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Residential Construction with a Focus on Evaluation of the Life Cycle of Buildings

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Abstract: The article focuses on highlighting the role of life cycle costing (LCC) in the preparatory and implementation phase of residential projects. It involves the evaluation of several investment scenarios in the pre-investment phase, the choice between variants of the design of the entire building or its parts, and the choice of variants of structures and equipment with acceptable parameters. An innovative method of evaluating the life cycle of buildings is described in the article. This method was tested in selected residential projects realized by Skanska in the Czech Republic. Experience from construction practice shows that the choice of variants, constructions, or equipment of buildings only on the basis of the lowest acquisition costs (lowest bid prices) is wrong. The LCC calculation tool has been designed to model life cycle costs of individual variants of construction designs with different input parameters. It is possible to analyze the components or equipment that have the greatest impact on total life cycle costs. The article presents a tool that evaluates the long-term economic efficiency of the proposed residential buildings in terms of analysis of life cycle costs. The article will also expand the knowledge of the professional and general public about the importance of examining investment and operating costs already in the phase of construction preparation.

Keywords: life cycle costing; residential construction; software; data; environment

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1. Introduction

1.1. Construction's Life Cycle Costs (LCC)

The article deals with the description of the innovative method and LCC calculation tool for evaluation of construction's life cycle costs (LCC). Life cycle costing and analysis are primarily a tool for informed decisions. The analysis is important in finding the best solution when the environmental and long-term sustainability aspects are taken into account. Life cycle assessment of investment residential projects is also part of the building quality assessment system. Life cycle costing should be undertaken for each construction project (residential buildings, industrial buildings, transport infrastructure, etc.).

From the point of view of LCC, green buildings are also widely discussed at present. From an economic point of view, however, the reduced costs for the operation of green buildings are compensated right at the beginning of their construction by increased costs for their construction. The cost-saving benefits can only be seen from an environmental point of view thanks to the ecosystem services provided by green buildings [1].

The cost of creating an LCC model is very minor in comparison with the total construction and operating costs of a construction over its lifetime. The chapters of the article comprehensively describe the method of approach to the issue, which arose in cooperation between the private and university environment. Bringing new knowledge and innovative ways of working to solve specific situations in the application of LCC in residential buildings are gradually clarified in the article and summarized in the final chapter.

The aim is to find the optimal solution of modern residential construction in terms of technical, economic, and environmental aspects. Life cycle costing is important for both the construction company and the potential users of the buildings. Both of these parties are clearly, in advance, informed about the total cost of construction from the beginning to the end of life of building. It is important to realize that not only investment costs but also operating costs play an important role in achieving optimal value for money. Finding the optimum design options will better achieve the desired benefit of the end user.

Authors [2] dealt with the determination of construction costs of three different construction systems. The construction systems considered are reinforced concrete framing, structural steel framing, and cold-formed steel framing. In terms of LCC, cold-formed steel framing is 13.4% higher than the other mentioned construction systems.

Authors [3] analyzed the construction industry of the Czech Republic and identified leaders in this industry using artificial neural networks (ANN). In this context, authors [4] carried out an assessment of the economic added value of construction companies using ANN. Following this finding, value generators of companies operating in the construction industry were subsequently identified [5].

As authors [6] find, the value added in the construction sector behaves very procyclically with sectoral unemployment anticipating the upward trend of overall unemployment rate in the economy in bad times but lags behind in good times. Workers in the construction industry are significantly more vulnerable to unemployment throughout the economic cycle than workers in other industries [7]. As the construction sector is very sensitive to institutional shocks [8], legal framework and other institutional factors can help sustain the construction sector stability throughout the economic cycle [9].

1.2. Life Cycle Assessment (LCA)

To apply life cycle assessment (LCA) and LCC, it is necessary to know the total life of buildings. Authors [10] dealt with the life of the building and for this purpose created a prediction model based on deep-learning and traditional machine learning. Da-ta on the lifespan of buildings in South Korea was used to create this prediction model.

The life cycle assessment is also closely linked to the recycling potential and the environmental impact of materials incorporated in buildings. Authors [11] deal with the demolition of the building, in order to test its applicability at the end of its life and assess the recycling potential of the existing building.

The aim of the owner and real estate management of a residential building is to make decisions that ensure that the building will always be well traded on the real estate market (both in terms of long-term lease and possible sale), there will be no excessive degradation of individual structural elements (especially elements of long-term life), and at the same time the accumulated funds invested in its maintenance and renewal will be minimized in the long term. Achieving this state—the optimum of the total costs incurred—is not an easy task at all. The investor and a construction company are required to use appropriate LCC assessment tools already in the early construction preparation phase. The owner and real estate management of a residential building should also have a long-term strategic plan for maintenance and renovation and a plan for further development of the building, to which the LCC assessment can make a significant contribution.

Life cycle assessment and life cycle costing is a method that is used to evaluate the total cost of ownership of a building. LCC is a method to help determine the cost of construction work and to facilitate decision-making in cases where there are alternative ways to achieve the objectives for the customer and the future user of the construction and where these alternatives differ, not only in initial costs but also in subsequent operating costs. The method makes it possible to compare these alternatives on the same basis [12].

Life cycle costing is particularly useful for estimating total costs at the early stage of a project. The operating costs that will be incurred during the life cycle of the building represent a multiple of the original construction costs. Decisions in the construction preparation phase significantly affect the total life cycle costs. Key cost factors include, in particular, the size of the building, the number of structural elements, technical and mechanical service equipment, and the choice of construction materials [13].

Deciding on the optimal variant of construction is very time consuming and a complex process. This is due to the complexity of the building permitting process and the complicated technological processes during construction. The ESORD IT tool tries to solve this problem using computer algorithms with multi-criteria analysis. This IT tool allows to compare different types of solutions based on mathematical calculations using the Monte Carlo method. By using this IT tool, the investor and clients can better optimize future cash flow plans [14]. According to study [15], investors in residential projects can also be foreign investors without a negative impact on the economy of the Czech Republic.

Life cycle analysis and life cycle costing methods can be used successfully, for example, when planning residential heating systems. The article [16] describes the use of small thermostats that will save energy without reducing the user comfort of living. The study found that heat pumps are now often installed in new well insulated homes and are considered an environmentally friendly alternative to fossil fueled heating systems.

PFI/PPP (Private Finance Initiative/Public Private Partnerships) projects must also address the long-term financial efficiency and technical performance, given their long service life for the public and private sectors. The application of whole life costing in PFI/PPP projects is addressed, for example, by publication [17]. Other authors are dealing with the topic of nearly Zero Energy Building (nZEB), cost-optimal level, reconstruction and building certifications [18–20].

The article [21] deals with the search for a cost-optimal level of energy consumption in buildings. The cost-optimal level should be used to set cost-effective minimum legislative requirements for newly built or renovated buildings with regard to the lowest possible total costs and with a minimized impact on the environment, i.e., with the minimum primary energy consumed. To determine the cost optimum, parameters such as different values of the heat transfer coefficient of peripheral structures, various heating sources, methods of water heating, ventilation systems, lighting, etc., are alternatively determined for reference buildings. This article is followed in a given field of research, for example, by articles [21–23]. In connection with these legislative requirements, many biogas plants have been built, where energy is obtained from plant biomass. The energy thus obtained used in buildings then makes these buildings environmentally friendly for a long time [24].

The professional literature does not clearly define the evaluation of buildings in terms of their long-term sustainability. The three basic pillars of building sustainability are considered: the environmental pillar, the economic pillar, and the social pillar [25–27]. Commonly used building rating certification systems (for example, LEED, BREEAM, WELL, DGNB, SBToolCZ) define a rather long list of criteria [28,29].

The paper [30] presents the results of an LCA study comparing the most commonly used building materials with some eco-materials using three different impact categories. The aim is to deepen the knowledge of energy and environmental specifications of building materials. The paper [31] highlights the importance of LCA as a decision-making support tool. It discusses LCA methodologies and applications within the building sector, reviewing some of the life-cycle studies applied to buildings or building materials and component combinations within the last 15 years in Europe and the United States.

Many authors examine the life cycle costs of individual building materials, especially concrete [32–34]. They often focus on the link between the energy consumption needed to produce the building material and the overall environmental footprint [35–37] and the use of this material over its lifetime. These authors strive to find the optimal building materials and technologies in terms of minimal environmental footprint and reasonable production and maintenance costs. In this context, it is necessary to mention a study [38] that deals with the use of various environmentally friendly additional cementitious materials in terms of sustainability, cost, and durability for future implementation in buildings.

1.3. 3D Printing and Digitization

The combination of 3D printing of buildings and life cycle assessment for many authors [39–41] is becoming an innovative topic. Preparation of 3D building models requires very detailed planning of all structural elements of the building. This source data can also be used for life cycle assessment. The created 3D model of the building also allows to design various variants of the technical and economical solution which also have an impact on the total life cycle costs of the building. 3D planning can thus apply similar principles as used by the LCC calculation tool presented in this article. A similar approach can also be applied to constructions using BIM (Building Information Modeling) [42].

Digitization also has great potential for reducing energy consumption and related environmental impacts. However, the empirical evidence gathered in the article [43] suggests that this is often accompanied by only small effects. For example, the effects of energy savings in smart homes and smart metering technologies tend to be modest, in the low single-digit percentage range.

When calculating the life cycle costs of a construction, it is important to set the correct time interval. The authors [44] state the usual interval of 50 years. The problem is the different service life of individual structures and materials. The simplified approach may not fully respect recovery and maintenance cycles.

Table 1 shows the usual structure of life cycle costs that are used in the Czech Republic.

Table 1. Structure of life cycle costs.

Cost Section	Type of Costs	Example of Costs
Investment (acquisition) costs	Design and other fees	Design work
	Construction costs	Realization of construction
	Land	Acquisition of land
	Secondary costs related to locating the building	Construction site equipment during construction
	Costs related to machines, equipment, inventory	Object inventory
Operation costs	Power supply costs	Electrical energy
	Water and wastewater costs	Water supply
	Waste disposal costs	Waste disposal
	Service fees, insurance	Construction insurance
	Security costs	Building security
	Administrative fees	Property tax
Maintenance costs	Maintenance costs	Maintenance of building elements
Renovation costs	Renovation costs	Modernization of building elements
End of life costs	Liquidation costs	Disposal of the building
	Cost of recovery of rubble	Materials recycling
	Landscaping costs	Terrain work

2. Materials and Methods

The Life Cycle Cost represents the total costs spent in connection with the product service life. In case of the building industry, they include the costs of the procurement of construction and engineering structures, costs of maintenance and renovation of structures and equipment, operating costs and costs related to the end of the life cycle. Most evaluation cases address costs spent in the building economic life interval.

When deciding on the selection of options, only purchasing costs are often assessed which is a mistake because the operating, maintenance, and renovation costs are not taken into account. The costs spent in the building operation phase make up a significant part of the building LCC.

A general description of the LCC is given in international standards ISO, specifically in ISO 15686-5 (730951) Buildings and other structures—Life cycle planning, Part 5: Assessment of LCC that provides a general guideline for the execution of building, other structures and components´ LCC analyses. The LCC assessment should account for the costs and cash flows resulting from project phases, operations, and other building life cycle phases until its demolition.

The calculation of the *LCC* is an economic method of the evaluation that takes into consideration all relevant costs incurred within a defined time interval whereby it takes into account also the time value of money (by the calculation of *the LCC net present value*). The net present value for the analyzed period is the current value of future costs to be spent during the project life cycle. As the calculation of the *LCC* deals with costs rather than revenues, it is more practical to treat the costs as positive values in this particular case. The calculation of the LCC indicator can be written as the following general relationship:

$$LCC = \sum_{t=0}^{T} \frac{C_t}{(1+r)^t} \tag{1}$$

where:

C_t—annual cost in individual years of the project life cycle in EUR after deducting positive cash flows.

r—discount rate (p.a.).

t—year of evaluation taking values from 0 to T.

T—length of the evaluated period in years.

The LCC analysis becomes a natural component of the investment project evaluation. Experience from the execution of practical development projects indicates that the identification of options, structures, or equipment of buildings based solely on the lowest acquisition costs (the lowest price quotation) is a mistake. The investors´ activities should focus on economically sustainable projects. That means projects with the lowest *LCC*. This may be achieved by the integration of the LCC analysis to the building design.

The developed solution, the functionality of which is described in the next section, is a proper tool for the informed decision making.

2.1. LCC Calculation Tool

The LCC calculation tool (application software) was developed by the authors' team for optimization of decision making in residential construction. The LCC calculation tool is used for the calculation of the *LCC* for ground structures in Microsoft Excel. The LCC calculation includes the costs of acquisition, maintenance, service, renovation, and energy consumption for designed development project options.

It is a complex tool, the operation of which is subject to the entry of input values to several separated topic-related spreadsheets. This separation was chosen for the sake of better clarity of data entered to the SW. The tool offers the possibility of the entry of several options of the design. Each option makes it possible to follow up to a 60 year period of the project including the possibility to postpone the starting date of its operation. This time shift takes into account a postponement and the lead time of the construction works.

The proposed structure of the LCC calculation tool is based on scientific and business principles associated with long-term research work of the authors of the article at the Czech Technical University in Prague [45–47], a detailed analysis of available scientific research work of other researchers (key sources are part of Section 1) and practical experience from the cooperating multinational construction company Skanska, which was also the application site of the created LCC calculation tool. Based on these aspects, a clear architect LCC calculation tool was created. The structure of the LCC calculation tool itself is shown below (Figure 1), where each part (highlighted in blue) represents a key section of the LCC calculation supplemented by demands from both the market and academic environment.

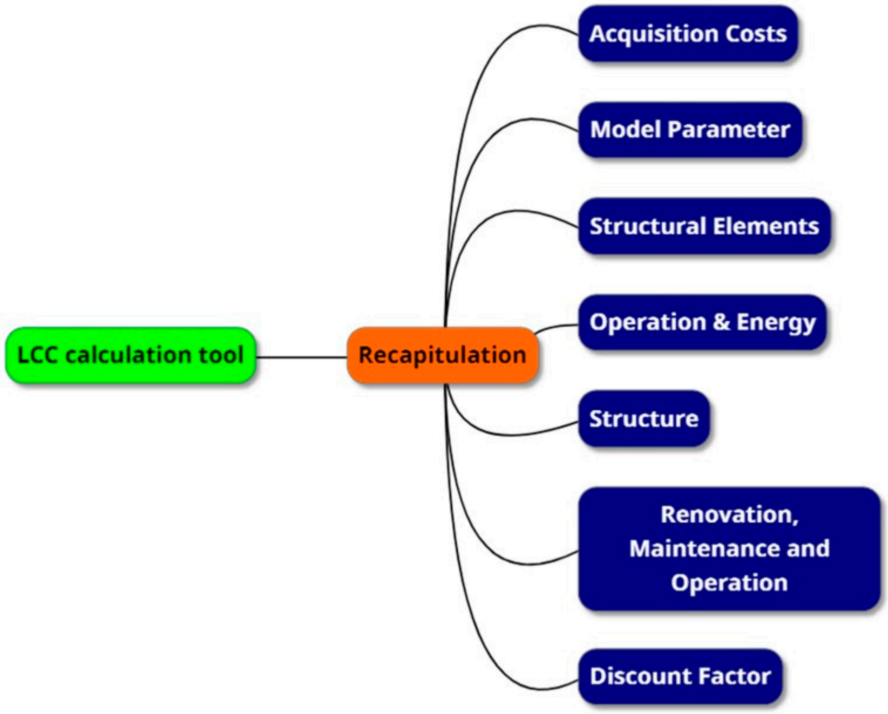

Figure 1. Structure of the LCC calculation tool.

A benefit of the SW tool is the possibility to model the life cycle costs for individual design options with different input parameters. That means that the user can choose the more efficient solution for him/her. For instance, he/she may find out what will be the impacts of a more expensive but energy saving option like not only on energy costs but on the total LCC, too. Similarly, if he/she includes a "maintenance" free equipment that requires higher acquisition costs, there is an apparent impact residing in the reduction of the maintenance costs but also in the value of the total costs of this project design option.

The following subsections describe individual spreadsheets that are included in the calculation of the LCC in the designed SW tool.

2.2. Recapitulation

The spreadsheet Recapitulation is used to summarize the basic identifiers of the project and a clear summary of the individual variants of the LCC calculation. The software shows both figures and graphic representation of individual LCC sections and the total LCC of the project including key parameters of the calculation (the nominal discount rate and the monitoring period duration).

The following calculation scheme (sum of partial parts) is used for the calculation of the total present value of the LCC in all project options:

- Acquisition costs of structures included in the maintenance, operation, and service (part 1) (C_{A1}).
- Costs of maintenance, service, and operation (C_{M1}).
- Renovation costs (C_R).
- Acquisition costs (part 2) (C_{A2}).
- Costs of service and maintenance costs (C_{M2}).
- Property insurance (C_I).

The total present value of the *LCC* in all project options is calculated according to the following formula:

$$The\ total\ present\ value\ of\ the\ LCC = C_{A1} + C_{M1} + C_R + C_{A2} + C_{M2} + C_I \quad (2)$$

The components of the calculation scheme are converted to the current value in individual periods using the discount factor.

To compare the individual investment variants, two additional indicators were further defined:

- LCC per 1 m^2 of the floor area—the lower the value of the indicator, the more advantageous is the proposed investment variant in terms of *LCC*.

$$LCC\ per\ 1\ m^2\ of\ the\ floor\ area = \frac{The\ total\ present\ value\ of\ the\ LCC}{The\ general\ gross\ floor\ area} \quad (3)$$

$$\begin{aligned} The\ general\ gross\ floor\ area \\ &= net\ floor\ area\ of\ apartments \\ &+ floor\ area\ of\ shared\ premises \end{aligned} \quad (4)$$

- LCC efficiency indicator—the higher the value of this indicator is achieved, the more the investment variant takes into account the principles of *LCC*. This is a dimensionless number.

$$LCC\ efficiency\ indicator = \frac{The\ total\ construction\ costs}{The\ total\ present\ value\ of\ the\ LCC} \quad (5)$$

2.3. Acquisition Costs

The spreadsheet *Acquisition Costs* is used for the calculation of the total acquisition construction costs of individual project options. Acquisition costs are divided into two groups. The first group (C_{A1}) are the structures´ acquisition costs included in the maintenance, operation, and renovation. The calculation of service, maintenance, and renovation costs (C_{M1}) for this group of construction elements is based on individual basis. This means that data on service life, maintenance intensity, service intensity, and operating costs are entered individually for each element. The other category includes remaining acquisition costs (C_{A2}), where the maintenance, service, and renovation costs are expressed by a lump sum (C_{M2}).

Principle of calculation of key cost items:

- The total acquisition construction costs (C_A) are calculated as the sum of acquisition costs of individual structural elements that are compliant with the usual structure of company budgets.
- From the set of structural elements, those for which maintenance costs are calculated individually (C_{A1}) are excluded.
- The calculation of remaining acquisition costs (i.e., for other structures) is the deduction of the C_{A1} from the total acquisition construction costs (C_A).
- The calculation of service, maintenance, and renovation costs *(C_{M2})* is based on a percent rate defined by the SW user from the basis of acquisition costs (C_{A2}).
- The insurance calculation is based on a percent rate defined by the SW user from the basis of the total acquisition construction costs.

The acquisition construction costs (C_A) are calculated according to the following formula:

$$C_A = C_P + C_{FW} + C_{SUB} + C_{SUP} + C_{IF} + C_{FFE} + C_S + C_{EW} \quad (6)$$

where:

C_P—Preliminaries.
C_{FW}—Facilitating Works.
C_{SUB}—Substructure.
C_{SUP}—Superstructure.
C_{IF}—Internal Finishes.
C_{FFE}—Fittings, Furnishings, and Equipment.
C_S—Services.

C_{EW}—External Works.

$$C_A = C_{A1} + C_{A2} \tag{7}$$

The service, maintenance, and operation costs (C_{M1}) are calculated according to the following formula:

$$C_{M1} = C_M + C_S + C_E + C_G + C_W \tag{8}$$

where:

C_M—building maintenance and renovation costs,
C_S—costs of servicing technologies and equipment,
C_E—electricity consumption costs,
C_G—natural gas consumption costs,
C_W—water consumption costs.

The service, maintenance, and renovation costs (C_{M2}) are calculated according to the following formula:

$$C_{M2} = C_{A2} * \ I_C * 100 \tag{9}$$

where:

I_c—index for calculation of the service, maintenance and renovation costs. In the case study, an index value of 1 is used.

The insurance costs are calculated according to the following formula:

$$The\ insurance\ costs = C_A * \ I_I * 100 \tag{10}$$

where:

I_I—index for calculation of the insurance costs. In the case study, an index value of 0.2 is used.

The cost items are converted to the current value in individual periods using the discount factor.

2.4. Model Parameter

The Model Parameters spreadsheet is used for the entry of key inputs for the calculation of the net present value of total LCC such as the length of the monitoring period, inflation rate, actual discount rate, anticipated postponement of the project commencement, and anticipated construction period for designed options. Expected postponement of construction start and the estimated construction time immediately affects the building operation starting date and related calculation of maintenance, service, etc., costs.

Other entered inputs that affect the additional indicators are the floor area of apartments, floor area of shared premises, number of apartments, and parking spaces.

Principle of calculation of key cost items:

- The general gross floor area = floor area of apartments + floor area of shared premises,
- The operation starting date = expected construction works starting date delay + estimated construction time + 1,
- The nominal discount rate is based on the inflation rate and real discount rate:

$$\text{Nominal discount rate} = \frac{(1 + \text{actual discount rate})}{(1 + \text{inflation rate})} - 1 \tag{11}$$

2.5. Structural Elements

The spreadsheet Structural Element is used for the entry of key inputs for the calculation of the present net value of the total LCC such as the acquisition price, area, service life, maintenance costs, individual structural element service regularity, and costs.

Moreover, the spreadsheet allows to insert to the structural elements the degree of maintenance level *lu*. Maintenance level *lu* is used to adjust the service life and maintenance costs (for details see the Table 2 below—initial values).

Table 2. Maintenance level.

Maintenance Level *lu*		Annual Costs	Service Life
P	Sub-standard maintenance	Reduction by 20%	Reduction by 5%
S	Standard maintenance	No change	No change
N	Above-standard maintenance	Increase by 20%	Increase by 5%

Table 2 describes the coefficients of *lu*, where the basic assumption is the fact that in the case of sub-standard (P) or above-standard (N) maintenance, the maintenance costs of the component are reduced/increased by 20%. The selected method of maintenance subsequently has an effect on the service life of the given structural element (reduction/increase by 5%, possibly no change). These proposed values are based on long-term university research already mentioned [45–47]. However, as indicated above, these are design values that can be adjusted individually for each element.

The worksheet allows the user to enter key and additional inputs, including verbal characteristics of the project in variants. The service costs per year correspond to one of the higher values:

- The service costs (percent-based derived) = annual maintenance costs (at the standard maintenance) per a unit of measure (MU) × percent of annual maintenance costs per the MU.
- The service costs (the value per the MU is entered manually).

2.6. Operation and Energy

The spreadsheet *Operation and Energy* is used for the calculation of energy price during the monitoring period for individual design options. Consumption of three types of energy is monitored: electricity, gas, and water. In most cases, the proposed technologies (air conditioning, heating, elevators, or lighting) do not consume water as a source of energy. However, regarding the consumption of water in the household, throughout the building, office buildings, and apartment buildings have different water consumption. With a higher emphasis on ecology, it is possible to design the use of sanitary equipment with reduced water consumption (toilets, shower heads, irrigation systems, etc.). The cost of annual water consumption can be compared to the cost of electricity consumed within a given building.

The calculations are based on designed energy consumption for individual technological systems included in the project (usually in the document called Building energy performance certificate (BEPC)). The calculations are based on the energy price prevailing at the time of the conclusion of this spreadsheet. To estimate the price in the following monitored years, a percentage increase in energy prices is used, which can take into account the development of market prices. This makes it possible to include the current prices in the calculation at any time as the input conditions. Each option specifies eight pre-defined technologies that could be included in the project. Moreover, there is a so-called optional item available that can be used for the entry of any technology whatsoever that has been added to the project. It is not always necessary to take into account all technologies, but only those that have a great impact on costs. The last item is the section Others that reflects the remaining energy consumption from the BEPC.

For the calculation, it is necessary to enter the input information, which are the annual total energy consumption according to PENB (Energy performance certificate of the building) (the input value for the calculation of the section Others), the Current Price (the input value for the calculation in the auxiliary table on the spreadsheet *Discount Factors*), and the anticipated price growth.

For selected components, the energy consumption, the risk of increasing energy consumption, and the device recovery cycle are entered. Energy consumption is based on the project design.

The auxiliary price calculation table on the Discount factor spreadsheet calculates first the price growth and then the individual measure unit prices are discounted. This way, calculated prices are entered into summary calculations that are located below the options on the spreadsheet Operation and Energy.

The total price for each technology is the sum of annual costs of the given energy. The sum of energy costs within the entire monitoring period is calculated as the sum of all costs for individual types of energy and technology.

The calculations of all technologies are designed in the same way and, therefore, only the assignment of the amount of energy consumed to the right input parameters is important. These parameters are entered for individual technologies or to the section "Optional Item". In the section Others, chosen technologies are deducted from the total energy consumption. This guarantees that the entire project costs (not only chosen technologies) are accounted for.

2.7. Structure

On the spreadsheet *Structure*, there is a key calculation tool for the partial parameters of the total net present value of the LCC such as the service life including *lu* (maintenance level), number of renovation cycles in the MP (the monitoring period), acquisition costs, renovation costs, maintenance costs including the *lu*, the number of service cycles in the MP and costs of service of structural elements of individual design options.

Moreover, the spreadsheet makes it possible to enable or disable individual structural elements that are included or are not included in the calculation of the total net present LCC value.

Principle of calculation of key cost items:

1. The service life including the *lu* = the service life × maintenance level *lu* (the service life according to the standard level).
2. Acquisition costs = area × measure unit price.
3. Renovation costs = acquisition costs × number of renovation cycles during the LCC monitoring period.
4. Maintenance costs including the *lu* = maintenance costs/year × area × LCC monitoring period.
5. Service costs = number of service cycles in the monitoring period × service costs/year.

The cost items are converted to the current value in individual periods using the discount factor.

2.8. Renovation, Maintenance, and Operation

The spreadsheet Renovation, Maintenance, and Operation is primarily designated for the graphic representation of acquisition costs, renovation costs, maintenance costs, service costs, and operation costs broken down to individual years converted to the present value using the discount factor. The spreadsheet includes seven diagrams (one for each option) that are accompanied with auxiliary calculations. A summary table is available for the service, renovation, and maintenance with three maximum and minimum cost values for individual structural elements.

2.9. Discount Factor

The spreadsheet Discount Factor is an auxiliary spreadsheet for the calculation of discount factors for individual intervals of the entire monitoring period for individual design options. This also includes auxiliary calculations for the determination of the energy price measurement unit and it also monitors the development of prices of electricity, gas, and water.

The input values used for the calculation of discount factors are based on the spreadsheet Model Parameters and the input values used for the calculation of the energy price based on the spreadsheet Operation and Energy.

Principle of calculation of key items:

- The following formula is used for the calculation of the discount factors:

$$\text{Discount factor} = \frac{1}{(1+i)^n} - 1 \tag{12}$$

where:

I—nominal discount rate.

n—relevant period.

- The nominal discount rate is based on the inflation rate and real discount rate (Equation (11)).

The monitoring period, i.e., the number of intervals n, may range from the minimum value of 0 to the maximum of 65 years. The reduction of inflation rate and the actual discount rate, i.e., the total nominal discount rate is based on the actual condition of the national economy and enterprise parameters when assessing projects.

In the energy price development calculation, the growth/drop is considered according to the previous year value. The discounted price in the period is calculated by multiplying the price of the period and a discount factor for the same period. Thus, it is calculated for all energy and all variants of the project.

3. Results

The building with basic parameters specified in the Table 3 was entered to the LCC calculation tool. The building (an apartment house) is located in Prague in the Czech Republic. The design envisaged five space heating and water heating options. None of the options will change the civil engineering design of the building.

Table 3. Building basic data.

Built up area (m^2)	612.76
Number of above ground floors	6
Number of underground floors	1
Number of apartments	22
Number of apartment users	72
Number of non-residential (commercial) units	1
Number of users of commercial units	5
Number of parking places (units)	28 + 5
BEPC category	B

For a more detailed breakdown of the gross floor areas (GFA) see the following Table 4. This information is given for the use hereof to better understand the project.

Table 4. Building area and bay data.

General gross floor area (m^2)	4905.60
Gross floor area of underground floor (m^2)	3776.20
Basement gross floor area (m^2)	1129.40
Floor area of apartments (m^2)	1743.49
Enclosure (m^3)	15,315.00

Energy/media consumption data was calculated based on the above information on the building as in the design documentation and energy performance certificates. These values are assumed in the model presented. The total energy supplied per annum, i.e., 227,879 kWh, is to be considered to be the most important value. This value is defined in more detail in the following Table 5. The average temperatures in the heating season in the given locality are used for the calculation. Heat losses include all structures, including additional phenomena such as infiltration and ventilation. The total value of heat losses is determined from the energy label (BEPC).

Table 5. Building energy balance.

Building thermal loss, power required for heating (kW)	120
Power required for warm water heating in peak hours (kW)	25
Annual energy demand for heating (kWh/year)	157,466
Annual energy demand for warm water heating (kWh/year)	70,413
Total energy supplied (kWh/year)	227,879

Table 5 further describes the values found for the power required for heating and hot water. Here, too, it is clear that water is not taken as a source of energy, but as a medium in which a certain amount of electricity or gas must be used in order for water to be usable for ordinary household activities. The exact power to ensure the difference between heat losses is based on reference variant 1, which is also included in the BEPC. Each technology has a different performance.

An indicative project budget (building costs) was drawn up based on the design documentation for the joint building permit and the Czech Republic Customary Pricing System (the II/2020 price level). For a recapitulation of individual cost groups and total building costs without assessed space and water heating options, see the following Table 6.

Gas-fired condensation boilers were chosen as the reference option for the LCC analysis. This option envisages the installation of a central boiler room with two series-connected boilers with the total capacity of 140 kW. In general, this is a very common heating method in the Czech Republic. The following variants are the most commonly used, available on the construction market or even state-supported heating and hot water options for residential real estate. The tool itself does not offer these options. This means that a market analysis of the offered structures must first be performed, which are then incorporated into the model.

Investment technological systems and construction works costs related to their procurement and operation were calculated for each option (Table 7). Moreover, the calculation includes operational costs, i.e., costs of the consumed energy, water, system operation, and maintenance costs and technological systems renovation.

The monitoring period was set to 20 years taking into account the service life of the technology systems assessed as their standard service life is maximum 20 years, as a rule, if not subject to a major renovation investment. After 20 years, the utility control center is considered obsolete, and it is supposed to be refurbished. The monitoring period of 20 years is recommended also by local legal regulations reflecting mainly the Directive 2010/31/EU of the European Parliament and of the Council of the European Union on the energy performance of buildings [48] and other European legislative documents dealing with LCC and energy performance. The heat source is supposed to be partly renovated; it resides in the replacement of the most stressed component of each system. A 4% discount rate was considered in the LCC calculation model. The discount rate is set the same for all variants so that the result is comparable. The change in discount rates can be changed when creating scenarios of economic development. The issue of combining the discount and inflation rates is addressed using the real and nominal discount rates. The values then enter into all calculations of dynamic economic indicators.

Table 6. Building costs of the concerned project.

Buildings Costs Recapitulation	Price Ex VAT (EUR)
Ground works	483,671.23
Foundation structures	428,790.66
Vertical and complete structures	496,146.35
Horizontal structures	626,364.59
Finish, floors, and installation of windows and doors	581,251.15
Tubing—connection line	31,543.71
Other structures and works, demolition	179,531.29
Floor covering	63,139.59
Thermal insulation	75,725.79
Lighting structures	257,088.09
Carpentry structures	44,243.80
Dry work structures	6845.76
Tinsmith′s structures	4104.45
Locksmith′s structures	165,674.70
Floors	216,201.56
Finishing works	83,478.01
Sanitary systems—internal sewer system	58,944.74
Sanitary systems—internal water pipeline	68,768.86
Sanitary systems—fittings and fixtures	93,329.17
Central heating—distribution pipelines	49,120.61
Central heating—fittings	24,560.31
Central heating—floor heating, bathroom electric ladders	143,132.94
Electric installation and heavy current systems	186,658.33
Electric installations—communication systems	29,472.37
Ventilation—forced air extraction	34,384.43
Total price ex VAT (EUR)	4,432,171.20

Table 7. Description of options.

Space Heating and Warm Water Heating	Energy Carrier	Heat Source
Option 1 (reference)	Gas	2 gas-fired condensation boilers
Option 2	Gas, solar energy	2 gas-fired condensation boilers, 16 plate photothermic collectors
Option 3	Ambient energy, electric energy from the distribution network	1 thermal pump, 1 electric boiler
Option 4	Energy from air, electric energy from the distribution network	2 thermal pumps, 1 electric boiler
Option 5	Biomass	2 pellet boiler

For an economic comparison of individual options see the following Table 8. The option 1 is the most beneficial from the point of view of investment costs. Nevertheless, from the point of view of operating costs, it is not an advantageous technology for the residents or operator, as the case may be. On the other hand, the low investment costs can counterbalance the high operating costs and this makes this option one of the most acceptable.

Table 8. Results resulting from the model.

Space Heating and Warm Water Heating	Option 1	Option 2	Option 3	Option 4	Option 5
Investment costs (EUR)	28,127.93	67,103.04	110,177.54	98,903.9	35,327.84
Energy costs (EUR/year)	9973.74	8895.1	5481.62	7375.36	9244.54
Total energy costs (EUR)	199,474.71	177,902.01	109,632.43	147,507.23	184,890.89
NPV energy costs (EUR)	135,546.32	120,887.32	74,497.02	100,233.57	125,636.38
Operating costs (EUR/year)	12,147.41	11,068.78	7655.3	9549.04	11,418.22
Operating costs (EUR/kWh)	0.053	0.049	0.034	0.042	0.05
Total operating costs (EUR)	242,948.27	221,375.57	153,105.99	190,980.79	228,364.45
Total operating costs including the energy price energy increase (EUR)	283,578.2	257,611.48	224,520.17	287,066.49	228,364.45
NPV operating costs (EUR)	165,087.31	150,428.31	104,038.02	129,774.57	155,177.37
NPV operating costs including the energy price energy increase (EUR)	189,098.96	171,843.16	145,648.32	185,760.02	155,177.37
Maintenance and renovation costs (EUR/year)	732.94	1457.78	1284.6	2793.98	1123.33
Total maintenance and renovation costs (EUR)	14,658.87	29,155.63	25,692.01	55,879.58	22,466.62
NPV maintenance and renovation costs (EUR)	9997.73	19,852.39	17,378.32	37,915.75	15,340.58
LCC costs including the energy price energy increase (EUR)	326,365.00	353,870.15	361,146.18	441,849.97	286,158.92

In the last variant, an increase in pellet prices was not considered, due to low price fluctuations on the market for this fuel. Short-term fluctuations occur in the pellet market, of course, but in the long run the model and results are not fundamentally affected. The fact of relative price stability is substantiated by a study focusing on the prices of this heating source [49]. Thus, Table 8 shows the same values in the rows Total operating costs and Total operating costs including the energy price energy increase.

Compared to other options that are based on the exploitation of renewable sources, the reference option has significantly higher operating costs. They account for up to 83 % of the total cost of the life cycle as can be seen in Figure 2.

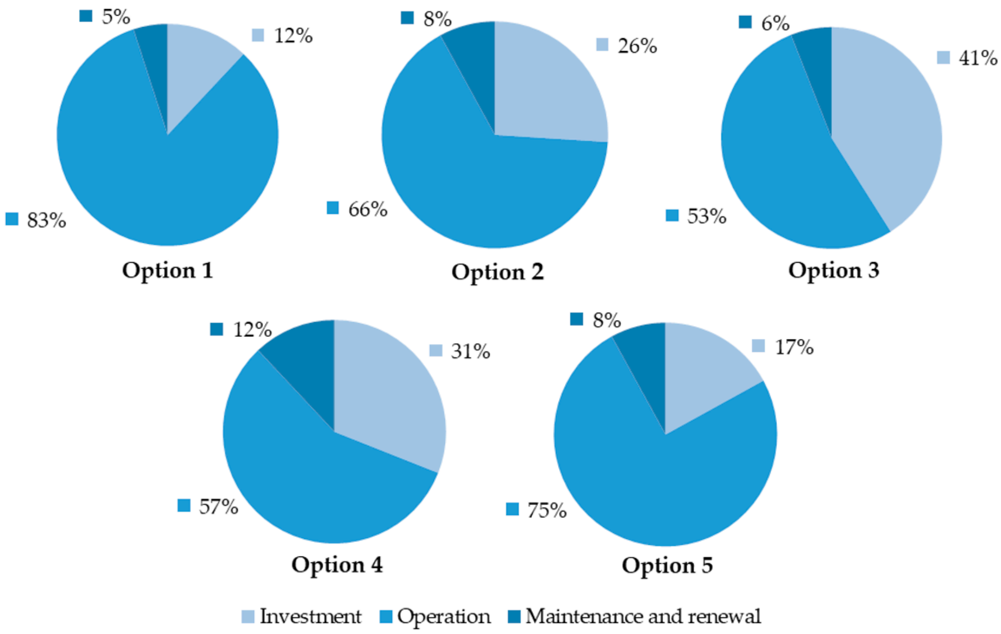

Figure 2. Comparison of the results of all options.

In spite of this, it is the cheapest option for the monitored period (without the prediction of the energy price increase) mainly because it is related to significantly lowest investment costs. Life cycle costs are similarly high for the option 5, where the energy carrier is biomass. When predicting the energy price increase, this option is favored as no price increases are assumed for pellets. This makes this option the best one when assessing the energy price increase. Unfortunately, it is the only option exploiting renewable energy sources that can compete with costs spent in connection with the use of fossil fuels even without government support. Natural gas costs can be reduced by the installation of photothermic collectors. High acquisition costs of this technology make this a disadvantage. Thermal pumps show the worst results in spite of significant reduction of operating costs. If we account for the relatively high anticipated increase in the price of electric energy, the ground-to-water thermal pump option is less favorable than the solar collector option. What is an advantage of these options is the possibility to reverse the operation of the thermal pump and its use as a source of cooling. This reversed function can be used, for example, on the top stories of a building where local cooling units are supposed to be installed. However, heat pumps generally proved to be more suitable for buildings that have high requirements to both heating and cooling. An advantage of all technologies assessed that make use of renewable energy sources is the possibility of government subsidies but they are not the main topic of this paper.

The options are compared also based on an index when the life cycle costs as shown in the Table 8 are divided by the gross flow area of the building taken from Table 3, see Figure 3.

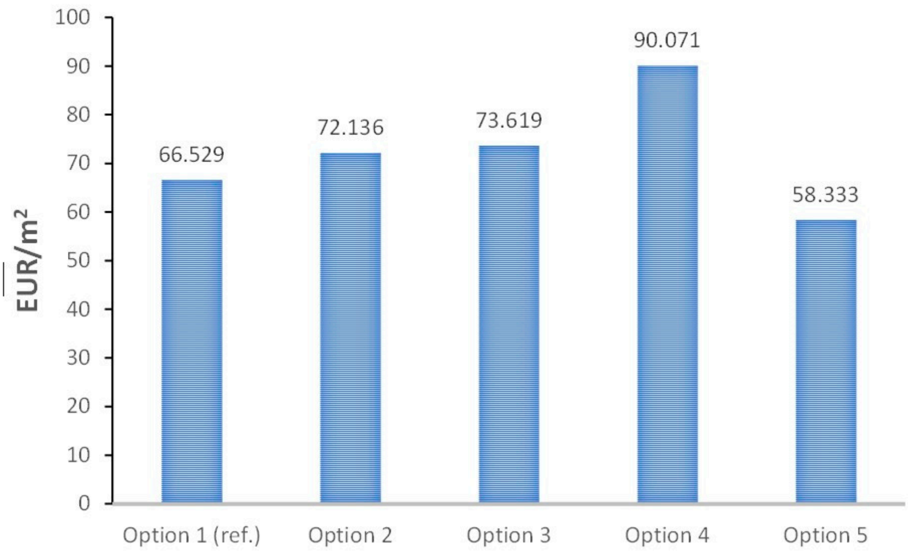

Figure 3. LCC/GFA building costs (EUR/m^2).

What stem from this comparison at first glance are the costs in EUR per 1 m^2 of the building. This index may be operatively monitored when optimizing future building designs. Changes in the design and the building size may not always have an impact on the total costs per 1 m^2.

4. Discussion

When deciding on the choice of investment options, often only the costs of acquiring the construction are considered, but the costs of operation and maintenance of the construction are often neglected. The presented software tool calculates the life cycle costs of buildings so that the user cannot ignore the individual components of these costs. This comprehensive tool accompanies users from the initial entry of input values to the definition of various variants of an investment project. The software offers modeling of the lifetime costs of individual project variants in relation to different input parameters. The user is therefore able to choose an effective solution for him.

These approaches are also confirmed by the authors of this article [50]. This paper compares two main economic evaluations which mainly could use LCCA (Life-cycle cost analysis). To indicate the effect of economic evaluation a case study was examined also. In this research LCCA comprises three main components which are direct costs, indirect costs, and salvage value.

The investor must be aware that the LCC also covers the cost of demolishing the building. Authors [51] dealt with the influence of the use of wooden structural elements on the overall LCC of buildings. As a result, the LCCs of timber structures can be lower, as at the end of their service life (60 years) the costs of their demolition are much lower than for reinforced concrete structures.

In a similar way, the authors used the LCCA in the article [52] to examine the level of comparison of road treatment costs. The road treatment simulation uses road deterioration models. Based on the LCCA, the NPV analysis showed that the rigid pavement treatment cost ratio is more economical than the flexible pavement.

An investor who wants to optimize their project can become a user of the LCC calculation tool. For example, in order to obtain a better energy assessment or even a certificate proving the degree of impact of the implementation and operation of the construction on the environment. These are therefore designers, project managers, and budgeters. On the other hand, the tool can also be used by a general contractor. However, this depends on the type of contract concluded. An example could be a situation where the general contractor participates in the savings of the project, where they are subject to life cycle costs. The most advantageous type of contract will be Integrated Project Delivery, where the investor, designer, and general contractor have a common goal, and that is the implementation of a quality building. The use by small investors in family houses is beneficial, but the implementation is complicated to control, as these investors are often not in the field of construction or do not have enough funds to hire consultants, etc.

Sustainable development and environmental protection are key issues for today's society. According to [53], LCC can be used to optimize the investor's decision-making process regarding the selection of individual structural elements of various materials. This is another advantage of the model we use.

One of the aims of the study was to determine the most suitable source of heating and hot water preparation already in the design phase of the building. One of the results of this study is the finding that energy calculations can be performed at different levels of project preparation and at different levels of information. It turns out that energy calculations in the very early stages of a building design, when only a small amount of information is available, should only be used to compare different energy alternatives. However, the results show that even these early estimates can outline the right direction regarding how to achieve significant energy savings in the long life cycle of a building. At the moment of more advanced design phases of the building it is already possible to perform energy calculations at the level of individual rooms of the building and finally the result of energy consumption will be significantly more accurate. However, the use of more sophisticated methods for calculating energy consumption is time consuming and errors can occur because the amount of input data is significantly higher.

5. Conclusions

The paper investigated the potential role of LCC calculations in planning, construction, and operation phases of residential development projects. The paper tested the impact of five variants of heating and hot water preparation on life cycle costs (LCC). The LCC tool developed by the co-authors of this article was used for testing.

Life cycle costing should be made for each construction project (residential buildings, industrial buildings, transport infrastructure, etc.). LCC analysis becomes an important basis for the investor's decision to find the best variant of the building design, taking into account also environmental aspects and long-term economic impacts. LCC calculation can be used as an important marketing tool for future users of the building. It can be expected that in the future, clients will take much more into account both environmental aspects and the circular economy. The LCC model also provides relatively accurate information on future costs of operation and maintenance of the building, which will increase the credibility of a planned investment project.

The cost of creating an LCC model is very minor in comparison with the total construction and operating costs of a construction over its lifetime. At the same time, the savings achieved can be huge if the right decisions are made regarding the technical solution of the building. The sooner the LCC model is designed, the sooner and more efficiently it is possible to control the total investment and operational costs.

The created LCC model is an essential tool for determining the total cost. However, there are several pitfalls that must be calculated when working with the tool. This is a preset structure of building sections, which corresponds to the customs in the Czech Republic. For further use, it is possible to use prepared editable items. A general limitation is the need for a large amount of data and accurate information on the project design in order to avoid a large number of scenarios with a large variance of variables. The results would then be incomparable. Due to the different options for setting up the model, it is important that its management does not become a static calculation before starting the project, but changes over time and is updated. The update is a fundamental factor of success at a time of uncertain development in the prices of building materials and energy.

The tool is set up primarily for buildings and residential buildings, due to the high energy consumption during the operation of the building. However, it is also possible to use it for industrial buildings, because building sections do not differ as much. The operation of industrial buildings is also high in terms of cost. On the other hand, the model does not include the costs of operating production facilities located in this type of construction. Therefore, only the construction is always assessed, not the user appliances and equipment. In order to be used for the assessment of transport structures, the structure of the construction sections would have to be extended in terms of construction costs and the calculation of energy consumption would have to be adapted, as transport structures do not have the energy performance certificate. Research should be extended to this type of construction and the current state of the building tool should be further developed to eliminate limitations.

The tool can be considered innovative for several reasons. It is a tool enabling a variant solution of LCC calculation with dynamic interconnection for costs associated with the consumption of electricity, gas, and water. For these items, it is often difficult to predict the evolution of both consumption and costs themselves. For this reason, it includes not only the discount factor, but also the rate of growth of energy prices in the relevant energy markets, including the prediction of changes in consumption itself. The tool can therefore also be used in the case of the sale of real estate, when it is appropriate to know the future costs related to the operation adapted to the new owner. The basic innovative benefits of the tool are interconnection of data across individual calculations, adaptability of the calculation method according to project needs (costs, consumption, etc.), applicability to public and private projects and real functionality of adding new arbitrary technologies to the calculation, e.g., at the level of other energy sources (hydrogen, core, etc.).

The applicability of the presented methodology and the LCC calculation tool was verified on the example of a life cycle cost analysis for a building (an apartment house) located in Prague. On the basis of documents obtained from the engineering organization and on the basis of project documentation, a preliminary LCCA was prepared for the purposes of strategic decision-making, which confirmed the correctness of the decision to acquire the building in the proposed low-energy standard. Based on the project documentation for the building permit, expert estimates, and information from the engineering organization, a detailed LCCA was prepared for one of the key components—the heating system. The result is one of the bases for completing the subsequent stage of project documentation. Further analyses and refinements of the life cycle costing are planned after the completion of the project documentation for the construction assignment.

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