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ENERGY RETROFITTING OF RESIDENTIAL BUILDINGS

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Abstract-*Due to worldwide concern about global warming new and effective solutions for energy saving are being developed and implemented. The final thesis addresses various challenges related to the energy retrofitting of multi-storey residential buildings and research on the efficiency of different measures for energy sufficiency improvement of residential buildings. In the first chapter of thesis the principals of energy saving, and energy retrofitting of buildings are analysed, followed by exploring of legal regulation and financial frameworks for innovative buildings modernisation methods.*

The practical part of the thesis presents the research on the energy efficiency improvement measures and building retrofitting scenarios, which are adopted in European countries. Three case studies for energy retrofitting of residential buildings, located in Kaunas, were analysed and the most efficient retrofitting scenario was selected by implementing life cycle cost analysis and marginal costs method. The conducted research showed sufficiency of these for assessment of energy saving efficiency in buildings.

***Keywords**: Energy retrofitting of building;Building life cycle cost;Marginal costs; Building retrofitting measures;Residential buildings*

Introduction: Entire world is suffering from global warming, because of excess carbon emission. Our oil resources and other natural energy resources are going to finish in next few decades. Because of excess using of non-renewable energy resources and increasing pollution, global temperature and CO_2 quantity in air is increasing tremendously. According to data from NASA, the amount of CO_2 was 32billion metric ton on 2012, and it was predicted the value will reach up to 43.2 billion metric ton by 2040. Generally building sector is one of top sector of generating greenhouse gases [1]. Building construction is highly related to large energy consumption and it have significant impacts on the environment. During construction heavy amount of energy required to complete the construction activities. Building activities are also related to waste generation, greenhouse gases production, and large amount of water consumption. According to data in Australia almost 7.6% of total primary energy consumed on the time of construction of buildings (both nonresidential and residential buildings). And almost 6% of greenhouse gases produced along with large amount of construction waste [2]. According to international outlook 2016 (U.S. energy admiration) data energy consumption of entire world is increased by 37% in the last 25 years. OCED (Organization for Economic Co-operation and Development) countries will increase 20% of energy consumption from 2012 to 2040, where non OCED countries having 70% of increasing energy consumption [3]. Entire world nowadays is more concentrated on energy saving and toward greater use of renewable energy resources. Global trends like green buildings, zero energy buildings, passive house and energy retrofitting buildings can provide large contribution towards energy savings. In all IEA (International Energy Agency) counties up to 40% of total energy is consumed by buildings, including human activities. Buildings are generally responsible for high energy consumption, most of the energy used by thermal systems and humans comfort systems and other building services equipment's. Day by day science and technology improves and lots of electronic gadgets are coming in the market for human comfort and our energy consumptions also increasing day by. So, energy saving become a big challenging matter, 40% of total energy goes on building, so it can be reduced up to 50% and in some case, it can be reduced 100% by proper management.

Buildings retrofitting can provide from 20% to more than 50% of energy saving in buildings. So, it can make a large contribution toward protecting our world from excess carbon emission. And it not only provides contribution towards energy savings, it also saves our money.

1. Building energy retrofitting practice in European countries and building energy norms

Buildingretrofitting and constructing nearly zero energy building was on existence from last few decades. Building energy retrofitting came in attention in building sector to enhance using of the renewable energy resources and to help reducing the climate change. European commission always remarking the need of improving building energy performance [4]. From the centuries buildings were constructed for getting certain comfort within their built environment. Nowadays new construction technologies, inventions and more efficient materials came into the market, which are widely used.

the year of 2007 in Italy energy uses in residential sector was reduced 20%. The improvement came because of using efficient lighting, proper thermal insulation and efficient air conditioning system. From the 2005 to 2012 almost 3.79 Mtoe/y, energy saved. In Italy almost 62% large buildings were built before 1970s [5]. US also showing the improvements in reduction of building energy. According to data, US reduced space heating consumption by 12%, in 1991 it was 53% and on 2011 it was 41% [6]. According to International energy agency report US, EU, and Russia showed huge improvement in energy consumption. On 1990 total energy consumption of those country was US (21%), EU (18%), Russia (10%), and by the 2011 it had huge improvement and reduced the energy consumption to 17%(US),13%(EU),5%(Russia) [7]. It has been observed that newly constructed buildings are consuming less energy for heating compared to before. Because Newly constructed building should follow the European norms. Following figure shows the figure of heating energy consuming data according to the building construction time. Germany, Portugal and Slovenia showed huge development in term of building energy saving [8].

In Europe almost 40% of total building constructed before 1960, those building have low insulation level. That's why those buildings required retrofitting to increase the energy efficiency. In Lithuania almost 12% of building constructed before 1960 and almost 70 % of total building constructed during 1960 to 1990. In Europe almost 40% of the total buildings was constructed before 1960, so retrofitting of building is the most important and essential, because constructing new building will be much more expansive than retrofitting of existing building.

Space heating of building consumes lots of energy. In 2013 the space heating contributed 62% of total energy consumption of buildings in the Europe. Therefore, proper energy efficient retrofitting can provide better result in decreasing energy consumption [9].From the year of 2009 European Commission started retrofitting of existing government owned buildings, and structures. European commission set target to renovate at least 3% of total floor area of government owned buildings, and this process to continue till 2020 [10]. Energy efficient building retrofitting became popular and widely used throughout the Europe. Countries like Denmark, Sweden, Germany, Netherlands, Austria, Latvia and some others took part in the collaborative initiative, targeting at dissemination of good practice in retrofitting projects.

According to the European commission norms, EU norms and other legal requirements buildings are being allocated to the energy efficiency class by compliance with 8 different rating parameters.

The rating parameters are as follows –

- Heat loss of the building envelope
- Total required energy for building heating purposes.
- Airtightness of the building
- Technical indicators or MEV (mechanical extract ventilation) along with heat recovery system
- Thermal properties used between spans and floor partition
- C value
- Using of renewable energy resources

All the above requirements are very much and equally important for calculating the building energy efficiency rating. Any kind of priority are not subjected to given to any specific parameter. All the parameters are equally considered.

- Class A, if C < 0,5;
- Class B, if 0,5 ≤ C < 1;
- Class C, if 1 ≤ C < 1,5;
- Class D, if 1,5 ≤ C < 2;
- Class E, if 2 ≤ C < 2,5;
- Class F, if 2,5 ≤ C < 3;
- Class G, if C ≥ 3.

Where c value is changes according to conditions

When $\frac{\text{Qsum}}{\text{QN.sum}} \leq 1,\ C = \frac{\text{Qsum}}{\text{QN.sum}}$

When $\frac{\text{Qsum}}{\text{QR.sum}} \geq 1,\quad C = 1 + \frac{\text{Qsum}}{\text{QR.sum}}$

In the other cases $C = + \frac{\text{Q.sum} - \text{QN.sum}}{\text{QR.sum} - \text{QN.sum}}$

QN_{sum} = Building normative kwh/m^2.year

$QR._{sum}$ = reference kwh/m2.year and $Q_{sum} = calculated\ kwh/m^2.year$

Insulation system**:** For maintaining U-value, we should change our insulation system. Day by day technology is improving, lots of new innovative insulation materials came into the market. Although the initial costs are higher, the material can provide longer durability with proper working condition. We should use best insulation properties within economic cost. Where Economic cost means best product within the price range.

1.Table: Energy performance requirements for buildings in Europe [11]

<table>
<tr><td rowspan="2">Building element</td><td colspan="4">U-values, W/m^2. K</td></tr>
<tr><td>Class A++</td><td>Class A+</td><td>Class A</td><td>Class B</td></tr>
<tr><td>Roof</td><td rowspan="2">0.080 k</td><td rowspan="2">0.10 k</td><td rowspan="2">0.10 k</td><td rowspan="2">0.16</td></tr>
<tr><td>Flooring in contact with air</td></tr>
<tr><td>Building elements in contact with ground</td><td rowspan="2">0.10 k</td><td rowspan="2">0.14 k</td><td rowspan="2">0.14 k</td><td rowspan="2">0.25</td></tr>
<tr><td>Flooring over unheated basements and crawl</td></tr>
<tr><td>External walls</td><td>0.10 k</td><td>0.13 k</td><td>0.12 k</td><td>0.20</td></tr>
<tr><td>Windows and transparent building elements</td><td>0.70 k</td><td>1.0 k</td><td>1.0 k</td><td>1.6</td></tr>
<tr><td>Doors and gates</td><td>0.70 k</td><td>1.0 k</td><td>1.0 k</td><td>1.6</td></tr>
</table>

In the figure 9, the value of $k = 20/(\theta_i - \theta e)$; where k is temperature correction factor. And θ_iIs denoted as the indoor air temperature in °C and θ_e is outdoor air temperature in °C. In example if the indoor air temperature $\theta_i = 40$°C and outdoor temperature $\theta_e = 0$°C, then the value of k =0.5.

Retrofitting: Retrofitting of buildings is a concept of reconstruction of building, where old energy inefficient buildings are updated to a modern energy efficient building [12]. Energy retrofitting of building is called when an older building system turns into 20 % to >50% energy saver building system adding modern technology. Generally, energy retrofitting of building is classified into three different classes according to percentages of energy savings [13]. And those are-

- Normal retrofitting
- Standard retrofitting
- Deep retrofitting

There is lots of buildings energy retrofitting measures, which may be used to reduce the consumption of the constructing energy:

- Energy performance improvement measures (insulation, heat-insulating door and window frame, building shape, etc.)
- Renewable energy resources (ground source heat pumps, solar panels, photovoltaics)
- Movements for the development of indoor comfort situations (mechanical ventilation combined with heat recovery, efficient use of multi-functional equipment, improvement of boilers and air conditioning)
- Use of building energy management and monitoring system
- Use of energy efficient home equipment and compact lighting

Residential buildings energy retrofitting measures: Selection of energy retrofitting measures for residential building is individual and based upon the preferences and capabilities of the residents. The most popular measures used in the residential construction are as following [14]:

- Energy performance enhancement measures (proper insulation system, good heat-insulating doors and windows frames, and shape of building).
- Renewable energy resources (solar, panel, ground heating).
- Heating and cooling loads decreasing measures (passive heating and cooling technologies).

- Measures for increasing internal comfortless of building (mechanical ventilation system combined with heat recovery system, improving or replacing old boilers and air conditioning).
- Uses of BEMS (Building Energy Management and Monitoring System)
- Energy efficient appliances and efficient lightning.

2. Assessment of building energy retrofitting efficiency

From past few decades several papers and studies introduced the effective solution in building retrofitting sector. In the year 2012 the European Commission established Delegated Regulation [15]. To determine the cost optimum level of nominal energy performance of buildings, and European commission provide a guidance documents to implement the methodology at the national level. Building energy performance can be calculated by several methods like life cycle cost (LCC) methods, marginal cost method, Discounted cash flow(DCF) analysis method, multi-criteria approaches (MCA), Present cost value methides. Marginal costing method is so popular to calculate the energy performance efficiency.

Life cycle cost of building: Building life cycle refers to the use of full operation of building. In other word, the construction to demolition period is called life cycle of building (LCC). LCC is a tool which is used to calculate the overall cost performance of a project over time, which includes the initial investing cost of project and cost of maintenance along with cost of disposal. It is mainly used to evaluate different economic alternatives. In the building sector LCC method has been used from the early 90s. LCC method is a very important tool to access the environment building performance.

Life cycle cost (LCC): Life cycle cost of building can be referred as the total cost of build in its entire life cycle. Life cycle cost(LCC) consist of design cost, planning cost, construction cost maintenance cost, repairing cost, operation cost, social cost, environmental cost and disposal cost etc. The costs are discussed below:

Life cycle cost analysis (LCCA): LCCA is a methodto calculate the total or overall cost of the building, which provides the best economical alternative. The primary cost elements in the LCC calculation model are the following: The following equation has been developed for calculating the LCC in term of energy retrofit [60]

$$LCC_{ES}=IC_{PV}+NFOMC_{PV}+NRC_{PV}+RC_{PV}\pm SV_{PV}-\Delta EC_{PV}$$

Where,

LCC_{ES} = Present value of energy system LCC; IC_{PV} = present value of investment cost; $NFOMC_{PV}$ =present value of annually recurring non-fuel operational and maintenances cost; NRC_{PV} = present value of non-recurring non-fuel operational and maintenance cost; RC_{PV} = present value of recurring non-fuel operational and maintenances cost; SV_{PV} = present value of salvage value; ΔEC_{PV} = present value of annual energy saving costing

For calculating retrofitting effect on life cycle cost of building. Several methods are used like Life cycle cost (LCC), Discounted cash flow analysis (DCF), multi – criteria approaches (MCA). LCCA Tool also used to calculate the assess life cycle cost, LCCA tool was used in Empire state building energy retrofitting in 2008 [16]. LCC can estimate the overall costing of retrofitting and gives alternative solution. Along with it LCC can provide the optimal thickness of insulation material in building envelope and helps to get optimum solution for building energy solution [17].

Marginal cost method: In economics, marginal cost isthe growth or decrease in the overall value of a manufacturing run for making one additional unit of an item. In other word that is the cost of producing another production. Within the short run, the marginal cost is equal to the extra amount of variable factor that the organization must employ to increase the production, multiplied with the aid of how much the organization need so that it will get an extra variable aspect at every level of production at that time. Marginal cost method was first time used in swiss case study in term of building energy renovation [18].

$$M_{CE} = \frac{(CapCost_{\,n} - CapCost_{\,n-1})}{(Denergy_{\,n} - Denergy_{\,n-1})}; \text{ and}$$

$$AC_{EE} = \frac{a_n.Ivc\ Cost_n - a_0.Ivc\ Cost_0}{Denergy_{\,n} - Denergy_{\,n-1}}.$$

Where Cap cost and Ivc Cost was the initial investment cost and capital cost the project. Denergyfactor was the energy demand factor of the building, where n, n-1, and 0 was the energy demand level.

How LCCA helps to decision making for retrofitting, and retrofitting impacts on LCC: Using this LCCA methodology we can easily find out the performance year of building, annual operational expenses like energy costs, water consumption costs, maintenance, insulation costs, solar panel maintenance costs. Generally, the maintenance and operational costs are increasing every year. And in case of renovation of building, modernization costs after its useful life can be calculated according to the condition of building structures. Generally, life cycle cost of buildings calculates for 20 to 30 years. In simple word life cycle costs of buildings are the total cost of building, which include construction or renovation costs, maintenance and operating costs and annual energy costs. So, considering the total costs of building huge financial value is experienced every year, where electricity takes a sizable portion of it. Therefore, proper retrofitting can give bigger savings, that can really reduce life cycle costs of building.

3. Case studiesfor the assessment of retrofitting measures efficiency

The analyzed case studies are multi-story residential buildings in Kaunas, which are used for student residential purposes. Three apartments building case studies described below.

Case study 1: The building is situated in Gričiupio str. 13, Kaunas. This 12th floor building was renovated under Jessica fund. Building was constructed in 1980s with having 518m^2 of built up area and 3061.42m^2 floor area. The building was constructed using brick masonry, acrylic concrete. Buildings total facade area (expect windows and hole area) is 3536.11m^2. The facade wall heat transfer coefficient was 0.9 and 1.16 W/m^{2}K. Total useful area of the building is 3061m^2. Covering roof area is 622m^2 and heat transfer coefficient was 0.216 W/m^{2}K. The building was renovated from June 2014 to September 2015. In 2013 building was consuming 168.73 kWh/m^2/year energy for heating and 21 kWh/m^2/year energy for preparing hot water. 210.84 kWh/m^2 per year in total thermal energy was consuming by the building. The building was upgraded with various energy measures. Buildings plinth area and wall area was insulated using polystyrene panels. The thickness of the layer was 18cm for exterior surface. Roof was fully insulated followed by the thermal insulation norms. Windows was changed and few of them was upgraded. Doors were replaced, and leakage area were sealed. The maximum heat transfer coefficient for external doors in Lithuania is 1.4W/m2. Heating and hot water systems like piping exhaust were replaced. Ventilation systems and heat recovery systems were also replaced. Cold water systems also replaced and upgraded. And along with measures new HVAC system was installed and energy efficient bulb was used. After upgrading building was consuming 60.36 kWh / m^{2}energy per year for heating.

1. Fig: Energy retrofitting measure used in case study 1

Case study 2: The building is situated in Vydūnas al. 25A, Kaunas. The building renovation was approved by Ministry of the Environment of the Republic of Lithuania under Jessica fund. The 4th floor apartment building was constructed in 1960s. Building was certified as D Energy class in 2013. Total use full area of the building is 3784.52m^2. Total floor area of the build is3784.52m^2. Total façade wall area (except windows and hole area) is 2150.24 m^2 and the façade wall heat transfer coefficient was 1.05 W/m^2 K. Covering roof area is 1161.19m^2 and heat transfer coefficient was 0.25 W/m^2 K. The building was renovated from June 2014 to September 2015. Building was consuming 161.64 kWh/m^2/year energy for heating. The building was upgraded with various energy measures. Buildings plinth area and wall area was insulated using polystyrene panels. The thickness of the layer was 18cm for exterior surface. Roof was fully insulated followed by the thermal insulation norms. Windows was changed and few of them was upgraded. Doors were replaced, and leakage area was sealed. The maximum heat transfer co-efficient for door in Lithuania is 1.4W/m2. Heating and hot water systems like piping exhaust were replaced. Ventilation systems and heat recovery systems were also replaced. Cold water systems also replaced and upgraded. And along with measures, new HVAC system was installed, and energy efficient bulb was used. After upgrading building was consuming 47.20 kWh / m ^{2} energy per year for heating.

2.Fig: Energy retrofitting measure used in case study 2

Case study 3: The building is situated in Vydūnas al. 25, Kaunas. The 4th floor apartment building was constructed in 1960 with brick masonry materials. Building was certified as D Energy class in 2013. Total useful area of the build is3658.54m^2. Total facade wall area (expect windows and hole area) is 2160.09 m^2 and the façade wall heat transfer coefficient was 1.05 W/m^2 K. Covering roof area is 1180.77m^2 and heat transfer coefficient was 0.25. The building was consuming 171.93 kWh/m^2/year thermal energy before renovation. Building was consuming 129.88 kWh/m^2/year energy for heating and 21.05 kWh/m^2/year energy for preparing hot water. The building was upgraded with various energy measures. Buildings plinth area and wall area were insulated using polystyrene panels. The thickness of the layer was 18cm for exterior. Roof was fully insulated followed by the thermal insulation norms. Windows was changed and few of them was upgraded. Doors were replaced, and leakage area was sealed. The maximum heat transfer co-efficient for door in Lithuania is 1.4W/m2. Heating and hot water systems like piping exhaust were replaced. Ventilation systems and heat recovery systems were also replaced. Cold water systems also replaced and upgraded. And along with measures new HVAC system was installed and energy efficient bulb was used. After upgrading building was consuming 57.01 kWh / m^2 per year for heating.

3.Fig: Energy retrofitting measure used in case study 3

Marginal costs of different retrofitting scenarios

The following energy retrofitting scenarios were used in case studies:

1. S0-building as is
2. S1-Improvement of building thermal coating of walls and roof
3. S2-Replacement of windows and doors
4. S3-Replacement of heating system
5. S4-Replacement of MVS

2.*Table: Scenarios cost and energy requirements case study 1*

Scenarios and energy efficiency measures	Investment cost in Euro	Energy requirements kWh/m^2/year	Energy savings kWh/m^2/year	Per unit cost of investment Euro/m^2
S0-building as is	0	168,73	-	
S1-building thermal coating wall and roof	214214	123,57	45,16	50.418
S2-Replacement of windows and doors	218905	107,31	61,42	51.52
S3-Replacement of heating system	359072	63,96	104,77	84.51
S4-replacement of MVS	444507	60,36	108,37	104.62

Marginal cost calculation

Case Study 1

$M_{CE} = \frac{(CapCost_{\,n} - CapCost_{\,n-1})}{(Denergy_{\,n} - Denergy_{\,n-1})}$,

For S4: $M_{CE} = 5.586$, S3:$M_{CE} = 0.7610$,S2:$M_{CE} = 0.0678$, S1:$M_{CE} = 1.116$

3.*Table: Scenarios, investment cost and energy requirements for case study 2*

Scenarios and energy efficiency measures	Investment cost in Euro	Energy requirements kWh/m^2/year	Energy savings	Per unit cost of investment Euro/m^2
S0-building as is	0	161,64	-	
S1-building thermal coating wall and roof	147883	138,88	22,76	39.07
S2-Replacement of windows and doors	195331	124,24	37,40	51.61
S3-Replacement of heating system	317055	85,21	76,43	83.77
S4-replacement of MVS	392689	81,96	79,68	103.76

Case study 2

$M_{CE} = \frac{(CapCost_{\,n} - CapCost_{\,n-1})}{(Denergy_{\,n} - Denergy_{\,n-1})}$,

For S4, $M_{CE} = 6.150$, S3:$M_{CE} = 0.823$, S2:$M_{CE} = 0.857$, S1:$M_{CE} = 1.717$

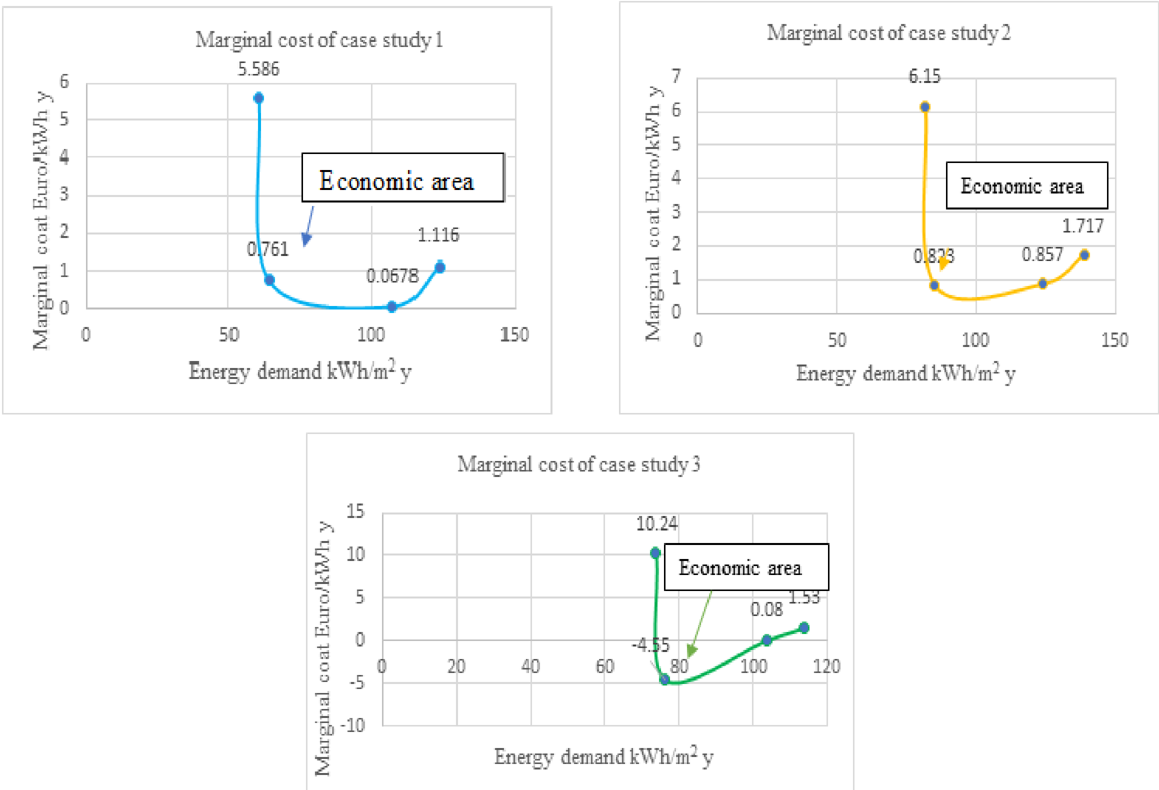
4.Table: Scenarios, investment cost and energy requirements for case study 3

Scenarios and energy efficiency measures	Investment cost in Euro	Energy requirements kWh/m^2/year	Energy savings	Per unit cost of investment Euro/m^2
S0-building as is	0	129.88	-	
S1-building thermal coating wall and roof	147422	113.86	26,32	40.295
S2-Replacement of windows and doors	157809	103.56	61,42	43.134
S3-Replacement of heating system	285216	76.10	53,78	77.96
S4-replacement of MVS	371048	73.81	56,07	101.41

Case study 3

$M_{CE} = \frac{(CapCost_{\ n} - CapCost_{\ n-1})}{(Denergy_{\ n} - Denergy_{\ n-1})}$,

For S4: $M_{CE} = 10.240$, S3:$M_{CE} = -4.55$, S2:$M_{CE} = 0.080$, S1:$M_{CE} = 1.53$



4.Fig: marginal costs of case studies

Above figures show the marginal costs method results. All three case studies show that after small renovation as per application of measure S1, energy efficiency increases insignificant. After using measure S2 all three case study buildings save bigger amount of energy. After providing energy measure S3 all the case study buildings showing significant benefits. And on average almost 70kWh/m^{2}y energy was consumed. But measure S4 is showing optimum level of energy performance because of bigger investment than required by the other measures. For all the case study buildings 1, 2 and 3, the preferable scenario is S3 - Replacement of heating system.

LCC calculation for case studies

For calculating life cycle cost of buildings, we consider the present value of maintenance and operating cost is 15% of total investment cost. Growth rate is considered as 3.5%. We don't have the salvage data. So, considering it as 0. And assumed unit price of electricity as 0.25 Euros/kWh. The equation of the energy life cycle costing of the buildings for 20 years will be.

$$LCC_{ES}=IC_{PV}+TMC_{PV}+\Delta EC_{PV}$$

Where

LCC_{ES} = Present value of energy system LCC; TMC_{PV} = Present value of total maintenance cost; IC_{PV} = present value of investment cost; ΔEC_{PV} = present value of 20 years energy cost

For case study 1

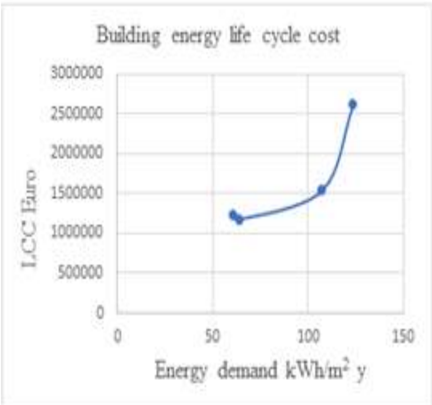
S1 _LCC_{ES}=214214+32132.1+148552.70 = 2612013.7 Euros; S2 _LCC_{ES}=1541816.49 Euros; S3_ LCC_{ES} =1181856.92 Euros; S4_ LCC_{ES} =1236828.14 Euros

For case study 2

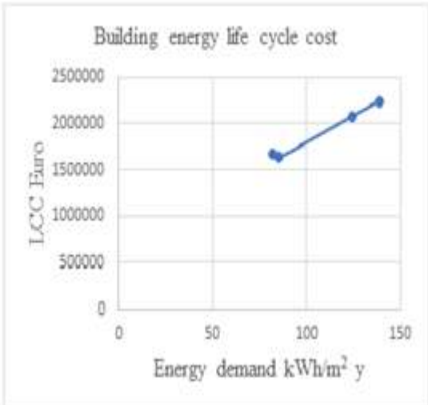
S1 _LCC_{ES}=2234314.29 Euros; S2 _LCC_{ES}=2071277.89 EUROS; S3_ LCC_{ES} =1631165.63 Euros; S4_ LCC_{ES} =1669808.71 Euros

for case study 3

S1 _LCC_{ES}=1805563.11 Euros; S2 _LCC_{ES}=1669510.04 Euros; S3_ LCC_{ES} =1421461.21Euros; S4_ LCC_{ES} =1487263.76 Euros



case study 1



case study 2

case study 3

5.Fig: life cycle cost of case studies

To calculate the most efficient and economic scenario, the LCC method has been adopted. Building energy life cycle costs are calculated for 20 years. Generally, the construction or retrofitting may require high investment cost, but in term of life cycle period it can provide better saving result. In the case study of all three buildings, low investment in measure S1 and S2 shows higher lifecycle cost value. Where by implementing scenario S3, life cycle costs drop very impressively. Due to high initial investment for S4, which had comparatively the same energy requirements as S3, its life cycle costs in all case studies increased compared to S3. Although the energy efficiency rate is little better for S4, S3 provides more savings in terms of its 20 years life cycle period. And S3 scenario provides almost similar energy consumption on all three buildings.

Conclusions

1. To improve the building energy performance, marginal cost and LCC method can be applied for definition of the best scenario or combination of measures. In the old existing buildings and new constructed buildings, it can help to reduce the total life cycle costs with satisfactory energy consumption rates.
2. For assessment of efficiency of retrofitting scenarios different strategies were analyzed. The most popular and adopted scenarios are S2 - Replacement of windows and doors, S3- Replacement of heating system and S4 - Replacement of MVS.
3. Analyzed case studies showed what scenario S3 is the most efficient scenario for building retrofitting under the defined conditions due to significant energy savings. Energy saving of S3 is higher than of scenarios S1 and S2. And the total life cycle cost for S3 is less than S4.
4. Sometimes initial investment of retrofitting measures can be higher and marginal cost can rise fast, but it can provide better results in terms of long time energy savings. In term of long payback period for owner, it may be difficult to handle the project because of high investment costs. The scenarios having higher energy savings along with high financial investment might not be best option. LCC helps to give the best scenarios choice for energy savings.

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