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Approach for Optimal Selection of Innovative Actions for Residential Heating Systems

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Urban housing is the largest consumer of energy in European countries, representing approximately 43 % of total energy consumption. The objective of a sustainable society is to enhance the energy efficiency of buildings and domestic heating systems, with the goal of achieving zero-energy buildings that rely on renewable energy sources for their energy supply. To accomplish this, the current buildings must be effectively renovated. This study presents a method for upgrading household heating systems when there are limited finances available for investment. The proposed mathematical model is derived from the analysis of the building's energy system and combines the thermal energy producer and consumer into a unified system. It allows for the analysis of the building's condition using energy, environmental, and economic key indicators while also suggesting appropriate innovative measures. A proposed approach is to pick effective creative measures for the analysed building and optimise investment in time. The case study for the education building in Ukraine showed that the implementation of such an approach enables significant savings of up to 60-85 % of energy and fuel resources spent on building heat supply with a simultaneous reduction of environmental emissions by 39 % from the initial state.

1. Introduction

The International Energy Agency's report (IEA, 2022) states that the world is currently in a crucial period for the development of energy systems, which should be more safe, sustainable and cost-effective. Within the European Union, the buildings utilise 43 % of energy and release 36 % of greenhouse gases during energy generation. Ensuring the sustainability of cities requires the renovation of buildings and their energy systems, together with the implementation of innovative technologies that utilise renewable energy sources to generate energy for heating and hot water supply demand.

To decrease energy usage for residential heating and cooling, the building's energy demand should be decreased. It can be done by the building energy system retrofit, which will inevitably depend on the energy level of the building envelope, making the retrofit of the building itself the important measure of all the innovations. In the review paper by Fahlstedt et al. (2022), the various approaches used to decrease carbon emissions by improving the building envelope in order to achieve zero-energy buildings were examined. Wu et al. (2017) discuss the utilisation of building refit and enhancement of the energy supply system, with an emphasis on cost reduction and the reduction of greenhouse gas emissions. An examination of various energy sources in terms of their cost and environmental impact on non-residential buildings in Ukraine was conducted by Polyvianchuk et al. (2023a). The study conducted by Sarmouk et al. (2022) investigated the most efficient incorporation of solar energy and gas boilers for heating systems in commercial buildings.

There is a limited number of studies that have been carried out to identify the optimal investment in building retrofit, and ongoing research is being undertaken at present. It is crucial to include the complete time span of

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building life cycles when doing optimisation, as highlighted by Richarz et al. (2022). This enables the identification of more practical approaches to constructing decarbonisation, when the investment choices are possible at various points over the building's lifespan and are flexible. The study conducted by Wirtz et al. (2023) examined the activities required for the transition to the 5th generation district heating system. Two investment strategies were employed: advance planning scenario and step-by-step implementation. Both techniques demonstrated cost savings in comparison to a single investment. The scenario that used the optimal investment pathway resulted in even greater savings, amounting to 17 % of the costs. The integrated approach, combining the selection of optimal building energy system renovation strategy and its investment in time using data-driven modelling, was proposed by Pedone et al. (2023).

To ensure the efficient allocation of investments over time for enhancing a building's energy system, a new method for optimising a multi-period investment strategy is necessary. The present work is based on previous research, utilising key performance indicators to estimate the effectiveness of each proposed innovation (Polyvianchuk et al., 2020), and integrates multi-objective optimisation to define the best strategy based on economic and environmental criteria (Polyvianchuk et al., 2023b). A new method for the optimal selection of the most efficient multi-period investments for the chosen innovation actions is proposed. This technique is particularly applicable in situations where financial resources are limited. A case study of a university building is provided, demonstrating the advantages of the multi-period investment technique over a lump-sum investment strategy.

2. Mathematical model of multi-period investment in retrofit of the building energy system

Accurate determination of the most effective combinations of refurbishment actions for a building's energy system based on their efficiency and prioritising their sequence and optimal timing requires a comprehensive mathematical model, which allows account for a thorough assessment of investment required with optimal pay-back periods. The proposed strategy is founded on the concurrent examination of the renovations from the perspectives of economics, environment, and energy.

The proper estimation of the optimal combinations of refurbishment actions for building energy systems according to their efficiency needs comprehensive mathematical modelling. The methodology of the proposed approach is summarised in Figure 1. It is based on the estimation of the initial condition of the building's energy system performed by the energy audit. The proposed energy retrofit measures are divided into three groups. The actions which can be done for thermal modernisation of the building envelope, such as insulation of the envelope walls, roof and windows, and improvement of the ventilation system, are included in the 1st group. The control system of climatic conditions in the rooms and the improvement of the insulation of all the connection tubes are in the 2nd group. The changes in the heating subsystems and implementation of renewable energy sources and heat pumps are related to the 3rd group. During the modelling, the highest priority is allocated to the 1st group of actions, then 2nd and 3rd, which allocates the sequence of the retrofit measures in time. These priorities will provide a systematic order of actions for the modernisation of the building. The first step will be to renovate the enclosing structures, followed by assessing the subsequent steps for reducing heat consumption in the building while avoiding unnecessary expenses.

Based on the existing state of the building, its thermal energy performance Δq^0 is estimated. For each retrofit measure proposed for the observed building, three performance indicators are estimated (Polyvianchuk et al., 2020). The energy performance indicator EPI_1 is defined as the ratio between current energy consumption and the value after implementing the retrofit action $\Delta\bar{q}$. The cumulative EPI_1 value includes the energy savings resulting from the modernisation of the building construction q_{cons} and fuel consumption V_{fuel}. The environmental performance indicator EPI_2 is determined based on the quantity of carbon dioxide emissions m_{CO2}, kg and the reduced level of pollution due to innovative measure Δm_{CO2}. The economic performance indicator EPI_3 is derived from the investment funds available, denoted as C_{in}, and the calculation of potential cost savings, represented as ∆c, throughout a single innovation period and in total, denoted as Δc. The priority of the performance indicators during the optimisation are set as weight coefficients when applying multi-objective optimisation (Polyvianchuk et al., 2023a). The primary objective of the present study is to determine the optimal allocation of investment capital over time.

To determine the optimal multi-period investment function, it is necessary to estimate the total investment costs throughout time, $F_{\Sigma-\text{ін}}(T)$. These expenses include the expenses generated from completed retrofit measures, $F_{f-\text{ін}}(T)$, as well as the running costs associated with unfinished measures, which will be implemented later, $F_{\text{т}-\text{ін}}(T)$. The relationship between the costs is depicted as follows:

$$F_{\Sigma-\text{ін}}(T) = F_{f-\text{ін}}(T) + F_{\text{т}-\text{ін}}(T) \tag{1}$$

The revenue of completed measures is estimated based on the overall possible pay-back cost and is determined as the difference between the total amount of the resources needed $F_{f-\Sigma}(T)$ and operating costs for the energy building system when part of the planned retrofit measures were not done yet $F_{(f-\mathrm{e})}(T)$:

$$F_{f-\text{iн}}(T) = F_{f-\Sigma}(T) - F_{(f-\mathrm{e})}(T) \tag{2}$$

The total amount of required investment $F_{f-\text{iн}}(T)$ for the multi-period retrofitting will allow to maximise the investment cost $F_{f-\Sigma}(T)$ through the introduced financial effect of the multi-period investment ΔF_{Σ} defined as follows:

$$\Delta F_{\Sigma} = \Delta F_{\text{iн}} - \Delta F_{(-\mathrm{e})} \tag{3}$$

where $\Delta F_{\text{iн}}$ is the reduction in investment due to earlier financing and associated pay-back revenue; $\Delta F_{(-\mathrm{e})}$ is the surcharge for energy supply throughout the funding period T_B, which is part of the overall investment period.

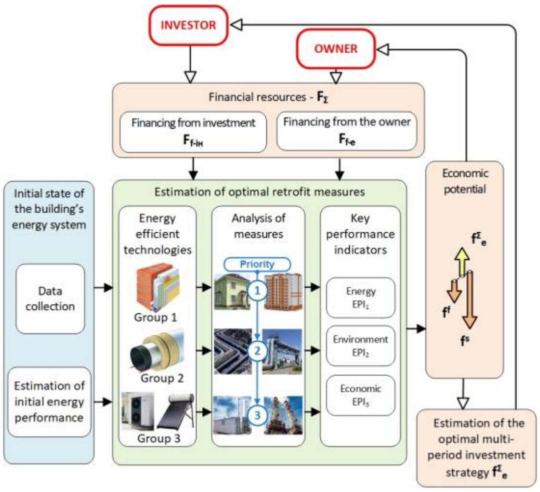

Figure 1: The flowchart of research methodology for estimation of the optimal multi-period investment in building energy system retrofit

For the optimisation of the ΔF_{Σ} function (Eq.(3)), the amount of required investment in time $F_{f-\Sigma}(T)$ should be defined. It is proposed to determine the $F_{f-\Sigma}(T)$ based on the division of funding periods on number of multi-periods T_B according to:

$$F_{f-\Sigma}(T) = C_e^{\Sigma} \cdot \left(\frac{T}{T_B}\right)^{a} \tag{4}$$

where the unknown parameter a needs to be approximated throughout the optimisation process. The number of implementation periods, $\mathrm{T_B}$ should be optimised as well. The parameters a and T_B. in the proposed technique are defined based on discrete values in the following ranges: $a = 0.25 \ldots 1.0$; a ranges from 0.25 to 1.0, while $T_B = 0,1,2,\ldots 10$. When $T_B = 1$ y, it corresponds to two stages of investment (initial and at the end of the year). The total investment required for retrofitting the building energy system $F_{(f-\mathrm{e})}(T)$ is defined by integration over the time period of the efficiency function of capital investment f_{e}^{2}, which presents the functional dependence on the financial resources allocated to the retrofitting over time $F_{f-\Sigma}(T)$:

$$F_{(f-\mathrm{e})}(T) = \int_0^T f_{\mathrm{e}}^{2}(F_{f-\Sigma}(T))dT \tag{5}$$

The expenses associated with compensating for the non-implemented actions $F_{\text{т-iн}}(T)$ are calculated based on the overall investment potential for all proposed retrofit measures f_e^{Σ} in each time period, excluding the revenue saved as a result of completed modernisation:

$$F_{\text{т-iн}}(T) = f_{\mathrm{e}}^{\Sigma} \cdot T - F_{(f-\mathrm{e})}(T) \tag{6}$$

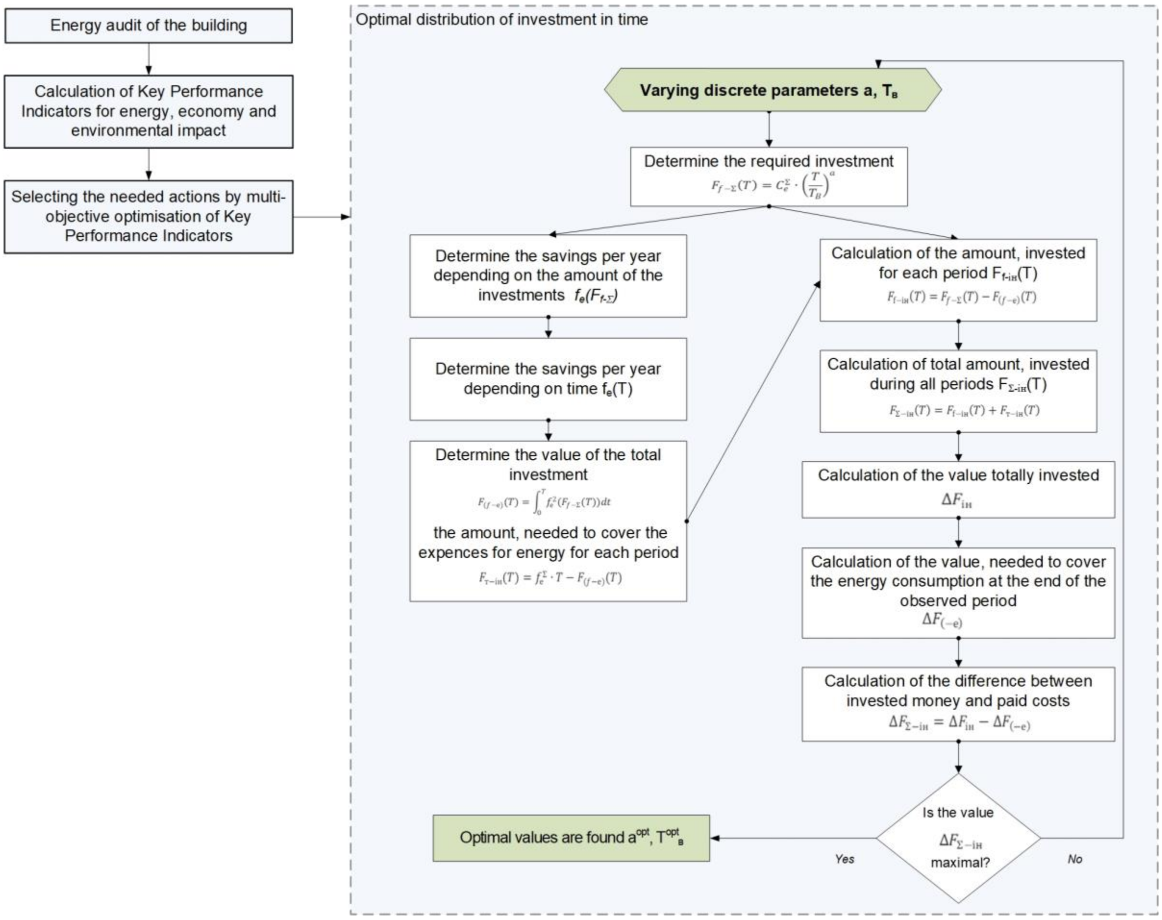

Figure 2: The flowchart of the optimisation algorithm for the optimal multi-period investment

By determining the maximum value of the target function presented in Eq.(3) within the specified range of parameters a and T_B, one can achieve the most favourable allocation of investment over time for the suggested retrofit measures. The mathematical model defined by Eqs. (1)-(6) was realised in Excel spreadsheets using VBA to accomplish the spreadsheets used for energy audits of the buildings. The general flowchart of the used optimisation method is presented in Figure 2. The proposed approach can be used for the estimation of the optimal investment strategy for retrofitting insufficient energy systems of buildings based on performance indicators for proposed retrofit measures, and its application is presented in the case study.

3. Case study

The building of the Vinnytsia National Technical University, presented in Figure 3a, was investigated. The building was built in 1986 and is a 3-story building with a total heated area equal to 2,282.0 m^2. The building uses the following types of fuel and energy resources: thermal energy in the form of hot water for heating needs; electricity is used to meet the needs of hot water supply and internal lighting. The existing heating system of the building is connected to the centralised district heating system operating on natural gas. Inside the building, the heating system is a two-pipe design with a lower distribution of the heat carrier and is equipped with iron sectional heating radiators without thermostats.

Table 1: Estimation of the key performance indicators representing the effectiveness of the building

	EPI_1		EPI_2	EPI_3
	q_{cons}, (kW·y)/m^2	V_{fuel}, 10^3 m^3	m_{CO2}, 10^3 kg	f_e^{Σ}, 10^3 EURO
Initial state	168.9	38.7	20.6	23.2
After proposed retrofit measures	67.4	10.6	5.6	6.3

The indoor heating system is designed to work at a temperature range of 95-70 °C; the actual temperature range in recent years has been close to 80-60 °C. The actual annual volume of thermal energy consumption by the building averaged over the last 3 y, is 385.5 MW·h. The actual average annual specific energy consumption per 1 m^2 of total area is 168.9 W/m^2. The calculated key performance indicators for the initial state of the building are presented in Table 1.

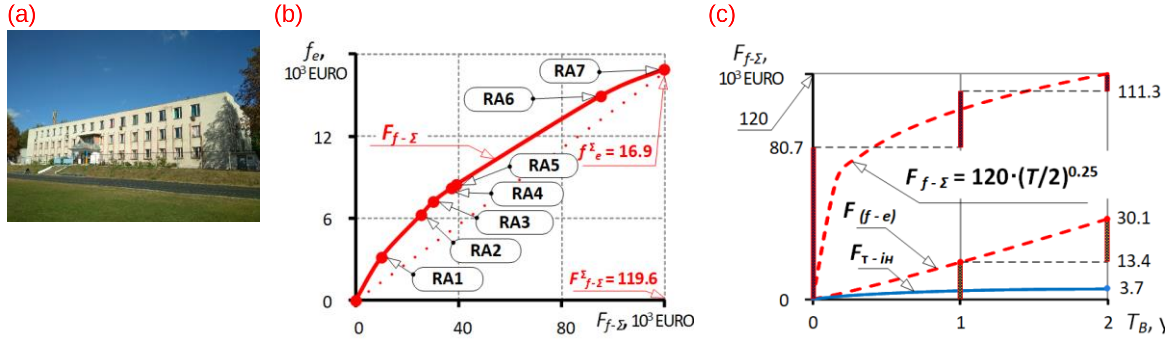

Figure 3: Retrofitting measures with optimised multi-period investment for the investigated building: (a) building photo; (b) distribution of the retrofit actions in time; (c) resulting investment parameters for the proposed time

After the analysis of the initial state of the building, the recommended retrofitting measures were proposed, and their effectiveness was calculated. To choose the most efficient measures, the priority was given to the economic (EPI_3) and energy (EPI_1) indicators, considering the pay-back period. Each of the possible retrofitting measures was classified according to the 1st, 2nd or 3rd group for proper allocation of the different steps of retrofit in time. The most efficient measures were selected. They are listed according to the optimal sequence of implementation are presented in Table 2. The step-by-step distribution of the measures in time based on the efficiency function of capital investment from financial resources allocated for each retrofitting measure is demonstrated in Figure 3b. The retrofitting measures RA1 and RA2 should be implemented in the beginning during the first investment period measures RA3-RA6 in the second, and RA7 in the 3rd investment period.

Table 2: Estimated efficiency of the proposed retrofitting measures

N	Description of the innovative retrofitting action (RA) / group	EPI_1		EPI_2	EPI_3	Investment cost, 10^3 EUR	Pay-back period, y
		q_{cons}, (kW·y)/m^2	V_{fuel}, 10^3 m^3	m_{CO2}, 10^3 kg	f_e^{Σ}, 10^3 EUR		
RA1	Thermal modernisation of the attic floor /1st group	23.0	5.26	2.80	3.16	10.03	3.2
RA2	Thermal modernisation of the ventilation system /1st group	22.5	5.16	2.75	3.09	15.33	5.0
RA3	Installation of gas condensation boiler / 3rd group	-	1.62	0.86	0.97	4.74	4.9
RA4	Installation of smart control system for heating / 2nd group	7.2	1.65	0.88	0.99	7.05	7.1
RA5	Thermal modernisation of the entrance doors /1st group	1.8	0.42	0.22	0.25	1.87	7.4
RA6	Thermal modernisation of the walls /1st group	47.0	10.77	5.73	6.46	56.07	8.7
RA7	Installation of solar collectors / 3rd group	-	3.25	1.73	1.95	24.53	12.6
	Total	101.5	28.13	15.0	16.88	119.63	7.1

Table 3: The resulting parameters of the optimised multi-period investment

Measurement units	Parameter							
	$F_{f-\Sigma}$	$F_{(f-e)}$	F_{f-iH}	F_{T-iH}	$F_{\Sigma-iH}$	ΔF_{iH}	$\Delta F_{(-e)}$	ΔF_{Σ}
10^3 EUR	119.6	30.1	97.9	3.7	111.6	18.1	-3.7	14.4
%	100	25.2	81.9	3.1	85.0	15.2	-3.1	12.1

The estimated parameters of the optimisation function are presented in Eq.(3), with the optimal values of the investment distribution over time (see Eq.(4)), where $a = 0.25$ and $T_B = 2$, corresponding to three investment periods, as shown in Figure 3c. The start of the 1st investment period concurs with the start of the retrofit, 2nd investment begins in 3.2 y, and 3rd in 3.3 y. The estimated payback period for the 1st investment period is 3 years; for the 2nd, it equals 3.5 y and 4 y for the 3rd investment period. The resulting optimal parameters of the mathematical model of multi-period investment given in Eqs.(1)-(6) are listed in Table 3 in EURO and in %, compared to the full lump-sum investment strategy. The decrease in the cost for the observed period is 18,100 EUR. It requires a longer retrofit period, which increases from 7.1 to 7.3 y compared to the lump-sum case.

4. Conclusions

The renovation of old buildings and their heating systems is required for the sustainable development of modern cities. The selection of modernisation actions should account for the efficiency of the measures, estimation of its cost, environmental impact and total consumption of energy. A mathematical model, which allows the estimate of the optimal multi-period investment in selected retrofit measures, is developed. The use of the model allows optimal distribution of the implementation of the proposed retrofit measures in time, reducing the total required costs. The application of the proposed approach for the retrofit of the University building allows to reduce heat energy consumption by 72.7 %. The implementation of optimal multi-period investment enables the decrease in the costs of investment resources by 15.2 % with the slightly increased retrofit period, which requires an additional 0.2 y compared to the strategy of lump-sum investment. A resulting positive integrated economic effect is equal to 12.1 %, which shows the benefits of the optimal investment strategy during the energy system retrofit. The adaptation of the current approach for building energy management systems integrated with electricity consumption and renewable energy sources is the subject of future work.

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