Heat recovery ventilation solutions for school building renovation – case study

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Abstract.
School building ventilation solutions have been mainly natural ventilation. Only in a few decades has the renovation of ventilation systems in school buildings started. However, there are still many buildings in Estonia that have natural ventilation or mechanical extract ventilation without heat recovery. Last solution can ensure indoor climate requirements in favourable climate conditions if well designed. However, this can lead to excessive heating energy use resulting in not adequate energy performance. Therefore, there is a need of ventilation system renovation to improve both IAQ and energy performance. Two solutions with different cost are studied in this paper: classroom air handling unit (AHU), and central AHU. The aim of this study is to determine which solution is better in energy efficiency if there is demand to renovate ventilation system in school building. The calculations have been done in standard and real use and climate. Study will show the cost-optimality of these solutions in school buildings. Two school building models were composed and building performance simulations (BPS) with the test reference year climate file were conducted to calculate the building energy use based on EN 16798-1:2019 and real use (where the building model was calibrated with monthly measured real energy consumption from year 2014). Previous studies show, that natural ventilation is an electricity saving solution, but not good for indoor climate. This study found that classroom-based solution is easier to build and the initial cost is lower. However, the energy saving for central ventilation solution will exceed the classroom solution of 29 kWh/m². Considering energy and cost calculations, the centralized mechanical ventilation with heat exchange will be slightly more cost-optimal solution in this case study as it gained 4 €/m² lower global cost than classroom-based solution.

Keywords. School building, mechanical ventilation, heat recovery, cost-optimality, energy efficiency.
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1. Introduction

Average school building is more than 30 years old and in acceptable condition, but not with a good indoor environment. The ventilation system has not been the priority of renovation. Quite a few school buildings have natural ventilation or mechanical extract ventilation without heat recovery.

Achieving a good indoor environment for study or work activity requires ventilation rates of the order of 8 l/s per person. That will prevent any impairment of pupils' performance due to inadequate ventilation. [1] The mechanical extract ventilation with window opening will achieve 2.3-3.8 l/s per person [2] and therefore do not fill this recommendation as well the supply temperature will be as low as outdoor air temperature. Furthermore, as mentioned in [2] that the air quality was judged by the students to be the worst in the mechanically ventilated classroom. Therefore, the final solution and maintenance plan should be advised.

The idea of this study is to determine which solution is better in energy efficiency if there is demand to renovate ventilation system in school building. Using a simulation method, the study will consider cost and show the change of heat and electricity energy use if the mechanical extract ventilation system (without heat recovery) will be replaced by mechanical ventilation system with heat exchanger in two possible solutions.

There was considered, that the air change rate is equal to renovated building models ventilation system and correspond to recommendations in [1].

2. Research Method

2.1. Description of the reference building

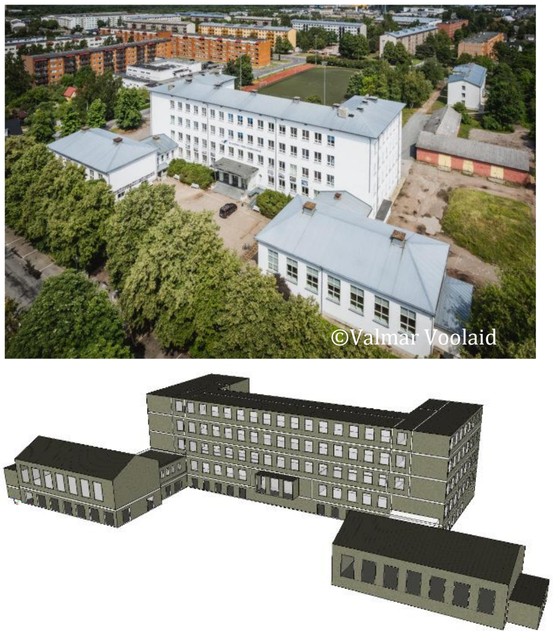


Fig. 1 - Reference building photo and IDA-ICE model

The reference building (Fig. 1) is one school building in Estonia, Kuressaare. The actual heated area is 5300 m². It includes the main body (classrooms, teacher offices, and library) and functional sections (canteen, hall, gym, and educational centre). The main body ventilation of the building has been renovated in 2005-2006 from natural ventilation solution to mechanical extract ventilation system (without heat exchanger) (Fig. 2). The construction of a ventilation system in the canteen, hall, and gym was in 2003. The educational centre was built as new in 2012 with mechanical ventilation with heat recovery.

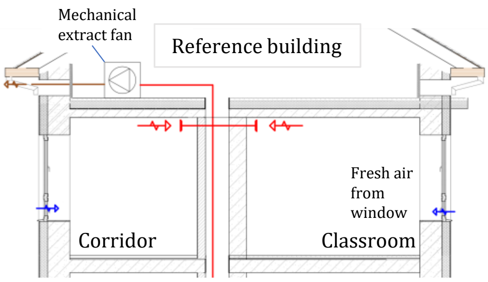


Fig. 2 - Principle of the reference ventilation system in a building

2.2. Simulation Model and Method

The simulation model (Fig. 1) has been built in the well-established and validated simulation software IDA ICE [3]. Model zones are described in Tab. 1.

The simulation model construction U-values was taken as similar as possible to reference building (Tab. 2) and thermal bridge values (Tab. 4) was taken as the average practice and some specific thermal bridges were calculated in the study [4]. Specific air leakage rate was taken 4 m³/(h m²) and infiltration 0.0556 l/(s m² external surface) was calculated according to regulation [5]. The average domestic hot water use is 172 l/m² floor area and year, and the distribution is 50% during 16. June to 14. August. The loss of the distribution system was taken by 3% of the heat delivered by the plant.

Tab. 1 - Building model zones quantity, area and share over total area

Zones	No. of zones	Area, m²	Share
Classrooms	14	1789	33%
Offices	2	191	3.5%
Library	1	86	1.6%
Staircase and corridor	7	2240	41%
Main body	**24**	**4306**	**78%**
Canteen	1	280	5.1%
Hall	3	368	6.7%
Gym	1	315	5.7%
Environmental education center	3	223	4.0%
Other	2	12	0.2%
Total	**34**	**5504**	100%

Tab. 2 - Building envelope area and U-values

Building envelope	Area [m²]	U-value [W/(m² K)]	% of total
Walls above ground	3487	1.06	48.17
Basement wall	319	1.34	5.55
External wall / Educational centre	158	0.19	0.39
Canteen wall	81	1.08	1.14
Staircase wall	342	1.49	6.64
External wall / Hall new part	62	0.19	0.15
External wall / Main	1772	1.11	25.63
External wall / Hall and Gym	707	0.92	8.47
External wall / Gym new part	47	0.35	0.21
Walls below ground	12	1	0.16
Basement wall below ground	12	1	0.16
Roof	1865	0.24	5.88
Roof / Educational center	67	0.14	0.12
Roof / Main	1798	0.25	5.76
Floor towards ground	1925	0.42	10.49
Floor / Educational centre	90	0.21	0.24
Floor / Hall new part	45	0.29	0.17
Floor / Main	1791	0.43	10.07
Windows	1056	1.05	14.41
3 pane glazing, clear, 4-12-4-12-4	1056	1.05	14.41
Doors	19	1.35	0.34
EST External door(2019), heated space	6	1.01	0.07
External door / Gym new part	13	1.49	0.26
Thermal bridges			20.56
Total	8364	0.92	100

Tab. 3 - Model description

	Model 1: Reference building	**Model 2: Classroom-based ventilation system**	**Model 3: Central ventilation system**	**Required air flow for main body, l/(s*m²)**	**Actual air flow in RB, l/(s*m²)**
Classrooms	Mechanical extract ventilation without heat recovery	Classroom-based	Central AHU	2.5-4	0.6
Offices				1.5	0.55
Library				1.5	0.55
Staircase and corridor		Mechanical extract ventilation without heat recovery		1	0.38
Canteen and kitchen	Kitchen AHU	Kitchen AHU	Kitchen AHU	1	1
Hall	Hall AHU	Hall AHU	Hall AHU	1.5	1.5
Gym	Gym AHU	Gym AHU	Gym AHU	1.5	1.5
Environmental education center	Edu Center AHU	Edu Center AHU	Edu Center AHU	2.5	2.5
*Average air flow, l/(s*m²)*	0.72	1.89	1.89	1.89	0.72

Tab. 4 - Thermal bridges of the reference building

Envelope	Thermal bridge, W/K/(m joint)
External wall / internal slab	0.3
External wall / internal wall	0.0686
External wall / external wall	0.2
External windows perimeter	0.4
External doors perimeter	0.3
Roof / external walls	0.53
Roof / internal walls	0.024
External walls, inner corner	-0.2

After the constructions were set similar to the reference building, the lighting, equipment, and ventilation usage was adjusted until the simulation output will fit with the reference building actual metered energy consumption from utility bills, to calibrate the model. According to ASHRAE guideline 14 [6], the model will be considered calibrated if the building performance simulation (BPS) achieves an approximate mean bias error (MBE) of ±5% and a CV(RMSE) of 15% compared to monthly energy use. This building model energy simulation gets CV(RMSE) 10% and MBE 1.1% for electricity and respectively 17% and -4.9 % for heating energy use. Regarding to that, we have only the main heat and electricity meter and cannot determine the specific energy use, the model considered to be calibrated enough to go further on comparison.

Four simulation models were composed. Models with two different ventilation solutions with required air flows were composed (model dissimilarities are described in Tab. 3). Furthermore, there has been composed two reference building model: one with actual air flows (RB_actual) and another with required air flows (RB_req_air). The principles of the ventilation system are described in Fig. 2, Fig. 3. There are two types of AHU heat exchangers used in the model: cross-flow plate and non-hygroscopic rotor heat exchanger. In detail, see AHU parameters in the Tab. 5.

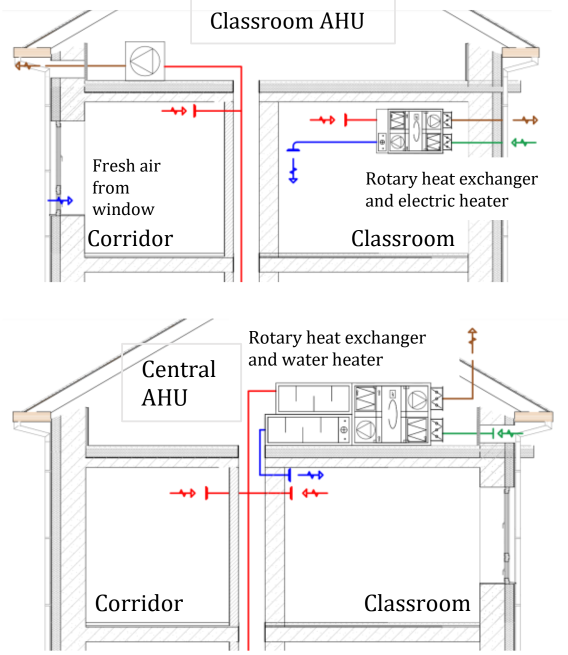


Fig. 3 - Principle of the classroom-based and central ventilation system

Energy simulations for each model for the purpose of comparison, was conducted with real use that is corresponding to calibrated model. The climate file was test reference year (TRY) that is described in T. Kalamees and J. Kurnitski study [7]. Finally, the simulation with standard use from national regulation [5] was done to normalize the usage and climate and find the impact of usage on energy efficiency.

The focus of this study is on the main body of building that include classrooms, offices, library, staircases, and corridors (Tab. 1).

Tab. 5 - Air handling units parameters

AHU (heat exchanger type)	SFP, kW/(m³/s)	Heat exch. Effective-ness, %	Min. allowed leaving temp., °C
Kitchen AHU (plate)	2	70%	0
Hall AHU (plate)	2	60%	1
Gym AHU (plate)	2	70%	0
Edu Center AHU (plate)	1.67	70%	1
Mechanical extract fans (-)	0.9	-	-
Classroom AHU (rotor)	1.5	80%	0
Central AHU (rotor)	1.67	80%	-5

2.3. Indoor Climate Control

The main purpose of these solutions is to ensure good indoor climate conditions in main body of building. Therefore, the concentration of CO_2 and the indoor temperature were considered during simulations. The limits for a good indoor climate are under 800 ppm of CO_2 concentration and room air temperature between 21-25° C. As the building do not have cooling, overheating was considered during 1. May-15. June and 15. Aug-30. Sept

2.4. Economic calculation method

The cost has been asked from representatives who work or have been working in a ventilation contracting or designing company. The authors get one approximate evaluation for each solution and one exact example for the cost of a real school building central ventilation renovation completed in 2020. Both ventilation system solutions have been evaluated in detail, and the cost determined for each part in the system, design and building process. In a classroom-based ventilation solution, the cost has been evaluated for one classroom and then multiplied with 28 classrooms. However, the cost is evaluated by the prices in 2020. The economic prospect has been evaluated by the extra cost per saved delivered energy and global cost calculations according to [8] and EN 15459-1:2017 [9], where the equations 1-3 were used:

$$C_g = \frac{C_I + C_a \cdot f_{pv}(n)}{A_{floor}} \tag{1}$$

where, C_g is the cost related to global incremental energy performance, NPV, €/m²; C_I is the construction cost related to energy performance included in the calculations, €; C_a annual energy cost during starting year, €. For heating energy (district heating) price in 2020 was 0.058 €/kWh and price of electricity 0.076 €/kWh (VAT incl.); $f_{pv}(n)$ is present value factor for the calculation period of n years; A_{floor} is heated net floor area, m².

$$f_{pv}(n) = \frac{1-\left(1+\frac{R_R - e}{100}\right)^{-n}}{\frac{R_R - e}{100}} \tag{2}$$

where, R_R is the real interest rate, %; e is escalation of the energy prices of 2%; n is the number of years considered, i.e. the length of the calculation period is 20 years. For the real interest rate the following equation was used:

$$R_R = \frac{R - R_i}{1 + R_i/100} \tag{3}$$

where, R is the market interest rate 5% and R_i is the inflation rate for 2020 -0.5% and for 2019 2.3% according to Bank of Estonia.

3. Results and Discussion

Following section will introduce the results on the energy efficiency and cost-optimality of two school ventilation solutions. The indoor climate condition has been controlled for Model 2 and Model 3. Average air flow for both models is 8 l/s per person (ca 2.9 l/(s*m²)) and the room temperature setpoint during heating period is 21° C. These conditions are providing a good indoor climate: CO_2 concentration is under 800 ppm during all usage time and the room temperature is 21° C during heating period. However, during the cooling period and the school usage time, the room temperature will rise by more than 25° C in total around 400 ° Ch. That is not within the boundaries of national regulation [10]. Therefore, this building needs shading or cooling in the cooling period.

In general, these two solutions are different in the renovation process. The classroom-based ventilation system is easy to build and therefore a faster solution for renovation if there is an urgent need of good air change rate. However, central ventilation solution demands to close the school for several months (Tab. 6).

Tab. 6 - Renovation work for two solutions

	Classroom-based ventilation solution	Central ventilation solution
AHU and ducts installation	classroom	main body
Electrical installation	classroom	at the place of central unit
General construction and finishing work	classroom	main body
Renovation work duration	week	several months

3.1. *Two ventilation solution energy consumption*

The main body electricity consumption (Fig. 4) did not differ in between the two models with two ventilation solutions that much as for heating consumption (Fig. 5). However, the electric heater increases the electricity use about 3.8 kWh/m²a to the classroom-based system. Therefore, the electricity consumption is higher than for the central ventilation system (Fig. 6). Obviously, the influence is also on AHU fans, but the difference is minor.

Zone heating is the highest energy-consuming component for both models (Fig. 6). However, classroom-based model will consume 32 kWh/m² more heat in zones than model with central ventilation, because of mechanical ventilation without heat exchange in corridors and staircaises (that will occupy 41% of main area (Tab. 1)).

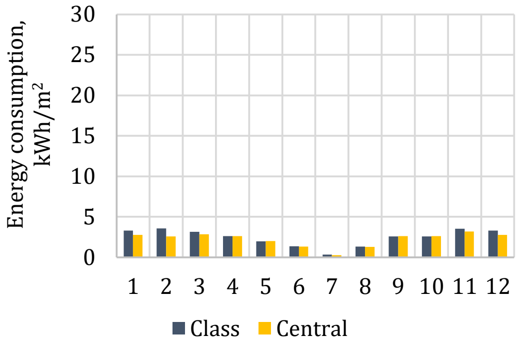


Fig. 4 - Total monthly electricity consumption of the main body for the two ventilation solution models

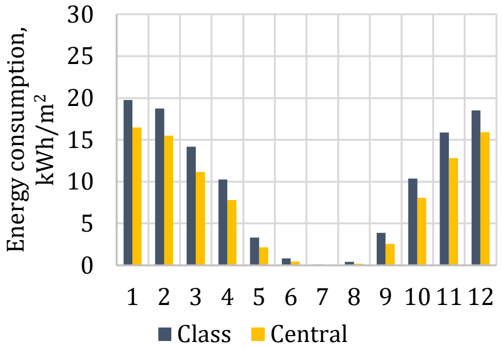


Fig. 5 - Main body total monthly heating energy consumption for two ventilation solution model, kWh/m²

3.2. *Total building energy consumption*

Energy simulation with whole model of real use shows that the best solution is a ventilation system with central AHU that will service the main body of the building. The primary energy was calculated with PE factors: 0.65 for efficient district heating and 2 for electricity. The lowest primary energy (PE) consumption (Fig. 7) is for model with central ventilation system (159.4 kWh/m²) and almost equal PE consumption is for models RB_actual and Class. Compared to the actual reference building, the delivered energy saving in total is 43 kWh/m² (153 kWh/m² compared to the RB with required air flow) for the model with central ventilation system. Saving is 14 kWh/m² (124 kWh/m² compared with RB with required air flow) for model with classroom-based ventilation system. (Fig. 8)

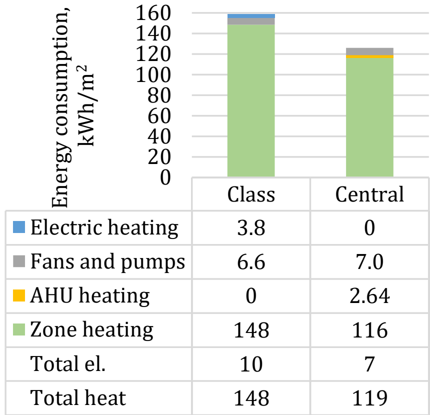


Fig. 6 - Annual energy consumption of the main body for two ventilation solutions

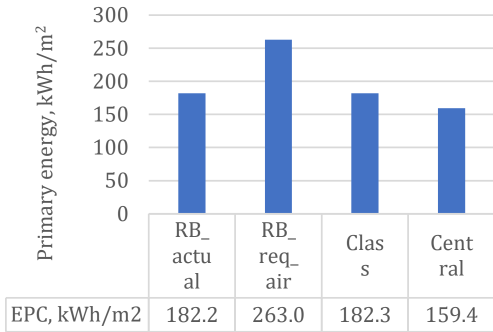
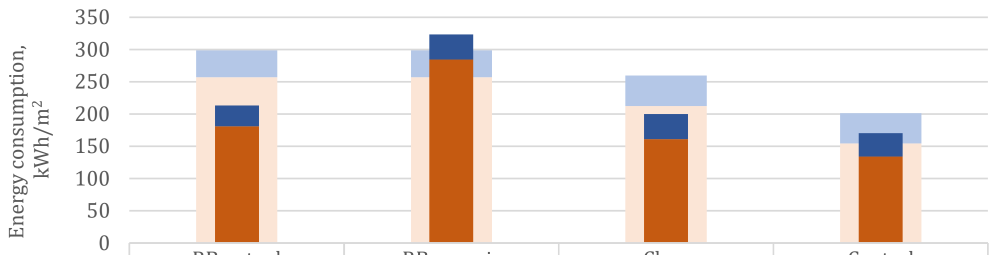


Fig. 7-Primary energy consumption for each model

3.3. *Comparison of the real and standard use of building*

Comparing the BPS based on standard (EN 16798-1:2019) use with real performance (Fig. 8), the energy consumption relative change will vary 6-30%, depending on model. Electricity consumption between the two solutions will differ 2.7 kWh/m² in real use and 0.5 kWh/m² in standard use. However, the heating consumption difference between two solution is 27 kWh/m² in real use, but 58 kWh/m² in standard use. The 31 kWh/m² difference comes as a result of air flow in the building. As for real use, only the main body have 3 l/(s*m²) air flow and other parts have 1-1.5 l/(s*m²). However, in standard use the regulation sets to have a total building of 3 l/(s*m²).



	RB_actual	RB_req_air	Class	Central
Electricity_STD	41.5	41.5	47.4	46.9
Heating_STD	257	257	213	155
Electricity	32.2	39.1	38.7	36.0
Heating	181.3	284.5	161.2	134.4

Fig. 8 - Delivered energy consumption for each model with real and standard (STD) use, kWh/m²

3.4. Practice and Profitability of Two Ventilation Solutions

The renovation of ventilation in school buildings is not straightforward. It needs good preparation and planning. The solutions in this study are almost contrary as explained previously.

Tab. 7 – Renovation cost for two solutions (20% VAT incl.)

	Classroom-based ventilation solution	**Central ventilation solution**
Ventilation system materials and installation, €	312,000	330,000
Additional construction work and finishing, €	56,000	126,000
Electrical installation, €	57,600	50,000
Design and project managing cost, €	17,000	30,000
Margin, %	20%	20%
Total cost, €	531,120	643,200
Total cost, €/m² per renovated section area	123	150
Total cost, €/m² per total heated area	97	117

In this case, the renovation of the central ventilation system will cost about 117 €/m² total heated area and the classroom ventilation solution about 97 €/m² total heated area. However, central ventilation solution is still that much energy efficient, that due to good energy savings, the extra cost per saved delivered energy is almost 2.6 times lower for central ventilation solution. (Fig. 9) Compared to the reference model with the same air flow, the extra cost per saved delivered energy is minimal. (Fig. 10)

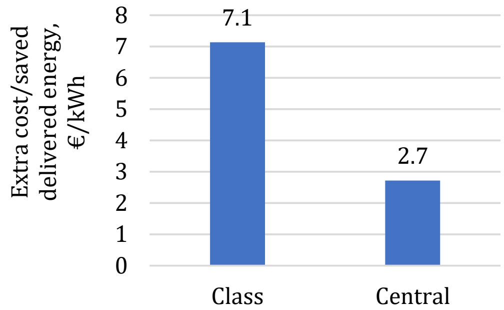


Fig. 9 - Extra cost per saved delivered energy (compared with RB_actual)

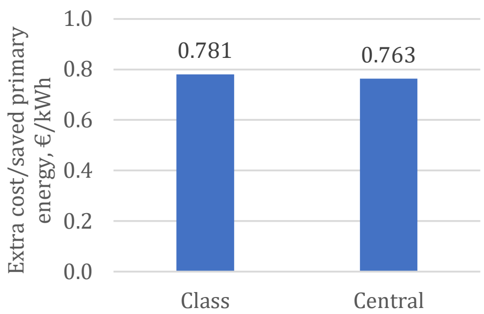


Fig. 10 - Extra cost per saved delivered energy (compared with RB_req_air)

In Fig. 11 and Fig. 12 can see that the central ventilation system will be the best option considering the energy efficiency and cost-optimality with about 4 €/m² lower global cost. The reference building that will achieve indoor climate conditions has almost 10 €/m² higher global cost and 80-100 kWh/m² higher primary energy consumption than renovation solutions. However, the actual case has the lowest global cost, but will not achieve the indoor climate requirements.

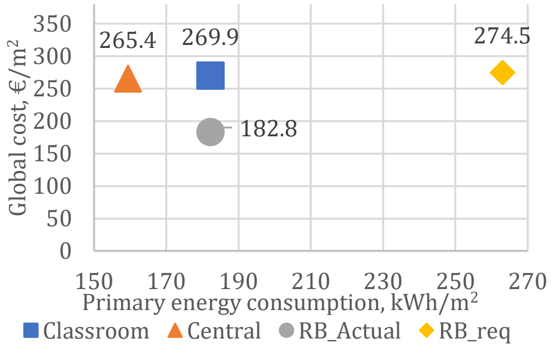


Fig. 11 - Global cost with calculations of 2020 interest rate and inflation

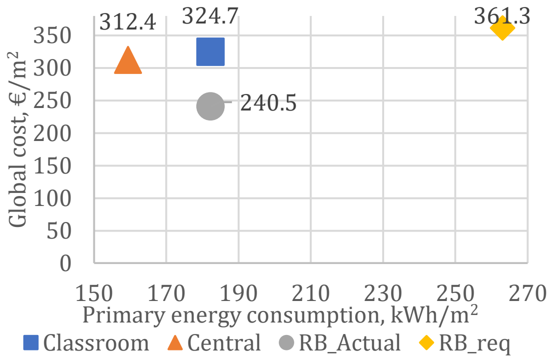


Fig. 12 - Global cost with calculations of 2019 interest rate and inflation

4. Conclusions

Two school building models were composed and building performance simulations (BPS) with the test reference year climate file were conducted to calculate the building energy use according to the EN 16798-1:2019 and the real use. The result of calculations will show the change of heat and electricity energy use if the mechanical extract ventilation system (without heat recovery) will be replaced by mechanical ventilation system with heat exchanger.

There have been compared two possible solutions:

- classroom-based mechanical ventilation with heat recovery that will serve only classrooms (mechanical extract fan for corridors)
- central mechanical ventilation with heat recovery that will serve the main body

Classroom-based solution is easier to built and the initial cost is lower. However, the energy saved is only 14 kWh/m² (124 kWh/m² compared to the RB with required air flow) compared to a central ventilation solution that will save 43 kWh/m² (153 kWh/m² compared to the RB with required air flow). Considering energy and cost calculations, the centralized mechanical ventilation with heat exchange will be the cost-optimal solution in this case study as it gained about 4 €/m² lower global cost. However, the global cost differs only 70-80 €/m² between the cost-optimal solution and the reference building, where the requirements are not up to the standards.

The limitation of this study is the calibration rate, as the model meets only partially the recommendations of calibration due to incomplete energy meter data. Therefore, next studies should be done with buildings that have more specific data on energy consumption. This study considered the savings in test reference year climate. Further studies should calculate saving also in real climate conditions as recommeded in ASHRAE Guideline. Furthermore, the results show that the energy consumption will differ up to 30% between standard and real use. Therefore, next studies should consider normaization aspects in energy calculations. The profitability of solutions is reasonable as it will not consider the indoor climate - in school we can not save energy at the expense of study environment. Further studies should include the indoor environment, so it can be used for government support system.

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Data sharing not applicable to this article as no datasets were generated or analysed during the current study

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