematical model according to the environmental impacts (a) and economical costs (b).

by the NER indicator, and secondly the optimal insulation thickness according to the economic scope, by the IRR indicator, in the unit of *mm*. Additionally, the tool provides the annual heating energy demand of both environmental and economic optimal scenarios as shown in Table 3; this way the there is no need to make another simulation to calculate the energy demand for the prioritization input data.

2.2. *Prioritization tool*

In the second stage, the LCA based prioritization tool is applied to identify the renovation strategies with the highest environmental and economic performance according to the LCA goal and scope defined in this methodology. The tool can assess passive, active and RES integration based strategies, measuring their impacts by the impact indicators and assessing each strategy's performance. The result of the tool is the prioritization of renovation strategies according to the environmental improvement that each strategy can provide by the NER, and the financial affordability of the economic investment by the IRR. The previous optimization tool ensures the optimal thickness of passive envelope insulation based strategies, so only these optimal thicknesses are assessed in this tool for the insulation-based strategies. The tool has a parallel scheme as the optimization tool, divided into three blocks: the input data (entry); the data flow and mathematical calculation (process); and the output data (results); also the functionality is similar with an . *xlsx* file for the input data, a . *py* script for the data flow and mathematical calculation, and an . *xlsx* file exported by the script as the output data.

2.2.1. *Input data*

The input data to be introduced in the . *xlsx* file are organized into two categories, the scenarios data (input_a) and the materials & processes data (input_b), as it is shown in Table 4.

The first category of the scenarios data (input_a) demands the parameters to describe each scenario with the application of different renovation strategies (see Table 4). The tool can assess all the *n* scenarios included in this data category, introduced in *n* rows in the input_an of the excel file. The data has a parallel structure as in the optimization tool, being the same for the parameters of RSL_B, S and IR. The demanded specific parameters are composed by the energetic data, and the operational processes and the materials applied by each strategy. The energetic data to be introduced is relative to the heating and DHW separately, with the parameters of annual energy demand (Ed_H, Ed_W), energy efficiency of the system (Ee_H, Ee_W), distribution losses (El_H, El_W) as the ones already in the optimization tool. Moreover, the prioritization tool includes the energy generation parameters, distinguishing the energy generation as heat (Egh_H, Egh_W) and as electricity (Ege_H, Ege_W), both separately for heating and DHW. In addition, the parameters of operational processes and the materials and processes of the renovation strategy are included. For the calculation of the energy demands, as for the optimization tool, the methodology suggest the use of "complete level" calculation, such as Design Builder [30].

Table 3
Output results of the Optimization tool.

Data category	Output	Tool code	Unit
Results *(output)*	Optimal thickness according to the NER	opt_env	mm
	Energy demand (heating) of the optimal environmental solution	ed_env	KWh/ m^2·yr
	Optimal thickness according to the IRR	opt_ec	mm
	Energy demand (heating) of the optimal economic solution	ed_ec	KWh/ m^2·yr

The second category of the materials and processes data (input_b) is the LCI analysis of the assessed strategies, in the same way as the previous tool (see Table 4).

2.2.2. *Data flow and mathematical calculation*

For the calculation process, the script calculates all the impact indicators for each stage in each scenario and the prioritization indicators in each scenario by the equations of the Annex 1, assessing the sustainability if each renovation strategy and its relative improvement provided.

First, the impact of the operational stage is calculated separately for the heating and DHW processes, in the baseline scenario and in the scenarios with the renovation strategies applied; the calculation departs from the energy demand of heating and DHW, calculating the impacts separately by the energetic data and processes' data, in the units defined as the FU. In this stage, the yearly environmental impact remains constant; however, the economic cost suffers a yearly increase due to the EPI parameter.

Secondly, the embodied impacts and costs are calculated. The stage relative to the production of the materials (A1-3) is calculated with the impact caused before the construction process. The next stage, the construction and installation process (A5), is also calculated by an initial impact divided into the FU, but only the economic cost is taken into account following the boundary conditions. During the use of the building, the maintenance cost is taken into account by the economic cost. This indicator calculates the yearly cost taking into account the IR

Table 4
Input parameters for the Optimization tool.

Data category	Input	Tool code	Unit
Scenarios data *(input_a)*	Reference service life of the building (RSL_B)	rslb	yr
	Heating surface (S)	s	m^2
	Inflation rate (IR)	inf	%
	Annual heating demand (Ed_H)	ed_h	KWh/m^2·yr
	Annual domestic hot water (DHW) demand (Ed_W)	ed_w	KWh/m^2·yr
	Energy efficiency of the heating system (Ee_H)	eef_h	%
	Energy efficiency of the DHW system (Ed_W)	eef_w	%
	Energy distribution losses in heating (El_H)	el_h	%
	Energy distribution losses in DHW (El_W)	el_w	%
	Energy generation as heat for heating (Egh_H)	egh_h	%
	Energy generation as heat for DHW (Egh_W)	egh_w	%
	Energy generation as electricity for heating (Ege_H)	ege_h	%
	Energy generation as electricity for DHW (Ege_W)	ege_w	%
	Heating operational energetic processes	pr_h	–
	DHW operational energetic processes	pr_w	–
	Thickness of the insulation	th	dm
	Material of renovation strategies	mat_n	–
	Material measurement/quantity	mat_n_med	(unit)
Materials & Processes data (LCI) ***(input_b)***	Conversion factor of operational energy processes as GWP	gw_b6	KgCO_2 eq./MJ
	Conversion factor of operational energy processes as NRPE	pe_b6	MJ/MJ
	Economic cost of the operational energy processes	fc_b6	€/MJ
	Energy price increment (EPI)	fc_in_b6	–
	Reference service life of the material	rslm	yr
	Production impact of the materials as GWP	gw_a13	KgCO_2 eq./(unit)
	Production impact of the materials as NRPE	pe_a13	MJ/(unit);
	Production economic cost of the materials	fc_a13	€/(unit)
	Construction/installation cost of the materials	fc_a5	€/(unit)
	Maintenance annual economic cost of the materials	fc_b2	€/(unit)·yr
	Conversion factor from material measuring unit to FU	conv	m^2·yr/(unit)

calculated during the RSL_B. Furthermore, during the use of the building, in the case where the RSL of the building is longer than the RSL of certain material or system the replacement is needed, as its estimated service life will be over. In the replacement life stage, two sub-stages can be distinguished; the production of the material and the construction process, assessing the production stage (B4 A1-3) in the environmental and economic field, and the construction and installation process stage (B4 A5) only in the economic field. In the production replacement (B4 A1-3), the environmental costs are the same as in the initial A1-3 stage, assuming that the environmental impact of the material will not change; besides, the economic cost will change due to the economic IR, and the cost will be calculated in the year when the RSL of the material is ended. The same happens with the construction economic cost (B4 A5), being the cost calculated by the IR, in the year when the RSL of the material or system is over.

Finally, the script calculates the prioritization indicators (NER, IRR) using the impacts of the renovations strategies and the baseline scenario (equations in Annex 1), quantifying the improvement provided by the renovation of the building, in the environmental field and the economic field as shown in Fig. 3.

2.2.3. *Output data*

The results are given as in the previous tool, by an exported *. xlsx* file including the all the input data, as well as an additional sheet with the output indicators as the results (see Table 5). There are three types of output indicators: the energy consumptions, the impact indicators, and the prioritization indicators.

3. Case study and results

The presented methodology for the enviro-economic assessment of renovation strategies is tested in a case study of a block of flats of 28 dwellings located in Vitoria-Gasteiz, north of Spain (Cfb climatic zone), built in 2001 (see Table 6). The dwellings are organized in four floors; seven dwellings in each floor with two vertical communication cores. The thermal envelope is composed by a double façade with basic thermal insulation layer of 3 cm, openings with double-glazing and aluminium frame and pitched roof with basic insulation layer of 4 cm. The HVAC installations of the building are only basic individual gas boilers for heating and DHW.

As it is demanded for the input data of the tool-kit, a dynamic energy simulation is done using the model shown in Fig. 4, by the software Design Builder [30] and the climatic data from Weather for Energy Calculation [32]. The indoor conditions, the occupation and use schedules as well as the base temperature are determinated by the Spanish construction technical code (CTE) [35]. This simulation allows to calculate the energy demand of the building for heating and DHW demanded by the tool-kit.

3.1. *Application of the optimization tool*

For the application of the optimization tool four insulation based renovation strategies have been analysed, two external thermal insulation composite systems (ETICS) and another two applications of the inner insulation with interior cladding, each of them with a common insulation material, extruded polystyrene (XPS), and with a material with lower embodied environmental impact, wood fibre insulation (see Table 7). The thermal conductivity of both insulation materials is considered the same (λ = 0,040 W/m·K) but the impact and costs are completely different.

The data input will be provided by the case study characteristics;

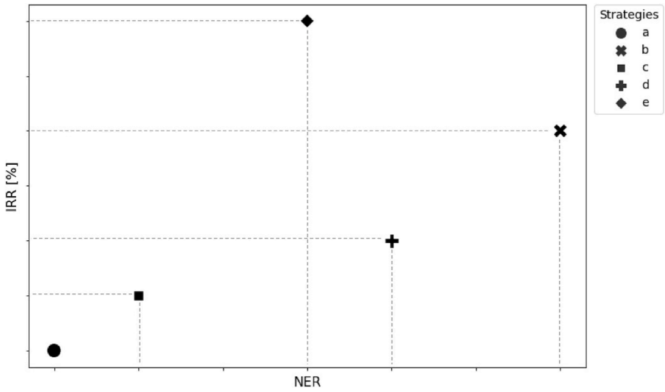

Fig. 3. Environmental and economic assessment of renovation strategies with life cycle approach by prioritization indicators.

Table 5
Output results of the Prioritization tool.

Data category	Output	Tool code	Unit
Results *(output)*	Energy consumption in heating (Ec$_H$)	ec_h	MJ/m^2·yr
	Energy consumption in DHW (Ec$_W$)	ec_w	MJ/m^2·yr
	Energy consumption total (heating + DHW) (Ec$_T$)	ec_t	MJ/m^2·yr
	Global warming potential in stage B6 in heating (GWP$_{B6\text{-}H}$)	gw_b6_h	KgCO$_2$ eq./m^2·yr
	Global warming potential in stage B6 in DHW (GWP$_{B6\text{-}W}$)	gw_b6_w	KgCO$_2$ eq./m^2·yr
	Global warming potential in stage B6 in total (GWP$_{B6}$)	gw_b6	KgCO$_2$ eq./m^2·yr
	Global warming potential in stage A1-3 (GWP$_{A1\text{-}3}$)	gw_a13	KgCO$_2$ eq./m^2·yr
	Global warming potential in stage B4 (A1-3) (GWP$_{B4\ A1\text{-}3}$)	gw_b4_a13	KgCO$_2$ eq./m^2·yr
	Global warming potential total (GWP)	gw_t	KgCO$_2$ eq./m^2·yr
	Non-renewable primary energy in stage B6 in heating (NRPE$_{B6\text{-}H}$)	pe_b6_h	MJ/m^2·yr
	Non-renewable primary energy in stage B6 in DHW (NRPE$_{B6\text{-}W}$)	pe_b6_w	MJ/m^2·yr
	Non-renewable primary energy in stage B6 in total (NRPE$_{B6}$)	pe_b6	MJ/m^2·yr
	Non-renewable primary energy in stage A1-3 (NRPE$_{A1\text{-}3}$)	pe_a13	MJ/m^2·yr
	Non-renewable primary energy in stage B4 (A1-3) (NRPE$_{B4\ A1\text{-}4}$)	pe_b4_a13	MJ/m^2·yr
	Non-renewable primary energy total (NRPE)	pe_b6	MJ/m^2·yr
	Full-cost in stage B6 in heating (FC$_{B6–H}$)	fc_b6_h	€/m^2·yr
	Full-cost in stage B6 in DHW (FC$_{B6-W}$)	fc_b6_w	€/m^2·yr
	Full-cost in stage B6 in total (FC$_{B6}$)	fc_b6	€/m^2·yr
	Full-cost in stage A1-3 (FC$_{A1\text{-}3}$)	fc_a13	€/m^2·yr
	Full-cost in stage A5 (FC$_{A5}$)	fc_a5	€/m^2·yr
	Full-cost in stage B2 (FC$_{B2}$)	fc_b2	€/m^2·yr
	Full-cost in stage B4 (A1-3) (FC$_{B4\ A1\text{-}3}$)	fc_b4_a13	€/m^2·yr
	Full-cost in stage B4 (A5) (FC$_{B4\ A5}$)	fc_b4_a5	€/m^2·yr
	Full-cost total (FC)	fc_t	€/m^2·yr
	Net energy Ratio (NER)	NER	–
	Internal Rate of Return (IRR)	IRR	%

Table 6
Characteristics of the case study.

Characteristics of the case study	Location	Vitoria - Gasteiz (Spain)
	Köppen-Geiger climatic zone	Cfb
	Local climatic zone (TBC)	D
Building factors	Year of construction	2001
	Heated surface	2083,52 m^2
	No. Of stories	Ground +4
	No. Of dwellings	28
	Façade (double layer with basic insulation) transmittance [W/m^2·K]	0,67
	Roof (pitched with basic insulation) transmittance [W/m^2·K]	0,57
	Window (aluminium frame with double glazing) transmittance [W/m^2·K]	5,01/2,55 (frame/glazing)
	Heating system	Individual gas boiler
	DHW system	Individual gas boiler
	Ventilation system	Natural ventilation

these data as well as the data of the materials and processes and the calculation assumptions are specified in the Annex 2. Firstly, for the general data of the first category, the RSL$_B$ is considered 50 years; the heating surface is considered the habitable net surface of the dwellings; and for the IR a rate of 1,5% has been assumed. Secondly, four scenarios have been calculated with the thicknesses of 20, 40, 100 and 180 mm; the annual Ed$_H$ has been calculated by the energy simulation mentioned before; the energy efficiency of the heating system has been assumed to be 0,8, as the gas boilers are not in the best conditions; the energy distribution losses has been considered null because the heating system is inside the thermal envelope; finally, the processes and materials used are chosen, natural gas for the heating and the corresponding materials. Thirdly, the LCI analysis is carried out by the products' EPDs, the Ecoinvent database [33] and construction prices database of Spain [36].

The calculation process carried out inside the script is explained in Fig. 5, showing how are the optimal thickness identified for the strategy A1 (ETICS with wood fibre insulation). The reduction of the operational environmental impact and economic saving increase while the thickness increases, but with a reducing slope; besides, the embodied impact and cost increases constantly. The functions of the NER and IRR draw a similar curve, showing a clear maximum point as the predicted optimal thickness. This way the script calculated the optimal thickness according to the environmental impact (Fig. 5a) and the economic cost (Fig. 5b).

The results of Table 8 show that the optimal thicknesses can differ depending on the assessment field, environmental or economic, the strategy applied and the material of each strategy. In the case of the environmental evaluation the ETICS strategy show a lower optimal solution (37 mm, 26 mm) due to the higher potential of insulation because the solution does not generate thermal bridges, unlike the interior cladding solution (142 mm, 91 mm). Moreover, in the economic field, happens the same, being lower the optimal thickness of the ETICS solution (52 mm, 62 mm), than the interior cladding (94 mm, 109 mm). Besides, the insulation material have the opposite behaviour in the environmental and economic evaluation; in the environmental field the optimal thickness for wood fibre insulation (37 mm, 142 mm) is higher than for the XPS insulation (26 mm, 91 mm); however, for in the economic optimization the optimal thickness for the wood fibre insulation (52 mm, 94 mm) is lower that the thickness for the XPS insulation (62 mm, 109 mm). The reason is that the wood fibre insulation has a lower embodied environmental impact but a higher price, reaching to the optimal thickness in a smaller thickness due to the logarithmic tendency of the optimization curve of the operational reduction. Furthermore, the tool analysed the thickness in the range between 20 mm and 180 mm, and even other studies evaluated a wider range with a maximum thickness of 400 mm [15] the optimization tool's show that the results are not close maximum value of 180 mm (the maximum optimal thickness is 142 mm). This results matches the position of overheating due to the increase of insulation [16,37], avoiding the extra insulation above the optimal thickness that reduces its performance and can cause overheating.

3.2. Application of the prioritization tool

For the overall evaluation of passive, active and RES integration strategies, the prioritization tool is applied. Fifteen strategies have been evaluated (see Table 9), including two levels for each one of the four optimized strategies, with the optimal environmental economic thicknesses (A1env, A1ec, A2env, A2ec, B1env, B1ec, B2env, and B2ec). As another type of passive strategy, four types of replacement of the windows have been evaluated (C1, C2, C3, C4) including two levels of efficiency and two materials, aluminium with a high environmental embodied impact and wood with a lower embodied impact, and two types of glass, low emissivity double glass and triple glass. As a RES integration, a centralized solar thermal panel system has been evaluated to aid the existing heating and DHW system (D). Moreover, as an active strategy, a centralized heat pump is evaluated to replace the heating and DHW system (E), and as the last strategy, the centralized heat pump connected with photovoltaic (PV) panels (F) as the combination of active and RES integration strategy.

The data input is introduced evaluating all the strategies in one single step. For the scenarios data, new parameters are demanded

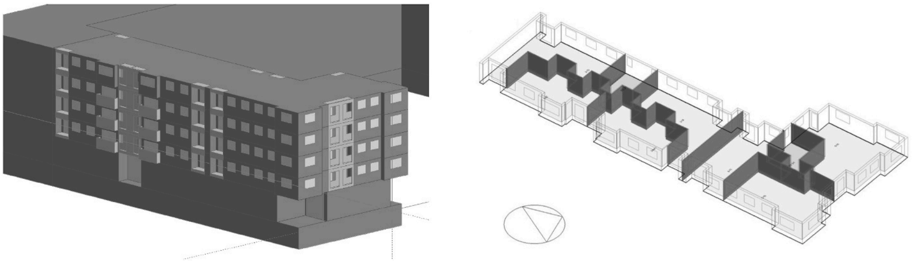

Fig. 4. Energy simulation model of the case study in Design Builder.

Table 7
Envelope insulation based passive renovation strategies evaluated by the optimization tool.

Code	Strategy
A1	ETICS with wood fibre insulation
A2	ETICS with XPS insulation
B1	Interior cladding insulation with wood fibre insulation
B2	Interior cladding insulation with XPS insulation

including the energy demands of each one of the scenarios, the energy generation and the efficiency of the processes, all of them separately for heating and DHW. For the materials & processes data, the LCI is introduced including the data about of all the processes and materials of the fifteen strategies, also from EPDs, the Ecoinvent database [33] and construction prices database [36]. All the input data of the case study can consulted in the Annex 2.

For the prioritization, the comparison with the baseline is the most important factor: the improvement reflected as the reduction of the operational environmental impact and economic costs and the embodied impact and cost attributed to the renovation strategies. In terms of impact indicators, Fig. 6 shows the reduction of environmental impact as the NRPE and the reduction of economic full-cost, representing the impact and costs saved by each strategy in comparison with the baseline scenario as positive values (positive reduction) and the embodied impact and costs as negative values (negative reduction). Afterwards, the script calculates the prioritizing indicators to quantify the environmental improvement with the NER and the financial affordability of the investment with the IRR. As the reflect of the prioritization indicators, Fig. 7 shows the relation between the environmental prioritization (NER) and the economic prioritization (IRR) of the evaluated strategies, showing that the difference in the level of each strategy does not differ the prioritization indicators as much as it does the difference between strategies. In this situation, regarding the passive

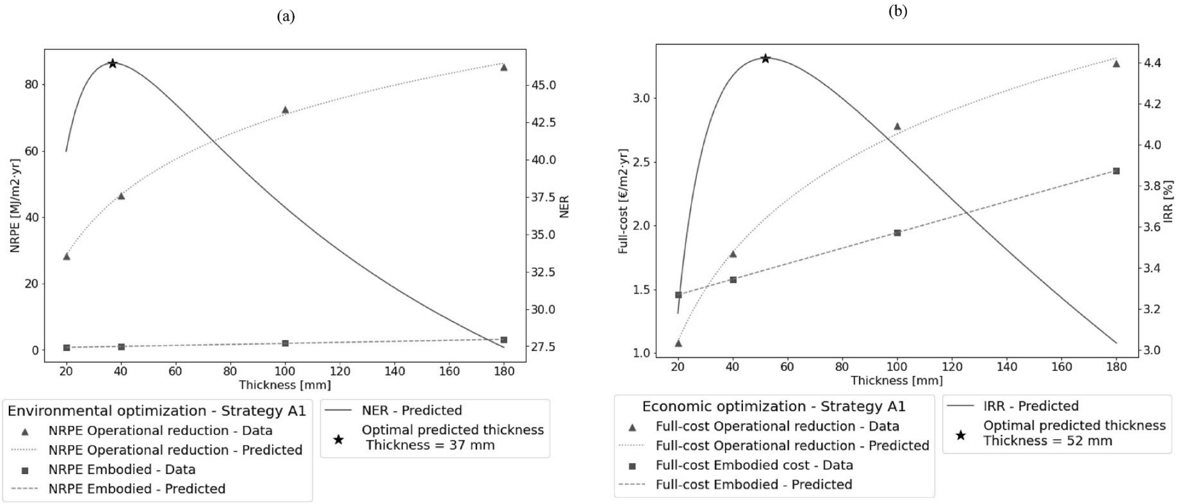

Fig. 5. Optimization of insulation thickness of the strategy A1 (ETICS with wood fibre insulation) by the regression mathematical model according to the environmental impacts (a) and economical costs (b).

Table 8
Optimization tool output data (results) showing the optimal thinness of the analysed envelope insulation based strategies, according to the environmental and economic evaluation.

Code	Strategy	Optimal Environmental Thickness [mm]	Optimal Environemtnal Ed_H [KWh/m^2·yr]	Optimal Economic Thickness [mm]	Optimal Ecnomic Ed_H [KWh/m^2·yr]
A1	ETICS with wood fibre insulation	37	58,54	52	56,91
A2	ETICS with XPS insulation	26	60,22	62	56,07
B1	Cladding insulation with wood fibre insulation	142	55,77	94	57,88
B2	Cladding insulation with XPS insulation	91	58,04	109	57,12

Table 9
Renovation strategies evaluated by the prioritization tool.

Code	Strategy
A1env	ETICS with wood fibre insulation - optimal environmental
A1ec	ETICS with wood fibre insulation - optimal economic
A2env	ETICS with XPS insulation - optimal environmental
A2ec	ETICS with XPS insulation - optimal economic
B1env	Interior cladding insulation with wood fibre insulation - optimal environmental
B1ec	Interior cladding insulation with wood fibre insulation - optimal economic
B2env	Interior cladding insulation with XPS insulation - optimal environmental
B2ec	Interior cladding insulation with XPS insulation - optimal economic
C1	Window replacement – Aluminium efficient frame and low emissivity double glass
C2	Window replacement – Wood efficient frame and low emissivity double glass
C3	Window replacement – Aluminium advanced frame and triple double glass
C4	Window replacement – Wood advanced frame and triple glass
D	Solar thermal panels – Centralized auxiliary system for heating and DHW
E	Heat pump - Centralized system for heating and DHW
F	Heat pump with PV panels - Centralized system for heating and DHW

strategies, the replacement of windows (strategies C1, C2, C3, C4) are not economically affordable and do not offer a significant environmental improvement. Moreover, the interior insulation strategies (strategies B1env, B1ec, B2env, B2ec) have a better economic performance but do not either have a consistent environmental improvement. Besides, even if the ETICS with XPS insulation (strategies A2env, A2ec) have a better performance (both environmental and economic), the ETICS with wood insulation (strategies A1env, A1ec) achieves values above the 4% of IRR and 45 of NER, being the best passive strategy. For the active and RES strategies, the auxiliary solar heat (strategy D) does not have any economic affordability and the NER is not considerable, however, for the strategy of the centralized heat pump for heating and DHW (strategy E) and the same strategy adding the electric supply by PV panels (strategy F) obtains much superior values on the prioritization indicators, considering them the strategies that the highest improvement can offer in terms of environmental impact reduction and the most affordable investment in terms of economy, according to the evaluation carried out by the tool.

3.3. Sensitivity assessment

As previous studies have shown, the residential buildings of the EU have many similarities [12,38,39] and the constructive characteristics will remain fixed during time; however, many calculation input parameters can differ. The present section analysis the sensitivity of the methodology, evaluating the influence of the most uncertain and differing parameters. The differing parameters can influence the environmental results, the economic results, or both. The research is aware that all the non-fixed parameters can influence the results but only the parameters that differ considerably during the time-life of the building are analysed: Ed_H, IR and EPI. This sensitivity and uncertainty assessment is carried out in both tools, evaluating the variation of the results.

3.3.1. Parameters to assess the sensitivity

The Ed_H can differ due to many factors, being the user behaviour and the base temperature the most influential ones according to previous studies [40–43] and being necessary to consider that may be changes in the Ed_H of the building during the time. Furthermore, the climate change can alter the Ed_H of the residential buildings reducing it [44]. However, high base temperature can increase the Ed_H comparing to the one calculated by the regulation standard base temperature values as it is studied previously [42]. Following this, the study evaluates the scenarios with the Ed_H alteration of + -15% (below and above) of the values calculated initially by standard parameters (from CTE), assessing the variation in both the environmental and economic field.

The variation of the IR is one of the most uncertain economic parameters, with an IR of the euro area of 8,9% in July 2022 comparing to the 2,2% in July 2021, 1,0% in 2020, and the average of 2,06% in the last 30 years [45]. The present study analyses the scenarios where the IR is duplicated and quadruplicated from the initial scenario of 1,5%, with the 3% and 6% of IR, assessing only the variation in the economic field.

The EPI, directly related to the IR, is also suffering big differences during time the last years due to the pandemic and world political and economic alterations. According to the harmonised index of consumer prices (HICP) the EPI in the euro area in July 2022 was 41,9%, in July 2021 9,6% and in July 2020–3,5% [46]. The initial EPI applied in the case study of 3% for gas and 4% for electricity are stablished from the point of view of an average values of a stable situation with higher values for the electricity than the gas; however, it is important to take into account that the last months the rates has increased rapidly, being

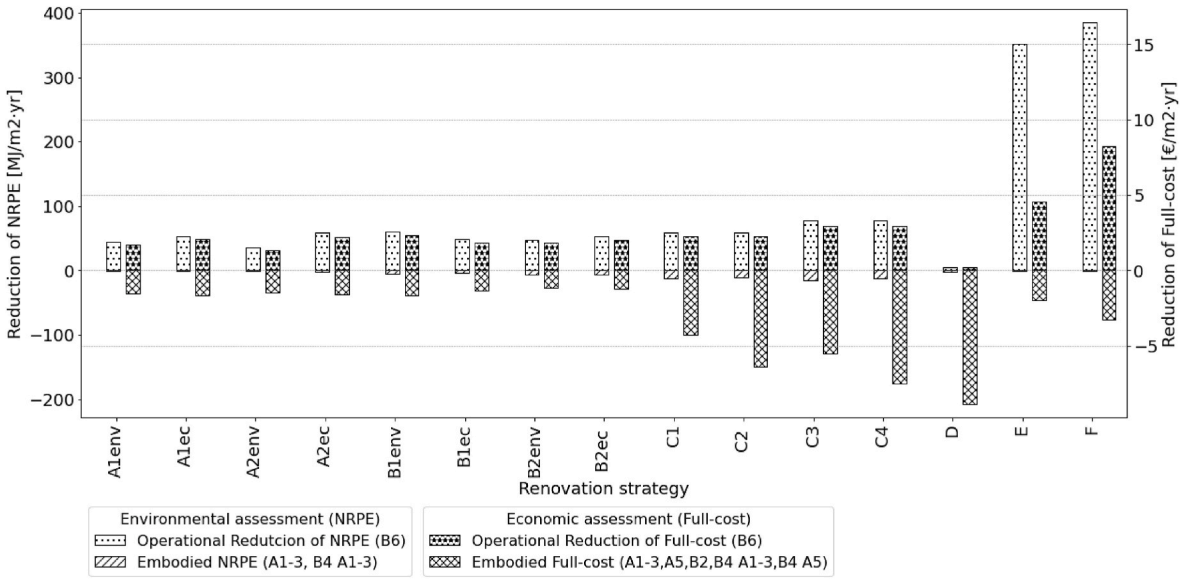

Fig. 6. Reduction of environmental impact (NRPE) and economic cost (Full-cost) by renovation strategies.

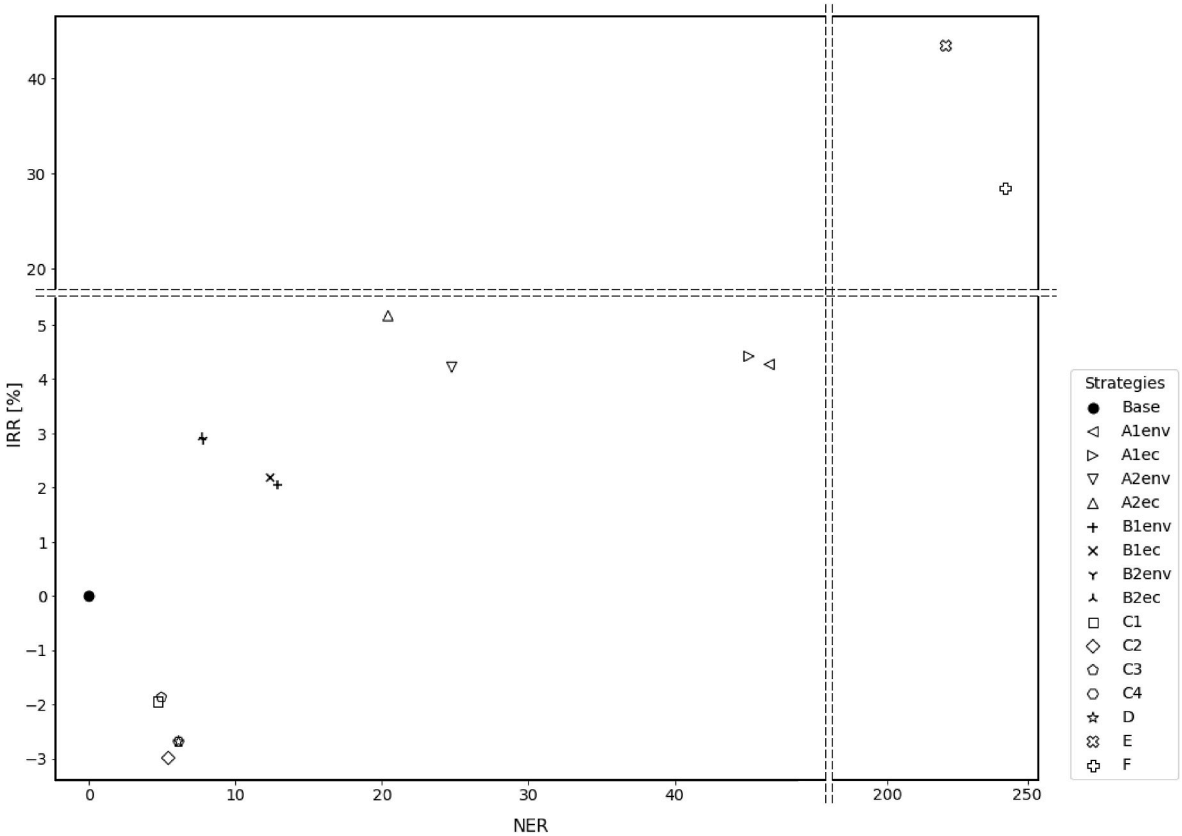

Fig. 7. Prioritization tool output data (results) showing the environmental and economic prioritization of the renovation strategies by the indicators of NER and IRR.

higher the EPI of the gas [46]. Following this, the scenarios with the EPI of 6% and 9% are evaluated, for both gas and electricity, assessing the variation only in the economic field.

Furthermore, as the IR and the EPI are directly related, the combination of both parameters alteration are analysed. When the IR suffers an increase, generally the EPI also does, being the EPI higher than the general IR according to the last trends [46]. Following these last statistics, the first combination analyses the scenario with the IR of 3% and the EPI of 6%, and the second combined scenario with the IR of 6% and the EPI of 9%.

3.3.2. *Sensitivity assessment of the optimization tool*

Table 10 shows the results of the sensitivity assessment carried out for the optimization tool The environmental optimization is only affected by the EdH variation, resulting null the result of the optimal insulation thickness; however, the mathematical function differs showing a dispatch in the axis of NER as it can be appreciated in Fig. 8 Nevertheless, the study is aware that the proportional reduction of the baseline and renovated scenario are not equal and it may be a variation of the optimal thickness with more accurate EdH data, but the main result is that the EdH does not have a significant affection the optimal thickness of thermal insulation based strategies according to the NER.

The economic optimal solutions are analysed by the three parameters alterations (Ed$_H$, IR and EPI) and by the combination of the two economic parameters (IR and EPI). Fig. 9 shows that not all the parameters cause a variation of the optimal economic thickness of the insulation, being the IR and the combination of the IR and EPI the parameters that can differ the results; however, all the parameters have an influence in the IRR. Moreover, not all the strategies suffer a variation even with the most influential parameters, due to the need, or not, of replacement of materials and the maintenance costs of certain strategies. Focusing in the optimal economic thicknesses variations of the A1 strategy, the results show that a higher IR derives to a higher value of the optimal thickness with a lower IRR, with an increase of the optimal

Table 10
Sensitivity assessment of the optimization analysing the variation of the optimal thickness.

Scope:	Environmental optimal thickness [mm]			Economic optimal thickness [mm]								
Strategy	*Initial*	*Ed$_H$ −15%*	*Ed$_H$ +15%*	*Initial*	*Ed −15%*	*Ed +15%*	*Inf 3%*	*Inf 6%*	*EPI 6%*	*EPI 9%*	*Comb 1*	*Comb 2*
A1	37	37	37	52	52	52	66	132	52	52	65	129
A2	26	26	26	62	62	62	79	164	62	62	79	161
B1	142	142	142	94	94	94	95	95	94	94	94	94
B2	91	91	91	109	109	109	109	110	109	109	109	109

Ed$_H$: energy demand alteration; *Inf:* economic inflation alteration; *EPI:* energy price increment alteration; *Comb 1:* Inf of 3% and EPI of 6%; *Comb2:* Inf of 6% and EPI of 9%.

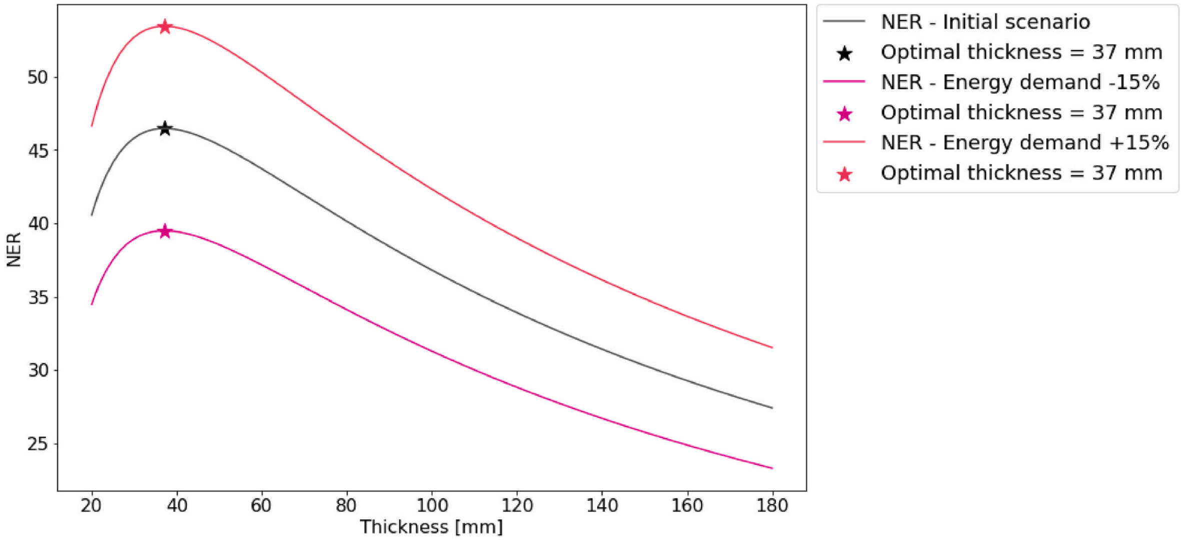

Fig. 8. Sensitivity assessment of the environmental optimization according to the NER variation in function of the insulation thickness for the strategy A1 (ETICS with wood fibre insulation).

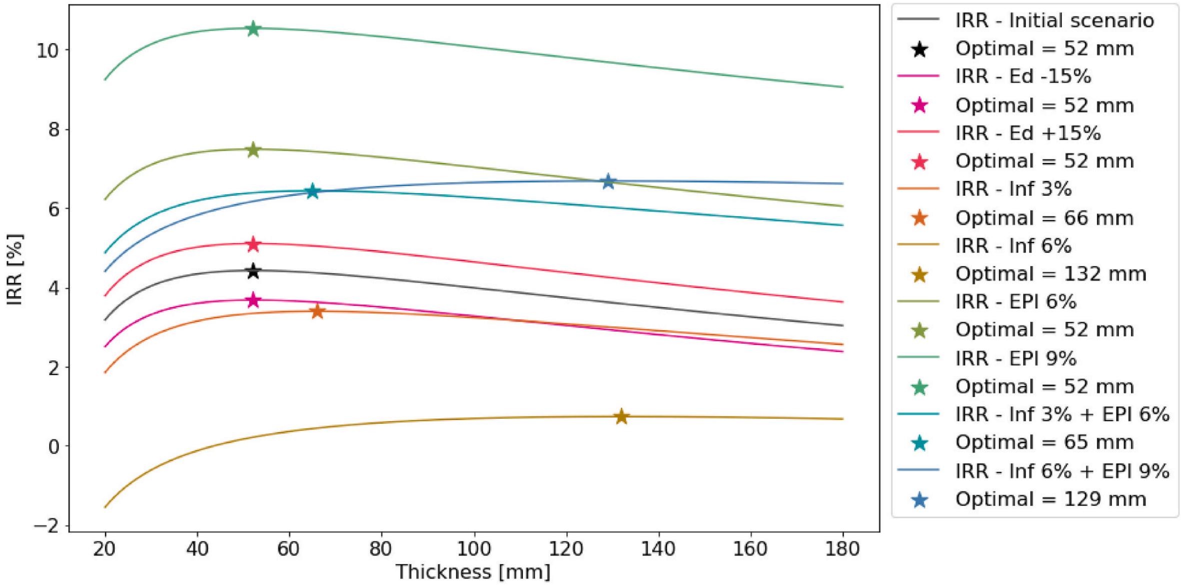

Fig. 9. Sensitivity assessment of the economic optimization according to the IRR variation in function of the insulation thickness for the strategy A1 (ETICS with wood fibre insulation).

thickness of 27% with the IR of 3%, and an increase of 154% with the IR of 6%, comparing to an initial inflation rate of 1,5%. Besides, it is important to take into account that, as mentioned before, the IR is directly related with the EPI, showing that the combination of both increases the optimal thickness, almost as much as the IR by only itself (25% with the IR of 3% and 148% with and the IR of 6% for the A1 strategy), but with a positive influence in the IRR; this means that the higher values of the IR and the EPI means the need of a thicker insulation for the optimal economic scenario, with a better economic scenario with a higher IRR.

3.3.3. Sensitivity assessment of the prioritization tool

For the sensitivity assessment of the prioritization has been followed the same technique, assessing only the Ed_H in the environmental field and all the sensitivity for the economic field as it is shown in Table 11.

The environmental prioritization indicator of NER is clearly influenced by the Ed_H decrease or increase, being this variation negative in the scenario where the Ed_H is increased and positive when the Ed_H is decreased, with the same numeric value. However, the influence is not the same for all the strategies, being a variation of the NER above the 75% for all the optimized insulation based passive strategies (A, B), and much higher in the case of RES strategy (D), being able to cover a higher proportion of the energy demand by RES solutions. However, in the case of the active solutions (E, F), based on the use of highly efficient system like heat pumps and the integration of PV systems don not present a significant variation, less than 4%, due to the decrease or increase of the energy demand.

In the case of the economic prioritization indicator, the IRR, the three parameters, and the combination of the two economic parameters have an influence as Table 11 shows, presenting different possible scenarios

Table 11
Sensitivity assessment by the results variation in the prioritization indicators (NER, IRR).

Scope:	NER variation in %Ed$_H$		IRR variation [%]							
Strategy	Ed$_H$ −15%	Ed$_H$ +15%	Ed$_H$ −15%	Ed$_H$ +15%	Inf 3%	Inf 6%	EPI 6%	EPI 9%	Comb 1	Comb 2
A1env	108,9%	−108,9%	97,9%	–	−28,3%	−105,9%	71,9%	143,3%	42,9%	33,5%
A1ec	88,1%	−88,1%	79,6%	−169,9%	−24,4%	−95,2%	69,5%	138,5%	45,5%	51,1%
A2env	141,6%	−141,6%	123,7%	–	−34,4%	−119,4%	72,7%	145,0%	37,7%	21,6%
A2ec	79,9%	−79,9%	68,1%	−120,3%	−23,6%	−88,6%	59,8%	119,1%	36,6%	36,9%
B1env	77,3%	−77,3%	118,1%	−232,8%	−0,5%	−1,5%	145,6%	291,7%	145,6%	291,2%
B1ec	99,5%	−99,6%	138,6%	−751,4%	0,0%	−1,4%	135,9%	271,4%	135,9%	270,9%
B2env	101,8%	−101,7%	114,8%	–	−0,3%	−1,4%	103,4%	206,9%	103,4%	206,6%
B2ec	90,3%	−90,4%	103,4%	−251,9%	0,0%	−1,0%	102,7%	205,1%	102,4%	204,8%
C1	79,4%	−79,1%	91,3%	−209,7%	−42,1%	−133,8%	146,7%	293,3%	103,6%	151,8%
C2	79,3%	−79,2%	55,5%	−132,1%	−26,1%	−84,3%	94,6%	189,0%	67,6%	100,7%
C3	56,2%	−56,2%	71,7%	−120,3%	−43,9%	−140,1%	152,9%	305,9%	107,5%	157,8%
C4	56,0%	−56,2%	47,6%	−81,0%	−29,4%	−94,4%	105,6%	210,8%	75,1%	111,5%
D	1025,3%	−1025,6%	91,4%	–	−39,0%	–	44,3%	79,6%	32,5%	45,6%
E	3,9%	−3,9%	2,3%	−2,3%	−14,8%	−38,1%	6,4%	15,9%	−8,7%	−24,1%
F	2,6%	−2,6%	1,5%	−1,5%	−16,9%	−44,3%	8,8%	21,9%	−8,4%	−24,4%

Ed$_H$: energy demand alteration; *Inf:* economic inflation alteration; EPI: energy price increment alteration; *Combination 1*: Inf of 3% and EPI of 6%; *Combination 2*: Inf of 6% and EPI of 9%.

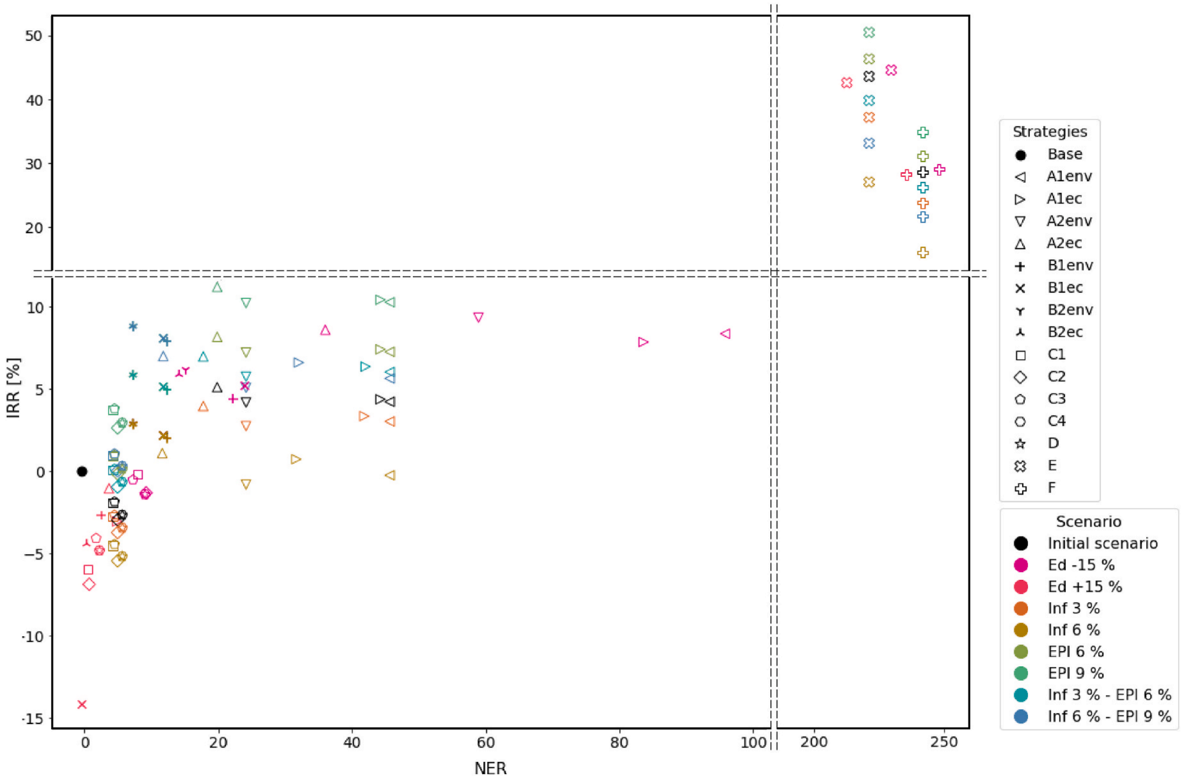

Fig. 10. Sensitivity assessment of the prioritization indicators (NER, IRR).

that differ from the initial results as it can be appreciated in Fig. 10. For the Ed$_H$, as it happens with the NER, the IRR increases when the Ed$_H$ decreases, and vice versa, the IRR decreases when the Ed$_H$ increases; this result is determinant to take into account to maximize the economic affordability of the energy renovations. For passive strategies (A, B, C) and also RES (D) the variation is significant, being proportionally higher the decrease of the IRR caused by an increase of the energy demand than in the opposite situation; however, for the active strategies (E, F) the variation is relatively low. Analysing the effect of the economic inflation rate, a higher inflation (by itself) causes a reduction of the IRR in general, but in the case of the solution where there is no need of replacement of materials and the maintenance cost is low the IRR does not suffer much alteration. The EPI causes the opposite by itself, increasing the IRR when the EPI is higher. The correct way to analyse these two economic indicators is to combine them, as the IR and EPI are directly related; following this, the scenarios with an increment of the IR and EPI, the IRR is increased in the case of the passive strategies (A, B, C) and RES (D) in a significant way; nevertheless, the active strategies (E, F) suffer a light decrease of the IRR. This last factors is important to take into account where the last months the IR and EPI are significantly accelerated, showing that is possible a dramatic change in the scenarios of the investments related to energy saving. However, even if for the active the IRR is decreased caused by a higher IR and EPI, the level of the financial IRR is still much higher than the other analysed strategies as it shows Fig. 10.

As the results of the prioritization, the comparison of the strategies taking into account the scenarios with parameter variations is similar, and in the case of the decision making process the election of the strategy does not have a significant influence the alteration of these parameters. Nevertheless, it is important for the assessment of the environmental and economic performance because even if the most effective strategy can be the same, the environmental improvement that can be provided is not the same, and the same happens with the economic performance, suffering important variations in the feasibility and profitability of the investment.

4. Discussion

The developed methodology, which is based on two tools for the assessment of different renovation strategies for residential buildings, serves to optimize and prioritize renovation strategies according to the environmental and economic aspects specified in the LCA scope. The optimization tool provide the capacity to optimize the thickness of envelope insulation based passive strategies, and the prioritization tool prioritize the strategy that provides the highest relative energetic improvement and the highest economic feasibility. The methodology is applied in the case study of a multifamily residential building, but it can be applied to any type of residential building with a significant heating energy demand.

The LCA scope specified follow the current trends of the latest life cycle perspective methodologies and standards. For the FU the methodology specifies the use of the heated net area of the building responding to the importance of the definition of the FU [47], using the m^2*/year* as it is the most used unit that allow the comparison between different scenarios and situation according to the latest reviews [11,12]. The assessed operational energy use of heating and DHW has been considered answering to the main thermal energy use as the major energy consumption of the residential buildings in Europe, with over 62% of the final energy consumption for space heating and over 15% for water heating [48]. The boundary conditions definition follows the results of a previous studies arguing the low contribution of certain life stages in energy renovation strategies on residential buildings, by a deep literature review and the exhaustive sensitivity assessment carried out analysing the potential simplifications of the life-cycle boundaries [10]. This assumption is corroborated by more studies, demonstrating the low environmental impact of the life stages of construction (A5) and maintenance (B2) [49–52], however these life stages do have a high contribution in the economic assessment [49], assessing these stages for the economic costs but not the environmental impact, as it does the methodology proposed by Van Gulck et al. [15]. Other studies also reached to the same conclusion about the end of life stages, arguing an energy use below 1% in this stage [53,54]. According to the latest review, the life stages with the highest frequency on the analysed LCA methodologies are the product stage (A1-3), replacement (B4) and operational energy use (B6) [12]. In the case of the quantification of the environmental impact, the impacts are assessed at the midpoint level with a limited number of indicators as most of the methodologies does [12], one for the potential impact, the GWP, and the indicator of NRPE to assess the resource use, as it is described by the standard EN-15978:2012 [13]. This analysis attributes an environmental impact to the FU of the renovation strategy in the analysed scenario, as a fraction of the theoretical total impact of the process and its life cycle known as the attributional LCA (ALCA) [55]. Instead, the consequential LCA (CLCA) represent the changes derived to a decision in the global environment applied in the studio of the decarbonizing of the electricity generation sector in the province of Alberta (Canada) by long-term bottom-up analysis to identify marginal sources as a consequence of policy making [56]. Whereas the CLCA is directly focused to assess the effect of certain decision-making, the renovation process in this case, the ALCA covers the evaluation of the potential effect of the renovation processes by assessing the change of the impacts in different scenarios [57]. Moreover, the methodology uses the prioritization indicators to evaluate the potential effect; in this way, the studio considers the ALCA with prioritization indicators is considered as the most appropriate framework because the methodology is focused to assess specific scenarios instead of an overall analysis. Following this, average data is used in the in the LCI but the methodology also allows to freely choose the input data; thus, evaluations with marginal data can be done, by scenarios with different energy mixes for the operational impact that could potentially evaluate long-term effects of decision-makings.

The key elements of the methodology are the mentioned prioritization indicators, which provide a higher level of assessment over the quantification of impacts and costs. On the one hand, for the environmental assessment, the NER assesses the improvement provided by the renovation, calculated by the NRPE, as the energy use is the most representative factor in the environmental impact of buildings according to the literature [58]. The methodologies published lately [12] does not take into account any indicator that assess the relative energetic improvement, measuring the impacts being not possible to compare among different energy demands scenarios and being not as useable as the comparative indicator. The present research consider the normalized single score methods with end-point level evaluation, like Eco-indicator99 [59], ReCiPe [60] can be very useable to assess the impact of certain product or process, like a renovation of a building, but the use of indicators that quantifies the relative improvement can be useable an easy understanding in the case of the evaluation of building renovation strategies. On the other hand, the economic prioritization is carried out by the IRR, assessing the economic feasibility and profitability that the economic investment; this financial indicator is commonly used to evaluate an economic investment's theoretical performance [61–63] so it can measure the expected economic impact that can a renovation strategy have, going one step forward in the economic assessment of renovation strategies with life cycle approach. As the environmental NER prioritization indicator does, the economic IRR also reflects the relative improvement of the economic scenario, but using a normalized financial indicator. Moreover, the IRR offers the opportunity to compare strategies in different temporal locations that is not possible by the commonly used NPV because the economic net value differs along time due to the economic inflation.

In terms of the optimization of the envelope insulation based strategies, the recent study by Van Gulck et al. [15] carries out the optimization by calculating several values from 6 cm up to 40 cm, every 2 cm, using the NPV for the economic evaluation and the score based evaluation system of SimaPro software for the environmental field; the case study is an apartment building in Flanders with an uninsulated façade ($U = 1.76\ W/m^2{\cdot}K$) and the application of the ETICS with EPS insulation on the facade. According to the study by Van Gulck et al. [15] the optimal economic value is the thickness of 14 cm, with the lowest NPV, much lower than the value obtained in the present study for the similar strategy (ETICS with XPS), 6,2 cm, even if the original façade has a minimum insulation ($U = 0.67\ W/m^2{\cdot}K$). Although the difference between the resultant values, that can be due to different parameters of location, building age, material etc., it is clear that the optimal solution cannot be the lowest possible values of transmittance by the highest thickness of the insulation. For the environmental evaluation, the study Van Gulck et al. [15] concluded that the optimal thickness is 40 cm, with the lowest environmental impact score, but showing almost a null improvement in the highest thicknesses; furthermore, according to the present study optimal thickness is 2.6 cm, with a significant discordance. The reason can be that the compared study evaluates the total environmental impact while the present study uses the NER indicator, ergo, the relative improvement provided by the renovation strategy, that the authors believe that is a better quantification in order to evaluate renovation strategies as mentioned before (Section 2).

In the case of the prioritization tool, comparing the results of the present study with similar ones, the study by Galimshina et al. [16] concluded that the replacement of windows with more efficient ones cannot be part of an optimal solution for building renovation, regardless

Table 12
Computational times.

Code	Process	Time [ms]
Optimization script	Input data importation	59, 31
	Environmental optimization	50,83
	Economic optimization	12.633,33
	Output data exportation	153,80
	Total optimization script	12.897,27
Prioritization script	Input data importation	45,92
	Enviro-economic assessment	986,54
	Output data exportation	153,49
	Total optimization script	1.185,95

of the original building's energy performance, as it does the present study, where the window replacement (strategy C) show the lowest environmental and economic performance (see Fig. 10); both studies show that the embodied impact and cost of the window replacement are high compared to the savings provided. Furthermore, according to the same study by Galimshina et al. [16] the replacement of the heating system has better environmental results that envelope renovation strategies, completely in accordance with the present study, concluding that the optimal renovation strategy is the installation of a new heating system; the difference is that the study by Galimshina et al. [16] proposes a biomass system and the present methodology heating pump, even so, it is clear that both studies agree that the optimal solution can be based in the improvement of the performance of the heating system with lower impact in the operational energy use stage.

In terms of the application of the methodology, the sensitivity assessment shows the importance of the dynamic evaluation for the evaluation of building renovation strategies, due to the differing parameters, like the analysed ones, able to change significantly the resulting scenarios. The uncertainty of the input data requires analysing different scenarios, and the proposed methodology allows as it is done with the case study, analysing the effect of input parameter in the enviro-economic assessment of building renovation strategies.

Moreover, the developed method typology, both tools – optimization and prioritization – are run in one single step departing from the energy demands of the building, providing a simplified methodology. The script is written in Python 3 programming languages using the Pandas package [64] based in the simplified mathematical operation of multi-dimensional arrays and matrices by Numpy library [65] allowing a low computational time (see Table 12). It can be appreciated that the calculation time for the economic optimization is much higher that other operations, caused by the analysis of all the possible scenarios for every unit of thickness analysed due to the calculation complexity explained in the methodology. The optimization is based in a non-linear regression model as it happens with several prediction models according to the latest literature [22–24]; it is calculated from the data-driven fitting process of the operational impact and cost reduction (non-linear logarithmic), energy demand (non-linear, logarithmic) and embodied impact and cost (linear). The optimization problem is solved calculating the maximum point of the regression curve, by the only single first null derivate, as concave down function. Nevertheless, for the environmental regression model takes a convex shape in the higher values of the thickness (in the case study in $x = 69$, as second null derivative); however does not have any effect in the optimization problem.

In addition, the light programming allows the implementation of the code in other scripts, making technically possible and easy the implementation of the developed methodology in other programmes.

5. Conclusions

The enviro-economic assessment for renovation of residential buildings with life cycle perspective is necessary for carrying on efficient renovation processes. The paper describes the scientific path of the development of the tool-kit based methodology applied in a case study, together with the results that can the methodology provide explaining its functionality. Firstly, the optimization tool calculates the optimal thickness for envelope insulation based strategies according to the prioritization tool, for the optimal environmental scenario and the optimal financial scenario, using the prioritization indicators. Secondly, the prioritization tool provides a detailed diagnosis of passive and active renovation strategies scenarios, with all the environmental impacts and economic costs of all the stages, and the final relative improvement NER and financial IRR. Furthermore, as it is shown in the sensitivity assessment, the study reclaims the importance of a dynamic evaluation, analysing a range of values for the uncertain input parameters, covering the variation of the results that can be caused by the differing of certain parameters, being possible and easy to carry out by the present tool-kit based methodology. The results are given independently for the environmental and economic evaluations, in both the optimization and prioritization tools; this way the results allow the interpretation in a simplified manner with the two prioritizing indicators reflecting the relative performance of each renovation strategy. Moreover, the main evaluation indicators used by both tools, the prioritization indicators (NER and IRR), have the capacity to assess, in the one hand, the relative environmental improvement of the strategy, and in the other hand, the feasibility and profitability of the economic investment, instead of reflecting only the environmental impact and economic cost, allowing the comparable evaluation.

In conclusion, the paper presents a useful methodology to answer to the need of an efficient, simple and complete assessment of renovation strategies for residential buildings. The tool-kit can be applied for science like the analysis of renovation strategies as well as for direct application on renovation projects of residential buildings. Furthermore, it can be a good methodology to evaluate building typologies to go forward the decarbonisation of the residential building stock in the development of decarbonisation mid and long-term strategies.

The tool-kit is available in open source in the GitHub repository (https://github.com/markelarbulu/LCA_residential_building_renovation.git).

CRediT authorship contribution statement

Markel Arbulu: Writing – review & editing, Writing – original draft, Visualization, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Xabat Oregi:** Validation, Supervision, Resources, Project administration, Investigation, Funding acquisition, Conceptualization. **Lauren Etxepare:** Writing – review & editing, Validation, Supervision, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgment

Part of the work presented in this paper belongs to the research project PIBA-PUE 2020(PUE_2020_1_0013) funded by the Department of Education of the Basque Government. Moreover, this research work is part of the corresponding author's Doctoral Thesis that aims to investigate the holistic assessment of technical renovation solutions of residential buildings in the Basque Country funded by the Predoctoral Training Programme for Non-Doctor Research Personnel of the Department of Education of the Basque Government (PRE_2021_1_0247).

Annex 1. Equations for the impact indicators and prioritization indicators

Impact indicators equations

Environmental impact indicators

$$GWP_{A1-3} = \sum_{m=1}^{m=k} EE_m \cdot Q_m \Big/ FU \tag{1}$$

$$NRPE_{A1-3} = \sum_{m=1}^{m=k} EE_m \cdot Q_m \Big/ FU \tag{2}$$

$$GWP_{B4(A1-3)} = \sum_{m=1}^{m=k} EE_m \cdot Q_m \cdot ((RSL_b \,/\, ESL_m) - 1) \Big/ FU \tag{3}$$

$$NRPE_{B4(A1-3)} = \sum_{m=1}^{m=k} EE_m \cdot Q_m \cdot ((RSL_b \,/\, ESL_m) - 1) \Big/ FU \tag{4}$$

$$GWP_{B6} = \sum_{n=1}^{RSL_b} \left(\sum_{m=1}^{m=k} \left[\left(\frac{ED_b}{\rho} + DL_b \right) \cdot CF_y \right] \right) \Big/ FU \tag{5}$$

$$NRPE_{B6} = \sum_{n=1}^{RSL_b} \left(\sum_{m=1}^{m=k} \left[\left(\frac{ED_b}{\rho} + DL_b \right) \cdot CF_y \right] \right) \Big/ FU \tag{6}$$

Economic impact indicators

$$FC_{A1-3} = \sum_{m=1}^{m=k} EC_m \cdot Q_m \Big/ FU \tag{7}$$

$$FC_{A5} = \sum_{m=1}^{m=k} (Q_m \cdot CC_m) \,/\, FU \tag{8}$$

$$FC_{B2} = \sum_{n=1}^{RSL_b} \left(\sum_{m=1}^{m=k} \frac{MC_m \cdot Q_m}{EMP_m} \right) \cdot (1 + IR_n) \Big/ FU \tag{9}$$

$$FC_{B4(A1-3)} = \sum_{m=1}^{m=k} EC_m \cdot Q_m \cdot ((RSL_b \,/\, ESL_m) - 1) \cdot (1 + IR_{ESLm}) \Big/ FU \tag{10}$$

$$FC_{B4(A5)} = \sum_{m=1}^{m=k} (([Q_m \cdot CC_m]) \cdot [(RSL_b \,/\, ESL_m) - 1]) \cdot (1 + IR_{ESLm}) \Big/ FU \tag{11}$$

$$FC_{B6} = \sum_{n=1}^{RSL_b} \left(\sum_{m=1}^{m=k} \left[\left(\frac{ED_b}{\rho} + DL_b \right) \cdot EP_y \right] \cdot \left[1 + EPI_y^n \right] \right) \Big/ FU \tag{12}$$

Prioritization indicators equations

$$NER = \frac{AEU1 - AEU2}{AEE2 - AEE1} \tag{13}$$

$$IRR\ (\%) = r_a + \left[\left(\frac{NPV_a}{NPV_a - NPV_b} \right) \times (r_b - r_a) \right] \tag{14}$$

Annex 2. . Input and output data of the case study

Table 1
Optimization tool. Scenarios data of the strategies A1 (input_a)

strategy	s	rslb	inf	th	ed_h	eef_h	el_h	process_h	mat_1	mat_1_med	mat_2	mat_2_med	mat_3	mat_3_med
base	2083,52	50	0,015	0	66,6	0,8	0	G	0	0	0	0	0	0,00
A1-20	2083,52	50	0,015	20	61,51	0,8	0	G	inw	1497,60	mrt	1497,60	0	0,00
A1-40	2083,52	50	0,015	40	58,22	0,8	0	G	inw	1497,60	mrt	1497,60	0	0,00
A1-100	2083,52	50	0,015	100	53,5	0,8	0	G	inw	1497,60	mrt	1497,60	0	0,00
A1-180	2083,52	50	0,015	180	51,19	0,8	0	G	inw	1497,60	mrt	1497,60	0	0,00

Table 2
Optimization tool. Scenarios data of the strategies A2 (input_a)

strategy	s	rslb	inf	th	ed_h	eef_h	el_h	process_h	mat_1	mat_1_med	mat_2	mat_2_med	mat_3	mat_3_med
base	2083,52	50	0,015	0	66,6	0,8	0	G	0	0	0	0	0	0,00
A2-20	2083,52	50	0,015	20	61,51	0,8	0	G	inx	1497,60	mrt	1497,60	0	0,00
A2-40	2083,52	50	0,015	40	58,22	0,8	0	g	inx	1497,60	mrt	1497,60	0	0,00
A2-100	2083,52	50	0,015	100	53,5	0,8	0	g	inx	1497,60	mrt	1497,60	0	0,00
A2-180	2083,52	50	0,015	180	51,19	0,8	0	g	inx	1497,60	mrt	1497,60	0	0,00

Table 3
Optimization tool. Scenarios data of the strategies B1 (input_a)

strategy	s	rslb	inf	th	ed_h	eef_h	el_h	process_h	mat_1	mat_1_med	mat_2	mat_2_med	mat_3	mat_3_med
base	2083,52	50	0,015	0	66,6	0,8	0	g	0	0	0	0	0	0,00
B1-20	2083,52	50	0,015	20	65,82	0,8	0	g	inw	1497,60	gyp	1497,60	clp	1497,60
B1-40	2083,52	50	0,015	40	62,3	0,8	0	g	inw	1497,60	gyp	1497,60	clp	1497,60
B1-100	2083,52	50	0,015	100	57,25	0,8	0	g	inw	1497,60	gyp	1497,60	clp	1497,60
B1-180	2083,52	50	0,015	180	54,77	0,8	0	g	inw	1497,60	gyp	1497,60	clp	1497,60

Table 4
Optimization tool. Scenarios data of the strategies B2 (input_a)

strategy	s	rslb	inf	th	ed_h	eef_h	el_h	process_h	mat_1	mat_1_med	mat_2	mat_2_med	mat_3	mat_3_med
base	2083,52	50	0,015	0	66,6	0,8	0	g	0	0	0	0	0	0,00
B2-20	2083,52	50	0,015	20	65,82	0,8	0	g	inx	1497,60	gyp	1497,60	clp	1497,60
B2-40	2083,52	50	0,015	40	62,3	0,8	0	g	inx	1497,60	gyp	1497,60	clp	1497,60
B2-100	2083,52	50	0,015	100	57,25	0,8	0	g	inx	1497,60	gyp	1497,60	clp	1497,60
B2-180	2083,52	50	0,015	180	54,77	0,8	0	g	inx	1497,60	gyp	1497,60	clp	1497,60

Table 5
Prioritization tool. Scenarios data (input_a)

strategy	s	rslb	inf	ed_h	ed_w	eef_h	eef_w	el_h	egh_h	egh_w	ege_h	ege_w	process_h	process_w	th	mat_1	mat_1_med	mat_2	mat_2_med	mat_3	mat_3_med
base	2083.52	50	0.015	66.6	19.58	0.8	0.8	0	0	0	0	0	g	g	0	0	0.00	0	0.00	0	0.00
A1env	2083.52	50	0.015	58.54	19.58	0.8	0.8	0	0	0	0	0	g	g	0.37	inw	1497.60	mrt	1497.60	0	0.00
A1ec	2083.52	50	0.015	56.91	19.58	0.8	0.8	0	0	0	0	0	g	g	0.52	inw	1497.60	mrt	1497.60	0	0.00
A2env	2083.52	50	0.015	60.22	19.58	0.8	0.8	0	0	0	0	0	g	g	0.26	inx	1497.60	mrt	1497.60	0	0.00
A2ec	2083.52	50	0.015	56.07	19.58	0.8	0.8	0	0	0	0	0	g	g	0.62	inx	1497.60	mrt	1497.60	0	0.00
B1env	2083.52	50	0.015	55.77	19.58	0.8	0.8	0	0	0	0	0	g	g	1.42	inw	1497.60	gyp	1497.60	clp	1497.60
B1ec	2083.52	50	0.015	57.88	19.58	0.8	0.8	0	0	0	0	0	g	g	0.94	inw	1497.60	gyp	1497.60	clp	1497.60
B2env	2083.52	50	0.015	58.04	19.58	0.8	0.8	0	0	0	0	0	g	g	0.91	inx	1497.60	gyp	1497.60	clp	1497.60
B2ec	2083.52	50	0.015	57.12	19.58	0.8	0.8	0	0	0	0	0	g	g	1.09	inx	1497.60	gyp	1497.60	clp	1497.60
C1	2083.52	50	0.015	55.99	19.58	0.8	0.8	0	0	0	0	0	g	g	1	gl1	392.10	fra1	392.10	0	0.00
C2	2083.52	50	0.015	55.99	19.58	0.8	0.8	0	0	0	0	0	g	g	1	gl1	392.10	frw1	392.10	0	0.00
C3	2083.52	50	0.015	52.57	19.58	0.8	0.8	0	0	0	0	0	g	g	1	gl2	392.10	fra2	392.10	0	0.00
C4	2083.52	50	0.015	52.57	19.58	0.8	0.8	0	0	0	0	0	g	g	1	gl2	392.10	frw2	392.10	0	0.00
D	2083.52	50	0.015	66.6	19.58	0.8	0.8	0.05	4.352	11.748	0	0	g	g	1	stc	118.50	int	1.00	0	0.00
E	2083.52	50	0.015	66.6	19.58	4.74	3.75	0.05	0	0	0	0	e	e	1	aec	2.00	0	0.00	0	0.00
F	2083.52	50	0.015	66.6	19.58	4.74	3.75	0.05	0	0	14.05	5.22	e	e	1	aec	2.00	pv	84.00	0	0.00

Table 6
Optimization tool & Prioritization tool. Materials & processes data (input_b)

code	name	rslm	gw_b6	pe_b6	fc_b6	fc_in_b6	gw_a13	pe_a13	fc_a13	fc_a5	fc_b2	conv
0	(none)	50	0	0	0	0	0	0	0	0	0	1
g	Gas	50	0,0689	1,23	0,0209	0,03	0	0	0	0	0	1
e	Electricity	50	0,0632	1,74	0,0625	0,04	0	0	0	0	0	1
gl1	Glass - Double low emiss.	30	–	–	–	–	36,8	38,5	70,86	14,05	0	1
gl2	Glass - Triple	30	–	–	–	–	50,3	66,5	91,48	14,05	0	1
fra1	W. frame - Aluminium 2	30	–	–	–	–	117	1620	307,49	44,73	0,27	1
fra2	W. frame - Aluminium 3	30	–	–	–	–	150	2019	412,52	44,73	0,27	1
frw1	W. frame - Wood 2	30	–	–	–	–	30,1	1400	504,93	43,96	0,973	1
frw2	W. frame - Wood 3	30	–	–	–	–	42,7	1620	601,6	43,96	0,973	1
inx	Insulation XPS 100 mm	50	–	–	–	–	9,14	276	30,59	3,94	0,07	1
inw	Insulation wood 100 mm	50	–	–	–	–	−0,208	106,55	42,32	3,94	0,07	1
mrt	Mortar	25	–	–	–	–	3,61	13,7	1,38	4,86	0,887	1
gyp	Gypsum plac 15 mm	50	–	–	–	–	1,5	29,4	17,1	7,17	0,272	1
clp	Cladding profiles	50	–	–	–	–	2,35	40,8	0	0	0	3,5
stc	Colector solar (central)	30	–	–	–	–	56,81	791,51	838,795,745	83,7,446,809	71,5,153,191	1
int	Interacumlador	30	–	–	–	–	700,62	11,157	8265	0	0	1
aec	Aerotermia ACS + Calef.	15	–	–	–	–	2132	20,750,22	10,328	1089,44	642,954	1
pv	Placa PV	30	–	–	–	–	0,0139	0,189	306,543,333	43,22	422,2	1

Table 7
Optimization tool. Results (output)

Strategy A1			Strategy A2			Strategy B1			Strategy B2		
scope	th_[mm]	ed_opt	scope	th_[mm]	ed_opt	scope	th_[mm]	ed_opt	scope	th_[mm]	ed_opt
opt_env	37	58,54	opt_env	26	60,22	opt_env	142	55,77	opt_env	91	58,04
opt_ec	52	56,91	opt_ec	62	56,07	opt_ec	94	57,88	opt_ec	109	57,12

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2022.109813.

References

[1] European Commission, Energy efficiency in buildings [Online]. Available: https://ec.europa.eu/info/sites/default/files/energy_climate_change_environment/events/documents/in_focus_energy_efficiency_in_buildings_en.pdf, 2020.

[2] European Commission, Communication from the commission to the EUROPEAN parliament, the council, the EUROPEAN economic and social committee and the committee of the regions [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52022DC0240&from=EN, 2022.

[3] Eurostat, Final energy consumption by sector, accessed Sep. 01, 2022), https://ec.europa.eu/eurostat/databrowser/view/TEN00124/default/table?lang=en&category=nrg.nrg_quant.nrg_quanta.nrg_bal.

[4] European Commission, Directive (EU) 2018/844 of the European Parliament and of the Council of 30 may 2018 amending directive 2010/31/EU on the energy performance of buildings and directive 2012/27/EU on energy efficiency [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L0844&from=EN.

[5] European Commission, Commission recommendation (EU) 2019/786 of 8 may 2019 on building renovation [Online]. Available: https://data.europa.eu/eli/reco/2019/786/oj, 2019.

[6] M. Arbulu, X. Oregi, L. Etxepare, R.J. Hernández-Minguillón, Barriers and challenges of the assessment framework of the Commission Recommendation (EU) 2019/786 on building renovation by European RTD projects, Energy Build. 269 (Aug. 2022), 112267, https://doi.org/10.1016/j.enbuild.2022.112267.

[7] M. Arbulu, O. Grijalba, X. Oregi, Analysis of energy retrofit assessment methodologies in buildings by European research projects, Environ. Clim. Technol. 25 (1) (Jan. 2021) 265–280, https://doi.org/10.2478/rtuect-2021-0019.

[8] European Union, Level(s). https://ec.europa.eu/environment/topics/circular-economy/levels_en. (Accessed 18 May 2022).

[9] Green Building Council España, Hoja de ruta para la descarbonización de la edificación en todo su ciclo de vida [Online]. Available: https://gbce.es/wp-content/uploads/2022/02/BuildingLife_Hoja-de-Ruta-para-la-Descarbonización-de-la-Edificación.pdf, 2022.

[10] X. Oregi, P. Hernandez, R. Hernandez, Analysis of life-cycle boundaries for environmental and economic assessment of building energy refurbishment projects, Energy Build. 136 (2017) 12–25, https://doi.org/10.1016/j.enbuild.2016.11.057.

[11] A. Vilches, A. Garcia-Martinez, B. Sanchez-Montañes, Life cycle assessment (LCA) of building refurbishment: a literature review, Energy Build. 135 (2017) 286–301, https://doi.org/10.1016/j.enbuild.2016.11.042.

[12] C. Thibodeau, A. Bataille, M. Sié, Building rehabilitation life cycle assessment methodology–state of the art, January, Renew. Sustain. Energy Rev. 103 (2019) 408–422, https://doi.org/10.1016/j.rser.2018.12.037.

[13] European Committee for Standardization, "EN 15978, Sustainability of Construction Works - Assessment of Environmental Performance of Buildings - Calculation Method, 2012, 2012.

[14] T. Malmqvist, et al., Life cycle assessment in buildings: the ENSLIC simplified method and guidelines, Energy 36 (4) (2011) 1900–1907, https://doi.org/10.1016/j.energy.2010.03.026.

[15] L. Van Gulck, S. Van de Putte, M. Delghust, N. Van Den Bossche, M. Steeman, Environmental and financial assessment of façade renovations designed for change: developing optimal scenarios for apartment buildings in Flanders, July, Build. Environ. 183 (2020), 107178, https://doi.org/10.1016/j.buildenv.2020.107178.

[16] A. Galimshina, et al., What is the optimal robust environmental and cost-effective solution for building renovation? Not the usual one, Energy Build. 251 (2021), 111329, https://doi.org/10.1016/j.enbuild.2021.111329.

[17] European Committee for Standardization, "EN 16627, Sustainability of Construction Works - Assessment of Economic Performance of Buildings - Calculation Methods, 2016, 2016.

[18] H. Esen, M. Inalli, M. Esen, Technoeconomic appraisal of a ground source heat pump system for a heating season in eastern Turkey, Energy Convers. Manag. 47 (9–10) (Jun. 2006) 1281–1297, https://doi.org/10.1016/j.enconman.2005.06.024.

[19] H. Esen, M. Inalli, M. Esen, A techno-economic comparison of ground-coupled and air-coupled heat pump system for space cooling, Build. Environ. 42 (5) (May 2007) 1955–1965, https://doi.org/10.1016/j.buildenv.2006.04.007.

[20] M. Esen, T. Yuksel, Experimental evaluation of using various renewable energy sources for heating a greenhouse, Energy Build. 65 (Oct. 2013) 340–351, https://doi.org/10.1016/j.enbuild.2013.06.018.

[21] Interest rate calculator. https://www.easycalculation.com/mortgage/interest-rate.php. (Accessed 10 October 2022).

[22] N. Pachauri, C.W. Ahn, Regression tree ensemble learning-based prediction of the heating and cooling loads of residential buildings, Build. Simulat. 15 (11) (Nov. 2022) 2003–2017, https://doi.org/10.1007/s12273-022-0908-x.

[23] I. Zapirain, G. Etxegarai, J. Hernández, Z. Boussaada, N. Aginako, H. Camblong, Short-term electricity consumption forecasting with NARX, LSTM, and SVR for a single building: small data set approach, Energy Sources, Part A Recover. Util. Environ. Eff. 44 (3) (Sep. 2022) 6898–6908, https://doi.org/10.1080/15567036.2022.2104410.

[24] S. Taheri, P. Hosseini, A. Razban, Model predictive control of heating, ventilation, and air conditioning (HVAC) systems: a state-of-the-art review, July, J. Build. Eng. 60 (Nov. 2022), 105067, https://doi.org/10.1016/j.jobe.2022.105067.

[25] P. Hosseini, S. Nikbakht Naserabad, A.H. Keshavarzzadeh, N. Ansari, Artificial intelligence-based tri-objective optimization of different demand load patterns on the optimal sizing of a smart educational buildings, *Int. J. Energy Res.*, no. April (May 2022) 1–24, https://doi.org/10.1002/er.8095.

[26] P. Hosseini, Deep-learning neural network prediction of a solar-based absorption chiller cooling system performance using waste heat, PC, Sustain. Energy Technol. Assessments 53 (Oct. 2022), 102683, https://doi.org/10.1016/j.seta.2022.102683.

[27] ISO 14040:2006, Environmental Management – Life Cycle Assessment – Principles and Framework." p. 20.

[28] P. Hernandez, P. Kenny, From net energy to zero energy buildings: defining life cycle zero energy buildings (LC-ZEB), Energy Build. 42 (6) (Jun. 2010) 815–821, https://doi.org/10.1016/j.enbuild.2009.12.001.

[29] OECD, OECD Data Webpage, 2022 accessed Aug. 24, 2022, https://data.oecd.org/price/inflation-cpi.htm.

[30] Design Builder simulation tool [Online]. Available: https://designbuilder.co.uk/.

[31] U.S. Department of Energy's (DOE), Building technologies office (BTO), "energy plus energy simulation tool [Online]. Available: https://energyplus.net/.

[32] Ashrae, International weather files for energy calculations 2.0 (IWEC2) [Online]. Available: https://www.ashrae.org/technical-resources/bookstore/ashrae-international-weather-files-for-energy-calculations-2-0-iwec2.

[33] Ecoinvent centre, Swiss centre for the life cycle inventories, Ecoinvent." [Online]. Available: https://ecoinvent.org/.

[34] F. Pedregosa, G. Varoquaux, A. Gramfort, V. Michel, B. Thirion, Scikit-learn: machine learning in Python, J. Mach. Learn. Res. 12 (2011) 2825–2830 [Online]. Available: https://jmlr.csail.mit.edu/papers/v12/pedregosa11a.html.

[35] Ministerio de Transportes Movilidad y Agenda Urbana, Gobierno de España, "CTE - código técnico de la Edificación [Online]. Available: https://www.codigotecnico.org/.

[36] S.A. Cype Ingenieros, Generador de precios de la construcción [Online]. Available: http://www.generadordeprecios.info/.

[37] M. Etxebarria-Mallea, X. Oregi, O. Grijalba, R. Hernández-Minguillón, The impact of energy refurbishment interventions on annual energy demand, indoor thermal behaviour and temperature-related health risk, March, Energy Pol. 153 (Jun. 2021), 112276, https://doi.org/10.1016/j.enpol.2021.112276.

[38] M. Cellura, F. Guarino, S. Longo, M. Mistretta, Different energy balances for the redesign of nearly net zero energy buildings: an Italian case study, Renew. Sustain. Energy Rev. 45 (May 2015) 100–112, https://doi.org/10.1016/j.rser.2015.01.048.

[39] M. Economidou, B. Atanasiu, C. Despret, J. Maio, I. Nolte, O. Rapf, Europe' s buildings under the microscope: a country-by-country review of the performance of the buildings, 2011 no. October. 2011. [Online]. Available: https://www.researchgate.net/publication/271200847_Europe's_buildings_under_the_microscope_A_country-by-country_review_of_the_energy_performance_of_buildings.

[40] C. Jimenez-Bescos, X. Oregi, Implementing user behaviour on dynamic building simulations for energy consumption, Environ. Clim. Technol. 23 (3) (2019) 308–318, https://doi.org/10.2478/rtuect-2019-0097.

[41] X. Oregi, C. Jimenez-Bescos, Evaluating the effect of different base temperatures to calculate degree-days, Environ. Clim. Technol. 24 (2) (2020) 364–372, https://doi.org/10.2478/rtuect-2020-0079.

[42] X. Oregi, N. Hermoso, E. Arrizabalaga, L. Mabe, I. Munoz, Sensitivity assessment of a district energy assessment characterisation model based on cadastral data, Energy Proc. 147 (2018) 181–188, https://doi.org/10.1016/j.egypro.2018.07.053.

[43] E. Cuerda, O. Guerra-Santin, J.J. Sendra, F.J. Neila, Understanding the performance gap in energy retrofitting: measured input data for adjusting building simulation models, Energy Build. 209 (Feb. 2020), 109688, https://doi.org/10.1016/j.enbuild.2019.109688.

[44] Y. Yang, K. Javanroodi, V.M. Nik, Climate change and energy performance of European residential building stocks – a comprehensive impact assessment using climate big data from the coordinated regional climate downscaling experiment, Appl. Energy 298 (Sep. 2021), 117246, https://doi.org/10.1016/j.apenergy.2021.117246.

[45] Eurostat, Inflation rate in the euro area, Accessed: Sep. 01, 2022. [Online]. Available: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Inflation_in_the_euro_area#Euro_area_annual_inflation_rate_and_its_main_components.

[46] Eurostat, HICP energy price, accessed Sep. 01, 2022), https://ec.europa.eu/eurostat/databrowser/view/PRC_HICP_MANR__custom_3293664/default/table?lang=en.

[47] M.R.M. Saade, G. Guest, B. Amor, Comparative whole building LCAs: how far are our expectations from the documented evidence?, June 2019, Build. Environ. 167 (Jan. 2020), 106449, https://doi.org/10.1016/j.buildenv.2019.106449.

[48] Eurostat, Disaggregated final energy consumption in households - quantities, accessed Aug. 31, 2022, https://ec.europa.eu/eurostat/databrowser/view/nrg_d_hhq/default/table?lang=en.

[49] K. Allacker, Sustainable building: the development of an evaluation method, Diss. Abstr. Int. 12 (71) (2010).

[50] P. Ylmén, D. Peñaloza, K. Mjörnell, Life cycle assessment of an office building based on site-specific data, Energies 12 (13) (Jul. 2019) 2588, https://doi.org/10.3390/en12132588.

[51] I. Sartori, A.G. Hestnes, Energy use in the life cycle of conventional and low-energy buildings: a review article, Energy Build. 39 (3) (Mar. 2007) 249–257, https://doi.org/10.1016/j.enbuild.2006.07.001.

[52] I. Zabalza Bribián, A. Aranda Usón, S. Scarpellini, Life cycle assessment in buildings: state-of-the-art and simplified LCA methodology as a complement for building certification, Build. Environ. 44 (12) (2009) 2510–2520, Dec, https://doi.org/10.1016/j.buildenv.2009.05.001.

[53] R.J. Cole, Energy and greenhouse gas emissions associated with the construction of alternative structural systems, Build. Environ. 34 (3) (May 1998) 335–348, https://doi.org/10.1016/S0360-1323(98)00020-1.

[54] G. Wadel, F. López, A. Sagrera, S. Prieto, Rehabilitación de edificios bajo objetivos de reduccín de impacto ambiental: un caso piloto de vivienda plurifamiliar en el área de Playa de Palma, Mallorca, EXTRA, Inf. la Constr. 63 (2011) 89–102, https://doi.org/10.3989/ic.11.067.

[55] Unep-Setac, Global Guidance Principles for Life Cycle Assessment Databases, 2011 [Online]. Available: www.unep.org.

[56] T.H. Mehedi, E. Gemechu, M. Davis, A. Kumar, A framework to identify marginal electricity production technologies for consequential life cycle assessment: a case study of the electricity sector, March, Sustain. Energy Technol. Assessments 47 (Oct. 2021), 101450, https://doi.org/10.1016/j.seta.2021.101450.

[57] T. Schaubroeck, S. Schaubroeck, R. Heijungs, A. Zamagni, M. Brandão, E. Benetto, Attributional consequential life cycle assessment: definitions, conceptual characteristics and modelling restrictions, Sustainability 13 (13) (Jul. 2021) 7386, https://doi.org/10.3390/su13137386.

[58] T. Ramesh, R. Prakash, K.K. Shukla, Life cycle energy analysis of buildings: an overview, Energy Build. 42 (10) (2010) 1592–1600, https://doi.org/10.1016/j.enbuild.2010.05.007.

[59] Pré Sustainability, Eco-indicator99 manuals. https://pre-sustainability.com/articles/eco-indicator-99-manuals/. (Accessed 31 August 2022).

[60] National Institute for Public Health and the Environment of Netherlands, ReCiPe model. https://www.rivm.nl/en/life-cycle-assessment-lca/recipe. (Accessed 31 August 2022).

[61] N. Kleanthis, D. Koutsandreas, C. Karakosta, H. Doukas, A. Flamos, Bridging the transparency gap in energy efficiency financing by co-designing an integrated assessment framework with involved actors, Energy Rep. 8 (Nov. 2022) 9686–9699, https://doi.org/10.1016/j.egyr.2022.07.066.

[62] M.A. William, M.J. Suárez-López, S. Soutullo, M.M. Fouad, A.A. Hanafy, Enviro-economic assessment of buildings decarbonization scenarios in hot climates: mindset toward energy-efficiency, Energy Rep. 8 (Nov. 2022) 172–181, https://doi.org/10.1016/j.egyr.2022.05.164.

[63] E. Szafranko, Assessment of the economic efficiency of energy-saving projects, methodology based on simple and compound methods, Energy Sci. Eng. 10 (2) (Feb. 2022) 423–438, https://doi.org/10.1002/ese3.1032.

[64] W. McKinney, Data structures for statistical computing in Python, Scipy, in: Proceedings of the 9th Python in Science Conference vol. 1, 2010, pp. 56–61, https://doi.org/10.25080/Majora-92bf1922-00a.

[65] C.R. Harris, et al., Array programming with NumPy, Nature 585 (7825) (Sep. 2020) 357–362, https://doi.org/10.1038/s41586-020-2649-2.