COST-OPTIMAL ENERGY RETROFIT FOR SERBIAN RESIDENTIAL BUILDINGS CONNECTED TO DISTRICT HEATING SYSTEMS

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Buildings are significant energy consumers and provide a notable potential to reduce primary energy consumption and increase energy efficiency. Cost-effectiveness of energy efficiency projects is of crucial importance for their implementation. Cost-optimality of different packages of energy retrofit measures is studied across the European Union, but Serbia mostly lacks such information. This paper analyzes cost-optimal solutions for Serbian residential buildings connected to district heating systems, considering three different scenarios related to the economic input parameters. Additionally, it considers the potential for primary energy savings beyond cost-optimality and associated costs. The optimal solutions, that correspond to minimal global cost or minimal primary energy consumption, are determined as the results of the combinatorial optimization problems. These problems are solved using the genetic algorithm and local search. The results are compared against the ones obtained with the sensitivity analysis. The global cost can be reduced by 8–43% in the cases of cost-optimal solutions, simultaneously saving 30–76% of primary energy. The potential to save primary energy is higher — it exceeds 70% in all the analyzed cases, but also requires higher global cost, sometimes larger than in the absence of the retrofit. The paper also emphasizes high dependencies of the results on very uncertain economic inputs.

Key words*: cost optimality, energy retrofit, metaheuristic optimization, primary energy, residential buildings*

1. Introduction

Buildings are significant consumers of energy worldwide, but also provide remarkable opportunities to achieve energy savings and increase overall energy efficiency levels. Identification of cost-effective and cost-optimal (CO) energy efficiency measures and packages have critical influence on energy policy instruments and choices regarding energy retrofit (ER) actions that are supposed to yield energy savings.

The European Union demands the member states to set minimal requirements for ER of existing buildings and construct nearly zero energy buildings in the future with the Directive [1]. The definitions of nearly zero energy definitions vary. The requirements are supposed to be set having CO options in mind [2, 3]. The same Directive requires taking into account cost-effectiveness when improving energy efficiency of buildings. The Directive [4] insists on cost-effective energy-saving measures and life-cycle cost analysis to reduce primary energy (PE) consumption (PEC) and decrease energy import, thus confronting the climate change and prevailing over the economic crisis. Reference [3] suggests the methodology to implement CO measures relying on the sensitivity analysis.

In the Republic of Serbia, district heating (DH) systems exist in 57 cities and municipalities and dominantly use natural-gas-fired boilers. Serbia is strategically oriented towards connecting additional households to the existing DH systems and increasing energy efficiency in heat use [5]. Therefore, the identification of CO ER measures and packages for the residential buildings connected to DH systems is very important for achieving their financial attractiveness and defining energy policy instruments. Although some recent research exists, *e.g.* [6], Serbia mostly lacks the information related to CO ER levels.

The considerations of cost-optimality, usually involve the criteria such as global cost (GC) and PEC. Additional criteria can be regarded as well, such as greenhouse gases emission [7-9] and thermal comfort [10, 11].

When identifying CO ER measures, the authors usually consider discrete decision variables and apply one of these three approaches: (1) the sensitivity analysis where one or more variables are parametrically varied [12], (2) the exhaustive search of all possible combinations of considered measures [8, 13], and (3) using some mathematical optimization method, usually metaheuristic, to find the optimum [14, 15]. The sensitivity analysis is simple, straightforward, not computationally intensive and very suitable for the interpretation, but can yield local optima. The exhaustive search is comprehensive and provides the accurate solutions, bun can be unacceptably computationally intensive, especially when detailed buildings simulations are applied. Metaheuristic optimization is often acceptably intensive but might yield near-optimal instead of optimal solutions.

Metaheuristics can be coupled with detailed buildings simulations [14], sensitivity analysis [16], artificial neural networks that predict energy performance [10] and scenario analysis [17]. Although buildings simulations offer high precision and can be useful to obtain the insight into desirable equipment operation modes [18], other assessment tools might be used [19], even various tools can be combined in a single optimization procedure [15].

Additional influences are also considered in the literature, *e.g.* the impact of the global warming on climate inputs [17], climate conditions on CO options [12, 20, 21], urban context [13], residents behavior and occupancy [22] *etc*.

This paper focuses on identifying CO ER measures for a strategically very important part of energy consumers — residential buildings connected to DH systems. It considers three typical buildings for Serbian urban areas: (a) a single-family building, (b) a small multi-story multi-family building, and (c) a large multi-story multi-family building. The paper examines three scenarios with different economic input parameters: (i) the realistic scenario (RS), (ii) the optimistic scenario (OS), and (iii) the pessimistic scenario (PS). Additionally, it uses both approaches that prevail in the literature — sensitivity analysis and classical optimization — and compares the results of the two.

The rest of the paper is organized as follows. Section 2 describes the problem, the buildings of interest and input parameters. Section 3 illustrates the methodology used for the research, including the mathematical model. Section 4 shows the results and discusses them. Section 5 contains the conclusions of the conducted research.

2. Problem formulation

The objective of this paper is to analyze CO ER measures applicable to DH-connected residential buildings in Serbian conditions, characterized with moderate continental climate in cities and relatively low energy prices, especially for the electricity purchased from the national grid. It aims to provide the information on possible economic and energetic results that can be achieved as a consequence of applying energy efficiency measures, as well as to identify preferable ER measures from the economic point of view. It also determines the potential for PE savings (PES) of such buildings, beyond CO levels.

The paper considers three very common types of existing buildings located in Serbian urban areas. All of them are located in the City of Niš and supplied with the district heat from the local DH plants that use natural-gas-fired boilers. It is assumed that they are cooled in the summer periods with electricity-driven air-to-air split-system air conditioners. The building A is a single-family two-story house with the floor area of approximately 185 m^2. It has the exterior masonry walls and the pitched roof made of wood and tiles. There is no insulation. The building B is a multi-family five-story building with the area of about 755 m^2. The exterior masonry walls are not insulated, while the flat roof is. The building C is a multi-family 15-story building of 5718 m^2. The exterior walls and flat roof are made of prefabricated concrete construction. All the buildings have old double single-glazed wooden windows.

One of the main presumptions is that the buildings are going to remain connected to the DH system of the City of Niš, having in mind the strategic importance of DH, especially when applied to the residential sector [5]. It is also assumed that the cooling systems are not going to be replaced.

Thus, only the following improvements of the buildings envelopes elements are considered: the insulation of the exterior walls and interior walls towards unconditioned spaces, the insulation of the floors towards the unconditioned basements, the insulation of the ceiling and flat roofs, as well as the replacement of the fenestration. The considered insulation materials are: the expanded polystyrene (EPS), extruded polystyrene (XPS) and stone mineral wool (SMW). It is worth saying that for some elements, *e.g.* exterior walls, SMW offers similar thermal conductivity to EPS, but has significantly higher price and thus cannot be competitive when cost-optimality is regarded solely, despite other advantages. The fenestration replacement options consider the frames made of the polyvinyl chloride (PVC), wood, aluminum (AL) and AL-wood combination, as well as several double and triple glazing choices fulfilled with inert gases.

PE conversion factors for DH and electricity are taken from [23] and have the values φ_{DH}=1.8 and φ_E=2.5, respectively. The initial constant and variable parts of DH price are $z_{DH,c}$=3.3 EUR/m^2 and $z_{DH,v}$=0.045 EUR/kWh, respectively. The constant part includes maintenance costs. The initial average electricity price is z_E=0.05 EUR/kWh. The observed horizon is 25 years. The residual values are calculated with the linear depreciation model. The economic lifetime of the fenestration is assumed to be 25–35 years, depending on the type and quality of frames. The lifetime of the insulation is 50 years, according to [3].

Uncertainties in the input parameters are taken into account by considering the realistic, optimistic and pessimistic scenarios. The terms optimistic and pessimistic refer to the possibility to achieve good economic results. For example, higher energy prices — that make ER measures more attractive — correspond to OS and vice versa. The most important uncertain parameters are the rates of energy prices growth. It is assumed that the electricity price is going to escalate with the real rates of: 6%, 10% and 12% per year for RS, OS and PS, respectively. The real increase rates of the district heating price foreseen are: 3%, 5% and 1% annually for RS, OS and PS, respectively. The investments can also vary depending on the demand and supply, as well as on some potential future incentives or tax relaxations. Therefore, the initial investment costs and residual values in OS are adopted to be 20% lower and in PS 20% higher compared to RS. The real interest (discount) rates for RS, OS and PS are defined as follows: r_R =3%, 1% and 5%, respectively.

3. Methodology

The used methodology aims to be compliant to the latest standards and to exploit a suitable metaheuristic optimization method — the genetic algorithm (GA). It combines scenario analysis with sensitivity analysis and optimization to derive the conclusions regarding CO ER measures and their economic and energetic results. It is also used to calculate PES potential beyond cost-optimality.

3.1. Decision variables

The approach applied here considers five integer decision variables:

1. The insulation of the exterior walls with 32 different options plus the one where no additional insulation is provided. There are two types of insulation: (a) classical EPS with the thermal conductivity λ=0.04 W/(mK), and (b) improved EPS with λ=0.032 W/(mK), each of which is considered in 16 variants with the thicknesses d=5–20 cm.
2. The insulation of the interior walls towards the unconditioned spaces with 10 different options plus the one where no additional insulation is provided. There are two types of insulation: (a) EPS with the thermal conductivity λ=0.04 W/(mK), and (b) SMW with λ=0.035 W/(mK), each of which is considered in five variants with the thicknesses d=5–15 cm. This decision variable is not applicable for the building A.
3. The insulation of the floors towards the unconditioned basements with four options related to XPS insulation with λ=0.04 W/(mK) and d=10–20 cm plus the one without insulation.
4. For the building A, the insulation of the ceiling towards the unconditioned attic with five different options of EPS with λ=0.038 W/(mK) and d=8–20 cm. For the buildings B and C, the insulation of the flat roofs with five different options of XPS with λ=0.035 W/(mK) and d=10–25 cm. The additional option without insulation is considered as well.
5. The replacement of the fenestration with 19 options plus the one without the replacement. Different combinations of double and triple glazing with inert gases, as well as frame materials (PVC, wood, AL and AL-wood) are considered.

It is not required that all the feasible solution must be in accordance with the current legislative [R07], because the legislative should depend on the results of such analyzes and not vice versa.

3.2. Mathematical model

The annual space heating and cooling needs, $Q_{H,nd}$ and $Q_{C,nd}$, are calculated according to ISO 13790 [24], monthly method, and expressed in [kWh a^{-1}]. Then, PEC related to space heating and cooling is calculated using non-dimensional heating system seasonal efficiency, η_{HS}, cooling system seasonal energy efficiency ratio, SEER, as well as PE conversion factors for DH system and electricity, φ_{DH} and φ_E, respectively:

$$E_{\mathrm{P}} = \frac{\varphi_{\mathrm{DH}} \frac{Q_{\mathrm{H,nd}}}{\eta_{\mathrm{HS}}} + \varphi_{\mathrm{E}} \frac{Q_{\mathrm{C,nd}}}{\mathrm{SEER}}}{A_{\mathrm{f}}} \tag{1}$$

For convenience, PEC is given per floor area, A_{f}, in [m^2], of the conditioned space, *i.e.* in [kWh m^{-2} a^{-1}].

GC is calculated for each year τ of the observed horizon according to EN 15459 [25], but also expressed per floor area, in [kWh m^{-2} a^{-1}], for convenience:

$$Z_{\mathrm{G}}(\tau) = Z_{\mathrm{INV}} + \sum_{\tau=1}^{n} \left(z_{\mathrm{DH,c}}(\tau) + \frac{z_{\mathrm{DH,v}}(\tau) \frac{Q_{\mathrm{H,nd}}}{\eta_{\mathrm{HS}}} + z_{\mathrm{E}}(\tau) \frac{Q_{\mathrm{C,nd}}}{\mathrm{SEER}}}{A_{\mathrm{f}}} \right) \frac{1}{(1 + r_{\mathrm{R}})^{\tau}} - \frac{Z_{\mathrm{RV}}}{(1 + r_{\mathrm{R}})^{n}} \tag{2}$$

where Z_{INV} is the total initial investment, expressed in [EUR m^{-2}], n is the length of the observed horizon, in years, $z_{\mathrm{DH,c}}(\tau)$ is the constant part of DH price including maintenance costs for the year τ, in [EUR m^{-2}], $z_{\mathrm{DH,v}}(\tau)$ is the variable part of DH price for the year τ, in [EUR kWh^{-1}], $z_{\mathrm{E}}(\tau)$ is the electricity price for the year τ, in [EUR kWh^{-1}], r_{R} is the non-dimensional real interest (discount) rate and Z_{RV} is the total residual (final) value for all the components at the end of the observed horizon, *i.e.* calculation period, in [EUR m^{-2}]. The final value is calculated assuming linear depreciation of the total initial investment.

3.3. Objectives

CO solution (COS) is the one with the lowest GC. Therefore, the objective of the optimization problem is:

$$\min\ Z_{\mathrm{G}} \tag{3}$$

Alternatively, when PES potential is estimated, the objective is to minimize PEC:

$$\min\ E_{\mathrm{P}} \tag{4}$$

The Pareto optimal solutions of the multiobjective optimization problem are found with the weighting sum method, *i.e.* using different linear combinations of the two objective functions.

3.4. Sensitivity analysis

The sensitivity analysis is performed by varying each decision variable at a time and choosing the best value, *i.e.* the best single measure for a particular decision variable. This approach is usually simple and efficient but can yield local optima rather than the global ones.

3.5. Optimization approach

The optimization problem formulated in this paper is combinatorial, which means that there is a finite set of combinations of the decisions values. The optimal vector of the decision variables is to be found among them. Although it is possible to search all the candidate solutions exhaustively, it is often not practical since it might require significant computational effort and time, especially when a large number of combinations are considered, or detailed building energy simulations are used.

In this paper, the combinatorial optimization problems of interest are solved with the genetic algorithm (GA). Since GA does not guarantee achieving global optimum, the local search is applied on the obtained solution in attempt to improve it further. For multiobjective optimization, *i.e.* when both GC and PEC are considered objectives, the Pareto optima are found with GA, using the weighting sum method.

4. Results and discussion

The baseline scenario is the "do-nothing" scenario, *i.e.* the alternative to ER that preserves the existing states of the buildings. Table 1 shows GC and PEC for this alternative. GC (including the investment, energy and maintenance costs and residual values) vary significantly for the three scenarios, being the highest for OS and lowest for PS, as expected. The building C has the lowest GC because it is insulated in the baseline scenario. PEC per 1 m^2 does not depend on the chosen scenario, because only the economic inputs differ for RS, OS and PS. PEC is similar for the buildings A and B (the difference is 7.3%), while C is initially notably better in this sense again due to the presence of the insulation.

Table 1. The summary of the global cost and primary energy consumption for the baseline

Building	**Scenario**	**Global cost** [EUR m^{-2}]	**Primary energy** [kWh m^{-2} a^{-1}]
A	Realistic	284.31	336.86
	Optimistic	492.87	336.86
	Pessimistic	178.20	336.86
B	Realistic	301.23	363.43
	Optimistic	525.94	363.43
	Pessimistic	187.96	363.43
C	Realistic	197.81	191.94
	Optimistic	349.29	191.94
	Pessimistic	122.55	191.94

Table 2. illustrates GC and PEC for COSs and the solutions with the highest PES, both obtained solving the combinatorial optimization problems from Section 3 with GA. COSs have minimal GC, according to Eq. (3). The solutions with the highest PES correspond to minimal PEC, *i.e.* Eq. (4).

Table 2. The summary of the global cost and primary energy consumption for optimal solutions

Building	**Scenario**	**Objective function**	**Global cost** [EUR m^{-2}]	**Global cost reduction**	**Primary energy** [kWh m^{-2} a^{-1}]	**Primary energy savings**
A	Realistic	min Z_G	213.21	25.01%	114.65	65.97%
		min E_P	231.24	18.67%	98.43	70.78%
	Optimistic	min Z_G	304.50	38.22%	99.99	70.32%
		min E_P	315.98	35.89%	98.43	70.78%
	Pessimistic	min Z_G	157.01	11.89%	183.13	45.64%
		min E_P	201.28	−12.95%	98.43	70.78%
B	Realistic	min Z_G	218.50	27.46%	102.90	71.69%
		min E_P	238.77	20.73%	85.13	76.58%
	Optimistic	min Z_G	302.18	42.54%	87.02	76.06%
		min E_P	305.00	42.01%	85.13	76.58%
	Pessimistic	min Z_G	171.86	8.57%	256.54	29.41%

		min E_P	220.92	−17.54%	85.13	76.58%
C	Realistic	min Z_G	171.61	13.25%	125.56	34.58%
		min E_P	201.71	−1.97%	54.08	71.82%
	Optimistic	min Z_G	253.70	27.37%	57.82	69.88%
		min E_P	260.29	25.48%	54.08	71.82%
	Pessimistic	min Z_G	112.73	8.01%	133.78	30.30%
		min E_P	184.44	−50.50%	54.08	71.82%

Under RS assumption, COSs can yield GC reduction of approximately 13–28% and PES of 34–72% compared to the baseline scenario. Lower values correspond to the building C, which has the lowest initial GC and PEC, and higher to A and B. For all three buildings, the optimal exterior insulation is the improved EPS of 14 cm thickness. The optimal insulation for the interior walls towards unconditioned spaces is regular EPS of 15 cm for the buildings B and C. The floors towards the basements should be insulated with XPS of 15 cm for A and 12 cm for B and C. The ceiling of the building A should have 12 cm EPS insulation, while the roofs of B and C should be insulated with 20 and 15 cm XPS, respectively. Buildings A and B should have the cheapest offered PVC fenestration, while the replacement of the fenestration is not optimal for C.

In OS, COSs result with 27–43% GC reduction and 70–76% PES. For all the buildings, the best considered insulation for the exterior walls is optimal (20 cm improved EPS), as well as the best options for floors and ceiling/roofs insulations. For the building B, the interior walls should be insulated with 15 cm EPS and for C with 15 cm SMW. The new, moderately expensive fenestration with triple glazing and argon fulfillment is optimal for all the buildings, having wooden frames for A and B and an AL frame for C.

PS offers lower GC reduction and PES for COSs: 8–12% and 30–46%, respectively. The optimal insulation of the exterior walls is regular EPS of 12 cm for the buildings A and C and 13 cm for B. The interior walls should be insulated with 8 and 10 cm EPS for B and C, respectively. The insulation of the first floor should be 12 cm EPS for A and 10 cm EPS for B and C. The ceiling of the building A should have 10 cm XPS insulation. It is determined that it is optimal not to insulate the roofs of the buildings B and C, as well as not to replace the fenestration for either building.

Figures 1–5 show PEC and GC for each measure considered during the sensitivity analysis. Only the measures related to the insulation of the exterior walls and the replacement of the fenestration differ among each other significantly in PEC or GC. Other types of ER are obviously useful, but similar in effects.

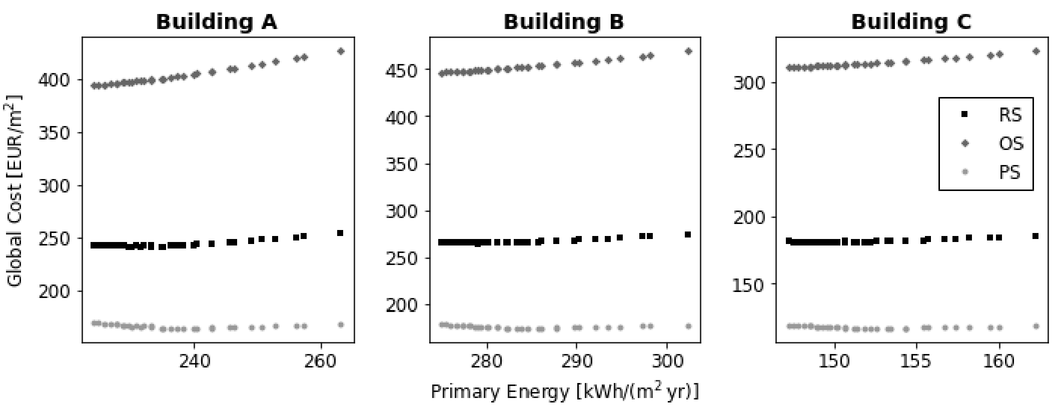

Figure 1. Primary energy and global cost for different insulations of the exterior walls

COSs obtained when the insulation of the exterior walls is analyzed are the same for all the buildings and scenarios, except for the building A in PS where the result is 13 cm regular EPS. When the insulation of interior walls is regarded, the best measures are also the same as the ones corresponding to COSs, except for the building B in OS where 15 cm SMW is obtained instead of EPS with the same thickness. For the insulation of the first floor, the best solutions are consistent with COSs. COSs for the buildings B and C in PS does not have an additional insulation of the roof, but the sensitivity analysis yields the solutions with 12 cm XPS. Other solutions are consistent with COSs. Finally, the results of the sensitivity analysis when considering the fenestration replacement are the same as in COSs for RS and PS, while for OS, the installation of less expensive fenestration is suggested.

Therefore, it can be concluded that in most cases, the results of the sensitivity analysis — where retrofit measures are examined one-by-one — are consistent with the COSs obtained by optimizing the packages of measures. In some cases, however, the sensitivity analysis suggests sub-optimal solutions that have slightly better insulation and worse fenestration. The differences are the consequence of the joint effects of multiple measures.

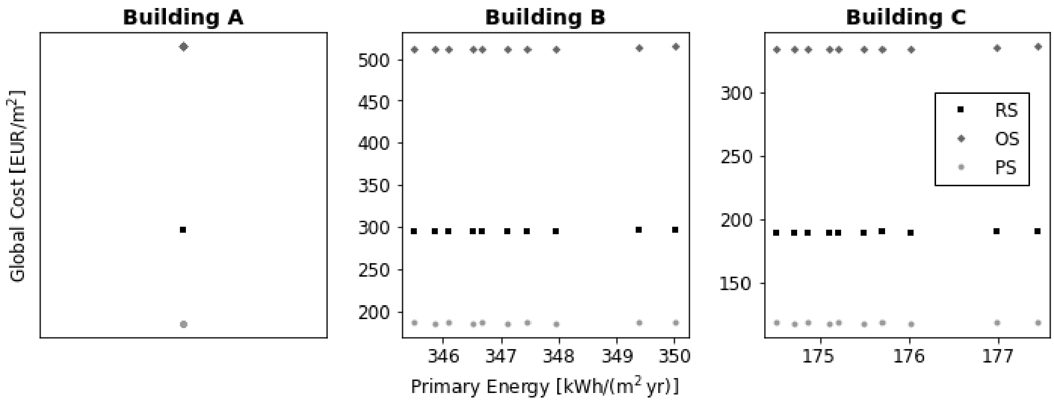

Figure 2. Primary energy and global cost for insulations of the interior walls

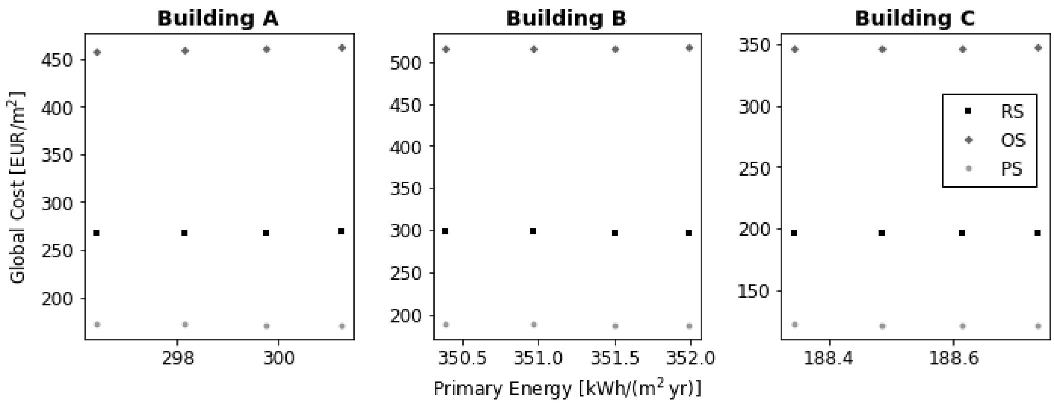

Figure 3. Primary energy and global cost for insulations of the floors towards the basements

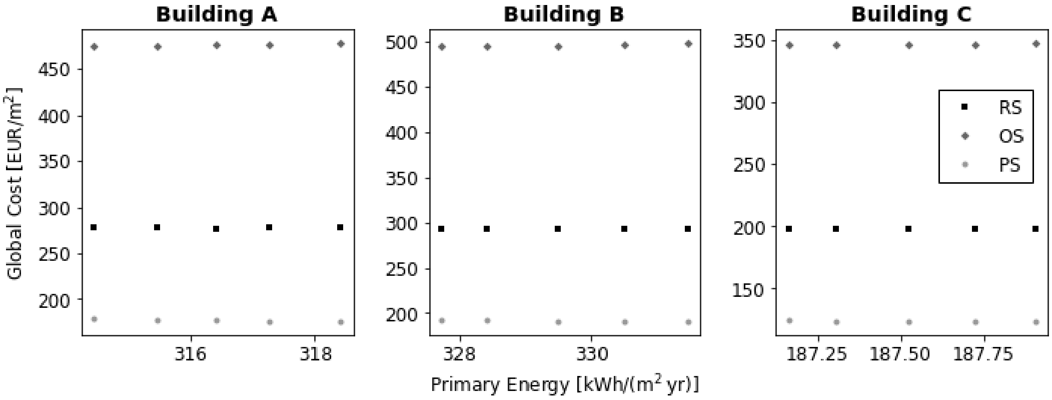

Figure 4. Primary energy and global cost for insulations of the ceiling towards the attic and roofs

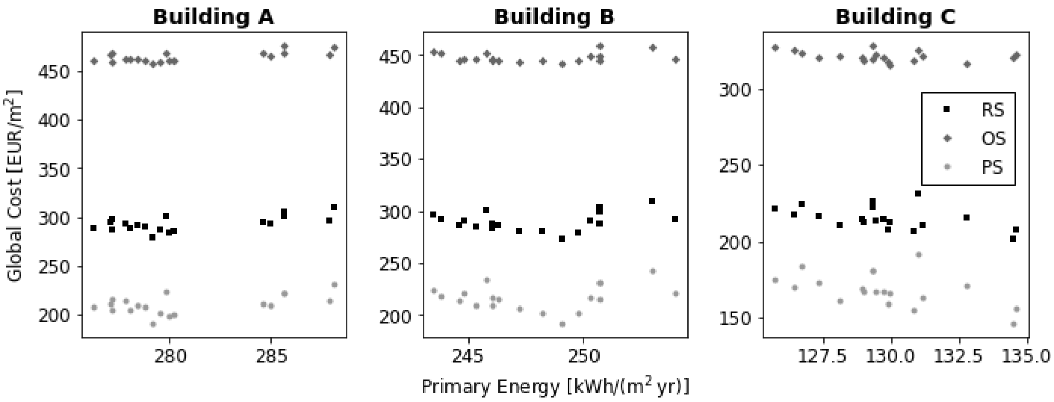

Figure 5. Primary energy and global cost for different types of fenestration

The potential for PES of the considered ER measures and corresponding GC is illustrated in Tab. 2 and Fig. 6.

As mentioned, Tab. 2 demonstrates possible PES when the objective functions are GC and PEC. The latter case illustrates PES potential when moving beyond cost-optimality, towards zero energy buildings. All the optimal solutions obtained with the objective function from Eq. (4) have the best (in terms of thickness and thermal conductivity) insulations offered and the fenestration with low thermal transmittances and low to moderate solar energy transmittances. The total PES potential is above 70% for all the buildings considered, being almost 77% for B. For PSs, PES potential is 1.6–2.6 times higher compared to the PES corresponding to COSs. Contrary, for OSs, these values are almost equal for all three buildings since the optimal solutions obtained when minimizing GC and PEC are very similar. For RSs, the significant difference among the two is only observed in the case of the building C.

Table 2 also shows the additional costs required to achieve better PES compared to COSs. For PS, GC reduction is negative, meaning that achieving almost full PES potential requires larger GC compared to the "do-nothing" alternatives summarized in Tab. 1. Opposite, OS have almost equal GC reductions for the cost- and PE-optimal solutions. Such solutions in RS have negative GC reduction only for the building C, while A and B are positive and the GC reduction differences between the cost- and PE-optimal solutions are 6–7%.

Finally, Fig. 6. displays the Pareto optimal curves when both GC and PEC are considered objectives simultaneously. It displays GC and PEC for the compromising solutions in between the cost- and PE-optimal ones. The curves that correspond to PS are the longest since the differences in the objective values are the highest. For OS, there are only few points on these curves due to the proximity of COSs and the solutions with lowest PEC, *i.e.* the similarity between the two.

A very important conclusion from Tab. 2 and Fig. 6. is that COSs and their fulfillment of the total PES potential significantly depend on the chosen economic input parameters. These parameters are very hard to predict, and it is very questionable how would and an investor or decision maker act in practice having these figures in mind. This raises the necessity to further consider various sets of inputs and define a high-quality compromise among the corresponding COSs.

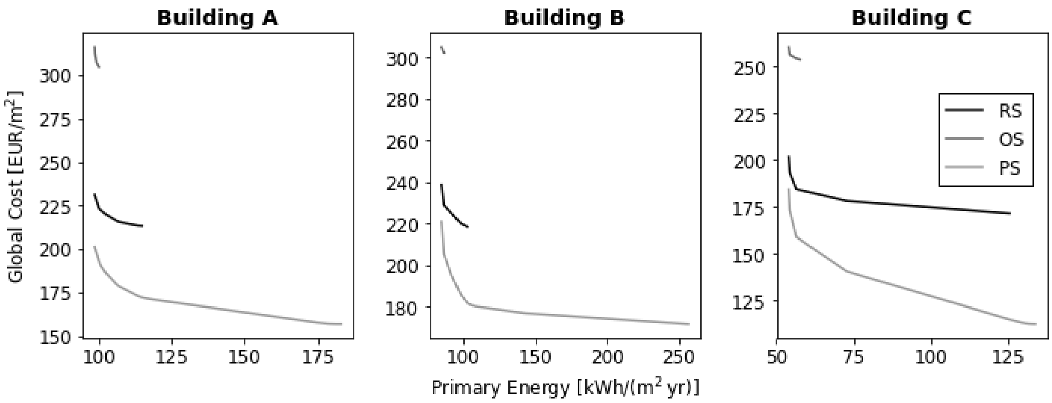

Figure 6. Pareto optima for multiobjective optimization problems

5. Conclusions

This paper aims to determine the cost-optimal energy retrofit measures for a strategically very important part of energy consumers in Serbian conditions — residential buildings connected to district heating systems. It analyzes the potential to reduce costs and the primary energy consumption by improving buildings envelopes in the cost-optimal manner. Additionally, it identifies the solutions with the lowest primary energy consumption, thus calculating the primary energy savings potential of the considered measures.

The paper analyzes some of the typical buildings for Serbian urban areas: a single-family, small multi-story multi-family, and large multi-story multi-family building. To take into account the uncertainties related to the economic input parameters, it examines different scenarios: the realistic, optimistic and pessimistic one.

The cost-optimal solutions are found as the result of the combinatorial optimization problem using the genetic algorithm combined with local search, as well as the solutions with the lowest primary energy consumption. The sensitivity analysis is also conducted to provide the insight into the effects of particular measures. In most cases, the results of the sensitivity analysis are consistent with the cost-optimal packages of measures, but in some cases, the sensitivity analysis yields sub-optimal solutions.

The reduction potential of the global cost heavily depends on the analyzed scenario, *i.e.* chosen economic input parameters and can be in the range 8–43% with the corresponding primary energy savings of 30–76%. Going further, from cost-optimal retrofit towards zero-energy buildings, the total potential for primary energy savings exceeds 70%, but yields higher global cost, in some cases larger than in the baseline scenario.

The paper shows the applicability of the used methodology, but also underlines high dependencies of the results on very uncertain economic inputs. Future work should focus on the consideration of this impact and discovering compromising solutions, applicable through different scenarios, *i.e.* sets of input parameters.

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