Coordinated energy-environmental-economic optimisation of building retrofits for optimal energy performance on a macro-scale: A life-cycle cost-based evaluation

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Abstract

Given that energy-efficiency policies focus on meso- or macro-scale interventions, it is imperative to establish a macro-scale evaluation approach for building retrofits to support policymaking in building energy conservation, management and sustainability. This study applies the generic idea of optimising the energy, economic and environmental outputs to propose a facile framework for evaluating the prospects of building retrofits on a macro-scale. Here, an extensive optimisation approach integrating life cycle cost evaluation and an environmental assessment is formulated, involving coordinated on-site survey, modelling and data analytics. The model framework is corroborated by a case study analysis focused on identifying the optimal retrofit solution for low-rise office buildings in Shanghai. Simulation results show that modifications in occupancy regime, improvements in natural ventilation, heating and cooling systems, cool roofs insulation and installation of renewable energy systems (such as geothermal and solar/photovoltaics) are the basic retrofit measures for a macro-scale intervention to attain maximum life-cycle benefits. Individually, an estimated investment cost for each retrofit project varied within RMB 1 − 5 million with a payback period < 13 years, depending on the building characteristics. Overall, an investment estimated investment cost of at RMB 1.7 billion (with a payback period of 6 years) is required to achieve ~ 80% energy reduction with a carbon dioxide savings of ~ 243 Gg-CO_2/yr. In summary, this study provides a guidance framework for stakeholders to evaluate investments on retrofit projects, including existing and prospective ones.

Abbreviations: BEC, Building Energy Consumption; CO_2, Carbon dioxide; EC, Energy Cost; EP, Energy Price; ERF, Energy-efficient Retrofit Framework; EUI, Energy Use Intensity; Gg, Gigagram; GHG, Greenhouse Gas; HSCW, Hot Summer and Cold Winter; HVAC, Heating, Ventilation and Air Conditioning; IC, Initial Investment Cost; IES-VE, Integrated Environmental Solutions Virtual Environment; IRR, Internal Rate of Return; KPIs, Key Performance Indexes; LCA, Life Cycle Assessment; LCC, Life Cycle Cost; LOBs, Low-rise office buildings; NPV, Net Present Values; NO_x, Nitrogen Oxides; PBP, Payback Period; PV, Photovoltaic; RES, Renewable Energy Systems; RMB, Renminbi; SO_2, Sulfur dioxide; TC, Total Cost; UL, Upgrade Level; W/W, Window-wall ratio; 3E, Energy, Environmental and Economic

Keywords: Low-rise; Office buildings; Retrofit measures; Life-cycle cost analysis; Shanghai

1 Introduction

To promote energy conservation, management and sustainability in the built environment, recent technological advancement focus on reducing the energy use intensity (EUI) and carbon emissions of existing buildings [1]. Employing retrofit measures is considered the primary approach to achieving this feat [2]. However, the selection of these measures is challenging given the complexities involved in identifying the optimal combination of retrofit measures [3]. Accordingly, several studies have devised either single- [4] or multi- [5] objective optimisation methods for selecting the best-suited combination of retrofit measures for specific building typologies.

Generally, the multi-objective optimisation approaches (with the integration of more objective functions) are more frequently used as it provides a broader assessment and offers a more realistic retrofit solution [6]. In these approaches, the general idea of optimising the energy, environmental and economic (3E) outputs using principal objective functions are emphasised [2]. Between them, eEconomic outputs are the most pragmatic and the common objective function is minimising the life-cycle costs (LCC), which is more extensive as it integrates various cost indicators, such as initial investment cost (IC), internal rate of return (IRR), lifecycle net present values (NPV) and payback period (PBP) [7]. Concerning energy outputs, the objective function is maximising the building energy performance. Here, the key decision variables are electricity and gas usage, energy conservation, renewable sources adaptability and conservation compatibility [8]. Regarding environmental consideration, minimising carbon dioxide (CO_2) emission is the primary objective function [9]. Nonetheless, emissions of other greenhouse gases (GHG) are considered in some cases. BesidesMoreover, certain studies also present social outputs as an additional optimisation criterion, with the objective function of establishing the best possible trade-off to improve occupant's comfort requirements [10].

Practically, these approaches are mostly tested on a micro-scale level (typical buildings) rather than on a meso- or macro-scale perspective (entire building stocks within a region) [11]. The few studies on a macro-scale perspective lack a multi-objective optimisation approach with more than two objective functions. This is due to the uncertainties and intricacies related to the scope and application of the approaches on a broader scale [12]. For instance, Lotteau *et al.* (2015) revealed that the most established practice for neighbourhood scale evaluation in most reviewed studies is the various adaptation of optimising the environmental objective function [13]. Similarly, Mastrucci *et al.* (2017) indicated that optimising the energy and environmental outputs is the widely applied approach for macro-scale assessments [12]. However, it is recommended to incorporate economic concerns into the energy and environmental outputs to improve comparability and interpretability of policy interventions at this scale, particularly for a long-term basis [14]. Most recently, Rogeau *et al.* (2020) adopted an economic approach to address multi-dimensional multiple-choice knapsack problems in retrofitting building envelopes and heating systems at a community level. Nonetheless, the approach involves a single-objective optimisation aimed at minimizing the economic variables (net present value and total costs of retrofit actions) [15].

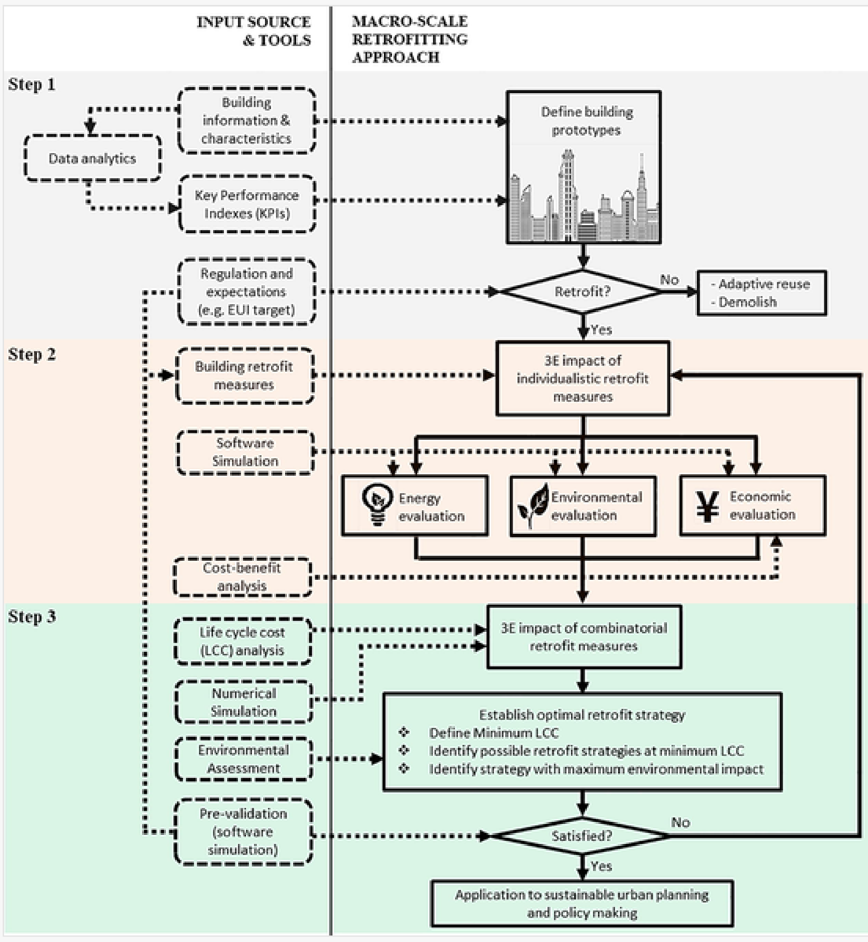
Given that energy efficiency policies focus on meso- or macro-scale strategies, it is meaningful to establish a holistic approach with broader assessment for building energy retrofits on the same scale [14]. Besides, a macro-scale optimisation approach for retrofit strategies provides decisive supporting background for a sustainably conscious society in aspects involving building energy conservation, management and policymaking [16]. In summary, an energy-efficient retrofit framework (ERF) with a thorough 3E evaluation and optimisation approach is required to establish a realistic retrofit solution on a macro-scale. Furthermore, emphasis should be on the economic impact (cost parameters) as a more pragmatic indicator for optimizing life-cycle benefits [17].

Hence, this study presents an ERF with a facile 3E multi-objective optimisation approach at the building level to estimate the effect of micro-scale retrofitting on a macro-scale intervention. The proposed framework involves coordinated approaches formulated to study the operational performance and determine the optimal retrofit solution for existing building stocks, with a focus on the economic evaluation. The economic evaluation is centred on a life-cycle cost (LCC) analysis using data from coordinated approaches involving on-site survey, modelling and data analytics and optimisation. Furthermore, The ERF is corroborated by identifying the optimal retrofit solution for low-rise office buildings (LOBs) in Shanghai as a case study analysis.

2 Framework scope and approach

The development of a macro-scale evaluation approach for building retrofits offers a more realistic insight into the 3E benefits on a broader scale, which is beneficial to sustainable urban planning and policymaking. Here, the formulated framework (Fig. 1) composed of three methodological steps with coordinated methods involving on-site survey, modelling, data analysis and optimisation.

Fig. 1



Proposed macro-scale retrofitting framework based on an LCC analysis.

The first methodological step (Fig. 1) focuses on establishing the prototypical buildings that can represent the entire building stock under investigation before the performance evaluation of the retrofit measures. The method involves the energy performance evaluation of the building components to determine the key performance indexes (KPIs) of the building stocks. Further elaboration on this approach and its different modes of application are reported in the literature [12]. In this study, the archetypes/prototypes approach is employed, which involves the classifications of building stock based on their building characteristics. The archetypes/prototypes are established using top-down macro-economic and statistic tools to analyse the empirical building data obtained from a large-scale on-site survey and surrogate sources. A detailed description of the methods under this step and the prototypes obtained thereafter are presented in the literature [18]. Each prototype represents a group of buildings and can be employed as the foundation for assessing the retrofit measures and to extrapolate the energy performance for the represented buildings.

Following the establishment of the prototypes, a 3E evaluation of the selected retrofit measures is conducted (Step 2)~~,~~ given that the buildings did not meet with the regulated targets and as such, require retrofitting~~for the buildings are not met and building retrofits are required~~. The tested retrofit measures are selected based on the analysis of several regulations (such as the EUI target) and policy priorities (such as improving energy efficiency via technologies and occupant behaviours and employing renewable sources to promote energy production) combined with reviews of related studies and reports on a broader set of interventions (i.e. analysing the efficiency of potential retrofit measures).

The specific outputs from step 2 serve as the input analysis (sensitivity analysis) required for step 3 – impact evaluation of the combinatorial retrofit measures. Here, an LCC-environmental evaluation approach using simplified numerical simulations is employed to identify the optimal retrofit strategy. The~~is~~ optimal strategy should not only be determined by the original capital of the investors but also, to maximise the life-cycle benefits of the retrofits [17]. Simply put, the investors can select the solution with the minimum total/life-cycle cost as the optimal retrofit strategy [10]. On this account, the LCC approach is utilized as it presents the life-cycle benefits of building retrofits. The LCC approach illustrates the compromise between energy-conserving benefits and cost parameters; therefore, offering a makeshift evaluation of energy & economic outcomes [19]. In the LCC approach, a set of optimal combinations of retrofit measures can be defined b~~B~~y ~~defining~~establishing the cost-efficient zone around the minimum LCC value~~, a set of optimal combinations of retrofit measures are obtained~~ [20]. Incorporating an environmental evaluation approach into the LCC method, the ~~several~~defined combinatorial retrofit strategies at minimum LCC are streamlined to a single optimum retrofit solution. It is worth mentioning that life-cycle assessment (LCA) is a more extensive method for appraising environmental concerns; however, assessing the CO_2-savings potential is adopted in this study given that the most often examined environmental concern in buildings is CO_2 emission [21]. Overall, the outcomes from this study are to:

1. Evaluate building retrofits on a macro-scale intervention using the effect of micro-scale retrofitting.
2. Identify the life-cycle benefits of possible combinatorial retrofit strategies at optimum economic impact (= at minimum LCC).
3. Establish the optimal combinatorial retrofit strategy.

3 Methods

The methods adopted in this study are described according to the three phases explained in the above-mentioned framework (Fig. 1). The first phase develops the archetypical/prototypical buildings (Step 1), which serve as case study buildings for assessing the impacts of the individual retrofit measures (Step 2). Lastly, the individualistic impact study is employed as a sensitivity analysis in evaluating the impacts of the combinatorial retrofit strategy on a long-term basis (Step 3). The optimum retrofit solution is defined using a life-cycle cost analysis by the combinatorial strategy with maximum 3E benefits.

3.1 Prototyping buildings

The detailed method for developing the building archetypes/prototypes is presented in the literature [18]. In summary, this method consists of three steps:

Step 1: Data analysis and classification of surveyed existing building blocks using well-defined performance indexes.

Step 2: Energy simulation using empirical building statistics and on-site measured data of necessary simulation parameters.

Step 3: Definition of building KPIs (such as building height, construction year and window-wall (W/W) ratio) to determine the prototypical buildings. Here, correlation and cluster analyses are employed.

3.2 Impact study of the individual retrofit measures

Concerning the individual performance assessment, a set of retrofit measures suitable for the specific building typology is identified before being assessed via simulation.

3.2.1 Identification of the specific retrofit measures

The general roadmap for the sustainable development of buildings involves a decrease in the energy demand [22], followed by an increase in the supply via the deployment of renewable energy systems (RES) — owing to its potential concerning space and energy savings [23]. Therefore, the identified retrofit measures should integrate technologies with energy-reducing and energy-producing capacities [24]. The technologies should be based on the directives from the building standards for the representative city, alongside appropriate literature [25]. Furthermore, adopting a questionnaire/survey method can substantiate the results of the identified retrofit measures.

3.2.2 Impact evaluation via simulation

To evaluate the individualistic 3E implications of each specific retrofit measures (sensitivity analysis), an appropriate energy simulation software was used to model the identified retrofit measures on each archetypical building. The simulation method is described in the literature [18]. Owing to the ease of accessibility, the consumption of electricity, CO_2 emission and cost parameters (including retrofit investment costs and payback period) are the selected decision variables for the 3E evaluation.

3.3 Impact study of the possible combinatorial retrofit strategies

Given the number of identified retrofit measures (N), there will be 2^N possible combinations of the retrofit measures for each building. A simulation of this scale is computationally expensive. Hence, a numerical simulation method (but simplified to reduce computational complexities) using the pre-simulated 3E impacts of the individual retrofit measures is suggested [20].

3.3.1 Energy evaluation

Using the simulated energy impact for each retrofit measure, the annual building energy consumption, BEC (E_T) for each combinatorial retrofit strategy can be calculated as [20]:

$$E_T = \left[\left(\prod_{j=1}^{N}(1 - IR_j)\right) \times TEC\right] - IR_{RES} \tag{1}$$

where j is the number of retrofit measures, IR_j is the impact of the retrofit measure on the energy consumption, IR_{RES} is the energy generated by the RES and TEC is the total energy consumption without implementing any retrofit activity.

3.3.2 Economic evaluation

The total life cycle cost (LCC) of the building was formulated and used as an objective function to evaluate the economic implication of the retrofit measures. Given that operating and maintenance costs reduce with time after retrofitting, a simplified LCC is calculated by [20]:

$$LCC = IC + NPV\,(EC) \tag{2}$$

where IC is the investment cost of the retrofit strategy (includes material, equipment and labour costs). $NPV(EC)$ is the net present value of the BEC cost over the building service life (N) and is calculated as:

$$NPV_i = \sum_{t=1}^{N}\frac{EC_t}{(1+i)^t} \tag{3}$$

where i is the interest or discount rate and EC_t is the annual energy consumption cost in the year t.

Assuming that the BEC is constant each year, EC_t can be calculated as:

$$EC_t = EC \times (1+k)^t \tag{4}$$

where EC is the initial annual energy consumption cost and k is the annual rate of increase in energy price per year.

For simplification, it was assumed that $i = k$ for each year. Hence, NPV_i is:

$$NPV_i = \sum_{t=1}^{N}\frac{EC \times (1+k)^t}{(1+i)^t}$$

$$= \sum_{t=1}^{N} EC$$

$$= EC \times N \tag{5}$$

Accordingly, the total LCC is computed by substituting Equation (5) into Equation 2:

$$LCC = IC + (EC \times N) \tag{6}$$

A fundamental assumption underlying this approach is that an increased initial cost can significantly reduce future energy costs (EC) after retrofitting [8].

3.3.3 Environmental evaluation

The considered environmental indicator is the amount of GHG saved while adopting the possible combinations of retrofit strategies. For simplicity, the saved total equivalent CO_2 (CO_2 saved) was used as the environmental indicator. This indicator was calculated using the equation:

$$CO_2saved = \sum_{j=1}^{n}\sum_{i=1}^{m}\alpha_i(\epsilon_0 - \epsilon_i)_j \quad (7)$$

where i is the specific GHG emission (e.g. CO_2, nitrogen oxides (NO_x), sulfur dioxide (SO_2) etc.), j is the specific retrofit activity, m is the number of GHG considered, n is the number of retrofit activity in the retrofit strategy, ϵ_0 is the amount of ith GHG emitted originally (without any retrofit), ϵ_i the amount of ith GHG emitted after retrofitting with jth retrofit activity, and α is the conversion factor for computing the equivalent CO_2 of ith GHG, in terms of global warming impact (=1, 0.0025 and 0.005 for CO_2, NO_x and SO_2, respectively).

4 Case study analysis

In this section, a case study of a specific building typology in a selected city is presented to highlight the potential of the proposed framework.

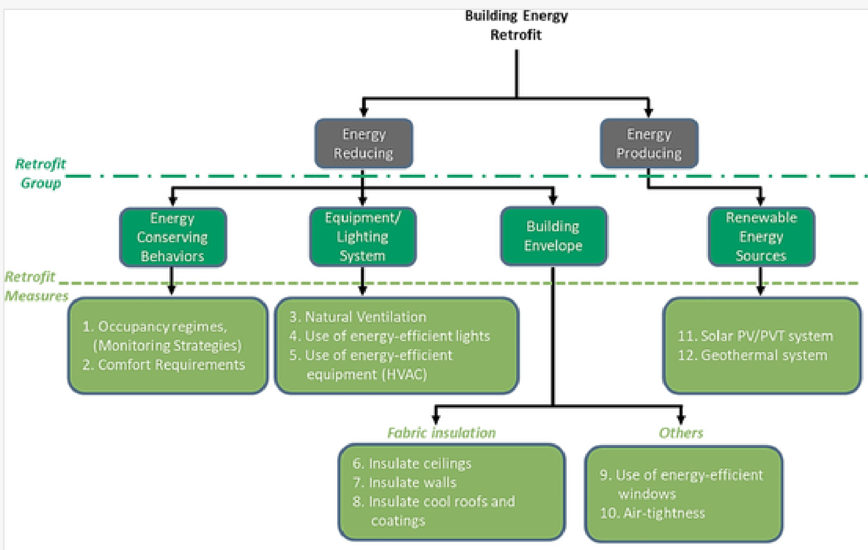
4.1 Selected city - Shanghai

The selected city is Shanghai, the most populous and industrial city in the hot summer and cold winter (HSCW) climate zone in China [18]. This city comprises of a large proportion of highly dense low-rise office buildings (LOBs) that are not usually considered in research studies. Moreover, the expanding urban development of Shanghai demands the retrofitting of these LOBs, which account for about 50% of the commercial building block [26]. Most importantly, this building typology is required to attain the set EUI target under China's regulation. In this regulation, commercial buildings should achieve the recommended annual EUI target (70 kWh/m^2) or at least, achieve the required target (85 kWh/m^2). Therefore, the development of a macro-scale analysis approach that reconciles energy, environmental and economic factors of retrofit measures for LOBs is essential.

4.2 Retrofit measures in Shanghai

The selected retrofit measures are based on prescriptive measures from Chinese commercial building standards for representative cities. Source documents are from the Ministry of Housing and Urban-Rural Development [27] and Chartered Institution of Building Services Engineers [28], alongside relevant literature [29,30]. Fig. 2 presents the twelve selected retrofit measures and their design specifications [31,32]. The selected measures are categorized into three main groups: demand-side, supply-side and energy-conserving (also known as a human factor). Kindly refer to the literature [29] for a detailed description of the classification groups.

Fig. 2



Retrofit Measures	Design Specifications
None	Original model based on 1980 or 2005 building codes [31]
1	Change occupancy period from 8 am – 6 pm to 9 am - 5 pm [28]
2	Reduce human comfort temperature requirement range by 1 °C [28] and adequate monitoring [32]
3	Reduce ventilation rate to 8 l/s/person [28]
4	Increase lighting efficiency to 9 W/m^2 [27]
5	Improve energy efficiency: 3.0 kW cooling seasonal EER, 3.5 kW cooling nominal EER, 5.2 chiller COP, and 0.9 kW heating SCoP [27]
6	Enhance insulation: 20 mm XPS [33]
7	Enhance insulation: 160 mm XPS [33]
8	Enhance insulation: 150 mm XPS [33]
9	Replace windows with triple-glazed (6low-E+12air+6+12air+6low-E) windows [33]
10	Change air-tightness infiltration to Na = 0.6 ach [28]
11	Install a PV system. Capacity: 8.3 kWh/m^2 [19]
12	Install a geothermal heat pump. Capacity: 50% of building energy demand [19]

Summary of the selected potential retrofit measures and their design specifications [19,27,28,31–33].

4.3 Results

The representative prototypes established from analysing the data ~~analysis~~ of existing LOBs are described in the literature [18]. The prototypes (Table 1) are ~~established~~ determined using statistical analysis of building architectural data collected from an on-site survey. The survey was conducted over 136 LOBs from Minhang district in Shanghai (with a total of 1121 LOBs). A brief description of the prototypical LOBs is as follows:

C1W2F5: Built before 2005 (C1) with 5 floors and W/W ratio = 0.2 – 0.4 (W2);

C2W1F3: Built between 2006 and 2015 (C2) with 3 floors and W/W ratio < 0.2 (W1);

C2W3F4: Built between 2006 and 2015 (C2) with 4 floors and W/W ratio > 0.4 (W3);

C2W3F6: Built between 2006 and 2015 (C2) with 6 floors and W/W ratio > 0.4 (W3).

Table 1

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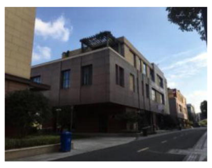
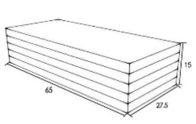
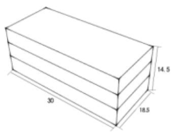
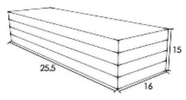
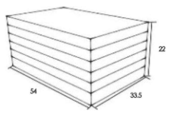
Description of prototypical LOBs in Shanghai [18].

Building characteristics	**LOBs models**			
	C1W2F5	**C2W1F3**	**C2W3F4**	**C2W3F6**
Representative buildings				
Representing share of building stocks	11.03%	22.79%	52.21%	5.15%
Construction year	2004	2014	2013	2013
No. of floors	5	3	4	6
Floor area (m^2)	1788	555	408	1809
L/W ratio	2.33	1.62	1.11	1.61
Length (m)	65 (55–75)	30 (22–38)	25.5 (21–30)	54 (45–63)
Height (m)	15	14.5	15	22
Window/wall ratio	0.25	0.13	0.46	0.44
Sketch Model				
Structure type	Brick/frame	Concrete	Concrete	Concrete
Heat and cold source type	Dispersion	Dispersion	Dispersion	Dispersion
Annual energy consumption (MWh/year)	1181.6	164.0	201.6	1266.8
EUI (kWh/m^2)	132.20	98.50	123.53	116.71

For further details of the C1W2F5, C2W1F3, C2W3F4 and C2W3F6 prototypes, kindly refer to the literature [18]. Using these prototypes, the 3E impacts of retrofit measures are evaluated. About the economic evaluation, the electricity price is averaged at 870 RMB/MWh for commercial buildings in Shanghai as of Nov 2019 [34].

4.3.1 Impacts of the individual retrofit measures

To assess the impact of each specific retrofit measures, the Integrated Environmental Solutions Virtual Environment (IES-VE) software is employed. The suitability of this software is discussed in the literature [18]. The weather data (temperature and relative humidity) used for the simulation were obtained using measuring devices installed within and outside the buildings (Fig. 3). Given that this study involves buildings within two construction periods, the actual daily internal and external weather data for two representative buildings within these construction periods (C1W2F5 and C2W1F3) were measured for one year.

Fig. 3

Position of installed measuring devices in the representative buildings: for C2W1F3 model (a) within, and (b) outside; and for C1W2F5 model (c) within and (d) outside.

Details of the measuring devices and the measured readings are presented in the supporting document (Tables S3 and S4). With these details, each retrofit measure is simulated individually over the different prototypes using design specifications as presented in Fig. 2. Justification for the selection of these retrofit measures and the adjusting parameters is elaborated in the supporting document (Section S1). Sequel to the simulation, the performance results over each prototype is compared with their respective original models to evaluate the corresponding change in energy consumptions, CO_2 emissions and PBP.

Tables 2–5 present the simulation results for each considered retrofit measure on the four representative prototypes. The presented results include the energy (total electricity consumption), economic (IC to implement each retrofit activity, annual electricity cost savings and payback period) and environmental (CO_2 emission) implications after retrofitting with each specific retrofit measure. It is worth mentioning here that these results serve as an input analysis for the subsequent impact evaluation for the combinatorial retrofit measures. As such, a simpler adaptation of the economic implications (as mentioned above) rather than the LCC is employed. Also, the environmental implication (CO_2 emission) of each retrofit measure is proportionate to its energy impact. Lastly, the RES were fixed for all the building models. Hence, their impacts (in percentage) are similar across all the prototypes.

Table 2

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Energy simulation results and cost data for C1W2F5 building model (building area = 8937.5 m^2).

Group	Activity	Initial Investment Cost (RMB)	Total energy consumption (MWh/yr)	Impact on Electricity (% decrease)	Annual Savings (RMB)	Payback Period (year)	CO_2 Emission (kg CO_2)
Original	None	–	1181.6 (EUI = 132.20 kWh/m^2)	–	–	–	613,260
Energy Conserving Behaviors	1. Occupancy regimes	12,691#	1062.7	10.06	103,416	0.1	551,557
	2. Comfort requirements	56,306 #	1126.3	4.68	48,110	0.9	584,550
Equipment/Lighting System	3. Natural ventilation	3,575#	1169.7	1.01	10,383	0.3	607,066
	4. Upgrade lighting	268,125#	946.3	19.91	204,673	1.0	491,160
	5. Upgrade HVAC	1,117,188‡	1022.9	13.43	138,059	6.4	530,899
Building Envelope	6. Insulate ceilings	143,894‡	1027.3	13.06	134,256	0.8	533,168
	7. Insulate walls	427,461‡	1044.3	11.62%	150,292	2.8	523,601
	8. Insulate cool roofs	32,461‡	1030.8	12.76%	131,172	0.2	535,008
	9. Upgrade Windows	190,487‡	1021.5	13.55	139,293	1.1	530,163
	10. Air-tightness	55,500‡	978.6	17.18	176,609	0.2	507,902
Renewable energy	11. Install solar/PV system	94,738‡	–	Provide 8.3 KWh/m^2*	12,908	6.4	574,751
	12. Install geothermal system	2,037,750‡	590.8	50 *	513,996	3.1	306,630

Table 3

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Energy simulation results and cost data for C2W1F3 building model (building area = 1665 m^2).

Group	Activity	Initial Investment Cost (RMB)	Total energy consumption (MWh)	Impact on Electricity (% decrease)	Annual Savings (RMB)	Payback Period (year)	CO_2 Emission (kg CO_2)
Original	None	–	164.0 (EUI = 98.52 kWh/m^2)	–	–	–	91,361
Energy Conserving Behaviors	1. Occupancy regimes	2,364#	143.2	12.73	18,166	0.1	79,734
	2. Comfort requirements	10,490#	149.1	9.11	13,001	0.6	83,041
Equipment/Lighting System	3. Natural ventilation	666#	160.6	2.08	2968	0.2	89,454
	4. Upgrade lighting	49,950#	134.9	17.75	25,330	1.6	68,385
	5. Upgrade HVAC	208,125‡	147.5	10.1	14,413	11.4	82,132
Building Envelope	6. Insulate ceilings	26,807‡	158.6	3.32	4738	4.5	88,325
	7. Insulate walls	237,222‡	151.8	7.47	10,660	17.6	84,537
	8. Insulate cool roofs	10,079‡	151.9	7.37	10,517	0.8	84,623
	9. Upgrade Windows	63,153‡	151.9	7.37	10,517	4.7	84,627
	10. Air-tightness	18,400‡	135.5	17.42	24,859	0.6	75,445
Renewable energy	11. Install solar/PV system	29,415‡	–	Provide 8.3 KWh/m^2*	4008	2.1	83,664
	12. Install geothermal system	379,620‡	82.0	50*	71,353	4.2	45,683

Table 4

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Energy simulation results and cost data for C2W3F4 building model (building area = 1632 m^2).

Group	Activity	Initial Investment Cost (RMB)	Total energy consumption (MWh)	Impact on Electricity (% decrease)	Annual Savings (RMB)	Payback Period (year)	CO_2 Emission (kg CO_2)
Original	None	–	201.6 (EUI = 123.53 kWh/m^2)	–	–	–	104,623
Energy Conserving Behaviors	1. Occupancy regimes	2,317#	175.9	12.73	22,327	0.1	93,973
	2. Comfort requirements	10,282#	184.0	8.71	15,277	0.5	95,478
Equipment/Lighting System	3. Natural ventilation	653#	195.0	3.27	5735	0.1	101,186
	4. Upgrade lighting	48,960#	166.2	17.55	30,781	1.2	85,214
	5. Upgrade HVAC	204,000‡	179.5	10.96	19,223	8.4	93,154
Building Envelope	6. Insulate ceilings	26,275‡	197.2	2.19	3841	5.4	102,327
	7. Insulate walls	164,053‡	190.2	5.65	9910	13.1	98,707
	8. Insulate cool roofs	7,409‡	191.0	5.28	9261	0.6	99,070
	9. Upgrade Windows	134,885‡	185.0	8.26	14,487	7.3	95,956
	10. Air-tightness	39,300‡	188.1	6.7	11,751	2.6	97,617
Renewable energy	11. Install solar/PV system	21,624‡	–	Provide 8.3 KWh/m^2*	2946	1.6	97,593
	12. Install geothermal system	372,096‡	100.8	50*	87,696	3.7	52,312

Table 5

The table layout displayed in this section is not how it will appear in the final version. The representation below is solely purposed for providing corrections to the table. To preview the actual presentation of the table, please view the Proof.

Energy simulation results and cost data for C2W3F6 building model (building area = 10854 m^2).

Group	Activity	Initial Investment Cost (RMB)	Total energy consumption (MWh)	Impact on Electricity (% decrease)	Annual Savings (RMB)	Payback Period (year)	CO_2 Emission (kg CO_2)
Original	None	–	1266.8 (EUI = 116.71 kWh/m^2)	–	–	–	657,523
Energy Conserving Behaviors	1. Occupancy regimes	15,413#	1135.6	10.36	114,179	0.1	589,390
	2. Comfort requirements	68,380#	1168.0	7.8	85,965	0.6	606,206
Equipment/Lighting System	3. Natural ventilation	4,342#	1225.5	3.26	35,929	0.1	636,087
	4. Upgrade lighting	325,620#	1064.6	15.96	175,898	1.2	532,849
	5. Upgrade HVAC	1,356,750‡	1135.6	10.36	114,179	9.4	556,390
Building Envelope	6. Insulate ceilings	174,749‡	1224.7	3.32	36,590	3.8	635,671
	7. Insulate walls	514,879‡	1182.3	6.67	73,511	5.5	550,076
	8. Insulate cool roofs	32,851‡	1180.8	6.79	74,834	0.3	612,885
	9. Upgrade Windows	403,627‡	1142.0	9.85	108,558	2.9	592,712
	10. Air-tightness	117,600‡	1138.1	10.16	111,975	0.8	590,722
Renewable energy	11. Install solar/PV system	95,877‡	–	Provide 8.3 KWh/m^2*	13,063	1.1	610,763
	12. Install geothermal system	2,474,712‡	633.4	50*	551,058	3.9	328,615

Table Footnotes

cost indicators were obtained from [36].

‡ cost indicators were obtained from [33].

* impacts were obtained from [19].

From Table 2–5, it is observed that the type of retrofit measure adopted plays a crucial role in the building energy reduction, CO_2 emission and payback period. The original BEC (and EUI) are 1181.6 MWh (132.20 kWh/m^2), 164.03 MWh (98.52 kWh/m^2), 201.6 MWh (123.53 kWh/m^2) and 1266.8 MWh (116.71 kWh/m^2) for the C1W2F5, C2W1F3, C2W3F4 and C2W3F6 models, respectively. The variation in BEC depends on the building area of the LOBs. A notable distinction is however observed in the building consumption variation of C2W1F3 and C2W3F4 models. The energy consumption of C2W3F4 is seen to be larger than that of C2W1F3 despite the larger building area of C2W1F3. The possible reason for this distinction is related to the large W/W ratio of C2W3F4, which has the potential of contributing to the large BEC depending on the building geometry and climate condition [35].

Also, it is observed from the simulation results that the most impactful retrofit measures are upgrades in lighting efficiency and air-tightness, owing to their high potential for energy reduction and reasonable annual energy savings. For example, the upgrade in the lighting and air-tightness over the C1W2F5 model showed ~ 20% and ~ 17% reduction in energy consumption with an estimated annual energy savings of RMB 204,673 and RMB 176,609, respectively. Moreover, the IC for these retrofit strategies are estimated at RMB 268,125 and RMB 55,500 with a payback period of 1 year and 0.2 years, respectively. The trend is also observed for the C2W1F3 model. Unlike the above models, the C2W3F4 and C2W3F6 models displayed a lower impact upon improvement of the building air-tightness. The lower impact in these models can be attributed to the effect of the large W/W ratio to BEC [37]. Other highly impactful retrofit measures are changes in occupancy regime and upgrade of heating, ventilation and air-conditioning (HVAC) system.

Besides, all other measures displayed a significant reduction in BEC, except for natural ventilation with an estimated 1–3% reduction per building. Specifically, building models built between 2006 and 2015 (C2W1F3, C2W3F4 and C2W3F6) displayed a reduction in energy consumption > 2%. In comparison to the approximate 1% reduction for the C1W2F5 model (built before 2005), it is evident that the improved features of recent buildings, particularly the building envelope, enable significant energy reduction when passive retrofit strategies are incorporated in the building design. Other retrofit strategies with significant energy reduction impact in C2 models than in C1 models include modifications in occupancy regimes and comfort requirements (energy-conserving behaviours).

Regarding other energy-reducing measures, a greater reduction in BEC was witnessed over the C1W2F5 than on the C2W1F3, C2W3F4 and C2W3F6 models. This trend is expected as an upgrade in the building facilities and equipment, relative to their previous status, is more substantial in older buildings than in recent buildings. Consequently, the magnitude of energy reduction should be more significant in C1W2F5 model than in the C2 models. For example, considering the building envelop measures (upgrade in ceilings, walls, cooling roofs and windows), an average reduction in BEC of approximately 13.63% was witnessed in the C1W2F5 prototype; but an average reduction of approximately 8.59%, 5.62% and 7.36% is witnessed over the C2W1F3, C2W3F4 and C2W3F6 prototypes, respectively.

From an economic perspective, the most effective energy-reducing measures with the longest PBP include the upgrade in the HVAC system and wall insulation. The long PBP is attributed to the high initial investment relative to the energy reduction impact. For example, these retrofit measures exhibited a PBP of 6.4 years and 2.8 years with an IC of RMB 1,117,188 and RMB 427,461 and a significant reduction in BEC by approximately 13% and 12%, respectively over the C1W2F5 model. For C2W1F3, upgrade of HVAC and wall insulation attained a PBP of 11.4 years and 17.6 years with an investment cost of RMB 208,125 and RMB 237,222, and energy reduction impact of 10% and 7%, respectively. Similarly, these measures presented a PBP of 8.4 years and 13.1 years with an investment cost of RMB 204,000 and 164,053, and an energy reduction impact of 11% and 7%, respectively for the C2W3F4 building model. Lastly, a PBP of 9.4 years and 5.5 years was obtained upon upgrade of HVAC and wall insulation with an investment cost of RMB 1,356,750 and RMB 514,879, and energy reduction impact of 10% and 7%, respectively. In overview, it is observed that an upgrade in HVAC showed the longest PBP for buildings with large building areas, while the upgrade in wall insulation displayed the longest PBP for buildings with small building areas.

On the other hand, observing changes in the occupancy regimes demonstrated to be the most effective energy-reducing measure with the shortest payback period. This measure resulted in approximately 10%, 13%, 10% and 13% reduction in the BEC for C1W2F5, C2W1F3, C2W3F4 and C2W3F6, respectively with an estimated payback period of 0.1 years. This finding demonstrates the importance of passive measures such as occupant's behaviour in developing a cost-effective retrofit strategy for buildings. Furthermore, the stipulated energy-producing measures (solar/photovoltaics (PV) and geothermal systems) displayed a reasonable PBP below 7 years despite the high initial investment cost. In total, these measures account for more than 38% of the total initial investment cost.

In summary, the optimal retrofit strategy should involve a combination of these individual measures to maximize the energy-saving potential of the building at a minimal economic implication. However, given that each specific measure displays varying 3E effects, a trade-off between these 3E factors is necessary to establish the optimal strategy. In this regard, an LCC evaluation approach is used to assess how the impact of each possible combination of retrofit solution based on an optimised objective function.

4.3.2 Impacts of the combined retrofit strategies

Given the number of individual retrofit measures, a total of 2^{12} or 4096 possible combinations measures are generated for each building model. For simplicity purpose, the solar/PV system was included in all possible combinations owing to its relevance as a relatively inexpensive RES to substantially reduce the building environmental impact. This is based on the theory that effective implementation of RES while reducing the consumption of carbon-based fuels is an inevitable means to a futuristic clean and sustainable energy system [38]. Hence, it is logical to incorporate a cheap RES into the retrofit strategy. Subsequently, 2^{11} (2,048) possible combinations are considered in this study (Table S5 of supporting document). The IC for implementing each combination of retrofit measures vary from zero (indicating the building model without any retrofit) to the maximum cost (when all retrofit measures are applied).

Using the simplified LCC computation, as discussed in section 3.3.2, the minimum LCC (depicting the optimal retrofit solution) is determined via seven steps [20]:

- ***Step 1:*** To compute the investment costs (IC) of each combinatorial retrofit strategy (=sum of the individual IC of all measures involved in the combination).
- ***Step 2:*** Using results from the IES-VE simulation of each significant retrofit activity on the building models, the annual energy consumption costs (EC) for each combinatorial retrofit strategy were then calculated using:

$$EC = E_T \times EP \qquad (8)$$

where E_T is the annual BEC (as explained in section 3.3.1 and EP is the electricity price (=*av.* 0.87 RMB/kWh for commercial buildings in Shanghai).

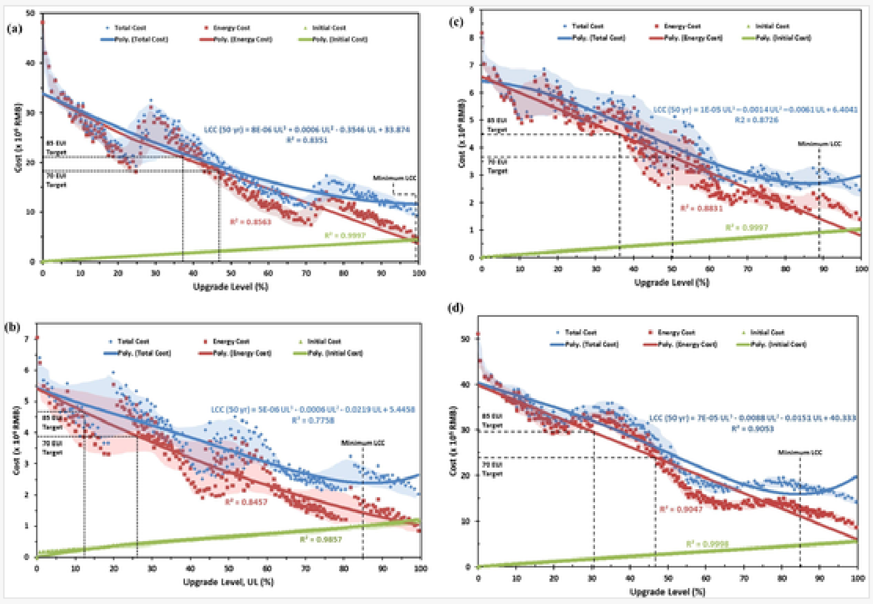
- ***Step 3:*** To compute the LCC or total cost for the combinatorial retrofit strategies (Equation 6).
- ***Step 4*** : IC is used as the criterion to classify the upgrade level (UL) of the building model. Here, the UL values are varied from 0 to 100% using matching IC values that are sorted in ascending order. For instance, a 0% UL value is assigned to the strategy with no incurred IC (i.e. no retrofitting), while a 100% UL value is assigned to the strategy with the highest IC (i.e. when all measures are applied).
- ***Step 5:*** To streamline the number of data points to avoid computational complexities. Here, a set of new data points for LCC evaluation is generated by computing the average of an 8-point bin (for each profile data).
- ***Step 6:*** Finally, the IC, EC and LCC against the UL profiles are represented by a third-order polynomial trendline to show the trend for the different cost parameters.
- ***Step 7:*** Using the polynomial trendline equation, the minimum LCC over a 50-years service life is determined using the differential method shown below:

$$\frac{\partial LCC\,(50)}{\partial UL} = 0 \qquad (9)$$

Here, a 50 years service life is applied based on Chinese regulations and standards for commercial buildings.

Following the 7 steps discussed above, Fig. 4 (a − d) shows the LCC evaluation plot (indicated as total cost, TC) for the C1W2F5, C2W1F3, C2W3F4 and C2W3F6 building models, respectively. The computed 2048 data points for the LCC, EC, and IC against UL plots for each prototype are presented in the supporting document (Table S6). The generated LCC trendline corresponds with the computed profile with an R^2 value of 0.8351 (Fig. 4a), 0.7758 (Fig. 4b), 0.8726 (Fig. 4c) and 0.9053 (Fig. 4d) for the C1W2F5, C2W1F3, C2W3F4 and C2W3F6 models, respectively. As observed in Fig. 4, the energy (denoted by EC profile) and economic (denoted by the TC profile) implications at minimum LCC are less than that required for the recommended (70 kWh/m^2) and required (85 kWh/m^2) EUI targets. This indicates that the optimal retrofit strategy (at minimum LCC) is adequate for achieving the EUI targets for all prototypical buildings.

Fig. 4



Optimal retrofit strategy (upgrade level) in terms of the minimum LCC (TC) evaluation for (a) C1W2F5, (b) C2W1F3, (c) C2W3F4, and (d) C2W3F6 building models [17].

Using the differential equation (Equation 9) and the trendline equation for the LCC profile for 50 years, the UL value for the minimum LCC is at about 99.10%, 84.92%, 88.72% and 84.65% for the C1W2F5, C2W1F3, C2W3F4 and C2W3F6 models, respectively. The minimum LCC (in million RMB) corresponding to these values are estimated at approximately 12.4, 2.4, 2.7 and 16.4 for C1W2F5, C2W1F3, C2W3F4 and C2W3F6, respectively, with an IC value (in million RMB) estimated at 4.2, 1.0, 0.9 and 4.5, respectively. These results confirm that a greater retrofitting intervention (defined by the UL value at minimum LCC) is required for the optimum energy performance of buildings before 2005 (C1W2F5) than after 2005 (C2W1F3, C2W3F4 and C2W3F6). In general, buildings with large building areas (C1W2F5 and C2W3F6) require a higher investment cost to achieve optimum performance. This is attributed to the high retrofitting cost associated with the large area and geometrical parameters (such as the W/W ratio). The results reiterate the effects of the building characteristics on retrofit design and the related investment cost [39,40].

Also, at the minimum LCC, an estimated 89%, 74%, 78% and 71% reduction in EC was witnessed over the C1W2F5, C2W1F3, C2W3F4 and C2W3F6 models, respectively from an initial EC of RMB 33.8 million, RMB 5.4 Million, RMB 6.5 million and RMB 40.3 million (deduced from the EC profile from Fig. 4). The estimated reductions in building energy cost also indicate an improvement in energy user intensity (EUI). For C1W2F5, the EUI is estimated to reduce from 132.20 kWh/m^2 to 13.69 kWh/m^2 at minimum LCC. Concerning the C2W1F3 model at minimum LCC, the EUI witnessed a reduction from 98.52 kWh/m^2 to 25.54 kWh/m^2. Similarly, a reduction in EUI value from 116.71 kWh/m^2 to 25.14 kWh/m^2 is observed for the C2W3F4 model at minimum LCC. Lastly, the C2W3F6 model displayed a corresponding reduction in EUI from 123.53 kWh/m^2 to 35.25 kWh/m^2 at minimum LCC. Overall, the EUI at minimum LCC is less than the regulated standard for commercial buildings in China (70–85 kWh/m^2, as depicted for each building model in Fig. 4).

At the stipulated minimum LCC value, the number of combinatorial retrofit strategies was identified for each studied LOBs. For the C1W2F5, C2W1F3, C2W3F4 and C2W3F6 building models, the minimum LCC occurs at UL ≈ 99%, 85%, 89% and 85%, respectively. At these exact UL values, a total number of 8, 12, 5 and 23 combinatorial retrofit strategies were recognized to realize the minimum LCC for the C1W2F5, C2W1F3, C2W3F4 and C2W3F6 models, respectively. These proposed strategies are presented in Tables 6–9.

Table 6

The table layout displayed in this section is not how it will appear in the final version. The representation below is solely purposed for providing corrections to the table. To preview the actual presentation of the table, please view the Proof.

Optimum retrofit strategies defined under the minimum LCC for the C1W2F5 building model.

Strat. #	Retrofit measures										
	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Measure 6	Measure 7	Measure 8	Measure 9	Measure 10	Measure 11
1	Occupant	Lighting	HVAC	Ceilings	Walls	Roofs	Windows	Air-tightness	Geothermal	PV	–
2	Occupant	Comfort	Lighting	HVAC	Ceilings	Walls	Roofs	Windows	Geothermal	PV	–
3	Occupant	Ventilation	Lighting	HVAC	Ceilings	Walls	Roofs	Windows	Air-tightness	Geothermal	PV
4	Occupant	Comfort	Ventilation	Lighting	HVAC	Ceilings	Walls	Roofs	Windows	Geothermal	PV
5	Comfort	Lighting	HVAC	Ceilings	Walls	Windows	Air-tightness	Geothermal	PV	–	–
6	Comfort	Ventilation	Lighting	HVAC	Ceilings	Walls	Windows	Air-tightness	Geothermal	PV	–
7	Occupant	Comfort	Lighting	HVAC	Ceilings	Walls	Windows	Air-tightness	Geothermal	PV	–
8	Occupant	Comfort	Ventilation	Lighting	HVAC	Ceilings	Walls	Windows	Air-tightness	Geothermal	PV

Table 7

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Optimum retrofit strategies defined under the minimum LCC for the C2W1F3 building model.

Strat. #	Retrofit measures										
	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Measure 6	Measure 7	Measure 8	Measure 9	Measure 10	Measure 11
1	HVAC	Ceilings	Walls	Roofs	Geothermal	PV	–	–	–	–	–
2	Comfort	HVAC	Ceilings	Walls	Geothermal	PV	–	–	–	–	–
3	Ventilation	HVAC	Ceilings	Walls	Roofs	Geothermal	PV	–	–	–	–
4	Comfort	Ventilation	HVAC	Ceilings	Walls	Geothermal	PV	–	–	–	–
5	Comfort	HVAC	Walls	Roofs	Air-tightness	Geothermal	PV	–	–	–	–
6	Occupant	HVAC	Ceilings	Walls	Roofs	Geothermal	PV	–	–	–	–
7	Comfort	Ventilation	HVAC	Walls	Roofs	Air-tightness	Geothermal	PV	–	–	–

8	Occupant	Comfort	HVAC	Ceilings	Walls	Geothermal	PV	–	–	–	–
9	Occupant	Ventilation	HVAC	Ceilings	Walls	Roofs	Geothermal	PV	–	–	–
10	Occupant	Comfort	Ventilation	HVAC	Ceilings	Walls	Geothermal	PV	–	–	–
11	Occupant	Comfort	HVAC	Walls	Roofs	Air-tightness	Geothermal	PV	–	–	–
12	Occupant	Comfort	Ventilation	HVAC	Walls	Roofs	Air-tightness	Geothermal	PV	–	–

Table 8

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Optimum retrofit strategies defined under the minimum LCC for the C2W3F4 building model.

Strat. #	Retrofit measures										
	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Measure 6	Measure 7	Measure 8	Measure 9	Measure 10	Measure 11
1	Occupant	Comfort	HVAC	Walls	Roofs	Windows	Geothermal	PV	–	–	–
2	Occupant	Comfort	Ventilation	HVAC	Walls	Roofs	Windows	Geothermal	PV	–	–
3	HVAC	Ceilings	Walls	Windows	Geothermal	PV	–	–	–	–	–
4	Ventilation	HVAC	Ceilings	Walls	Windows	Geothermal	PV	–	–	–	–
5	Occupant	HVAC	Ceilings	Walls	Windows	Geothermal	PV	–	–	–	–

Table 9

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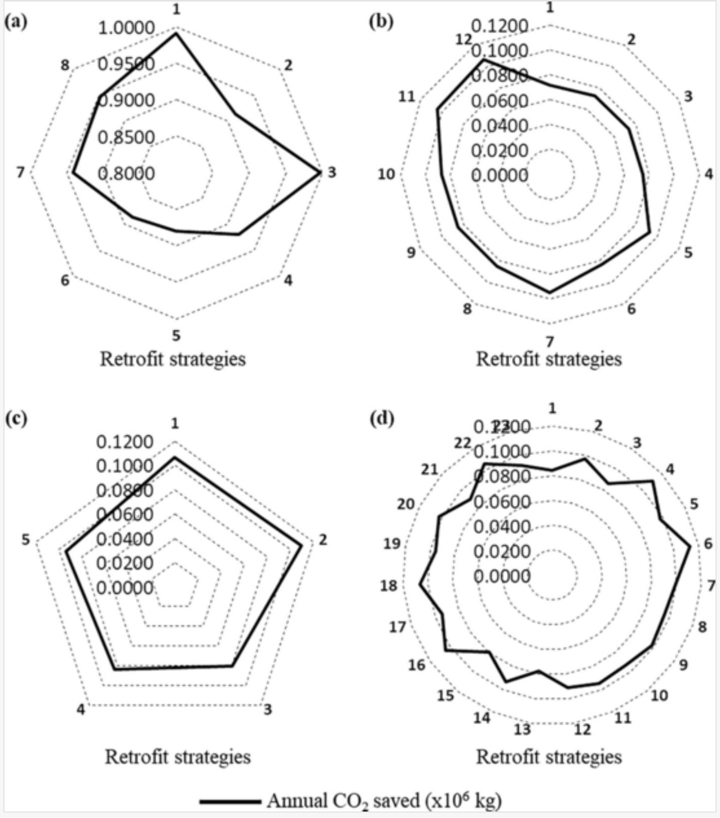
Optimum retrofit strategies defined under the minimum LCC for the C2W3F6 building model.

Strat. #	Retrofit measures										
	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Measure 6	Measure 7	Measure 8	Measure 9	Measure 10	Measure 11
1	HVAC	Ceilings	Walls	Air-tightness	Geothermal	PV	–	–	–	–	–
2	Occupant	Comfort	Ventilation	HVAC	Ceilings	Walls	Roofs	Geothermal	PV	–	–
3	Ventilation	HVAC	Ceilings	Walls	Air-tightness	Geothermal	PV	–	–	–	–
4	Occupant	Comfort	HVAC	Ceilings	Roofs	Windows	Air-tightness	Geothermal	PV	–	–
5	Occupant	Comfort	Lighting	HVAC	Windows	Geothermal	PV	–	–	–	–
6	Occupant	Comfort	Ventilation	HVAC	Ceilings	Roofs	Windows	Air-tightness	Geothermal	PV	–
7	Occupant	Comfort	Ventilation	Lighting	HVAC	Windows	Geothermal	PV	–	–	–
8	Occupant	HVAC	Ceilings	Walls	Air-tightness	Geothermal	PV	–	–	–	–
9	Occupant	Ventilation	HVAC	Ceilings	Walls	Air-tightness	Geothermal	PV	–	–	–
10	Comfort	Lighting	HVAC	Roofs	Windows	Geothermal	PV	–	–	–	–
11	Comfort	Ventilation	Lighting	HVAC	Roofs	Windows	Geothermal	PV	–	–	–
12	HVAC	Ceilings	Walls	Roofs	Air-tightness	Geothermal	PV	–	–	–	–
13	Lighting	HVAC	Walls	Geothermal	PV	–	–	–	–	–	–
14	Ventilation	HVAC	Ceilings	Walls	Roofs	Air-tightness	Geothermal	PV	–	–	–
15	Ventilation	Lighting	HVAC	Walls	Geothermal	PV	–	–	–	–	–
16	Occupant	Comfort	Lighting	HVAC	Roofs	Windows	Geothermal	PV	–	–	–
17	Lighting	HVAC	Windows	Air-tightness	Geothermal	PV	–	–	–	–	–
18	Occupant	Comfort	Ventilation	Lighting	HVAC	Roofs	Windows	Geothermal	PV	–	–
19	Ventilation	Lighting	HVAC	Windows	Air-tightness	Geothermal	PV	–	–	–	–
20	Occupant	HVAC	Ceilings	Walls	Roofs	Air-tightness	Geothermal	PV	–	–	–
21	Occupant	Lighting	HVAC	Walls	Geothermal	PV	–	–	–	–	–
22	Occupant	Ventilation	HVAC	Ceilings	Walls	Roofs	Air-tightness	Geothermal	PV	–	–
23	Occupant	Ventilation	Lighting	HVAC	Walls	Geothermal	PV	–	–	–	–
24	HVAC	Ceilings	Walls	Air-tightness	Geothermal	PV	–	–	–	–	–

4.3.3 Establishing the optimal retrofit strategy

To determine the optimal retrofit strategy from the possible combinatorial retrofit strategies at minimum LCC, it is logical to consider the environmental impacts of the identified retrofit combinations. Given that the tradeoff between the energy and economic implications are similar at the minimum LCC, it is intuitive to establish the optimum retrofit solution by simply evaluating the CO_2 saving potential of the identified possible retrofit combinations at the minimum LCC (Equation 7). The results of these computations are presented in Fig. 5. The optimum retrofit strategy should be that with maximum CO_2 savings.

Fig. 5



Schematic illustration of the optimum retrofit strategy with maximum CO_2 saved at minimum LCC for (a) C1W2F5, (b) C2W1F3, (c) C2W3F4, and (d) C2W3F6 building models. (Kindly refer to Tables 6–9 for the description of the respective retrofit strategy.)

Fig. 5 shows that strategy numbers 3, 12, 2 and 6 present the largest CO_2-savings at the minimum LCC for C1W2F5 (Fig. 5 (a)), C2W1F3 (Fig. 5 (b)), C2W3F4 (Fig. 5 (c)) and C2W3F6 (Fig. 5 (d)) building models, respectively. Concerning the C1W2F5 building model, retrofit strategy #3 comprising of all retrofit measures excluding the adjustment in comfort requirement (Table 6) is identified as the most optimal retrofit solution. This retrofit solution offers the maximum CO_2 savings of *ca.* 1.0 Gg-CO_2 at the minimum LCC (with UL ≈ 99%). About the C2W1F3 model, the optimal retrofit strategy was obtained with a *ca.* 0.11 Gg-CO_2 saving at minimum LCC (UL ≈ 85%). The corresponding retrofit strategy (strategy 12, Table 7) includes changes in occupancy regime, comfort requirements, upgrade in building facilities (ventilation and HVAC), upgrade in the building envelope (walls, roofs and air-tightness) and installation of RES (geothermal and solar/PV systems).

Pertaining to the C2W3F4 model, retrofit strategy 2 comprising of modifications in occupancy regime and comfort requirements, upgrade in building facilities (ventilation and HVAC) and envelope (walls, roofs and windows) and RES (geothermal and solar/PV systems) installation (Table 8) displayed the largest CO_2 savings of about 0.11 Gg-CO_2 at minimum LCC (UL ≈ 89%). Likewise, retrofit strategy 6 (combining changes in occupancy regime, comfort requirements, upgrade in building facilities (ventilation and HVAC), upgrade in the building envelope (ceilings, roofs, windows and air-tightness) and installation of RES (geothermal and solar/PV systems), as indicated in Table 9) presented the highest CO_2 saving potential of 0.11 Gg-CO_2 at the minimum LCC (UL ≈ 85%).

In summary, Table 10 compares the results obtained for each prototype with regards to the minimum LCC. For more realistic comparability and interpretability of the outcomes, an insight into the economic implications is necessary. Expectedly, the cost parameters (IC and LCC) at minimum LCC are higher for buildings with large building areas (C1W2F5 and C2W3F6). However, the PBP for these buildings is lower than that with smaller buildings areas. For instance, the PBP for investing in the retrofitting of large buildings is ~ 8 years in comparison to 13 years and 10 years of the smaller buildings, C2W1F3 and C2W3F4, respectively. The variation in the retrofitting economics is attributed to the greater impact of the retrofits with regards to the effects of the building geometry, as explained earlier.

Table 10

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Summary of the optimal retrofit solution from an LCC-based evaluation of retrofit measures for prototypical LOBs. (For a macro-scale intervention, the required primary and secondary retrofit measures are the measures observed in four and three prototypes, respectively.)

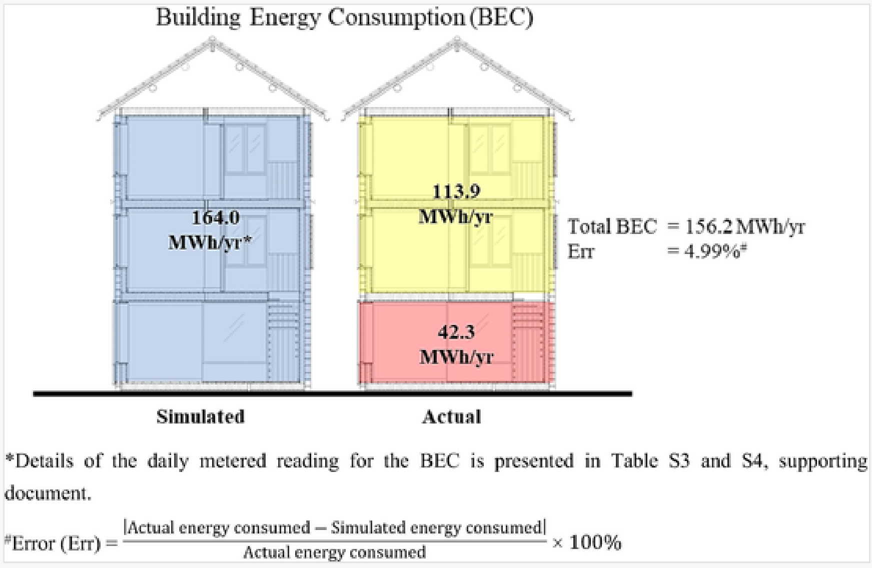
Building Prototypes	Retrofit measures												Energy reduction (%)	Annual CO_2 saved (Gg-CO_2)	IC ($\times 10^6$ RMB)	LCC ($\times 10^6$ RMB)	PBP (years)
	1	2	3	4	5	6	7	8	9	10	11	12					
C1W2F5	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	89	0.9970	4.2	12.4	8.2
C2W1F3	✓	✓	✓		✓		✓	✓		✓	✓	✓	74	0.1062	1.0	2.4	12.5
C2W3F4	✓	✓	✓		✓		✓	✓	✓	✓	✓	✓	78	0.1097	0.9	2.7	9.6
C2W3F6	✓	✓	✓		✓	✓		✓	✓	✓	✓	✓	71	0.1128	4.5	16.4	7.9

[Notation for the retrofit measures: 1 (occupancy regime), 2 (comfort requirements), 3 (natural ventilation), 4 (energy-efficient lightings), 5 (energy-efficient HVAC systems), 6 (ceilings insulation), 7 (wall insulation), 8 (roof insulation), 9 (energy-efficient windows), 10 (air-tightness), 11 (PV/solar system installation) and 12 (geothermal system installation).]

4.3.4 Simulation validation

Empirical validation of the simulation results was performed via a comprehensive comparison of the energy results with actual measurement for the representative building prototype, C2W1F3. The daily meter reading of the energy consumed by the representative building was collected for one year (from 17th Oct. 2018 to 16th Oct. 2019). Details of the actual metered energy data are shown in Table S4. Relatively, the deviation of the simulated result from the actual is observed to be within a ±5% error margin (Fig. 6). This demonstrates the reliability of the simulation software for this study.

Fig. 6



Validation of the simulated energy results with the actual energy consumption for a representative building model, C2W1F3. *Details of the daily metered reading for the BEC is presented in Table S3 and S4, supporting document. #Error (Err) = $\frac{|\text{Actual energy consumed} - \text{Simulated energy consumed}|}{\text{Actual energy consumed}} \times 100\%$

To further validate the outcome at minimum LCC, the combination of the nine individual retrofit measures is jointly simulated on the C2W1F3 model. Nevertheless, given that the simulation of solar/PV and geothermal systems are challenging with the IES-VE simulation software; these systems were excluded from the simulation process. As a result, the validation process is conducted with a two-step approach. The first step involves the energy simulation of the combinatorial retrofit solution without the geothermal and solar/PV systems. Subsequently, a mathematical approach is utilised to compare the software simulation results (from the first step) with that of the numerical simulation.

From the first step, the simulated building energy (electricity) consumption (E_S) is estimated at 115.76 MWh after retrofitting, which depicts a ~ 29% reduction from the original prototype. Under the second step, the RES systems produced a total of 86.63 MWh (E_{RES}). The geothermal and solar/PV systems were assumed to produce a fixed energy capacity of 82.02 MWh and 4.61 MWh, respectively. Assuming these systems are adequately simulated, then the resultant BEC (E_R) after retrofitting the nine retrofit measures is:

$$E_R = E_S - E_{RES}$$

$$= 29.13 MWh$$

This result depicts a ~ 82% reduction in BEC at minimum LCC. Compared with the predicted 74% energy reduction via numerical simulation, the outcome from the software simulation bears a close match of ~ 90%.

5 Discussion

The obtained results have significant relevance to guide decisions on sustainable policymaking and urban planning, and subsequent investments in this regard. First, it is observed from the analysed case study that incorporating building stock prototyping and sustainable impacts of retrofit measures (energy, environmental and economic) in decision-making provides an effective data-driven framework for evaluating the prospects of building retrofits. The formulated framework founded on a life-cycle cost analysis is effective in modelling building stocks and streamlining the several combinatorial retrofit strategies (at minimum life-cycle cost) to a single optimal retrofit solution. Therefore, allowing the selection of the optimum retrofit solution to maximize the investors' sustainable benefits, especially from an economic perspective.

Regardless of the numerous algorithms designed to assess retrofit measures, decisions concerning the most cost-effective optimal combination of retrofit measures for explicit building types are usually intricate. Hindered by the investor's original capital, the optimal retrofit strategy may include a combination of low-cost measures (with a negligible energy reduction potential) and expensive measures (with a net-zero energy (NZE) potential). Hence, the most suitable combinatorial retrofit solution should be determined not only by the investor's capital but also by the maximum life-cycle benefits of the selected retrofits. Accordingly, the LCC-based framework that offers a more pragmatic assessment over a long-term basis to investors is applicable. Moreover, it provides a more comprehensive background to improve comparability and interpretability of policy interventions at both micro and macro scale.

Specifically, the framework offers a realistic and simplified economic evaluation of retrofit interventions both on a micro and macro perspective by integrating dynamic (modelling of the energy performance of existing building) and static (numerical simulation using sensitivity analysis of the dynamic simulation as an input) modelling. From a micro perspective, observing a strict office policy that restricts the working period from 9am to 5pm (8 h daily) in Shanghai shows to be the most cost-effective retrofit measure with the highest impact on energy saving. Other passive measures such as adjusting the comfort requirements can also be implemented to augment this outcome. Here, a 1 °C expansion in the temperature range of the building is shown to significantly reduce the BEC by approximately 5%, 9%, 8% and 9% with a payback period of less than 1 year for the C1W2F5, C2W1F3, C2W3F4 and C2W3F6 building models, respectively. On the other hand, upgrade in wall insulation and HVAC are the most effective retrofit measures with the longest payback period. However, this depends on the building area and geometry. Wall insulation upgrade has the longest payback period for buildings with small building areas, while HVAC upgrade has the longest payback for buildings with large building areas.

From a macro perspective, this study suggests that the necessary retrofit measures (indicated as the primary measures in Table 10) to attain maximum life-cycle benefits should comprise of occupancy regime modification, natural ventilation and HVAC upgrade, roofs insulation improvement and RES (geothermal and solar/PV) Installation. Other relevant measures (depending on the building features) are changes in comfort requirement and enhancing wall insulations, windows energy-efficiency and air-tightness. Overall, a macro-scale estimation of the 3E implications for retrofitting existing LOBs at minimum LCC is presented in Table 11. To facilitate a sustainable city in the Minhang district of Shanghai, an estimated investment cost of RMB 1.7 billion is required to achieve ~ 80% reduction in BEC of LOBs with a CO_2-savings of ~ 243 Gg-CO_2/yr. By computing the PBP as the ratio of the initial investment cost to the annual energy cost savings, the investment is recovered in 5.9 years at this scale. This is considerably ~~lower~~more cost effective than the estimated PBP of 8–13 years with an investment cost ranging from RMB 1–5 million for each building at minimum LCC.

Table 11

The table layout displayed in this section is not how it will appear in the final version. The representation below is solely purposed for providing corrections to the table. To preview the actual presentation of the table, please view the Proof.

An LCC-based estimation of the 3E implications for retrofitting LOBs on a macro-scale in Minhang district, Shanghai (No. of LOBs surveyed = 136, Upscale factor = 8.24).

Prototypical buildings	Building share (%)	Initial BEC* (MWh/yr)	BEC reduction (%)	CO_2 saved (Gg-CO_2/yr)	IC# (10^6 RMB)	Macro-scale analysis Estimated BEC (MWh/yr)	Estimated energy saved (MWh/yr)	Estimated CO_2 saved (Gg-CO_2/yr)	Estimated IC (10^6 RMB)
C1W2F3	11.03	1181.6	89	0.9970	4.2	17724.95	15775.20	14.96	63.00

C2W1F3	22.79	164.0	74	0.1062	1.0	5083.08	3761.48	3.29	30.99
C2W3F4	52.21	201.6	78	0.1097	0.9	14314.73	11165.49	7.79	63.91
C2W3F6	5.15	1266.8	71	0.1128	4.5	8872.67	6299.59	0.79	31.52
Total	**91.18**					**45995.42**	**37001.76**	**26.83**	**189.42**
	(Others = 8.82%)						**(80% saved)**		
	Corrected estimation (for surveyed LOBs)					50444.64	40581.01	29.42	207.74
	Upscale estimation					415797.37	334494.93	242.51	1712.36

Table Footnotes

* BEC = Building energy consumption.

IC = initial investment cost.

Overall, this study highlights, on both micro and macro scales, the suitability of the formulated framework to building stakeholders. The framework offers a background for investors to compare the economic benefits of building retrofits within a short- and long-term scope; thereby providing a guide for political intervention. Also, the study fills the knowledge gap created by the lack of studies on small-size commercial buildings, particularly in a city like Shanghai that is predominated with old and highly dense low-rise office buildings. Given the nascent development state of the city, most of the building owners and the municipal government lack the adequate expertise or resources required to identify the most suitable retrofit measures on a neighbourhood/urban scale.

6 Conclusion

The significance of a macro-scale evaluating framework for building energy retrofits in a sustainably conscious society cannot be overemphasized given that ~~building~~ policies are ~~focused~~centered on macro-scale interventions~~, particularly~~ ~~sustainably conscious society~~. This study formulates and validates a facile framework with a comprehensive optimisation approach integrating building stock prototyping, life cycle cost evaluation and environmental assessment for evaluating the prospects of retrofit measures on a macro-scale. The model framework is based on a life-cycle cost analysis to establish the optimal retrofit strategy over a stipulated life span.

Based on the outcome of this study, the following conclusions are deduced:

1. The proposed data-driven framework is effective in modelling building stocks and streamlining the several combinatorial retrofit strategies (at minimum life-cycle cost) to a single optimal retrofit solution. Founded on a comprehensive economic evaluation approach, the framework integrates sustainable impacts of retrofit measures (energy, environmental and economic) in deciding the optimal retrofit strategy.
2. The study offers a more realistic and simplified evaluation of retrofit interventions both on a micro and macro perspective by integrating dynamic (modelling of the existing building energy performance) and static (numerical simulation using sensitivity analysis of the dynamic simulation as an input) modelling.
3. The model framework is corroborated by a case study analysis focused on identifying the optimal retrofit solution for low-rise office buildings (LOBs) in Shanghai (macro-scale) over a 50-year life span. The result establishes four prototypical LOBs that represent the existing building stocks. On a micro-scale, the observation of a strict office policy that restricts the working period from 9 am to 5 pm (8 h daily) shows to be the most cost-effective retrofit measure with the highest impact on energy saving. Upgrade in wall insulation and HVAC displayed the longest payback period for buildings with small and large building areas, respectively. Subsequently, the total/life-cycle cost at optimal retrofit varies within RMB 2 − 17 million per building.
4. At optimal cost benefits, an investment cost within RMB 1 − 5 million with a payback period < 13 years is estimated for each building, depending on the building characteristics. On a macro-scale, an estimated investment cost of RMB 1.7 billion (with a payback period of 6 years) is required to achieve ~ 80% energy reduction with a carbon dioxide savings of ~ 243 Gg-CO_2/yr.

In general, this study can aid investors to assess their retrofitting investment and provide a framework that guides the selection of an appropriate combination of retrofit measures on a macro-scale.

Author contribution statement

Dr Wu Deng: Conceptualization, funding acquisition, methodology, project administration, resources, supervision and writing - review & editing. ~~conceived and designed the research study, and revised the paper.~~ Dr Yuanda Hong: Conceptualization, data curation, formal analysis, investigation, methodology, project administration, resources, software, validation and writing - original draft. ~~Dr Yuanda Hong contributed to the design of the research analysis and partook in data collation and processing, data analysis, and wrote the paper.~~ Dr Collins I. Ezeh: data curation, formal analysis, investigation, methodology, resources, software, validation, visualisation and writing - original draft. ~~partook in data collation, processing and analysis and wrote the paper.~~ Dr Sung-Hugh Hong and Dr Yue Tang: Conceptualization, methodology, project administration, resources, supervision and writing - review & editing. ~~contributed to the design of the research analysis and paper revision.~~ Yuhui Jin and Yuanli Ma: data curation, formal analysis and writing - review & editing.~~partook in data collation and analysis.~~

Q4 Uncited references

[31,32].

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

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enconman.2021.114327.

Q5 References

The corrections made in this section will be reviewed and approved by a journal production editor. The newly added/removed references and its citations will be reordered and rearranged by the production team.

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Appendix A Supplementary data

The following are the Supplementary data to this article:

Multimedia Component 1

Supplementary data 1

Queries and Answers

Q1

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Q5

Query: Please note that as the reference supplied more than once, the repletion has been removed from the list. Please check, and amend accordingly.

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