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An innovative retrofit Motivation-Objective-Criteria (MOC) approach integrating homeowners' engagement to unlocking low-energy retrofit in residential buildings

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ABSTRACT

According to the EU Commission projection (2016/547/EU), the current average renovation rate is far below the expected rate of 3% to achieve carbon neutrality in building sectors by 2050. This is due to the fact that, during the building retrofit optimisation process, the decision-making criteria and objectives are generally optimised separately, and homeowners' motivations are often ignored or not carefully defined in most research. Limitations existed with a lack of in-depth and comprehensive understanding of the homeowners' motivations in undertaking building retrofit. To address this, we propose an inclusive Motivation-Objective-Criteria (MOC) approach, aiming to bring forward optimised decision-making for building renovation, accommodating different homeowners' retrofit motivations, objectives and criteria. Retrofit motivations are categorised into three typical types: 1) Self-living, 2) Rental or sale, and 3) Investment, under five objectives: Energy Reduction Rate (ERR), Initial Investment (II), Discounted Payback Period (DPP), Bills Reduction Rate (BRR) and Carbon Reduction Rate (CRR). A novel Multi-motivation Performance Factor (MPF) concept is proposed to assess the holistic post-retrofit building performance with comprehensive retrofit combinations. A UK semi-detached house is applied as the reference building to investigate the impact of homeowners' engagement on the decision-making of various retrofit measures.

According to the cost-optimal results neglecting homeowners' motivation, it is evident that the mismatch of optimal retrofit combinations occurs between the minimum Initial Investment (II) and Discounted Payback Periods (DPP), with optimal ERR of 72%-79% and 82%-93%, respectively. Comparing cost-optimal with multi-objective optimisation results, it is concluded that homeowners' retrofit priorities have an apparent influence on selecting optimised retrofit measures. Besides, party wall insulation is fundamental for self-living- and rental or sale-motivated types. The solar-assisted heat pump and air–water heat pump are not necessary under the retrofit motivation of the "investment" type. Moreover, the attic floor and external wall insulation are imperative for rental or sale- and investment-motivated types. The sensitivity analysis results are conducted in this research, indicating that the optimal retrofit measures and baseline energy consumption input are in good agreement, with a 10% discrepancy. Thus, the proposed inclusive Motivation-Objective-Criteria approach can incorporate homeowners' engagement in the building retrofitting design process, serving as a decision-making supporting tool to accelerate building retrofit with maximised user acceptance and market penetration.

1. Introduction

1.1. Background

The existing building stocks worldwide are highly energy-intensive, contributing to almost 40% of the world's total energy consumption and 33% of greenhouse gas (GHG) emissions [1].

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Nomenclature

Mx	Motivation x
Ob	Objective function
Subscripts and superscripts	
i	Retrofit combination number
k	Objective number
lo	Lower limit
set,up	Set upper values for the objective
up	Upper limit
BRR	Bill Reduction Rate
CRR	Carbon Reduction Rate
CNPV	Cumulative Discounted Net Present Values
COMB	Combinations
DHW	Domestic Water Heating
DPP	Discounted Payback Periods
ERM	Energy Retrofit Measures
ERR	Energy Reduction Rate
II	Initial Investment
NPV	Net Present Values
PIR	Polyisocyanurate
RB	Reference Building
VIP	Vacuum Insulation Panels

While in EU countries, building stock contributes to 40% of energy consumption and 30% of greenhouse gas (GHG) emissions [2]. Approximately 80% of existing buildings will still be in use by 2050 [3], of which 75% are energy-inefficient [2]. Improving building energy efficiency and ensuring reliable and sustainable usage of renewable energy resources have been considered as the key strategies set out by many EU countries and the UK, with the aim to accelerate the decarbonisation agenda for building sectors by 2050.

Building retrofit has long been considered, not only as the most effective approach to improve building energy efficiency, eliminate dependency on primary energy (natural gas, electricity) and reduce the associated carbon footprint but also as an evolving vehicle to continuously improve occupants' living standards (in the form of improved indoor comfort level, air quality and reduced noise level). These benefits, however, are not well articulated by policymakers and in building sectors and therefore are often not well received by the key stakeholders (i.e. homeowners, landlords, investors, SMEs). The obstacles to building retrofit are also multi-dimensional and vary largely according to the building typologies, energy usage by different occupants, and climatic conditions. For instance, the long and sometimes staged construction periods for building retrofits often disrupt the occupant's daily activities and even require the temporary evacuation of the property [4,5]. Most importantly, the relatively high initial investment costs and associated long payback period (reported in the UK [6], Germany [7] and Denmark [8]), and the unpredictable economic benefits (due to the lack of detailed costs records and demonstrable bill saving potentials) are the major barriers to stimulate bottom-up building retrofits, which homeowners and investors might otherwise initiate.

In light of the above, European governments have introduced increasingly ambitious policies to promote building renovation and energy efficiency, supporting the goal of becoming climate neutral by 2050. Energy efficiency has seen a gradual improvement in the last decade. In the UK, for instance, social rented dwellings demonstrated the most prominent enhancements in energy efficiency. According to the 2019/2020 English Housing Survey [9], 60% of social rented dwellings managed by housing associations were rated between EPC A and C and 50% of local authority dwellings. In contrast, such an EPC range was only achieved by 29% of the dwellings occupied by homeowners and 33% in the private rented sector. Clearly, the ambitious goals and incentives initiated by the government have seen immediate impacts on the energy-efficient improvement for social housing. This is primarily since social housings are often managed by local city councils and large building associations, who are generally the pioneers to promote building retrofits at the urban scale. Unfortunately, there is still a large gap for promoting low-energy building retrofit in private-owned housings due to a lack of awareness of the associated benefits for key stakeholders and the various obstacles listed above. Because of the lack of an official European definition, Research [10] stated that the major 14 countries within the EU have an average annual renovation rate of 1.10%, with the range varying from 0.08% (in Spain) to 2.40% (in Norway). To overcome this, the implementation of deep building renovation with high-efficiency alternative measures are urgently needed, which help to transform existing properties into near zero-energy buildings with enhanced indoor environmental conditions. If appropriately addressed using a novel user-centred and bottom-up approach, these challenges in the private-owned housing sector could present enormous opportunities to encourage and stimulate wide adoption of building retrofit among key stakeholders. Therefore, it is urgent to understand the barriers and potential impact factors behind low retrofit rates and identify a multi-objective approach that aims to tackle the low-energy retrofit trilemma (i.e., energy efficiency, cost-optimality) the key stakeholders' perspectives) in a holistic manner.

1.2. Literature review

1.2.1. Homeowners' engagement

Several studies [11-13] have been carried out to evaluate the barriers that prevent stakeholders from making firm decisions in implementing building retrofit and the impacts of homeowners' engagement on final retrofit choices. Barriers to the uptake of residential building retrofit can be summarised as: 1) Unsatisfied energy reduction rate performance [14,15]; 2) Exceeded equivalent carbon emission reduction rate [16,17] ; 3) Insufficient investment fund [18,19]; 4) Unacceptable payback periods [20,21]; 5) Unexpected annual energy bills for homeowners [22,23].

Martek et al. [11] reveal that most residential end-users do not purchase green home technologies, and without end-user 'buy-in', building energy sustainable retrofit transition will fail across Australia. Their findings concluded that effective financial incentives should be in place, with direct links to residential real estate markets, in order to promote low-energy building retrofit. Baumhof et al. [12] proposed a Motivation-Opportunity-Ability (MOA) approach to investigate various factors influencing the homeowners' energy-related retrofit decision-making process, taking a single and a two-family house in Germany as a case study. The authors summarised five positive elements in support of the retrofit decision-making process: energy bill savings, supporting social surroundings, owners' willingness to take out a loan, and intention to improve a building's structural condition. Matosović et al. [13] evaluated the homeowners' retrofit choices considering different income classes based on a Croatian case study. The results indicated that homeowners in all income classes had a similar level of willingness-to-pay for similar energy efficiency measures (which could lead to the reductions of the energy bills), with the main differences being their capacity to invest for the future. Mills et al. [24] concluded that it would often be the non-energy benefits (e.g. enhanced thermal comfort, advanced lighting technologies, and improved indoor air quality) that motivate retrofit decisions to adopt energy-efficient technologies. Saint-Gobain [25] investigated 3,000 homeowners and renters to list the most important features that they would want in their ideal home, and it is interesting that the top three responses related to security, running costs and the absence of damp or condensation.

Therefore, it is of great importance to apply a novel approach and establish a comprehensive linkage between the stakeholders' motivations/willingness towards various energy-efficient measures and their actual economic, energy-saving, and social benefits when adopting building retrofits. The established linkage should also be displayed in a user-friendly and accessible manner to increase awareness of the associated benefits among key stakeholders and decision-makers, thereby greatly motivating and maximising the market uptake of low-energy building retrofit towards 2050. Moreover, it is suggested that policymakers account for household status and annual income in future energy efficiency policies.

1.2.2. Reference building method

Selection of building retrofit measures, their applicability and associated energy saving potentials are inherently dependent on building typologies (i.e. residential, commercial, etc.), operating patterns and climatic conditions. This has been recognised by EPBD (European Performance Building Directive), which requires all EU member states to establish their Reference Buildings (RBs) to represent the diversification and functionalities of the national building stocks under different climatic conditions. Various scientific studies have identified reference buildings within this context, representing varying geographic and sectorial conditions for EU building stocks. Based on the source and the type of the data collected, these RBs can be categorised into two types [26]:

- **Hypothetical or example RB**: idealised buildings with assumed geometry and construction details, aiming to represent a large number of national building stocks.;
- **Real RB**: existing buildings with well-defined geometry, building fabric details, and internal energy demands that are able to facilitate characterisation of the general energy performance for substantial building stocks with similar building typologies and construction conditions.

The scientific community tends to adopt hypothetical RBs when conducting data-driven/statistical-based building energy performance analysis [27,28] and/or urban-scale building energy planning [29] under the entire EU building stocks [30]. While real RBs are often applied for one particular building typology under the same climatic condition [31,32], results are limited to the case study scale. Zangheri et al. [32] conducted cost-optimal comparisons covering an exhaustive set of passive and active renovation options for four building types (two residential and two commercial), aiming to represent the EU stock built between 1960 and 1970, in ten European climatic conditions. However, all the buildings analysed in this research were under unharmonised typologies, with different levels of details in global costs and primary energy consumption calculations, making comparison results less replicable.

Corgnati et al. [26] stated that a range of features including building forms (e.g. typology, construction period, geometry and size), envelope thermal conditions, installed building service systems, and the integration/operation of renewable resources should be considered when defining the RBs. Similarly, intending to create a harmonised EU building stock covering a range of building typologies, the EU funded TABULA project [33] defined a series of "agreed parameters of a common classification, including construction year class, building size class, country, region or climate zone.

In summary, to investigate a particular building typology under the UK climatic context, the real RBs are recommended to be adopted due to their clear and feasible definitions in building physical, economic and energy consumption details.

1.2.3. Existing multi-objective optimisation methods

To identify the optimal retrofit solutions, multi-objective optimisation is the most commonly employed method, as it enables the identification of trade-offs between the competing objective functions. In general, two mechanisms for optimising the building retrofit are mainly applied in the reviewed research [34]: the deterministic method (where the weighted sum method is often used) and the non-dominated method (Pareto front [35]).

The essential concept of multi-objective optimisation is Pareto optimality [35], which performs the optimisation performed by combining a building energy simulation software (Energy Plus) and an optimisation tool (a genetic algorithm written in MATLAB). This is a multiple criteria decision-making tool engaged with more than one objective function to be optimised simultaneously. However, all Pareto optimal solutions are acceptable without the subjective preference information, with less opportunity to interact with the stakeholders [36]. Moore et al. [37] proposed a community-level energy retrofit evaluation framework to determine Pareto optimal retrofit solutions for single-detached houses, which can be used to explore the trade-off between life cycle environmental and economic performances of building retrofits.

The Pareto method could achieve the visualisation of the trade-offs in retrofit planning, but several drawbacks have been highlighted:

1) It may not be appropriate to use the Pareto optimisation method when the homeowners' preferences conflict with the technical retrofit results, for example, the homeowners tend to have insufficient funding or lack of willingness to purchase the technologies that are optimised from the combinations [36].
2) Most previous studies [38-40] used mathematical models based on various assumptions. The assumptions used in quantitative models may not reflect real homeowners' motivations and preferences (such as self-living, rental or sale, and investment) in the decision-making process [41].
3) The decision-making of building retrofitting is a complex process involving numerous factors. However, most processes consider pre-defined and pre-evaluated intervention options/solutions [38]. Since this method often involves a minimal domain of renovation solutions, there is no guarantee that the final solution is the best from the decision-makers perspective. However, when a large domain of renovation solutions need to be defined and combined, this method becomes very complex and difficult to obtain meaningful results.

In order to correctly identify relevant parameters that can influence the selection of the retrofit technology, Seghezzi et al. [42] investigated several parameters based on a literature review, considering the building morphology, and employing interviews and discussions together with the actors involved in a building retrofit operation. These interviews were necessary to properly set the parameters and validate different points of view during the building process. Moreover, Chen et al. [43] also indicate that the final retrofit solution is not always a case of selecting the most cost-effective combination measures with the highest energy saving and lowest carbon emissions. Based on the survey conducted in the EU project RezBuild, the weighting factors (in the range of 0–1) representing various stakeholders' preferences were summarised. The energy, economic, environmental and social ranking factor (EEES) was calculated as the sum of the total multiplications between the various factors and the relevant weighting factors. Results concluded that stakeholder's satisfactions had gained increasing importance in measuring the success of projects, under the constraints of "iron" triangle: time, cost and quality.

Hence, to ensure that the model constraints are satisfied and the conflicting objectives are optimised simultaneously, the weighted sum method [44] is applied to transform the original problem into a single objective optimisation problem, where the decision makers' preferences could be involved by determining the multi-objective criteria and transform the output of each sub-objective function at the same scale. Moreover, to drive the building renovation agenda towards a user-centric manner, optimisation models specifically designed for the homeowners' involvement with different motivations need to be developed [44]. The objective functions can also be combined into one scalar function by applying constant weighting factors. This enables the benefits of conducting building renovations (such as energy bills, energy certification, discounted payback periods, initial investment cost) to be well articulated for various stakeholders, offering great flexibility and robustness to make relevant decisions decision-makers. Therefore, it is crucial to establish a practical and user-friendly multi-objective optimal approach to capture homeowners' preferences on proposed retrofit solutions and their combinations, as this could greatly facilitate the final decision-making process.

1.3. Research gaps

According to the analysis above, it is significant to understand homeowners' motivations for undertaking building renovations and how the stakeholders could easily adapt to the innovative technologies. According to the motivations (or willingness) for the stakeholder to undertake renovation for residential buildings, the following categorises are defined and classified: 1) retrofit to self-living, mainly for homeowners who will tend to focus on the energy bill savings and initial investments when implementing renovation; 2) retrofit to rent or sale, mainly for landlords whose renovation decisions would be more anchored by reasonable initial investment and the predicted post-retrofit EPC level (decided by the energy-saving potential); 3) retrofit as an investment, mainly for building investors who will more focus on the payback period and initial investments. Therefore, six main retrofit objectives for residential building retrofit are summarised as below, which can also be mutually interacted with each other:

1) Improve the indoor comfort level [45-51] ;
2) Energy-saving [45-54];
3) Reduce energy bills cost [45,52-55];
4) Improve the value of the properties as a financial investment [52,54] ;
5) Meet Government legal regulations for the minimum EPC (Energy Performance Certification) grades to sale or rent [47,51-53,55-57];
6) Reduce carbon emissions [46,48,49,51,55,56]
7) Reduce global cost or lifecycle cost [45,47,51,52,54]

Table 1 summarises previous research outcomes on building retrofit multi-objective optimisation results according to the defined retrofit motivations and objectives. The discounted payback period includes the comprehensive economic indicators as the net present values calculate it. Meanwhile, the net present values also comprise a series of costs, such as annual maintenance, operation, and replacement costs. Therefore, the proposed discounted payback periods calculation method jointly considers global cost and net present value by the lifecycle cost. Therefore, applying the comprehensive economic indicator of discounted payback periods (DPP) will outperform the approach which solely considers global cost or net present value.

Moreover, it is apparent that several limitations exist in multi-objective optimisation regarding the motivations for building retrofit, which can be summarised in the following perspectives:

1) Lack of in-depth and comprehensive understanding of the homeowners' motivations to undertake building retrofit. Most research focused on retrofitting to improve building energy efficiency and energy-cost optimum solely for self-living purposes. However, little attempt has been made to investigate other retrofit motivations such as retrofit for sale, rental, and investment.
2) Lack of inclusive decision-making models considering comprehensive retrofit objectives with homeowners' engagement. Energy-savings is the primary goal for the research works listed in Table 1. However, other objectives (such as energy bill reduction, financial investment to improve home values in the building market, and the requirements under EPC regulations) are addressed in the practical retrofit projects, which affect the retrofit strategies and final decision-making process dramatically.

In general, the decision-making criteria and objectives are optimised separately in the literature [58-60], and homeowners' motivations are ignored or not carefully defined in these research works. In order to tackle this and promote bottom-up building renovation which will be motivated by the homeowners, this paper establishes an innovative Motivation-Objective-Criteria (MOC) approach integrated with homeowners' engagement to support the decision-making process for selecting building retrofit measures, according to different homeowners' retrofit motivations, objectives and criteria. Adopting the MOC approach at the pre-retrofit design and decision-making process of building renovation will enable the key stakeholders (users, employers, and suppliers) with access to transparent and well-quantified energy, economic, environmental, and social benefits, thereby immensely stimulating the future Renovation Wave [61] driven by the end-users.

2. Methodology

This paper establishes a method to solve the conflicts between householder preferences and the selection of maximised retrofitted energy-saving measures in which the decision-making strategies are multi-objective and are affected by both human weights (subjective factors and requirements) and criteria (objective conditions, such as regulations and legislation, limited funds). The weighted sum method (WSM) is adopted to evaluate the comprehensive energy-retrofit combinations for analysing and discussing the impacts of different motivations weights on selecting retrofit technologies and combinations. Apart from homeowners' motivations, the impacts of building locations on the decision-making of retrofit measures are also considered.

Table 1
Summary of the previous studies on building retrofit multi-objective optimisation based on different retrofit motivations and objectives.

Ref.	Country/City	Optimal method	Retrofit motivations	Retrofit objectives							Optimised results
				Comfort	Energy	Bill	Investment	EPC	Carbon emissions	Global cost	
[45]	Perugia, Italy	Cost-effective optimal	Profitable investments	√	√	√				√	1) Energy bills reduce to 52 €/year (priority in OB2);2) Energy bills reduce to 32 €/year (priority in OB1).
[46]	Abu Dhabi, UAE	Energy Plus-MATLAB coupling matrix	Self-living	√	√				√		Energy savings of 24.4% can be achieved without any effect on the comfort and well-being of building occupants
[47]	Aachen, Germany	NSGA-II algorithm and Pareto-front optimum	Self-living	√	√			√		√	The optimised energy reduction rate is 80.3% with an initial investment of 183 €/m^2 under requirements of low carbon emissions and low investment costs
[48]	Abu Dhabi, UAE	multiple linear regression surrogate model	Self-living	√	√				√		Providing occupants with control over their building systems can mitigate uncertainty in human actions on the built environment's performance.
[49]	Abu Dhabi, UAE	MATLAB-Energy Plus coupling engine	Self-living	√	√				√		Energy savings of 19% are observed without compromising thermal comfort levels.
[52]	London, UK	N/A	Rental		√	√	√	√		√	Based on widely available socio-demographic and business data, seven retrofit behaviour typologies are concluded.
[53]	Hubei, China	Linear regression	Rental		√	√		√			The optimisation model considered retrofitting a building's walls, windows, and roof and installing a rooftop PV system to achieve better energy performance.
[56]	Oslo, Norway	Energy Limiting Difference (ELD) - EPC optimisation method	Rental		√			√	√		Retrofit combination level 'Extensive Retrofit' indicates the potential energy-saving range of 51%–83%, with all the COMBs satisfying the EPC grade B and most of the COMBs reaching EPC grade A.
[54]	Albuquerque, New Mexico	Linear regression	Self-living		√	√	√			√	The results of the model show that the budget of $11,000 for energy retrofitting of the case study can minimise the total LCC of the building for the homeowner
[57]	Bucharest, Romanian	House of Quality (HoQ) model	Self-living and rental	√				√			The better the stakeholder's satisfaction, the more efficient the retrofit process and the EPC improvement.
[55]	Salford, UK	Survey, questionnaires and empirical research	Rental, sale and investment		√	√		√	√		The findings are relevant for the social housing sector and effectively deliver programmes such as the Green Deal and the Energy Company Obligation within the UK.
[51]	Dublin, Ireland	Three-stage decision-making process	Self-living	√	√			√	√	√	The optimisation model considered retrofitting a building's walls, windows, and roof and installing a rooftop PV system to achieve better energy performance. Requirement on the EPC rating is taken as one of the objectives to ensure policy compliance, and a tax incentive program is considered in the model to maximise economic offset to the long payback period of the envelope retrofit.

The structure of this research paper is presented in the flowchart shown in Fig. 1:

1) Definitions of three motivations including self-living, rental or sale and investment, and their relevant objectives, weights and selection hypotheses (section **2.1**);
2) Definitions of Weighted Sum Method (WSM) and assessments using a multi-motivation performance factor (MPF) to optimise the energy-retrofit combinations (section **2.2**);
3) Calculation methods for the lifecycle energy and cost performance, and its post-retrofit assessment factors (section **2.3**);
4) Reference building analyses in the UK context including baseline descriptions and complex technological combinations (section **3**);
5) Results and discussions covering: i) Baseline model validation (section **4**) ii) Analyses of cost-optimal decision-making optimisations without considering homeowners' engagement (section **4.1**); iii) Analyses of the impact of homeowners' moti-

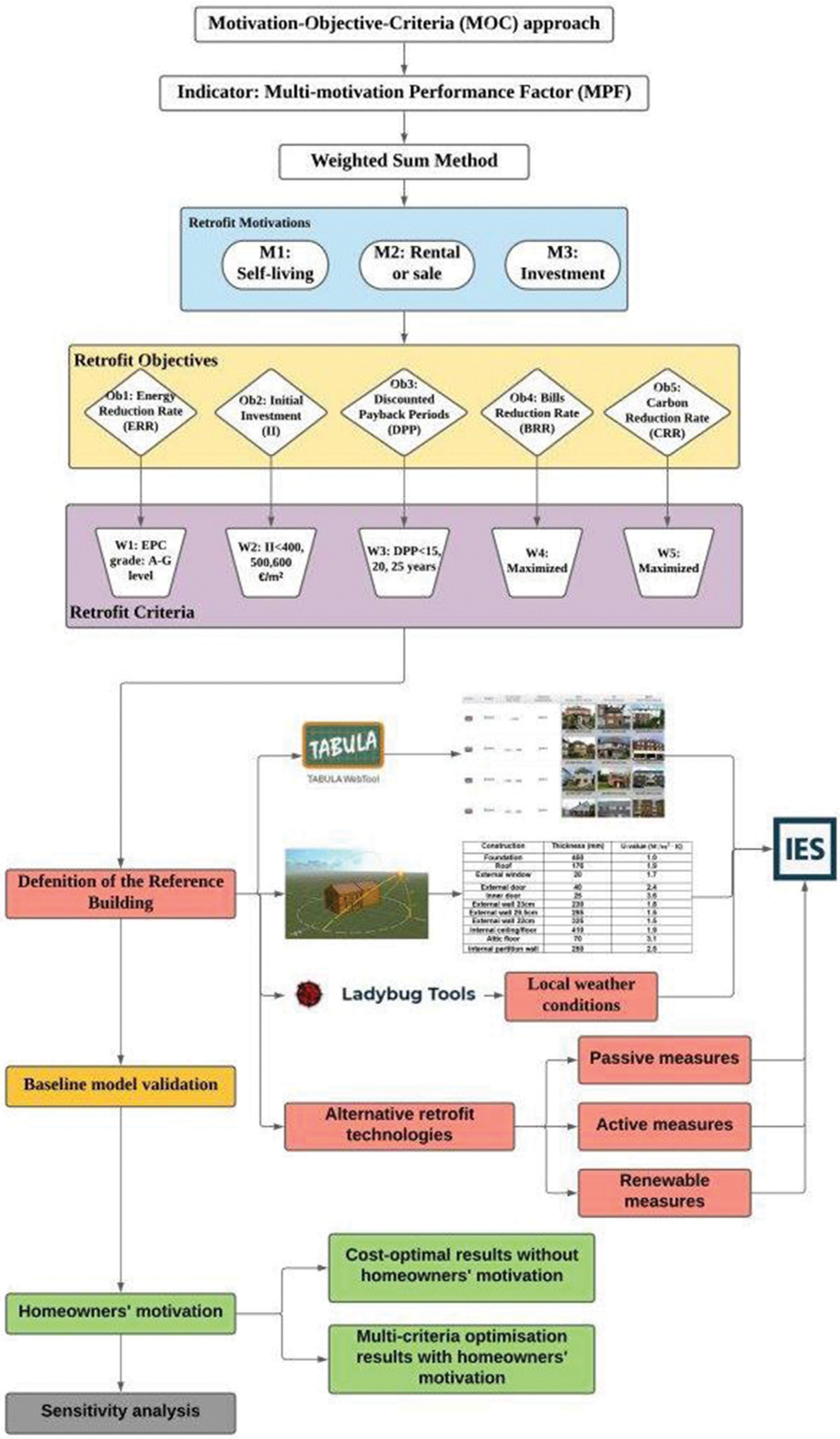

Fig. 1. Flowchart of the research structure.

vations on optimised retrofit combinations and their characteristics considering homeowners' engagement (section **4.2**); iv) Sensitivity analysis (section **4.3**).

2.1. Multi-objective assessment approach

The proposed MOC approach is established upon a number of possible motivations or purposes for undertaking residential building retrofit, including 1) Self-living; 2) Rental or Sale; 3) Investment.

To make decisions on comprehensive energy-retrofit combinations considering the retrofit motivations from the decision-makers' perspectives, a multi-motivation performance factor (MPF) is proposed to evaluate the overall performance with the comprehensive energy retrofit combinations. The homeowners or investors are considered the critical stakeholders for the decision-making stage of most residential buildings. The actual weights of each motivation objective defined by the proposed Multi-motivation Performance Factor (MPF) can be adjusted according to the homeowners' preferences and financial conditions. The global optimum with maximum MPF is decided according to homeowners' different weights of motivations. Thus, the optimal energy retrofit combinations can be obtained from those combinations that can achieve the maximum value of the MPF.

$$MPF\ (i) = \sum_{i=1}^{n} W_k Ob_k(i)\ (i = 1,\ 2,\ \ldots,\ n;\ k = 1,\ 2,\ 3,\ 4, 5) \quad (1)$$

Where,

Ob_1 – To achieve expected/required or higher **Energy Reduction Rate (ERR)**;

W_1 - The weighted score for Ob_1;

Ob_2 – To reduce the **Initial Investment (II)** to an affordable level;

W_2 - The weighted score for Ob_2;

Ob_3 – To reduce the **Discounted Payback Period (DPP)** to a profitable performance;

W_3 - The weighted score for Ob_3;

Ob_4 – To achieve expected/required or higher **Bills Reduction Rate (BRR)**;

W_4 - The weighted score for Ob_4;

Ob_5 – To achieve expected/required or higher **Carbon Reduction Rate (CRR)**;

W_5 - The weighted score for Ob_5;

According to the key stakeholders' various retrofit motivations, the following five objectives are considered, including Energy Reduction Rate (ERR), Initial Investment (II), Discounted Payback Period (DPP), Bills Reduction Rate (BRR) and Carbon Reduction Rate (CRR). Therefore, the Weighted Sum Method (WSM) is defined to evaluate the overall performance of comprehensive energy retrofit combinations, with the individual function defined for each objective shown in Eqs. (2)–(8):

$$Ob_1\ (i) = ERR\ (i),\ \ \eta_{ERR,\ lo} \leqslant ERR\ (i) \leqslant \eta_{ERR,\ up} \quad (2)$$

$$Ob_2\ (i) = \min(II(i))/II(i)\ ,\ II\ (i) \leqslant C_{set,up} \quad (3)$$

$$Ob_3\ (i) = \min(DPP(i))/DPP(i)\ ,\ DPP\ (i) \leqslant T_{set,up} \quad (4)$$

$$Ob_4(i) = BRR\ ,\ BRR\ (i\ ) \geqslant \varphi_{set,lo} \quad (5)$$

$$Ob_5\ (i) = CRR\ (i),\ \ \eta_{CRR,\ lo} \leqslant CRR\ (i) \leqslant \eta_{CRR,\ up} \quad (6)$$

subject to:

$$\mathrm{W_k}\mu(0,1),\ \mathrm{k} = 1,\ 2,\ 3,\ 4,\ 5 \quad (7)$$

$$\sum_{\mathrm{k}=1}^{5} \mathrm{W_k} = 1,\ \mathrm{k} = 1,\ 2,\ 3,\ 4,\ 5 \quad (8)$$

The stakeholders looking to sell or rent their properties will value ERR significantly, which is directly related to the EPC level. $\eta_{\mathrm{ERR,\ lo}}$ and $\eta_{\mathrm{ERR,\ up}}$ are the lower and upper bound of the energy reduction rate; $\eta_{\mathrm{CRR,\ lo}}$ and $\eta_{\mathrm{CRR,\ up}}$ are the lower and upper bound of the carbon reduction rate; $\mathrm{C_{set,up}}$ is the upper bound of the investment cost, subject to the availability of funding or financial incentives; $\mathrm{T_{set,up}}$ is the upper bound of the discounted payback periods, due to an acceptable/affordable upper bound of the investment cash return, especially for the stakeholders who view the benefits of energy savings and immediate property market value increase after retrofit; $\varphi_{\mathrm{set,lo}}$ is the lower bound of the annual energy bills reduction rate for homeowners; the subscript "i" indicates the various retrofit combination numbers while the subscript "min" indicates the minimum outputs of the objective functions.

Energy Performance Certificates (EPC) provide information on the building energy efficiency and how it could be improved. Buildings are rated on a scale from A - G, with A being the most efficient. There are seven of these bands on an EPC which are run on a sliding scale from 'A' (the most energy-efficient) to 'G' (the least efficient). They are also colour coded for ease of reference from dark green (an 'A' rating) to red (a 'G' rating). Most homes in the UK fall into a 'D' band.

The EPC assessment records specific information such as the size and layout of the building, how it has been constructed, and how it is insulated, heated, ventilated, and lighted [62]. The EPC is produced using a UK Government calculation methodology [11,12]. In addition, the EPC calculation methodology was also mentioned by Qu et al. [56]. More detailed technical information on the calculation methodologies can be found in Appendix A.

Obviously, the optimised multi-objective results are influenced by the subjective evaluation of weights scores in different cases. The final decision is selected under the negotiated weights values between the key stakeholders and the government requirements. Sensitivity analysis can be used by adjusting the values of the weights of each item from W_1 to W_5 to investigate the influence of each criterion on the final decision-making optimised results.

2.2. Retrofit motivations, objectives and weights

This research is built upon an EU Horizon 2020 funded project SureFit [63], aiming to achieve fast-track and affordable building retrofits for five selected demo site buildings in Norway, Greece, Portugal, the UK, and Spain. Using the SureFit project as an example, the five demo site project leaders (University of Nottingham-UK, Aalto University-Norway, ISQ-Portugal, FMS-Spain, AMS-Greece) work closely with the occupants to collect pre-retrofit survey results, with the aim to understand the occupants' motivations and preferences for the retrofit process. Moreover, the demo site leaders act as project coordinators who liaise with homeowners to emphasise retrofit motivations and preferences through surveys and questionnaires. In order to capture various homeowners' retrofit preferences and motivations, the "lessons learned" online survey covered a wide range of questions from multi-objective perspectives (1. reducing energy bills; 2. reducing energy consumption to achieve certain EPC level; 3. Reducing carbon emission; 4. Initial investment; 5. Discounted payback periods) was designed and distributed within Surefit project partners and their clients, who represent a wide range of stakeholders. Meanwhile, to make the weighting factor more reliable to reflect the homeowners' motivations and perspectives, 42 surveys were collected with the weighting factors (in the range of 0–1) to represent various homeowners' preferences as summarised in Appendix B. A higher weighting factor value means that the stakeholders expressed special attention in this respect. In Table B.1, Appendix B, the numerical weighting score "1" stands for the most attractive and beneficial objectives while "0" indicates lack of interest. Finally, the average weighting scores of the abovementioned five multi-objective perspectives are calculated in Table 2, referring to the survey data in Appendix B. In Table 2, the weighting of each objective is described as Mx, with × varied from 1 to 3 representing the three types of motivations for undertaking building renovation.

Regarding the survey results, although a few homeowners also considered the environmental impact in the pre-retrofit design, the average weighting scores of CRR (W_5) are zero in the three motivations, as shown in Appendix B. This is due to the fact that there are no transparent links between the economic benefits reflected in

Table 2
Weight assumption of five motivations.

Type of Motivations	Code	ERR (W_1)	II (W_2)	DPP (W_3)	BRR (W_4)	CRR (W_5)
Self-living	M1	0	0.3	0.1	0.6	0
Rent or Sale	M2	0.6	0.2	0.2	0	0
Investment	M3	0	0.4	0.6	0	0

CRR. All other four weighting scores impact the household carbon emission reduction directly or indirectly.

For self-living-oriented motivation (M1), homeowners seek to reduce their energy bills compared with pre-retrofit scenarios [7,64]. Occupants face ever-increasing financial burdens due to the rise of energy prices, especially those whose dwellings are at low energy-efficient levels. In addition, the degradation of existing buildings, poor insulation and inefficient energy systems will cause unnecessary energy consumption, leading to poor indoor comfortable conditions. However, due to financial issues, in most cases, the retrofit investment capacity is limited and affected by the affordability of the homeowners [65,66]. During the retrofit process, homeowners prefer to seek energy-economic measures with shorter payback periods, reinforcing usability and building efficiency rather than some less cost-effective components [67,68]. Therefore, in the M1 scenario, the bills reduction rate (BRR) is the homeowners' first-order consideration, with initial investment (II) as the second-order consideration and the last of discounted payback periods (DPP). Thus, in the weighted sum method, the weights of first-order motivation (W_4) are assumed higher than the weights of the second and last order motivations (W_2 and W_3).

In rental or sale-oriented motivation (M2), homeowners tend to achieve a higher building energy efficiency represented by Energy Reduction Rate (ERR). Due to regulations and legislation in most EU countries, the rental and sale of residential properties must satisfy a minimum energy performance certification (EPC), linking with the ERR ranges [69,70]. In addition, homeowners will consider the initial investment and payback periods to pursue a balance between them [71,72]. Thus, in the weighted sum method, the weights of first-order motivations (W_1) are assumed higher than the other two motivations (W_2 and W_3) with the same weights.

In investment-oriented motivation (M3), homeowners wish to make profits by adopting renovations, which can be achieved with shorter payback periods, lower initial investment costs and associated risks [73,74]. However, selecting the initial investment as an individual objective and criteria is a crucial subject to funding availability and affordability of the homeowners [75,76]. Secondly, the initial investment, annual maintenance, operation, and replacement costs defined in lifecycle cost, allow net present values to be conducted, which could be valuable for comprehensive economic calculation of discounted payback periods. Therefore, global cost and net present value are represented by the lifecycle cost considered in the DPP calculation as the most significant factor, with the second-order initial investment cost (II). Thus, in the weighted sum method, the weights of first-order motivations (W_3) are assumed higher than the second-order weights (W_2).

The Energy Reduction Rate and Bills Reduction Rate are non-linear depending on energy-specific prices. However, it is still essential to keep both indicators due to the following reasons:

1) The potential energy reduction rate (ERR) will be at a fixed value when the retrofit combination is well-defined, however, energy bills reduction rate (BRR - calculated by the sum of electricity and natural gas bills reduction) will be influenced by the changing energy prices under the same BRR, since BRR is derived from the multiplication of energy reduction (ERR) and its price (according to the different energy sources). Besides, energy prices are subjected to different increasing rates from a long term perspective, which will affect the lifetime net present values of the energy bill savings. Therefore, defining bills reduction rate (BRR), on top of energy reduction rate(ERR), will allow the homeowners to evaluate the potential economic benefits of undertaking building renovation by jointly taking into the joint of both changing energy prices and their impacts on ERR;
2) Different retrofit combinations may have similar energy reduction rates (ERR), however, the proportions of thermal energy and electricity can be diversified, which may result in different energy bill savings;

According to the survey results, the retrofit motivations can be different, as defined in the section above (e.g. retrofit for rent or sale, retrofit for self-living). The willingness to invest in deep energy retrofit is relatively low because the potential of BRR as a result of undertaking renovation is not quantified and well communicated to the homeowners and investors.

2.3. Calculation method

This section introduces the calculation methods for pre/post-building energy performance and five objectives with the following 8 steps:

Step 1: Energy performance of building baseline and individual ERM calculated using IES VE software

Step 2: Comprehensive energy retrofit combinations generated in MATLAB

Step 3: Post-retrofit final energy consumption calculated in MATLAB

Step 4: Energy Reduction Rate (ERR) calculation for comprehensive retrofit combinations

Step 5: Carbon Reduction Rate (CRR) calculation for comprehensive retrofit combinations

Step 6: Initial Investment (II) calculation for comprehensive retrofit combinations

Step 7: Discounted Payback Period (DPP) calculation for comprehensive retrofit combinations

Step 8: Bills Reduction Rate (BRR) calculation for comprehensive retrofit combinations

The building's baseline energy performance is assessed in IES VE software evaluating thermal energy demand for space cooling, space heating and DHW, and electricity demand for fans, lighting, pumps, and equipment. The IES VE model needs to be set initially using:

- The thermal-physics features of building envelopes such as U-value of different facades and glazing types;
- Hourly schedules for different thermal zones including occupancy, DHW demand, people activity, ventilation need, lighting and household equipment power density;
- HVAC system and its operation schedules based on set-point temperatures;
- Different HVAC types for heating and cooling needs;

- Climatic boundary conditions include solar radiation, wind velocity and external temperature.

After the simulation of the baseline model in IES VE software, thermal and electricity demand are decoupled during the process in which the post-retrofit final energy consumption is assessed in MATLAB. In the meantime, thermal energy demand for space heating, space cooling, and DHW and direct electricity usage are simulated as input values to the next stage of the retrofit calculation process. In addition, random combinations of alternative retrofit measures are considered comprehensive retrofit combinations (COMB), where a set of energy retrofit measures (ERMs) are determined based on energy performance.

Operators 0 and 1 represent different technologies' absence and presence during the process. To explore all possible ERM combinations, n mixed variables are deducted in a continuous or discrete range. For instance, if thermal insulation is used as one of the ERMs in COMB1, the post-retrofit heating/cooling energy consumption is calculated by multiplying its corresponding heating/cooling demand efficiency with baseline heating/cooling demand values.

The heat pump system is also engaged in COMB1 with thermal insulation to replace the existing boiler. In that case, the post-retrofit heating/cooling energy consumption is calculated by multiplying its system energy efficiency due to different energy carriers with demand to energy conversion rates. Then, the final energy consumption is the coupled results of both thermal and electrical consumption.

Energy reduction rate (ERR) is proposed to determine the energy-saving potential for each retrofit combination, whose final energy consumption will be compared with that of the baseline reference building with the unit of percentage (%). As shown in Eq. (9), ERR can be calculated as the ratio between the post-retrofit scenario's primary energy consumption and the primary energy reduction between the post-retrofit and baseline model.

$$\mathrm{ERR} = \sigma(\mathrm{i})/(\sigma(\mathrm{i}) - \sigma(0)) \tag{9}$$

Where, $\sigma(\mathrm{i})$ is the final energy consumption (kWh/m^2) with the selected retrofit combination COMBi; $\sigma(0)$ is the baseline final energy consumption.

One of the purposes for ERR is to examine and compare the final energy consumption reduction between baseline and retrofit sceneries ($\sigma(\mathrm{i}) - \sigma(0)$) and economic benefits for post-renovation scenarios under different climatic conditions.

Carbon reduction rate CRR is proposed to determine the energy-saving potential for each retrofit combination, whose final carbon emission will be compared with that of the baseline reference building with the unit of percentage (%). As shown in Eq. (10), CRR can be calculated as the ratio between the post-retrofit scenario's carbon emission and the carbon reduction between the post-retrofit and baseline model.

$$\mathrm{CRR} = \lambda(\mathrm{i})/(\lambda(\mathrm{i}) - \lambda(0)) \tag{10}$$

Where, $\lambda(\mathrm{i})$ is the final carbon emission (kWh/m^2) with the selected retrofit combination COMBi; $\lambda(0)$ is the baseline carbon emission.

According to Statista, the average hourly labour cost is estimated as 28.5 €/h [77] and the installation cost as 34 €/m^2 [78]. The capital cost of each technology is referred to in section 3.3. The initial investment (II) is calculated by the sum of the capital cost of components and the labour cost for installation, as shown in Eq. (11):

$$\phi_{\mathrm{II}} = \phi_{\mathrm{capital}} + \phi_{\mathrm{labour}} \tag{11}$$

DPP is defined as variation and modification of payback period that accounts for the time value and uses discounted cash flows when calculating the payback period with the unit of years [79]. DPP represents the economic performance of a specific combination to assess the rapidity of the investment payback period. To assess DPP, the cumulative discounted net present values (CNPV) are calculated first through the difference of initial investment and the cumulative annual net cash flows in Eq. (12):

$$\mathrm{CNPV}(\mathrm{t} = \mathrm{n}) = \phi_{\mathrm{II}} - \sum\nolimits_{\mathrm{t}=1}^{\mathrm{n}} \mathrm{NPV}(\mathrm{t} = \mathrm{n}) \tag{12}$$

Therefore, DPP equals to 't = n' year when the CNPV (t = 0) = 0, with details in Eq. (13):

$$\mathrm{DPP}(\mathrm{i}) = \mathrm{n}, \mathrm{when CNPV}(\mathrm{t} = 0) = 0 \tag{13}$$

The Net Present Value Method (NPV) is the difference between the present value of cash inflows and the present value of cash outflows over a period used in capital budgeting and investment planning to analyse a combination retrofit's profitability. The following Eq. (14) [80] is used to calculate NPV of annual energy bill savings:

$$\mathrm{NPV}(\mathrm{t}) = \mathrm{R_d}(\mathrm{t}) \times (\phi_{\mathrm{b}}(\mathrm{t} = 0) - \phi_{\mathrm{b}}(\mathrm{t}) - \phi_{\mathrm{operation}}(\mathrm{t})) \tag{14}$$

The discount rate $\mathrm{R_d}(\mathrm{t})$ depends on the real discount rate $\mathrm{R_r}$ and the years (t) of the considered costs. The discount rate can be expressed as Eq. (15):

$$\mathrm{R_d}(\mathrm{t}) = (1/(1 + \mathrm{R_r}))^{\mathrm{t}} \tag{15}$$

Where t is the number of years and $\mathrm{R_r}$ is the real discount rate, which is closely related to market interest R and inflation rate $\mathrm{R_i}$. It can be calculated using Eq. (16):

$$\mathrm{R_r} = (\mathrm{R} - \mathrm{R_i})/(1 + \mathrm{R_i}) \tag{16}$$

The market values of interest & inflation rate and energy price & their increasing rate for Lisbon, Venice, Nottingham and Helsinki are shown in Table 3.

3. Definitions of residential reference building

3.1. The reference building

Between 1961 and 1975, new forms of houses were built with tight budgets, and many desired homes had fresh, colourful and open-plan interiors to throw out the old and embrace all things modern, making those multi-family semi-detached houses popular [83]. This led to the construction of many semi-detached houses featuring masonry walls with poor insulation, comprising around 7% (approximately 695,000 buildings) of the total UK building stocks [84]. Further, semi-detached housing accounts for approximately 59% of the total building stocks [84], which is the most popular type compared with detached houses (22%), terraced houses (18%) and apartment blocks (1%). According to Ref. [84], the

Table 3
Economic indicators and energy prices.

	Market interest rate R (%)	Inflation rate $\mathrm{R_i}$ (%)	Real discount rate $\mathrm{R_r}$ (%)	Electricity price increase rate (%)	Natural gas increase rate (%)	Natural gas price (€/kWh)	Electricity price (€/kWh)
UK-0.2203 [82]	Nottingham	0.57 [81]	0.7 [81]	0.689 [81]	5.89 [82]	12.99 [82]	0.0476 [82]

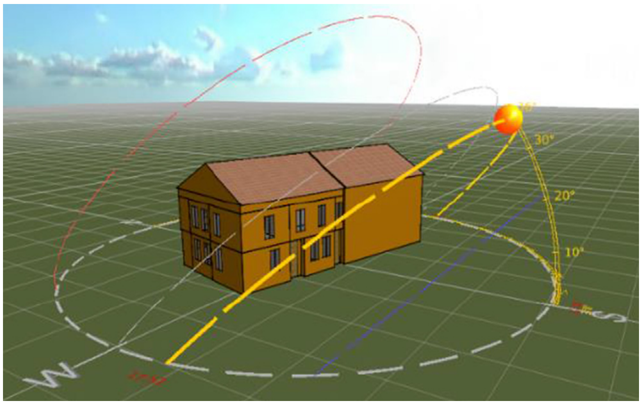

Fig. 2. Model of the reference building established in IES VE.

semi-detached multi-family houses comprising two individual dwellings constructed between 1961 and 1975 are usually dedicated to four occupants with an average floor area of 156 m^2 (range: 150 m^2-160 m^2). The average energy consumption for such a house would be about 402 kWh/m^2 to 425 kWh/m^2 per year [84], supplied by a gas condensing boiler. The building construction materials and U-value specifications are summarized in Appendix C, with pitched roof (U-value = 1.5 W/m^2K), concrete floors (U-value = 2.0 W/m^2K), masonry walls (U-value = 1.8 W/m^2K) and double glazing windows (U-value = 1.7 W/m^2K).

The reference building (RB) [85] defined in this research represents a residential building selected with the UK residential building taxonomy of building construction between 1961 and 1975. Construction during this period followed regulations in force at that time for new building's design, as summarised by the TABULA project [86]. The RB in this research case is a semi-detached two-family house under the social housing category with a total of 158 m^2 in floor area with four people on each floor. The building energy model was created as a baseline in IES VE [87] software to test different retrofit solutions, as shown in Fig. 2. The weather file was chosen from the Ladybug website [88] in epw. Format. The precise location and regulation for the weather file is UK - Nottingham – Watnall – ISD-TSY_3.

The ambient temperature parameter is **temperate oceanic climate,** which is quite cold, rainy winters and mild, relatively rainy summers, with 10.6 °C, −2 °C and 33.6 °C for average, minimum and maximum ambient temperatures. Solar radiation is 143 W/m^2 and 837 W/m^2 for average and maximum values.

This building is divided into seven building spaces: entrance hall, kitchen, dining room, living room, bathroom, bedrooms 1, 2 and storage room, shown in Fig. 3. The energy consumption of the RB was calculated using the simulation engine in IES VE. The final energy consumption of different energy retrofit combinations is evaluated as described in section 2.3 for space heating, DHW and electricity usage and calculation of the initial investment.

The UK residential building taxonomy indicated the thermal construction of the house. Specific layers, thermal conductivities, and the overall heat transfer coefficients (U-value) of the building elements are listed in Table 4.

The condensing boiler is powered by nature at a thermal efficiency of 96.80%. The maximum energy supply-related power is limited to 24.8 kW, with continuous 9.8 L/min hot water supply when ΔT keeps at 35 °C. The boiler supplies 65 °C for space heating and 62 °C for domestic hot water. The heating system functions less efficiently due to long term degradation. During other times, the radiators are turned off. Artificial lighting is halogen lighting bulbs with a power of 2.85 W/100 lx.

3.2. Alternative retrofit technologies

17 retrofit technologies were selected as alternative energy retrofit measures (ERM), categorised as passive, active, and renewable [56]. The information on the life cycle and costs of 17 ERMs are listed in Table 5. The detailed energy performances of each technology are listed in Appendix D.

Passive measures: ERM01-1 (Vacuum glazing insulation windows); **ERM01-2** (Triple glazing windows); ERM02-1 (Silicon-based vacuum insulation panels); ERM02-2 (Polyisocyanurate insulation panels); **ERM03-1** (Silicon-based vacuum insulation panels); **ERM04-1** (Starch aerogel insulation panels); **ERM05-1** (Silicon-based vacuum insulation panels); **ERM06-1** (Gypsum insulation); **ERM06-2** (Sealings of the windows and joint places).

Active measures: ERM07-1 (Mechanical ventilation with heat recovery); **ERM08-1** (LED lighting + Daylighting pipes).

Renewable measures: ERM09-1 (Multi-crystalline silicon PV glazing panels); **ERM09-2** (Thin-film PV glazing with high insulation); **ERM10-1** (Solar assisted heat pump); **ERM10-2** (Air-water

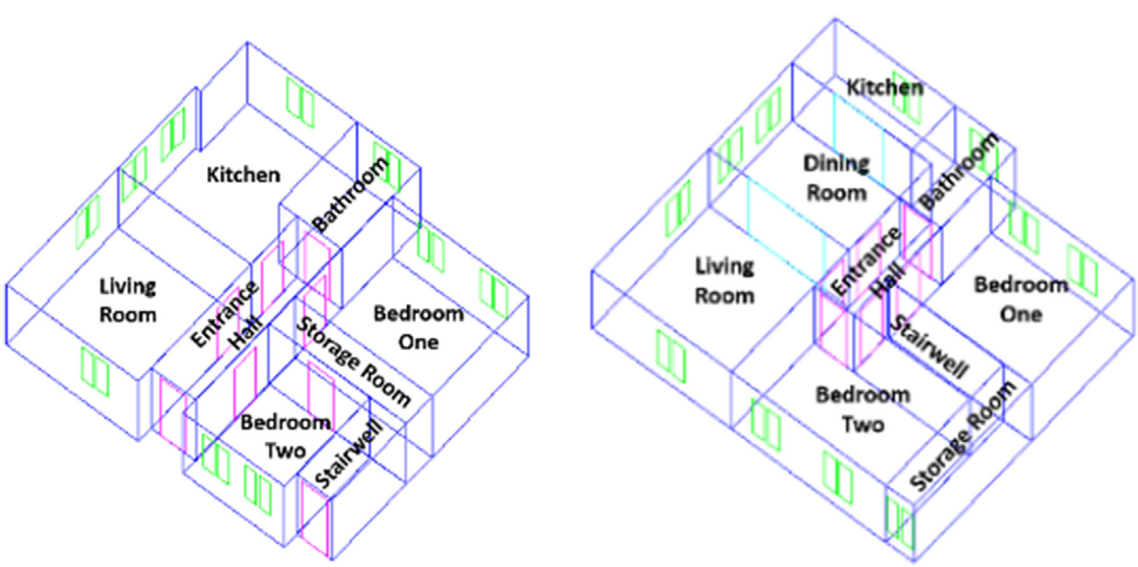

Fig. 3. 3D room layouts of the reference building (established in IES VE).

Table 4
Physical properties for the selected reference building.

Building Components	Total Thickness (mm)	Total U-value ($W/m^2 \cdot K$)	Thermal mass C_m ($kJ/m^3 \cdot K$)
Foundation	450	1.0	177.1
Roof	176	1.9	64.3
External window	20 (only glazing)	3.1 (only glazing)1.7 (including frame)	Visible light normal transmittance: 0.8
External door	40	2.4	33.5
Inner door	25	3.6	20.9
External wall 23 cm	230	1.8	152.8
External wall 29.5 cm	295	1.5	85.9
External wall 32 cm	325	1.5	152.8
Internal ceiling/floor	410	1.9	174.5
Attic floor	70	3.1	50.8
Internal partition wall	250	2.5	220.6

Table 5
Costs and Life cycle performances of selected ERMs.

Energy-efficient measures	ERM number	Unit cost	Life span (years)
Vacuum glazing window insulation	**ERM01-1**	563 €/m^2 [89]	30
Triple glazing window insulation	**ERM01-2**	336 €/m^2 [90]	30
Si-VIP external wall insulation	**ERM02-1**	92 €/m^2 [91]	30
PIR external wall insulation	**ERM02-2**	103 €/m^2 [92]	30
Si-VIP party wall insulation	**ERM03-1**	46 €/m^2 [91]	30
Starch aerogel attic floor insulation	**ERM04-1**	131 €/m^2 [93]	30
Si-VIP ground floor insulation	**ERM05-1**	92 €/m^2 [91]	30
Gypsum airtightness insulation	**ERM06-1**	122 €/m^2 [94]	5
Sealings of windows and joint places	**ERM06-2**	15 €/m^2 [95]	5
Mechanical ventilation with heat recovery	**ERM07-1**	60 €/m^2 floor area [96]	15
LED lighting + Daylighting pipes	**ERM08-1**	247 €/unit [97]	10
Multi-crystalline silicon PV glazing panels	**ERM09-1**	353 €/m^2 [98]	20
Thin-film PV glazing with high insulation	**ERM09-2**	1072 €/m^2 [99]	15
Solar assisted heat pump	**ERM10-1**	612 €/kW [100]	15
Air-water heat pump	**ERM10-2**	640 €/kW[101]	15
Potassium formate-water cascade air cooling dehumidifier	**ERM10-3**	97 €/kW [102]	15
Solar collector	**ERM11-1**	1122 €/unit [100]	10

Table 6
The baseline energy performance and validation.

	Simulation results by IES VE	On-site measurement results	Discrepancies
Final energy consumption (kWh/m^2)	419	421	−0.5%
Natural gas consumption (kWh/m^2)	284	289	−1.7%
Electricity consumption (kWh/m^2)	135	132	2.3%
Annual energy bills (€)	6820	6769	0.8%
Annual natural gas bill (€)	2138	2174	−1.7%
Annual electricity bill (€)	4682	4595	1.9%

heat pump); **ERM10-3** (Potassium formate-water cascade air cooling dehumidifier); **ERM11-1** (Solar collector).

4. Results and discussions

The baseline energy consumption and bills were calculated in IES VE building simulation software using Nottingham weather values for 2020 and compared with on-site measurement results, as listed in Table 6. The discrepancies between simulation and on-site measurement results were calculated by the ratio of their energy differences and the on-site measurement results, as shown in Eq. (17).

$$Energyperformancediscrepancy = \frac{Simulationresults - measurementresults}{Measurementresults} \tag{17}$$

In general, the final energy consumption had a discrepancy of −0.5%, with simulated results slightly lower than the on-site measurements. From the perspective of different energy sources, the simulated natural gas consumption and bills yield a −1.7% discrepancy compared with the measurement results. On the contrary, the simulated electricity consumption and bills had 2.3% and 1.9% discrepancies compared with the measurement results. As concluded in Ref. [44], the estimation of energy simulation with ± 5% uncertainty is usually reasonable. The model results in terms of this uncertainty range rarely affected the energy-saving performance, validating the effectiveness of the baseline model.

4.1. Cost-optimal results neglecting homeowners' motivation

As stated in section 1.2, homeowners' engagement is rarely addressed in pre-retrofit building design, leading to the fact that homeowners may be dissatisfied with the final retrofit choices of the design teams. According to the Energy Performance and Building Directive (EPBD) guidance [103], the cost optimum methodology is proposed and applied in most research to assure the trade-off between associated costs and energy consumption reductions. The optimal retrofit combinations will be those with minimum energy performance requirements with the lowest investment

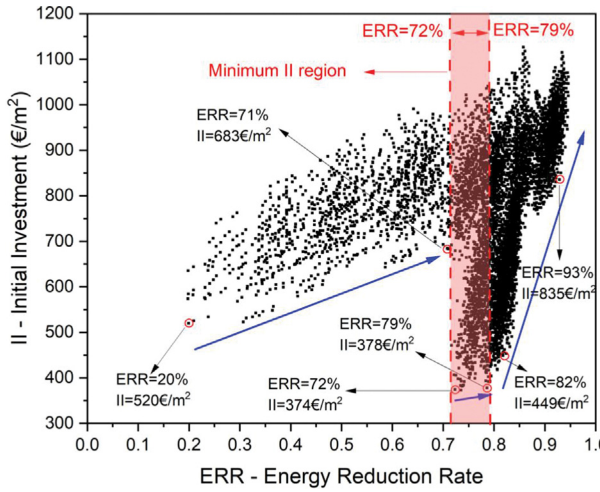

Fig. 4. Initial Investment (II) under full-scale energy reduction rate (ERR).

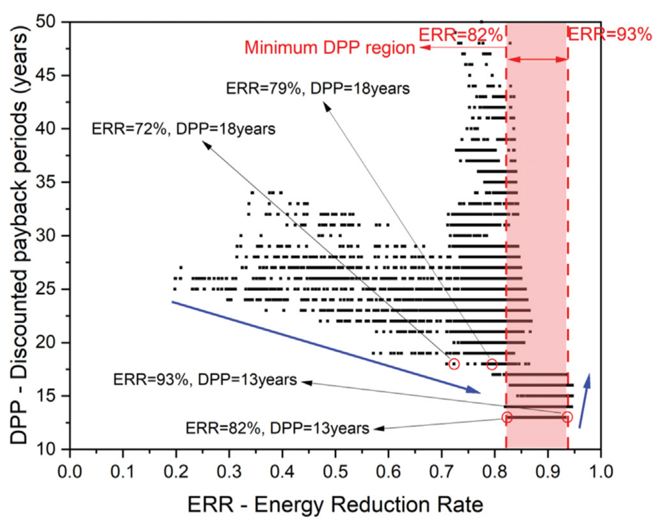

Fig. 5. Discounted payback periods (DPP) under full-scale energy reduction rate (ERR).

cost, which is technologically neutral and does not favour one technological solution over another. In this section, the cost-optimal results of comprehensive retrofit combinations are calculated in Fig. 4 with the minimum II region and Fig. 5 with the minimum DPP region under UK climate conditions. Table E.1 and Table E.2 in Appendix E show the assessment values and cost-optimal combinations.

As shown in the initial investment performance curves, the initial investment has an increasing rate under three stages, which includes 1) a slow increase with the enhancement of ERR without heat pump technologies, and 2) a dramatic drop outside specific ranges of ERR due to the lack of renewable technologies, such as PV panels and solar, with 3) rapid increase due to whole-house insulation and adoption of renewable technologies. Therefore, the cost-optimised II (minimum II region) is derived with 374–378 €/m^2 with energy reduction rates between 72% and 79%, respectively. It is significant to note that the rapid increase of initial investment may cause financial burdens when the energy reduction rates are beyond the cost-optimal level with a 35.1 €/m^2 increase in the initial investment for every 1% ERR increment.

However, the discounted payback periods are relatively high in the minimum II region with 18 years from the perspective of energy-economic purposes. DPP of comprehensive retrofit combinations is illustrated in Fig. 5, with the ERR ranging from 82% to 93% in the minimum DPP region, which results in a minimum DPP of 13 years. However, the initial investment has a surge increment to 449–835 €/m^2. Therefore, it is evident that the mismatch of optimal retrofit combinations occurs between the minimum II and DPP regions.

4.2. Multi-criteria optimisation results and discussion

In section 4.1, the optimisations of different combinations are analysed based on the cost-optimal assessment method. Nonetheless, the multi-objective method should be addressed and specified to provide a more comprehensive perspective by considering the impacts of retrofit motivations on decision-making retrofit measures. This section discusses three homeowners' motivations and priorities for building retrofit to achieve a multi-motivation optimisation process. It is noted that all the combinations and results are demonstrated with DPP lower than 50 years. Thus, the relationships of the priorities of each motivation and maximum MPF in different motivations are illustrated in Figs. 6-8. The results, including specific criteria, optimal combinations and other assessment values, are listed in Appendix F. The optimal technology selections from M1 to M3 are also discussed, as shown in Fig. 9.

Insufficient initial investment (II) is a significant limitation for those who retrofit their own house for self-living. Fig. 6. illustrates the maximum MPF trends with II increase in self-living type (M1), with assessment values and optimal combinations illustrated in Table F.1 and Table F.2 (Appendix F). It is evident that the optimised points of maximum MPF are more concentrated when II is greater than 600 €/m^2 with a maximum MPF of 0.408 and ERR of 93%. However, a high initial investment of 917 €/m^2 is required due to high-performance whole-house insulation materials and PV panels. Considering the limited funding, four criteria for initial investment are classified 1) II < 400€/m^2; 2) 400€/m^2 ≤ II < 500€/m^2; 3) 500€/m^2 ≤ II < 600€/m^2;4) II > 600€/m^2. It is noticeable that the optimised initial investment increases from 383 €/m^2 to 917 €/m^2, which is selected according to the maximum MPF in each criterion. It is also found that the DPP has a shorter period (from 19 years to 13 years) with the II increment. Meanwhile, there are four fundamental technologies for self-living motivated retrofit in the four criteria, including party wall insulation, ground floor insulation, efficient lighting improvement and solar-assisted heat pump. For II < 400€/m^2, only the three fundamental technologies

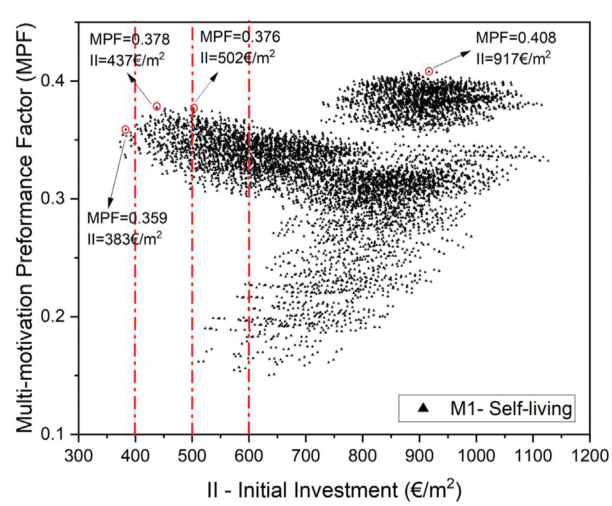

Fig. 6. The relation between II and MPF under M1 type.

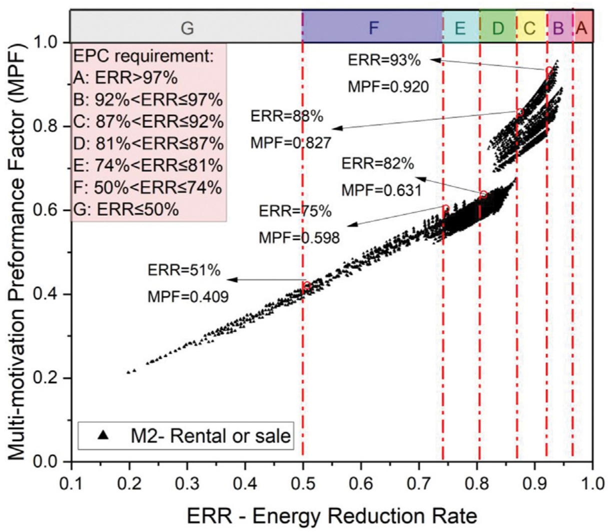

Fig. 7. The relation between the ERR and MPF under M2 type.

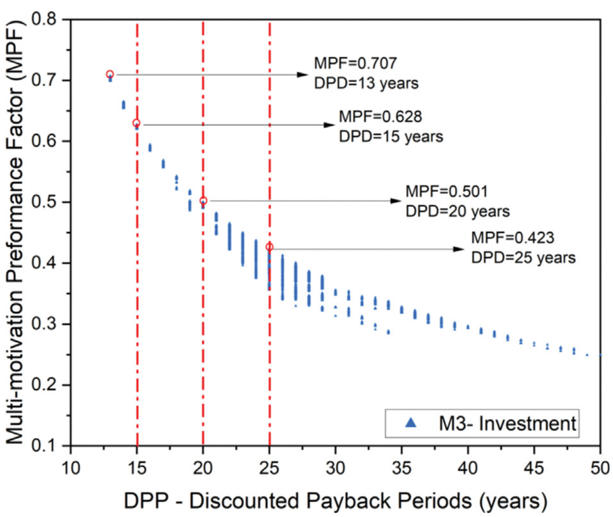

Fig. 8. The relation between DPP and MPF under M3 type.

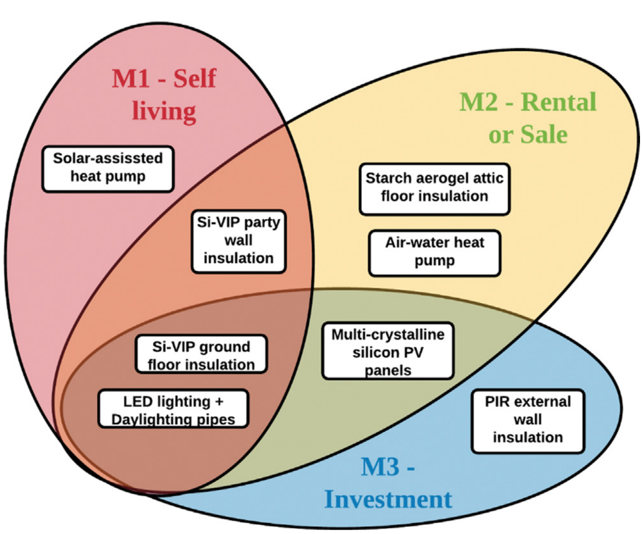

Fig. 9. Optimal technologies from M1 to M3.

are applied; For $400€/m^2 \leq II < 500€/m^2$, external wall insulation is also involved; For $500€/m^2 \leq II < 600€/m^2$, attic floor insulation is applied; For $II > 600€/m^2$, window glazing insulation and PV panels are applied. Airtightness insulation, heat recovery ventilation and solar collector are not suitable for self-living retrofit in the four criteria.

Achievement of the required Energy Performance Certification (EPC) level is essential for homeowners who retrofit to sell or rent. Hence, a minimum ERR for each EPC level is required for retrofit rather than higher ERR and EPC level achievement. According to the EPC calculation method described in section **2.3** and Appendix A, seven EPC levels from A to G has been converted to the indicator of energy reduction rate (ERR) for the reference building in the UK context. The relations between EPC and ERR are listed in Table 7:

Fig. 7. demonstrates the maximum MPF trends with ERR increase in the rental or sale type (M2), with assessment values and optimal combinations illustrated in Table F.1 and Table F.3 (Appendix F). The maximised MPF is selected at the lower bound of ERR ranges to obtain the optimised retrofit combinations in each EPC level. It is found that the maximised MPF increases from 0.409 to 0.920 when EPC is improved from level F to level A, with the ERR rising from 51% to 93%. It is also found that the II is relatively high; however, the DPP is reduced from 24 years to 13 years. There are four fundamental technologies for rental or sale motivated retrofit, including attic floor and ground floor insulation, efficient lighting improvement and PV panels. Specifically, glazing insulation is required to achieve level B, E and F; external wall insulation is required to achieve level B, D and E; party wall insulation is required to achieve level C, D and F; heat recovery ventilation and solar collector are only used in level F. It should be noted that the air–water heat pump is applied when level D and higher EPC is required due to significant energy reduction achievement. Airtightness insulation is unsuitable for rental or sale retrofit in all EPC levels. It is concluded that more insulation measures are applied when the EPC is higher than level C due to deep energy saving requirements or lower than level C as passive insulation retrofit measures could result in a relatively lower energy reduction.

A rapid return on investment with the discounted payback period (DPP) indicator is a significant limitation for those who retrofit for investment. Fig. 8. depicts the maximum MPF trends with DPP increasing in investment type (M3), with assessment values and optimal combinations illustrated in Table F.1 and Table F.4 (Appendix F). It is evident that the optimised points of maximum MPF are more concentrated when DPP is lower than 15 years with a maximum MPF of 0.707, DPP of 13 years, ERR of 61% and II of 870 €/m^2. It is found that the II is reduced from 870 €/m^2 to 392 €/m^2 with DPP increasing from 13 years to 25 years. Moreover, ERR increases from 61% to 93%. Therefore, four criteria are classified, including 1) DPP < 15 years; 2) 15 years ≤ DPP < 20 years; 3) 20 years ≤ DPP < 25 years; 4) DPP ≥ 25 years. There are three fundamental technologies for investment motivated retrofit for the four criteria: external wall insulation, efficient lighting improvement, and PV panels. For DPP < 15 years, no heat pump technology and whole-house insulation are applied, with ERR of 61%. However, the whole-house insulation enhancement measures are adopted in other criteria, with ERR increasing to 84%-93% and II declining to 392 €/m^2 when DPP is 25 years.

The optimal technology selections from M1 to M3 are summarised in Fig. 9 with two necessary technologies of ground floor insulation and efficient lighting improvement, which must be adopted regardless of the motivation preferences. Party wall insulation is the common fundamental technology for both self-living and rental or sale motivated types. Installing PV panels is fundamental for rental, sale, and investment motivations. From the perspective of applying heat pump technologies, solar-assisted and air–water heat pumps are selected by self-living and rental or sale

Table 7
The relations between EPC and ERR for the reference building.

EPC level	G	F	E	D	C	B	A
ERR range	≤ 50%	50%-74%	74%-81%	81%-87%	87%-92%	92%-97%	> 97%

types, respectively, not selected by investment type. The attic floor and external wall insulation are selected by rental or sale and investment types.

4.3. Sensitivity analysis with respect to input data

As shown in Fig. 9, most of the optimal technologies are summarised from the calculation in the perspective of motivation M1 to M3. The baseline energy consumption accuracy could bring uncertainties to the optimal retrofit measures in terms of the energy savings obtained by the model. In order to validate that the optimal retrofit measures selection in each motivation type will not be severely affected by the accuracy of energy savings figures obtained from the building energy simulation model, a sensitivity analysis is performed. The calculated baseline energy consumption input data was adjusted in uniform increments, with 10% (−5% to 5%). 20% (-10% to 10%) and 30% (-15% to 15%), which induces the adjustments of the energy savings in each retrofit combination.

It was observed from the model output that the optimal output selections of retrofit measures in each motivation type remained the same for 10% (−5% to 5%) adjustment of baseline energy consumption input data. With the adjustment of 20% (-10% to 10%), it is found that the vacuum glazing window insulation has also been adopted in self-living-oriented type (M1); Moreover, the gypsum airtightness insulation has been selected for rental or sale-oriented type (M2). In addition, for a 30% baseline energy consumption increment, the Si-VIP party wall insulation technology has been replaced by the PIR external wall insulation in common fundamental technologies of M1 and M2 types based on the optimal technologies with 20% adjustment of baseline energy. The optimal technologies from M1 to M3 with 20% and 30% of baseline energy consumption as the input data is shown in Fig. 10.

The final energy consumption discrepancy is −0.5%, validated with the on-site measurement results as mentioned before, where the range is within 10% (-5% to 5%) baseline energy consumption increment. It is concluded that the model result in terms of selected measures is robust against the baseline energy consumption input data. Meanwhile, compared with the average energy consumption ranging from 402 kWh/m^2 to 425 kWh/m^2 defined for the reference building with similar age and type, the baseline energy consumption has the discrepancy of −4.1% to 1.4%, locating in 10% baseline energy consumption differences, which indicates the result concerning the optimised retrofit measures by using the method proposed in this paper is not significantly affected by the baseline energy consumption estimation with an uncertainty range of ± 5%.

5. Conclusions

This paper establishes an innovative retrofit Motivation-Objective-Criteria (MOC) approach to support the decision-making process for selecting building retrofit measures, which adapts to different homeowners' retrofit motivations, objectives and criteria. With a clear understanding of purposes for homeowners to take retrofit measures for their properties, three retrofit motivations are proposed: M1-Self-living (homeowners will occupy the post-retrofit houses), M2-Rental or sale (the post-retrofit houses will be used for rental or sale) and M3-Investment (homeowners would like to profit from investment). Five main objectives are considered as the retrofit motivations, including energy consumption reduction (ERR), initial investment (II), discounted payback periods (DPP), bills reduction rate (BRR) and carbon reduction rate (CRR), where the corresponding weights are from W_1 to W_5, respectively. The assessment criteria for the three motivations vary: M1 type focuses on the initial investment limitations; the Energy Performance Certification (EPC) is the prior consideration for the M2 type; M3 type focuses on the discounted payback periods.

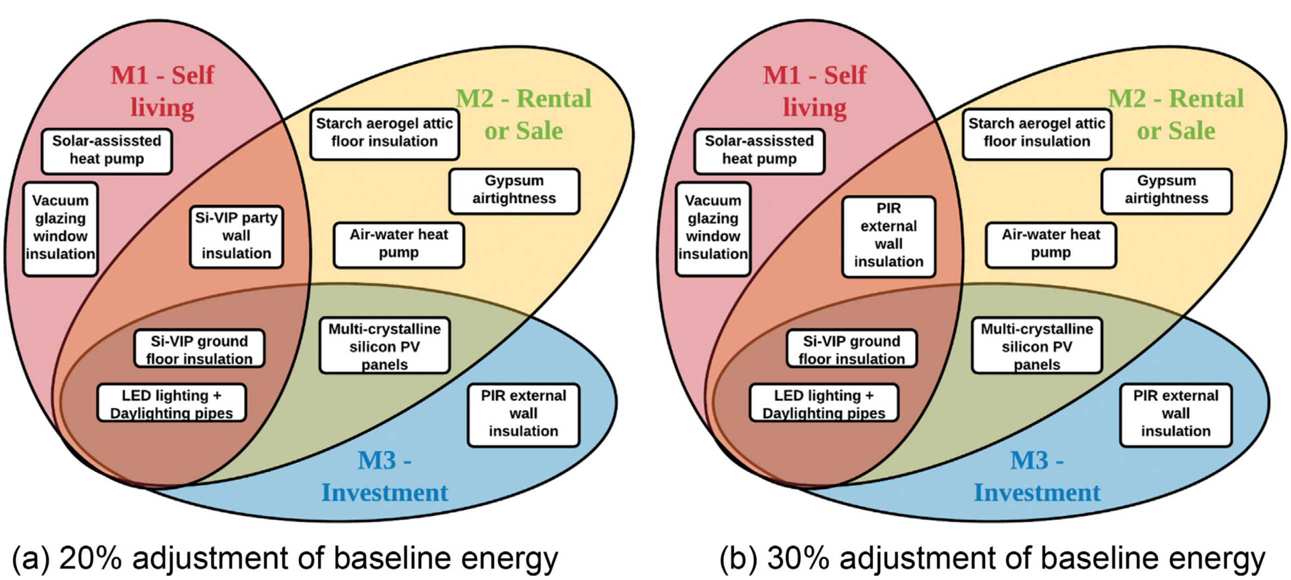

Fig. 10. Optimal technologies from M1 to M3 with 20% and 30% of baseline energy consumption as the input data.

To make the weighting factor more reliable to reflect the homeowners' motivations and perspectives, 42 surveys were collected from the five demo site leaders of the SureFit project as an example with the weighting factors (in the range of 0–1) to understand the occupants' motivations and preferences for the retrofit work.

A semi-detached multi-family house is applied as the reference building to demonstrate the proposed MOC decision-making approach to select comprehensive energy-retrofit combinations with and without the homeowners' engagement. The house was built in the 1960 s with a total floor area of 158 m^2, which has poor insulation and inefficient heating and cooling energy systems. According to the IES VE software simulation, the building baseline has a specific energy consumption of 419 kWh/m^2 in the UK context. By comparing the simulation results with on-site measurements, the final energy consumption has a discrepancy of −0.5%, with simulated results slightly lower than the on-site measurement. As concluded in Ref. [44], the estimation of energy simulation with ± 5% uncertainty is usually reasonable accuracy. The model results in terms of this uncertainty range will rarely affect the energy-saving performance, validating the effectiveness of the baseline model.

Alternative retrofit measures are selected and categorised as passive, active, and renewable. Without homeowners' engagement, cost-optimal retrofit combinations are discussed according to single-objective optimisation in DPP and II with the comprehensive range of energy reduction rates.

According to the cost-optimal results neglecting homeowners' motivation, it is evident that the mismatch of optimal retrofit combinations occurs between the minimum II and DPP regions, with optimal ERR of 72%-79% and 82%-93%, respectively. The optimisation results are compared to the cost-optimal (models without homeowners' engagement) and multi-objective (models with homeowners' engagement). It is concluded that homeowners' retrofit priorities have an apparent influence on the selection of retrofit measures as listed below:

1) Two necessary technologies of ground floor insulation and efficient lighting improvement must be adopted regardless of the motivation preferences;
2) Party wall insulation is the common fundamental technology for both self-living and rental or sale motivated types;
3) PV panels installation is the common fundamental technology for rental or sale and investment motivated types;
4) Solar-assisted heat pumps are suitable for the self-living motivated retrofit type, while the air–water heat pumps are selected for the rental or sale type. Neither are necessary for the investment type;
5) Attic floor and external wall insulation are essential for rental or sale and investment types, respectively.

Meanwhile, compared with the average energy consumption ranging from 402 kWh/m^2 to 425 kWh/m^2 defined for the reference building with similar age and type, the baseline energy consumption has the discrepancy of −4.1% to 1.4%, locating in 10% baseline energy consumption differences, which indicates the result concerning the optimised retrofit measures by using the method proposed in this paper is not significantly affected by the baseline energy consumption estimation with an uncertainty range of ± 5%

Therefore, the proposed inclusive decision-making approach can support the process of selecting building retrofit measures with substantial energy and economic benefits for different retrofit motivations (self-living, rental or sale, and investment), which will facilitate acceleration and success both technically and commercially.

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.

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Appendix A. Supplementary data

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