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ECONOMY OF TEMPERATURE CONTROL, HEAT COST ALLOCATION AND ADDITIONAL INSULATION IN MULTIPLE UNIT DWELLINGS IN LITHUANIA

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Abstract. The paper study the economy of improvements in the heating system and in a building in Lithuania and introduces the use of the cost of cold in heating calculations. A reduction in the cost of cold is the value of an increased indoor temperature. Supply water temperature control in the building eliminates the cold periods before and after the heating season. This reduces the cost of cold. Additional insulation both reduces the cost of cold and the cost of heat. Individual heat cost allocation reduces the cost of cold since every household can chose the temperature they are willing to pay for, if the heat transfer between the dwellings is compensated. The cost of cold is higher at the high price of heat p_h = 45 EUR/MWh. Better economic data is necessary to draw definite conclusions about the economy.

Keywords: economy, individual, heat cost allocation, multiple unit dwelling, heating, insulation

1. Introduction

A theory for the choice of the best quantity of a collective or public goods was developed by Erik Lindahl 1919 according to [1]. Heating was called semi-collective goods in [2]. Semi means that the access to the indoor temperature is limited to the members of the households. He assumed that the control of the indoor temperature is individual but it is in practice collective. The theory for collective goods was explained in [3]. [4] used the theory for public goods to find the best common indoor temperature in a building with two dwellings.

The demand curve for indoor temperature in Swedish multiple unit dwellings was determined in [5] as a straight line and in Swedish single unit dwellings in [6] and [7]. Heat cost allocation in homes with individual control and individual heat metering, individual temperature metering and collective allocation was described in [8].

The demand curve for indoor temperature as a collective goods was introduced in [9] and the reduced influence on the indoor temperature from heat transfer between dwellings with a fixed and variable part was described in [10].

If individual heat cost allocation from measured heat quantity is installed in a building with multiple unit dwellings and supply water temperature control then indoor temperature is changed from a collective to a private goods. If all dwellings have the same indoor temperature then it is collective and if everybody have their own then it is private. The value of having individual indoor temperatures compared to having the same can be calculated.

2. Problem formulation

A household hh chooses indoor temperature so that the sum of cost of cold and cost of heat is minimised. The cost of cold is the value of the inconvenience of having a low indoor temperature. If the hh in a building have individual indoor temperatures then every hh minimises its own sum of cost of cold and cost of heat. If the hh have a common temperature they must together find the common indoor temperature that minimises the sum of the sum of cost of cold for all hh and the sum of cost of heat for all hh. The value of introducing individual temperatures is the difference of the sums.

2.1 Individual temperature

If the individual indoor temperature in (Fig. 1) falls to t* then the hh starts to think it is a bit cold. If the indoor temperature falls to t then it is so cold that the hh starts to heat the building. The hh accepts a cost instead of letting the indoor temperature fall below t. The hh balances the costs of heat or the cost of indoor temperature against the cost of cold so that the sum is minimised at the temperature t, equation (1) and (Fig.1).

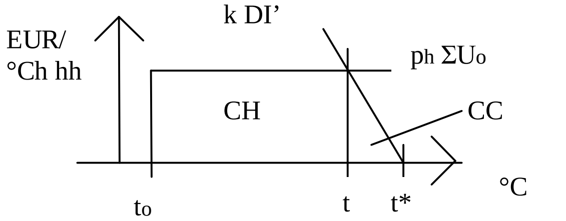

Fig. 1. Cost of Cold, CC and cost of heat, CH at indoor temperature t and outdoor temperature t_o

where k - a constant 1/°C^2, DI' - the disposable income per household and hour EUR/hh h, p_h - the price of heat EUR/MWh, ΣU_o - the specific heat demand for the heat loss to the outdoor air W/°C, t* - the highest demanded temperature or the highest temperature someone is willing to pay for °C.

$$t = t^* - \frac{p_h \cdot \Sigma U_o}{k \cdot DI'} \qquad (1)$$

The heat lost to the outside is used heat. Heat transferred to other dwellings is not used until it reaches the outside of the building. The cost of cold EUR/h hh at the indoor temperature, t is equation (2)

$$CC = \frac{k \cdot DI'}{2}\left(t^* - t\right)^2 \qquad (2)$$

2.2 Collective temperature

If many households share a building with supply water temperature control then they will get the same indoor temperature. It is a collective temperature t_c. The best collective temperature is the temperature that minimises the sum of cost of heat and cost of cold for the hh:s. The demand curves for three hh:s are shown in (Fig. 2).

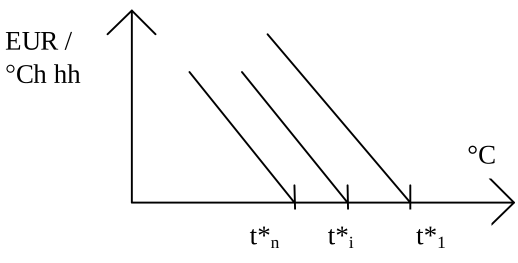

Fig. 2. Individual demand curves for indoor temperature

To be able to minimise the sum of cost of cold and cost of heat for the hh:s add the demand curves vertically and add the marginal cost of heat for the hh:s. If the hh:s t* belongs to a normal distribution with the standard deviation s*, the demand curves are added vertically and divided with the number of hh:s then we will get the demand curve in (Fig. 3). It starts at the highest demanded indoor temperature for any hh. The collective temperature t_c is higher than the average of individual temperatures t_i.

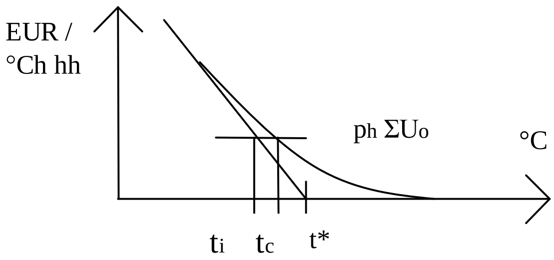

Fig. 3. Demand curve for a collective temperature t_c and for the average of individual temperatures t_i.

The dimensionless demand curve for a collective indoor temperature is found from a numerical integration of the normal distribution. The area under the demand curve or the dimensionless cost of cold is found after another integration. To calculate the cost of cold for a collective temperature the dimensionless demand curve in Table 1. is used. t* = 21.65°C, s* = 1.3°C and k = 0.004 1/°C^2 from [7], [8] and [11].

The dimensionless indoor temperature equation (3).

$$t^\circ = \frac{t^* - t}{s} \qquad (3)$$

The dimensionless reduction of indoor temperature equation (4).

$$t^\circ{}_i = \frac{p_h \cdot \Sigma U_o}{k \cdot DI' \cdot s} \qquad (4)$$

where s:

$$s = \sqrt{s^{*2} + s_b{}^2} \qquad (5)$$

where s_b - the standard deviation for the normal distribution of temperatures in the dwellings.

The marginal cost of cold MC EUR/°Ch, hh from equation (6).

$$MC = MC^\circ\left(t^\circ{}_i\right) \cdot k \cdot DI' \cdot s \qquad (6)$$

The costs of cold is CC EUR/h,hh from equation (7).

$$CC = CC^\circ\left(t^\circ{}_i\right) \cdot k \cdot DI' \cdot s^2 \qquad (7)$$

The reduction of costs RC at a change from a collective to individual indoor temperatures from equation (8). To get the cost of cold and reduction of costs per year multiply with the length of the heating season τ h/year.

$$RC = RC^{\circ}(t^{\circ}{}_i) \cdot k \cdot DI' \cdot s^2 \quad (8)$$

Table 1. Dimensionless average of individual, t°i and the collective temperature, t°c marginal cost of cold, MC° cost of cold, CC° and reduction of costs, RC° at the introduction of individual temperatures, from [11]

t°i	t°c	MC°(t°i)	CC°(t°i)	RC°(t°i)
2.0	1.99	2.01	2.50	0.50
1.8	1.79	1.82	2.12	0.50
1.6	1.58	1.62	1.78	0.50
1.4	1.36	1.44	1.47	0.49
1.2	1.15	1.26	1.20	0.48
1.0	0.90	1.08	0.97	0.47
0.8	0.65	0.92	0.77	0.43
0.6	0.35	0.77	0.60	0.39
0.4	0.00	0.63	0.46	0.33
0.2	-0.50	0.51	0.35	0.23
0.0	-2.00	0.40	0.25	0

If t°i is bigger than 2 the dimensionless cost of cold CC° can be calculated with equation (9)

$$CC^{\circ} = \frac{t^{\circ}{}_i{}^2}{2} + 0.5 \quad (9)$$

3. Building data

The building is 48 m long, 10 m wide and 13.5 m high. It has 150 windows, 2 m^2 each. It has 45 dwellings on 5 floors and an unheated cellar. The floor division is 2.7 m. The ventilation has an air change rate of 0.75 /h. There are 3 entrances and 3 stairs. The heated area on the 5 floors is 2400 m^2 according to [12]. The heated volume is 6480 m^3. The ventilation based on the air change rate is 4860 m^3/h or 1.35 m^3/s. The specific heat demand from Table 2 3.52 kW/°C + 1.35 m^3/s x 1.2 kg/m^3 x 1 kJ/kg°C = 5.14 kW/°C. The specific heat demand for heat loss out is in average 5.14 / 45 = 114 W/°C, dw.

Table 2. Heat transfer data for the building before additional insulation (*against cellar)

part	Area, m^2	U-value W/°C, m^2	kW/°C	Sum kW/°C
Wall	996+270	1.4	1.77	
Window	300	2.6	0.78	
Roof	480	1.0	0.48	
Floor	480	1.6	0.48	*
Doors	6	2.4	0.01	3.52

A heat meter HM for the building is installed (Fig. 5) and the heat cost is distributed to the households after area. After the heat use is known supply water temperature control SWTC in the building is installed. Then additional insulation add ins. and finally individual heat cost allocators and individual payment HCA. Approximate investments in Table 4.

Additional insulation reduces the specific heat demand for transmission from 3.52 to 1.92 kW/°C according to Table 3. Ventilation is still 4860 m^3/h or 1.35 m^3/s. The specific heat demand for the building becomes 3.54 kW/°C and for a dwelling 79 W/°C dw.

Table 3. Heat transfer data for the building after additional insulation (*against cellar)

part	Area, m^2	U-value W/°C, m^2	kW/°C	Sum kW/°C
Wall	996+270	0.4	0.51	
Window	300	2.6	0.78	
Roof	480	0.3	0.14	
Floor	480	1.6	0.48	*
Doors	6	2.4	0.01	1.92

Table 4. Investment in energy saving measures. The investments are approximate and only used to demonstrate the principles.

Measure	Quantity	Price	Sum
SWTC			6.000 EUR
HCA	45 dw	70 EUR/dw	3.150 EUR
Add ins, roof	480 m^2	10 EUR/m^2	
Add ins, walls	1266 m^2	40 EUR/m^2	55.000 EUR

To read the heat cost allocators, to calculate and send the bill to the households costs 10 EUR/hh yr. For all 45 dwellings in the building 450 EUR/yr. It is assumed that a full year with 20°C indoors during 230 days has 100 000°Ch degree hours. The degree hours are calculated with the same length of the heating season. Free heat from sun, persons, light etc is neglected.

4. No control in the building

The supply water temperature is controlled at the central heating plant for the district. The heating starts on the 1 October and stops the 31 Mars. Heating is used during 180 days. As a result the indoor temperature will be only 15°C for 15 days in both April and September. The other 30 days in April and September don't give any cost of cold or needs heating. During the winter the indoor temperature is 25°C during 180 day/yr with 0°C outdoors in average gives 108000°Ch. Heat for heating 5.14 kW/°C x 108 000°Ch = 555 MWh. p_h = 15 EUR/MWh gives 8325 EUR/yr and p_h = 45 EUR/MWh gives 24975 EUR/yr. The result is introduced in Table 7 and Table 8. All households have 25°C. This is higher than someone is willing to pay for so the cost of cold is zero (Fig. 4).

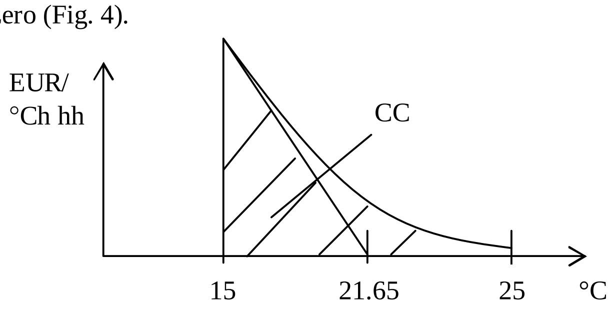

Fig. 4. The marked area is the cost of cold for tc = 15°C

The cost of cold during 30 days with 15°C for the 45 households is calculated with equation (3):
$t°_i = (21.65 – 15) / 1.3 = 5.19$
Equation (9) gives: CC° = 13.6
According to equation (7) and DI = 4000 EUR/hh yr, DI' = DI / 8760 h/yr = 0.5 EUR/h hh the cost of cold is:
CC = 13.6 x 0.004 1/°C^2 x 0.5 EUR/hh h x 1.3^2°C^2 = 0.046 EUR/hh h. 0.046 EUR/hh h x 30 days/yr x 24 h/day x 45 hh = 1489 EUR/yr. The result to Table 5.

5. Supply Water Temperature Control in the building (SWTC)

The first measure is to install a heat exchanger that separates the heating system in the building from the district heating network (Fig. 5). The heat exchanger and the automatic temperature controller TC is used to control the supply water temperature to the radiators to make the indoor temperature stable and the same in all dwellings during the full heating season now 230 days. No value for the separation of the heating system from the district heating system is added in the calculations. The temperature in the dwellings have a standard deviation s_b = 0.8°C. It depends on the design and balancing of the heating system. Equation (5) gives s = 1.6°C. It is assumed that the heating system is working and no renovation is necessary.

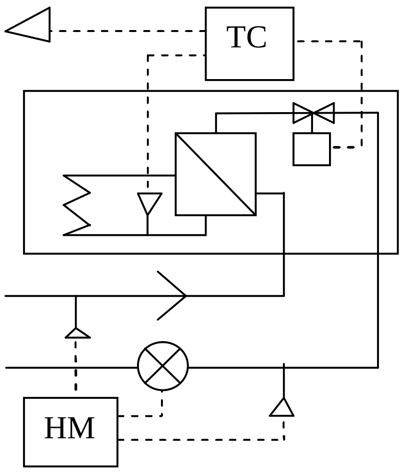

Fig. 5. Supply water temperature control after outdoor temperature and heat exchanger.

The collective temperature with SWTC at p_h = 15 EUR/MWh is calculated with equation (4).
$t°_i$ = 0.015 EUR/kWh x 0.114 kW/°C / (0.004 1/°C^2 x 0.5 EUR/h hh x 1.6°C) = 0.53. $t°_i$ = 0.53 and Table 1 gives $t°_c$ = 0.23 and the collective temperature from equation (3) t_c = 21.65°C – 0.23 x 1.6°C= 21.3°C. The indoor temperature is 21.3°C in average during the full heating season 230 days. The number of degree hours is 107176°Ch and the heat use 551 MWh. p_h = 15 EUR/MWh gives 8265 EUR/yr to Table 7. The cost of heat is distributed among the households after area.

The cost of cold at the collective temperature 21.3°C, s = 1.6°C and $t°_c$ = 0.23
CC°($t°_i$) = CC°(0.23) = 0.40 from Table 1.
0.40 x 0.004 1/°C^2 x 0.5 EUR/h hh x 1.6^2 °C^2 = 0.00205 EUR/hh h from equation (7). 0.00205 EUR/hh h x 230 days/yr x 24 h x 45 hh = 509 EUR/yr to Table 7.

The calculation of the other collective temperatures follows the same principles and the result is given in Table 5, Table 7 and Table 8.

Table 5. Calculation of collective temperature t_c with SWTC before and after additional insulation. Cost of cold CC for the building and heating degree hours/yr °Ch at t_c.

ph EUR/ MWh	ΣUo W/°C	s °C	t°i	t°c	tc °C	CC°	CC EUR/ yr	Degree hours °Ch/yr
					25	0		108000
		1.3			15	13.6	1489	
15	114	1.6	0.53	0.23	21.3	0.40	509	107176
15	79	1.6	0.37	-0.07	21.8	0.23	292	109936
45	114	1.6	1.60	1.58	19.1	1.75	2188	95032
45	79	1.6	1.10	1.02	20.0	0.98	1246	100000

6. Additional insulation

Add ins. is applied to the outside of the walls and in the attic under the roof Table 3. Add ins. changes the relative heat demand between the dwellings so the indoor temperature will differ. The heat demand on the top floor will be more reduced than on a floor in the centre of the building, here s_b still is 0.8°C. The collective temperature and the cost of cold after add ins. is calculated with equation (4), (5) and (7). They are shown in Table 5, Table 7 and Table 8.

7. Individual heat cost allocation

Individual heat cost allocation HCA involves the hh in the control of the indoor temperature. They can choose the temperature they are willing to pay for. Since the indoor temperature in a MU-dwelling do not fall to the outdoor temperature when the heaters are shut of. The heat from the heaters in a dwelling should be divided in a fixed part and a variable part. The indoor temperature falls to the balance temperature t_b (Fig. 6) where a dwelling without heating is in heat balance with the surrounding dwellings and the outdoor air. The fixed part is included in the rent.

The variable part (1 - Φ) should make the specific heat demand for a dwelling equal to the specific heat loss to the outdoor air or equal to the marginal heat loss to the outdoor air according to equation (10) and (Fig. 7).

$$(\Sigma U_o + \Sigma\Sigma U_{int})\cdot(1-\Phi) = \Sigma U_o \qquad (10)$$

where ΣU_o - the specific heat demand (transmission and ventilation) for heat loss to the outdoor air W/°C. $\Sigma\Sigma U_{int}$ -

the sum of specific heat transfer with the surrounding dwellings W/°C.

If the cost for the measured heat from the heat cost allocators are distributed among the hh without division into a fixed and a variable part then the indoor temperature would bee to expensive. The households would have to pay the marginal cost of temperature for both the heat transfer to the neighbours and to the outside.

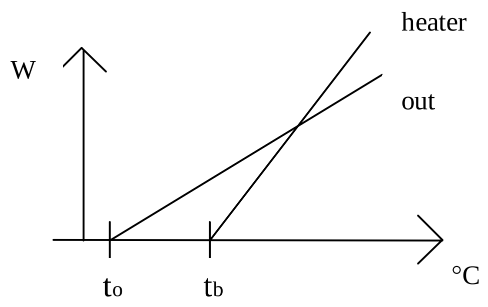

Fig. 6. Heat from heater and heat to the outdoor air W. Outdoor temperature, t_o. Temperature in a dwelling with closed heaters, t_b balance temperature.

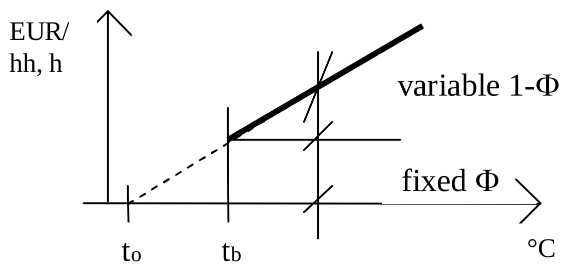

Fig. 7. Cost for heat from heater divided in a fixed and a variable part.

If a dwelling is situated under the roof and at the short wall of the building it has a big area against the outdoor air and the heat transfer out 126 W/°C (before additional insulation). The heat transfer to other dwellings is 195 W/°C. Heat for ventilation 0.03 m^3/s x 1.2 kg/m^3 x 1 kJ/kg°C = 36 W/°C. Total heat out 126 + 36 = 162 W/°C. The fixed part Φ according to equation (10) should be 195 / (162 + 195) = 0.55

If a dwelling is situated in the centre of the building the heat transfer out is only 48 W/°C. The heat transfer to other dwellings is 345 W/°C. Heat for ventilation 36 W/°C. Total heat out 48 + 36 = 84 W/°C. The fixed part Φ should be 345 / (84 + 345) = 0.80. It is assumed that every dwelling has the correct fixed and variable part.

Individual control of the indoor temperature means that the hh must do the control work them selves and that the valves on the radiators are working. No extra cost for this has been added in Table 4, Table 7 and Table 8.

The average indoor temperature with HCA t from equation (1) if the fixed and the variable part is adjusted to the new transmission data after add ins. is shown in Table 6, Table 7 and Table 8.

Table 6. Indoor temperature t and cost of cold CC with individual heat cost allocation HCA after additional insulation. Average disposable income DI = 4000 EUR/hh yr

ph EUR/ MWh	ΣU_o W/°C	t °C	CC EUR/yr	Degree hours °Ch/yr	E MWh/yr
15	79	21.1	75	106072	375
45	79	19.9	761	99448	352

8. Summary of costs and pay-off periods

The profitability is the relation between investment and in this case cost reduction. The reduced costs are the costs of heat or energy. The relation used is the pay-off period or investment divided by the cost reduction.

The degreehours from Table 5 and Table 6 together with the specific heat demand from Table 2, Table 3 and the price of heat gives the cost of heat in Table 7 and Table 8. The Cost of Cold in Table 5 and Table 6 is put into Table 7 and Table 8 where they are added into the sum of cost of cold and cost of heat.

Table 7. Cost of cold and cost of heat for the building at p_h = 15 EUR/MWh and average disposable income DI = 4000 EUR/hh yr

	Indoor temp °C	Cost of Cold EUR/yr	Cost of Heat EUR/yr	Sum EUR/yr
No control	25 or 15	1489	8325	9814
SWTC	t_c = 21.3	509	8265	8765
Add ins.	t_c = 21.8	292	5835	6127
HCA	21.1	75	5625	5700

With no control in the building and the low price of heat the cold periods in Sept and April gives a high cost of cold in Table 7. SWTC eliminates the cold periods so the cost of cold is reduced. The cost of heat is not changed since the cold periods needs heating to be eliminated. Additional insulation Add ins. makes a degree of heating less expensive so the indoor temperature increases. The increase is known as the take-back or rebound effect. Add ins. reduces the cost of cold and the heat cost. HCA will reduce the indoor temperature and as a result the cost of heat. When all hh get their own indoor temperature the cost of cold is reduced. The Engel number after SWTC is 8265 EUR/yr / 45 hh * 4000 EUR/hh yr = 4.6 %. (Ernst Engel 1821 -1896)

At the high price of heat in Table 8 and no control in the building the cold periods in September and April gives a cost of cold. At the high price of heat 45 EUR/MWh the indoor temperature is reduced to 19.1°C and the cost of cold will be higher than during the cold periods in Sept and April. The cost of heat is reduced due to the low indoor temperature.

Table 8. Cost of Cold and cost of heat for the building at the price of heat p_h = 45 EUR/MWh and average disposable income DI = 4000 EUR/hh yr

	Indoor temp °C	Cost of Cold EUR/yr	Cost of Heat EUR/yr	Sum EUR/yr
No control	25 or 15	1489	24975	26464
SWTC	t_c = 19.1	2188	21960	24148
Add ins.	t_c = 20.0	1246	15930	17176
HCA	19.9	761	15842	16603

Add ins. makes a degree of heating less expensive so the indoor temperature increases to 20.0°C. The Engel number after SWTC is 12.2 % and after add ins. 9 %. HCA will not reduce the indoor temperature since it is already low but the cost of cold is reduced. The cost reductions from the investments is calculated from Table 7 and Table 8 and given together with the investment from Table 4 in Table 9.

Table 9. Saving or total reduction of costs and Pay-off period. DI = 4000 EUR/hh yr.

		p_h = 15 EUR/ MWh		p_h = 45 EUR/ MWh	
Measure	Invest-ment EUR	Saving EUR/ yr	Pay-off yr	Saving EUR/ yr	Pay-off yr
SWTC	6000	1049	5.6	2316	2.6
Add ins	55000	2676	20.5	6972	7.8
HCA	3150	427-450 = -23	-	573-450 = 123	25

Both SWTC and add ins. in Table 9 gives the highest saving and shortest pay-off period at the high price of energy. If individual heat cost allocation HCA is introduced after Add ins. at p_h = 15 EUR/MWh the cost is not reduced so much that it will cover the cost for reading and administration of the meters 450 EUR. If HCA is introduced after add ins. at p_h = 45 EUR/MWh the cost of cold is reduced so much that it will cover the cost for reading and administration of the meters. The pay-off period for the investment in the meters are however long.

9. Conclusions

The use of both the cost of cold and the cost of heat makes it possible to calculate the value of measures that increases the indoor temperature, such as supply water temperature control in the building. Additional insulation reduces the cost of heat and the cost of a temperature increase. This gives a small increase in indoor temperature that reduces the cost of cold.

Individual heat cost allocation has been seen as a method to save energy but individual temperatures have a value that can be calculated if both the cost of cold and the cost of heat are used.

Since the investments are highly approximate no definitive conclusions can be made, but it is profitable to install supply water temperature control to get a constant and optimal indoor temperature during the cold part of the year. Additional insulation is probably profitable at the high price of energy p_h = 45 EUR/MWh.

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