

Article

Life Cycle Cost Analysis of a Single-Family House in Sweden

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Abstract: The objective of this paper was to explore long-term costs for a single-family house in Sweden during its entire lifetime. In order to estimate the total costs, considering construction, replacement, operation, and end-of-life costs over the long term, the life cycle cost (LCC) method was applied. Different cost solutions were analysed including various economic parameters in a sensitivity analysis. Economic parameters used in the analysis include various nominal discount rates (7%, 5%, and 3%), an inflation rate of 2%, and energy escalation rates (2–6%). The study includes two lifespans (100 and 50 years). The discounting scheme was used in the calculations. Additionally, carbon-dioxide equivalent (CO₂e) emissions were considered and systematically analysed with costs. Findings show that when the discount rate is decreased from 7% to 3%, the total costs are increased significantly, by 44% for a 100-year lifespan, while for a 50 years lifespan the total costs show a minor increase by 18%. The construction costs represent a major part of total LCC, with labor costs making up half of them. Considering costs and emissions together, a full correlation was not found, while a partial relationship was investigated. Results can be useful for decision-makers in the building sector.



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1. Introduction

In the European Union (EU), the building industry accounts for approximately 40% of the energy use, 36% of CO₂ emissions [1], and is responsible for a large proportion of natural resource use. To achieve climate goals in the building sector and in the society as a whole, the environmental impact from buildings needs to decrease. Nevertheless, there is a challenge to balance environmental, economic, and social aspects [2], since reducing the environmental impact may lead to higher economic costs as environmental degradation is often externalized in the economic system while reducing the environmental impact. From an economic perspective, life cycle cost (LCC) is considered as a well-known and suitable method for assessing costs on a long-term basis for buildings, which together with the life cycle analysis of a buildings environmental impact, could be useful to tackle the challenge in decision-making. The LCC is defined as a methodology for the systematic economic evaluation of costs during the estimated life period [3]. Thus, the LCC has been used for a long time for the estimation of total costs of a property from cradle to grave for decision-making purposes in the building industry.

1.1. Overview of LCC in Buildings

Performing a LCC analysis is appropriate when aiming to estimate relative costs and compare between different designs [4]. LCC that was previously used in the building sector shows different results depending on which economic parameters have been considered. The review by Islam et al. [5] summarizes and represents different case studies in the building industry from North America, Australia, and Europe using the LCC methodology. The results show that most case studies have included different economic parameters to decrease the uncertainty level, while the main limitation is that these case studies do not include LCC analysis for the whole life cycle of the building [5].



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According to Gundes, the LCC can be implemented for the whole building or on the component level [2]. Thus, LCC is used for calculating the low cost alternative by using different economic parameters. The used discounting, inflation, and escalation parameters in the analysis have a large impact on the prediction of LCC for a building [2]. Evaluation of construction costs considering LCC analysis on energy systems was included in the study by Marszal et al. [6]. In the study by Stephan and Stephan [7], they identified different energy reduction measures within various scenarios and found positive net present values, except for solar panels with a 50-year time horizon of a building. Moreover, building owners make early decisions about building design and energy systems while occasionally considering operational or replacement costs [8]. For instance, the LCC can provide crucial information to decision-makers (investors, users, and developers) regarding the operating costs of sustainable materials and building installations when making sustainable buildings [9].

Costs and emissions were analyzed simultaneously in some studies. An LCC was performed to reduce CO₂ emissions at the building component level in the UK construction sector by Pellegrini-Masini et al. [10]. In this study, the total costs of three case studies were analyzed for different energy demand reduction technologies during a period of 25 years. Moreover, Schmidt et al. [11] demonstrated combined LCA and LCC framework for a component of one building. In this paper, they analysed different building options by integrating costs and emissions as well as significant uncertainties in implementation of methods relevant for decision-makers in the building industry. In the study by Bartlett et al. [12], it is justified that consideration of total LCC with the environmental impact of buildings leads to a sustainable and beneficial outcome for both the environment and business in the long term, making savings from energy use that can return capital investment while creating long-term returns. However, Ramírez-Villegas et al. [13] presented various renovation strategies for a multifamily building in Sweden and stated in their findings that there is no significant relationship between costs and emissions.

Furthermore, Dunovic et al. [14] considered buildings as a complex process due to its long and unpredictable lifetime, high level of uncertainty and potential risks, which might affect the final decisions. The long lifespan of buildings leads to less accurate forecasts. Therefore, the uncertainty of costs during the operational phase of buildings depends on different parameters, such as the prediction of the inflation rate, energy prices, legislation, local taxes, materials, and labor costs [14]. Here, a sensitivity analysis by Salvado et al. [15] provides additional information based on most uncertainties, such as discount rates, time period, incomplete data regarding maintenance, repair, and replacement of building materials depending on their service life as well as predicted costs. Kovacic et al. [16] stated that parameters that increase uncertainty are time horizon (longer lifespan leads to higher uncertainty of operational costs), price evaluation (energy price development are more difficult to predict than labor costs), discounting rate (the choice of a discount rate has a great impact on LCC final results). According to ISO 15686-5:2008 [3], different discount rates, the period of analysis, and incomplete data for maintenance, repair, and replacement could have a large influence on the uncertainties in final results. Among different approaches, the general LCC tools in Sweden provided by the National Agency for Public Procurement include basic parameters used in the calculation for LCC. They include investment costs, operating and maintenance costs as well as other costs related to taxes, insurance, disposal, residual value etc. In order to use LCC tools, they define conditions for economic parameters, such as the discount rate, the lifespan, electricity costs, water and fuel costs, annual cost change, and financing costs. Further, the costs are discounted by using the present value method [17].

1.2. LCC Outcome Distribution

The benefits of using LCC in buildings are significant according to Bogenstätter [18]. In the study, he concluded that decisions made in the early design stages could predict up to 80% of operational costs as well as environmental impacts [18]. The LCC method

is beneficial for calculating cost optimization with the possibility to map the risks of a building regarding costs [9]. The total LCC considers annual operational, maintenance, and disposal costs according to [19]. Operating, maintenance, and refurbishment costs for new and existing buildings cover more than 80% of the total costs and they are predicted at the design stage by Boussabaine et al. [20]. In a case study by Ziemska [21], analyzing a single-family house, the results show the largest share of the total cost is attributed to running costs (68–72%), followed by the initial costs (26–30%), and then end-of-life costs (1%), estimating the whole life cycle. The LCC calculations exclude price changes during the life cycle. The author stated the necessity of providing full information about costs as a prerequisite for making rational decisions in the building sector for developing, constructing, and operating a single-family house.

Al-Hajj and Horner estimated the total operational and maintenance costs of a typical building. These costs account for about 1/6 of all other costs [22]. Furthermore, a review by Islam et al. [5] of the main LCC outcomes demonstrates high contribution to the construction phase (55–88%), operational phase (11–34%), maintenance (2–20%), and disposal (0–2%). However, there is a recently published case study that explores and encourages the evaluation of end-of-life costs within the circularity of one-family houses in the future [23]. For multi-storied residential buildings, the LCC analysis was conducted by applying an energy-efficient approach according to Mahajan et al. [24]. In the paper, the lifespan of 30 years is used, including capital costs of only 3% of the total building cost and achieving savings of 30% for operation and maintenance costs [24]. There are also studies, such as the study of McLeod & Fay, where only the investment costs of a building were taken into account by excluding operational and maintenance costs without considering the discount rate [25]. Han et al. [26] showed that initial construction costs and annual energy costs are significant contributors to the total LCC of an office building.

Some studies provide costs in a long-term scenario for an entire building. In the study of residential dwellings provided by Sterner [27], the initial construction costs are major contributors to the total LCC (around 56%), followed by energy costs (22%). Furthermore, the maintenance costs have shown a minor impact in total costs (around 2%) as a consequence of time-consuming data collection, while disposal costs were omitted [27]. In a similar study, the results show that construction costs represent 65%, operation costs 25% and maintenance costs 10% based on empirical data for 21 Swedish residential buildings [28]. Considering the results for a case study of a single-family house, the construction and the maintenance costs contributed 88% to the total LCC, while operation and disposal parts have shown minor costs [5]. Ziemska stated that in many cases an average consumer emphasizes initial investment costs by underestimating running costs for a single-family home that lasts 40–60 years. However, he claims that choosing energy-saving solutions will decrease the total costs for a single-family house in the future [21]. Findings from a Danish study where LCC data from 21 office buildings were compared show that construction costs amount to half of the total costs and the other half belongs to running costs [29]. In a Swedish case study [30], the construction phase dominated with 74% of total LCC, followed by operation and maintenance costs (18%) and design costs (8%).

1.3. Economic Parameters in LCC

Taking into account that a discount rate is significant for estimating future costs related to the operational phase of a building [31], most case studies applied different discount rates and the range varied from 2% to 8%, with a median of 4% [5,28]. In the case study by Svajlenka and Kozlovska, the economic evaluation of LCC for an actual family house based on wooden modern construction took into account discount rates of 1%, 3%, and 5% for the use phase, maintenance, and disposal costs [32]. Berggren et al. used the nominal discount rate of 7% and the inflation rate of 2% as a baseline [30]. Considering energy tariffs, data provided by [33] show that the energy prices increased over time almost 4% in Sweden, while for the case study a lower value of 2% was chosen [30]. In Sweden, the electricity price depends on different factors [34], thus in the study, data from an energy company

were used for the LCC calculations. The electricity price model used in the study represents a 37% higher daily price than the fixed price within specific months (1.47 SEK/kWh versus 1.07 SEK/kWh).

1.4. Life Cycle Length of Buildings

Regarding the life cycle length of buildings, the review written by Emekci et al. [9], includes publications with the LCC approach that classified the lifespan of buildings into three categories, <30 years, 30–50 years, and >50 years. Furthermore, Islam et al. [5] concluded that the lifespan was in the range between 35 and 70 years, while several studies used 50 years as the median [5,28–30]. For one office building located in the south of Sweden [30], the study includes the lifespan of 40 years. According to ISO 15686-5 [3], the period of LCC analysis should be based on the owner's preferences. Another observation made by Hamelin and Zmeureanu [35] is that choosing the lifespan of 50 years could give more reliable values. Especially regarding the buildings climate impacts, it should be long enough for making appropriate assumptions concerning the repair and maintenance costs for future forecasts.

1.5. Limitations in Previous Studies and Aim of This Study

According to previous studies including different economic parameters for calculation of total costs, some limitations were found. In most case studies, construction costs, operation costs, replacement costs and energy costs were included in the analysis without considering the total costs (A0-C4) for a building. Furthermore, most LCC calculations were made for multi-family houses and offices, with very few case studies considering single-family houses. In the building sector in Sweden, LCC analysis is used particularly for installation systems without considering the whole building [36]. Furthermore, there is a lack of studies considering the integration of costs and emissions of an entire single-family house through different life cycle stages. Previous studies mostly focused on LCA and LCC separately without using the same framework. The methods were mostly applied for one component and similarities and differences discussed between them.

The aim of this study was to estimate LCC for a single-family house, by considering different solutions. According to the goal of this study, three research questions were developed:

- How can different economic parameters, such as variations in: (a) discount rates (b) length of the life cycle, and (c) energy escalation rates, affect the results of the LCC in different life cycle stages and thus influence the way that LCC guides the decisions and design of a single-family building?
- How can the uncertainty level in future forecasts be decreased and thus influence the accuracy within data selection?
- How can the relationship between costs and emissions be analysed to create useful information for decision-making processes?

In our study two different lifespans were used, namely 100 and 50 years, considering various economic parameters through sensitivity analysis for a single-family house in Sweden. By considering different alternatives and incorporating them in the LCC, decision-makers could save costs in a long term by choosing cost-effective solutions for buildings. In order to obtain a better understanding of relations between LCA and LCC, we presented a combination of costs and emissions in the same framework, which is valuable for decision-making purposes.

2. Methodology

In this chapter, the methods used in the study are presented, starting with the LCC stages included, followed by different parameters used in the calculations, including the discounting scheme.

2.1. Life Cycle Cost

In this study, the LCC was used as a method to calculate the total costs during the building's lifecycle from cradle-to-grave. LCC steps include stages A0–C4 (from pre-construction and construction costs, followed by the maintenance, replacement, operational, and end-of-life costs). The LCC was performed by using One Click LCA software [37] that is in compliance with ISO 15686-5 standard [3] and follow the structure of EN 16627 standard [38]. The analysis cover costs involved over the lifespan of the building from the pre-construction stage until the end-of-life stage. The included LCC modules are presented in Table 1.

Table 1. LCC modules according to EN 16627 standard.

Pre-construction stage	Costs of purchase/rent the land	A0
Production stage	Raw material supply	A1
	Transport	A2
	Manufacturing	A3
Construction process stage	Transport to the building site	A4
	Installation into building	A5
Use stage	Use/application	B1
	Maintenance	B2
	Repair	B3
	Replacement	B4
	Refurbishment	B5
	Operational energy use	B6
	Operational water use	B7
End-of-life stage	Deconstruction/Demolition	C1
	Transport	C2
	Waste processing	C3
	Disposal	C4

The initial investment costs for building materials and installations were retrieved from the local supplier while other costs specific for the building, such as land purchase, permission from municipality, taxes were delivered by the founding company Dalarnas Försäkringsbolag (bank and insurance company). Costs that occurred under construction including labor costs were collected by the founding company and forwarded to the researchers. In the estimation, the aggregated module (A0–A5), construction stage includes investment-related costs consist of (A0) module presenting pre-construction costs for land purchase, municipality permissions, and taxes; (A1–A3) modules include costs for building materials and installations, as well as their transportation to the manufacturer, packing and distribution process. The costs occurring during the construction process on the building site (A4–A5) include labor costs, energy costs for the site work, transportation costs to the building site (indirectly included as a lump sum), use of equipment during the installation process, and waste costs. The use phase consists of running costs during the occupancy of the building, including replacement, energy, and water costs. The maintenance costs are provided as a lump sum based on average costs in Sweden [39] and inserted in the module (B1–B3). The expected replacement rates based on best Swedish practice and the program's default data for building materials and installations were included in the calculation within the aggregated module (B4–B5). Operational costs during occupancy of the building include electricity costs (B6) and water costs (B7). The energy use was simulated within an energy software Trä & Möbelföretagen (TMF) Energy, based on climate, building physics, occupancy, and energy systems calculations [40]. The software is specialized for the calculation of energy use of single-family houses according to Swedish building regulations. The electricity price was derived by Eurostat [41] by using historically based data. The water costs include an average water price per m³ provided

by The Swedish Water & Wastewater Association [42]. The end-of-life (C1–C4) costs were calculated as 2.5% of capital costs based on the software's default data. The stage includes aggregated calculated costs. The costs assume energy consumed and wastes produced during the demolition and disposal of building materials to the landfills.

In the LCC calculation, the present value (PV) formula was used for discounting future cash flows to present values [4]:

$$PV = F_t \times \frac{1}{(1+d)^t}$$

PV = Present value

t = Time in unit of year

F_t = Future cash amount that occur in year t

d = Discount rate used for discounting future cash amounts to the present value

For calculating all costs that appear through the building lifetime, the present value formula was applied. The general LCC formula for buildings was used in our case for summarizing all costs that occur from cradle-to-grave:

$$LCC = I + Repl + E + W + EOL$$

I = Investment costs

$Repl$ = Replacement costs

E = Operational energy costs

W = Operational water costs

EOL = End-of-life costs.

2.2. Parameters Used in Calculations

The nominal discount rate for Dalarnas Villa is based on average historic data from 2002–2019 provided by the funding organization Dalarnas Försäkringsbolag. The nominal discount rate based on that information and used in the study was 5%. However, a discount rate is unpredictable over a long time. In order to reduce risk, two additional values were included in the calculations (7% and 3%) to test the robustness of the calculation and the uncertainty level. Another important economic factor used in this study is the inflation rate. The average inflation rate is considered as 2% according to Sweden's central bank target, which is to hold the inflation around 2% to keep the inflation rate stable and low in the long term [43]. Two various lifespans of the building were used (100 vs. 50 years) to examine the difference within life cycle stages and costs. Economic parameters used in the study are listed in Table 2.

Table 2. Economic parameters used in calculations.

Parameters	Input	Description
Inflation rate, energy and water rate	2%	Inflation rate—Sweden's central bank; energy and water rate—software based data.
Discount rate	7%, 5% and 3%	Nominal discount rate 5% (Dalarnas Försäkringsbolag), two additional discount rates 7% and 3%.
Lifespan of the house	100 and 50 years	A 100-year lifespan based on previous estimated period for LCA—the same case study, 50 years additional analysis.
Electricity price	1.56 SEK/kWh	Eurostat (average price for period: 2009–2019), including taxes for household consumers.
Water price	23.6 SEK/m ³	Calculated for a family using 200 m ³ /y including taxes.
Energy escalation rates	2–6%	Range of possible escalation of energy price in future.
EOL as % of capital costs	2.5%	Data provided by the software.

Regarding data quality, specific costs for the case study were compared with average costs provided by the software for different sections of the house. The costs are given in SEK currency and correspond to 1 Euro \approx 10 SEK.

3. Case Study Building

In the study, a two-story wooden single-family house known as Dalarnas Villa with installed photovoltaic (PV) panels was used as the case study (Figure 1). The purpose was to build the house with eco-based building materials and smart energy systems that influence the reduction of climate impact in a long run and provide cost-effective solutions. Therefore, an analysis of the environmental impact of the building has been performed by using the life cycle assessment (LCA) in a previous study [44].



Figure 1. The study object Dalarnas Villa.

The house, constructed in 2019, is located in the middle of Sweden and has a total floor area of 180.4 m². It is financed by the insurance company Dalarnas Försäkringsbolag and includes collaboration with other important stakeholders such as Dalarna University (researchers and students), Fiskarhedenvillan AB (a house manufacturer and supplier for building materials), and other entrepreneurs for different energy systems. The building is well-insulated using cellulose insulation for the external walls and the roof, while wood fiber has been used as insulation for internal walls. The energy systems applied in the house consist of PV panels installed on the south-west roof side, an exhaust ventilation system, and a ground source heat pump. These installations are included in the calculation of operational energy costs. Tables 3 and 4 present the input data for building materials and energy systems used in the analysis.

Table 3. Input data including main building materials applied in the case study, modified [44].

Building Materials	Quantity	Description
Concrete	21.8 m ³	Reinforced concrete used for the foundation
Wood framework	23.4 m ³	Used for the construction
Wood panel	15.6 m ³	Used for the facade
Cross-laminated timber (CLT)	5.4 m ³	Used inside the house
Thermo-wood	4.4 m ³	Heat-treated wood used for balconies
Cellulose (loose) insulation	114.2 m ³	Installed in external walls and in the attic
Wood fiber insulation	5.7 m ³	Installed in internal walls
Expanded polystyrene (EPS) insulation	21.8 m ³	Installed in the foundation
Gypsum	1306.2 m ²	Used for external and internal walls
Floor internal	132 m ²	Parquet used for both floors
Plastic details	1521.8 m ²	Not defined
Windows	25 units	Triple-glazed with U-value 1.0. W/m ² K
Doors	15 units	Wooden internal doors combined with glass-wooden for external purposes
Roof	155 m ²	Steel

Table 4. Input data on building, climate conditions and energy; adapted [44].

General Information	Data	Unit	Reference
Indoor temperature	21.0	°C	¹ BEN 2
People	3.5	-	¹ BEN 2
Metabolic rate	80	W/person	¹ BEN 2
Attendance time:	14	h/day	¹ BEN 2
Warm water cons., specific	20	kWh/m ² /y	¹ BEN 2
Household electricity	30	kWh/m ² /y	¹ BEN 2
Building:			
Living area	150.4	m ²	² Dalarnas Villa
Garage	30.0	m ²	² Dalarnas Villa
Building envelope (A_{om})	446.5	m ²	² Dalarnas Villa
Mean U-value (U_m)	0.269	W/K m ²	² Dalarnas Villa
$U_m A_{tot}$	120.1	W/K	² Dalarnas Villa
Airtightness (q_{50})	0.18	l/s m ²	² Dalarnas Villa
Time constant	62	H	² Dalarnas Villa
Climate conditions:			
Outdoor temp. average	5.0	°C	³ SVEBY
Design outdoor temp.	-19.7	°C	⁴ TMF
Ventilation:			
Exhaust fan (demand control)	42	W	⁵ BBR 25
Design air flow	52.6	l/s	⁵ BBR 25
Heating:			
Ground source heat pump	5.3	kW	⁶ EN 14511
COP/P heat, nom 0/35 °C	4.62/6070	-/W	⁶ EN 14511
COP/P heat, nom 0/45 °C	3.44/5280	-/W	⁶ EN 14511
COP/P heat, nom 0/55 °C	2.64/4740	-/W	⁶ EN 14511
Solar energy:			
PV panels	32	m ²	² Dalarnas Villa

Notes: ¹ Normal use of household appliances for new houses and years according to BEN 2 “Boverket regulations and general advice on determining the energy consumption of the building for normal use and a normal year (BFS 2017: 6)”. ² Data based on specific case “Dalarnas Villa”. ³ SVEBY (Industry standards for energy in buildings) climate data based on SMHI (Swedish Meteorological and Hydrological Institute). ⁴ TMF-program for energy simulation. ⁵ BBR 25-Boverket building regulations. ⁶ Heat pump COP-coefficient performance and nominal heat production at the test points according to EN 14511.

In the study, specific building materials and installations for the house have different service lives. Energy systems (ventilation, solar panels and heat pump) applied in the case study are assumed to be replaced after their lifespan with the same technological

characteristics, despite their forecast for changing with another developed system in a long term. The reason of choosing the same components for the house when doing replacements is due to the high uncertainty level of future investment alternatives that mostly depend on occupant's preferences. The horizontal structure includes parquet used for flooring of the house, thermo-wood for balconies, roof, and plastic layers used for different purposes. The vertical section for external walls consists of a wood panel for facade, cellulose insulation, cross-laminated timber and gypsum. The vertical section for internal walls includes a wood framework, wood fiber insulation, and gypsum. Both sections include plastic layers. The foundation and substructure include reinforced concrete and EPS insulation boards. Wood panel for the facade, triple-glazed windows, roof and ventilation system, are estimated to be replaced approximately after 50 years; doors, parquet and solar panels after 30 years and heat pump every 20 years [44]. The calculation includes costs for purchased electricity based on simulations made in the program [40] that were transferred in the LCA [44] excluding measured data.

4. Results

4.1. The Influence of Varying Discount Rate and Life Cycle Length

The results in Figure 2 present the total LCC by using discount rates (7%, 5% and 3%) including the inflation rate of 2% for 100 years and 50 years lifespan. Construction costs are the same as they are already given in the present value, while the price change is visible during the use stage. When the discount rate decreases from 7% to 3%, the total LCC increases significantly by 44% for a 100-year lifespan, while investing in a 50-year lifespan, the total calculated costs are increased by 18%.

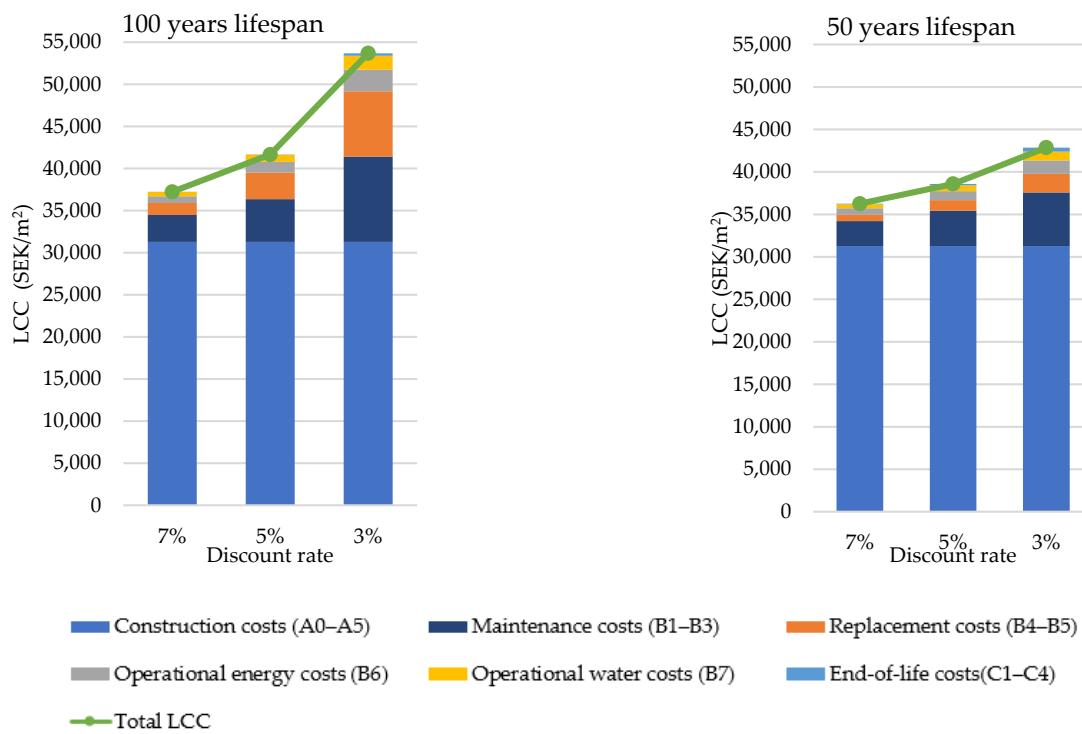


Figure 2. LCC including different discount rates and two life spans. Graph on the left side (100 years lifespan); graph on the right side (50 years lifespan).

The (A0–A5) life cycle stage representing the major part of the total LCC is demonstrated as an aggregated construction stage in the calculations. The classification of construction costs is demonstrated in Figure 3. Labor costs make up half of the total construction costs, followed by building materials costs which accounted for around 23%, installations

costs and pre-construction costs for 12% each, and the remaining 3% are related to other construction costs.

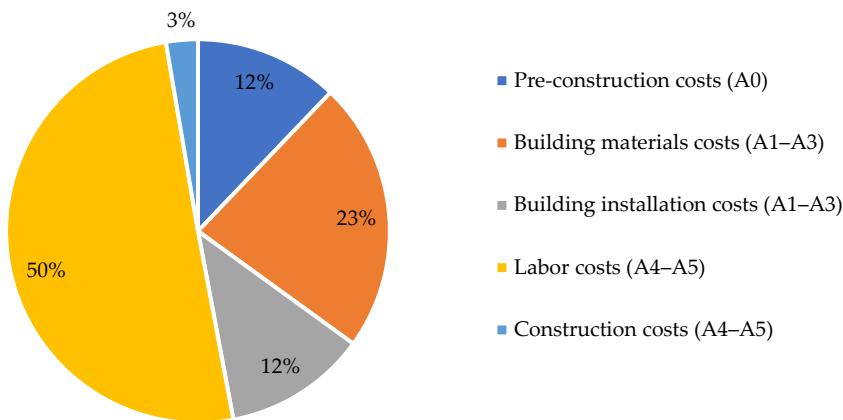


Figure 3. Breakdown of aggregated construction costs (A0–A5).

The cumulative chart in Figure 4 for LCC of the house is presenting costs from 10–100 years considering a 5% discount rate and 2% inflation rate that occur during the operational phase. Construction costs in the LCC module A0–A5 are omitted in this figure as they are already calculated in the present value, do not need discounting, and are therefore not influenced by different life spans. The findings show that the maintenance costs are the highest and grow with increased life length. Replacement costs start to increase greatly from year 30th to year 50th and continue with a significant increase after the 50th year because most installations have a replacement rate of 50 years. Operational and water costs were slightly increased over the time, while the end-of-life costs have shown the opposite trend.

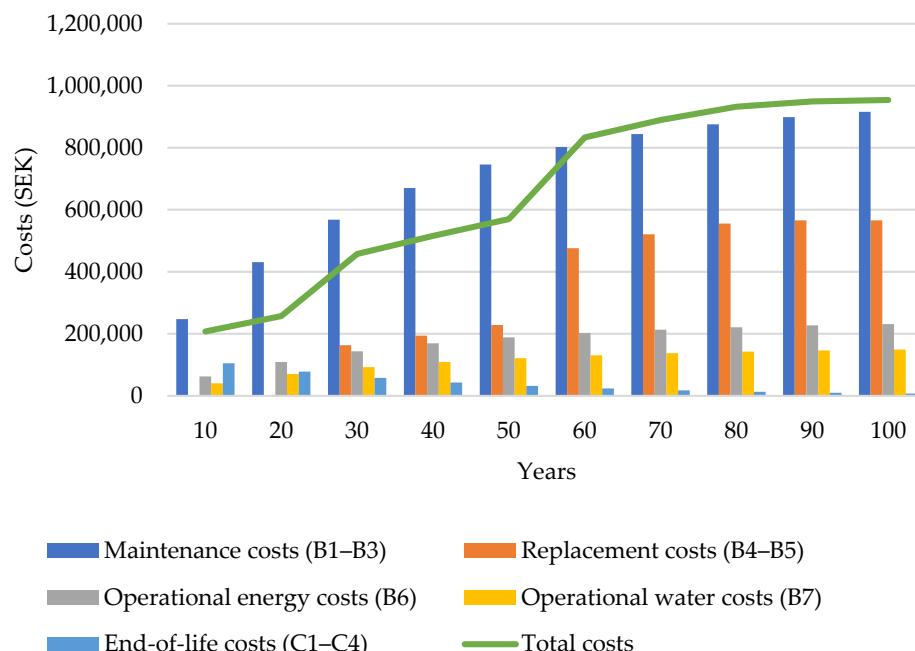


Figure 4. Running costs through different lifespans of the house.

4.2. Influence of Escalated Energy Rate

When analyzing the influence of an escalated energy rate, the operational energy cost analysis for a 100-year lifespan was performed by using escalation rates (2–6%), discount

rates (7%, 5%, and 3%), and the average electricity price of 1.56 SEK/kWh, including taxes provided by Eurostat [41] for household consumers (Figure 5).

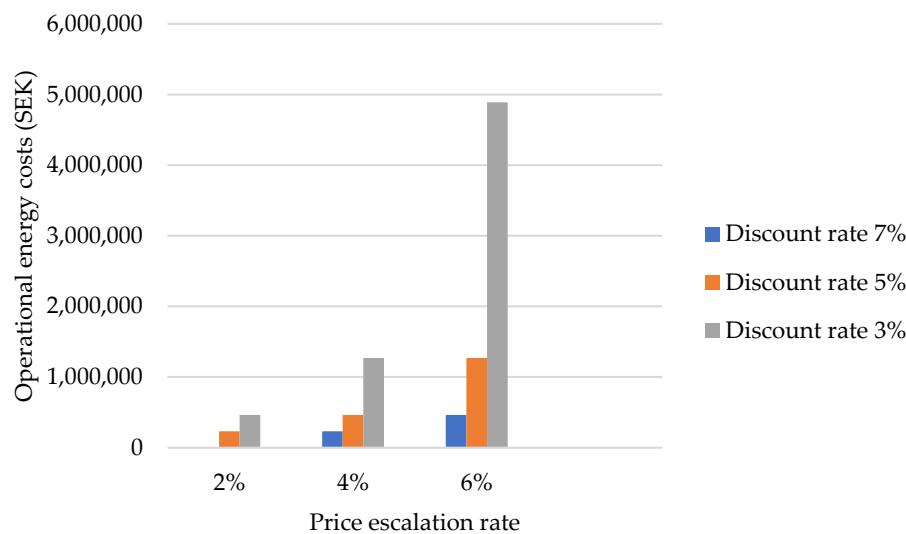


Figure 5. Total electricity costs estimation for a 100 years lifespan.

The results show that escalated energy rate will have an evident impact on the operational energy costs. It is clear that when increasing the escalation rate, the future energy costs grow significantly when using 3% discount rate and price escalation rate of 6%.

If the installed PV panels are excluded as an alternative in the calculation, additional energy has to be purchased from the grid. Without the PV panels, the operational energy costs will increase significantly, almost double when having a 5% discount rate and a 100-year lifespan (Figure 6).

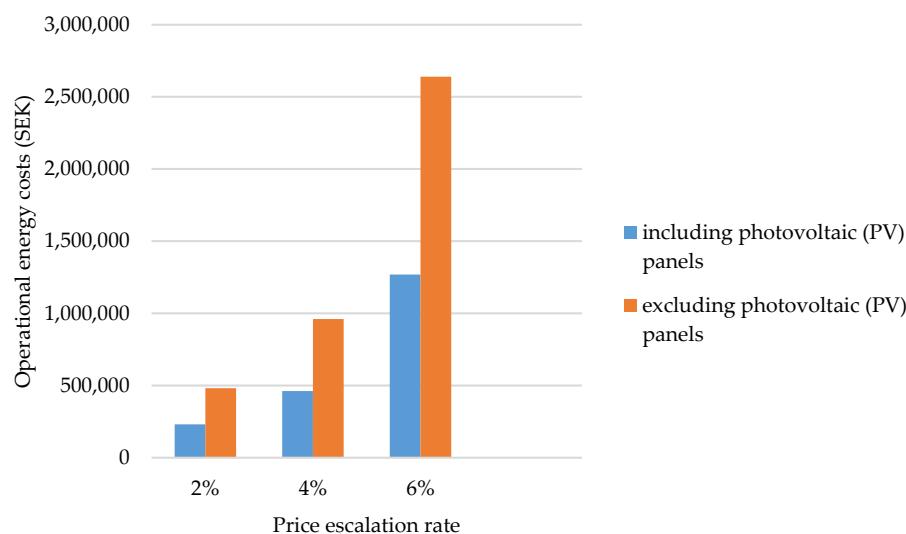


Figure 6. Energy costs estimation for PV panel system.

4.3. Data Quality—Average Data vs. Case Study Specific Data

To explore the difference between average and specific costs, a comparative analysis for different sections of the house is presented in Figure 7. The building material investment costs from the case study were mostly based on environmental product declaration (EPDs) data that are compared with manufacturer's prices based on average data provided by the software One Click LCA.

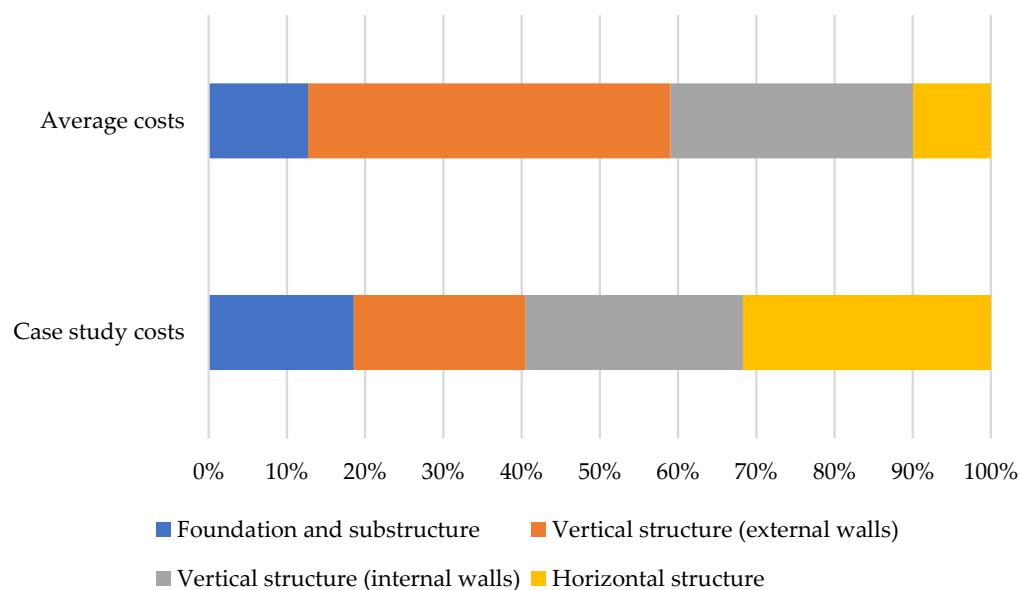


Figure 7. A comparison of case study specific costs and average investment costs presented within different structures.

The results show a significant difference in prices for building materials used in horizontal structures and external walls of the house. Costs can vary significantly when comparing building materials costs of a certain building with average based costs from the database available in the software.

4.4. Linked Costs and Emissions

4.4.1. Integration of LCA and LCC Results

In order to investigate the relationship between emissions and costs in the same framework a sensitivity analysis was conducted and results are presented in Figure 8. According to our findings, we pointed out that partial correlation is feasible. The highest costs are found in the production and construction stage of the house considering both lifespans, while running costs and end-of-life costs remain very low. From environmental point of view, we have noticed the largest share of CO₂e emissions in the production and construction stage for a 50 year-lifespan. The highest emitted emissions for the maintenance/replacement of building materials and installations are noticed during the 100-year lifespan of the house due to the frequent rate of replacement followed by the production and construction stage. Furthermore, emissions related to purchased electricity are significantly low and as well from economic perspective the costs remain low considering both time horizons. The relationship between costs and emissions was found during the maintenance phase in a 50-year lifespan, while the water use and the end-of-life of the house have the lowest costs and levels of emitted CO₂e emissions.

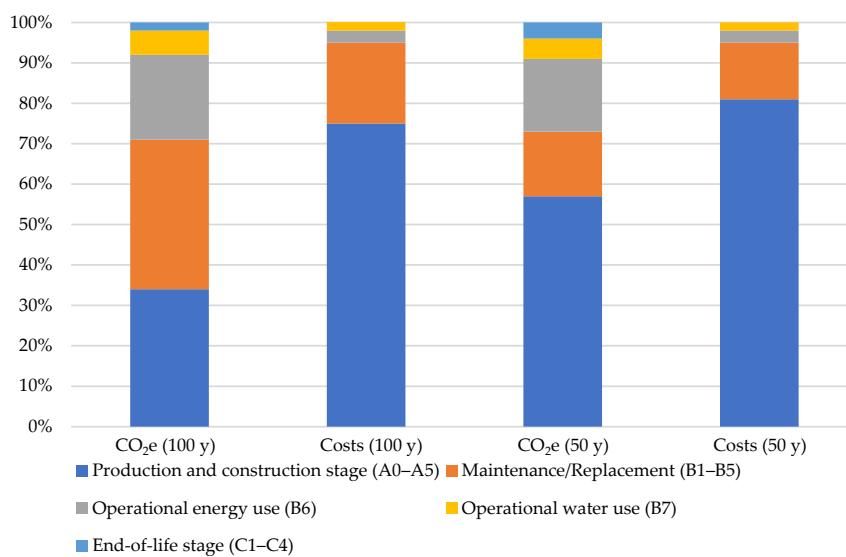


Figure 8. Integration of LCA and LCC results.

4.4.2. Environmental and Economic Relationship within Building Products

Figures 9 and 10 present the relationship between emissions and costs of building materials and installations within their production and replacement phase. The results indicate correlation for most building materials and installations, and thus they could be identified as environmentally and economically justified products. On the other hand, some building products have not shown the same trend. For example, concrete and PV panels display the enormous increase of embodied emissions during its manufacturing process, while these products are found profitable. Moreover, it was noticed that wooden based materials have dramatically low carbon emissions, while from an economic perspective they are considered as expensive solutions.

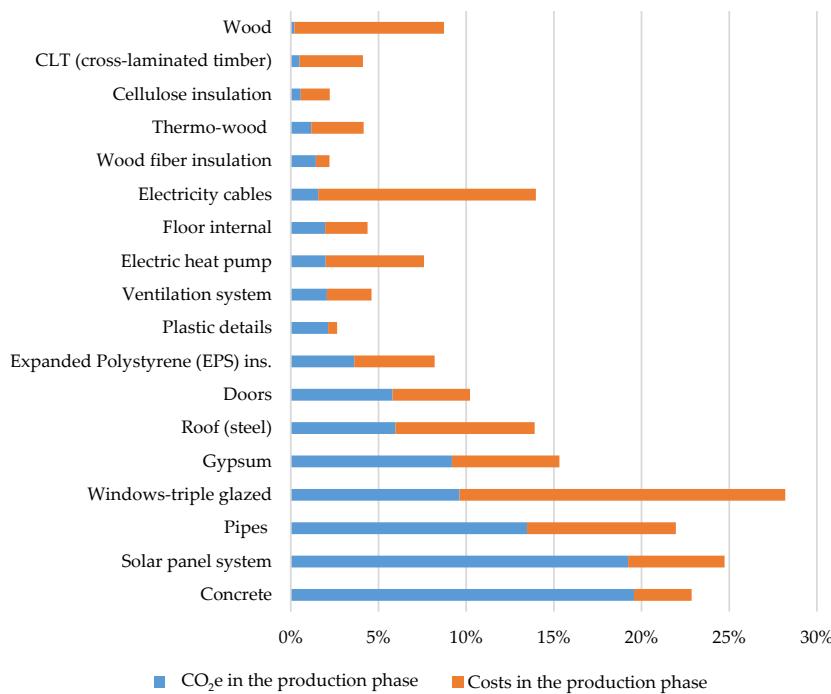


Figure 9. Production phase of building materials and installations: emissions vs. costs.

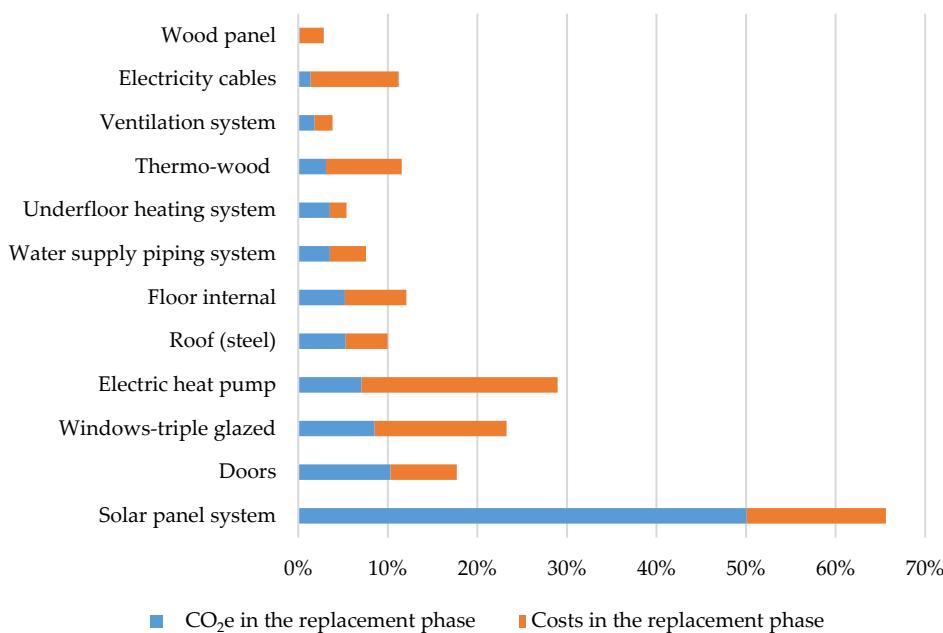


Figure 10. Replacement phase of building materials and installations: emissions vs. costs.

5. Discussion

The study has presented different LCC solutions influenced by various parameters used in calculations. As the house is constructed recently, it has not been possible to obtain measured running costs, hence assumed simulated data were utilized. In the study, it can be noticed the significant share of labor costs and that is due to high salaries in Sweden comparing with labor rate in other countries. Another observation was that having a discount rate of 5% and excluding the PV system will lead to significantly high operational energy costs. However, the main reason of varying different discount rates in the study is risk assessment and the evaluation of future alternative investments. It can be pointed out that it is beneficial to have a higher construction costs if it can lead to minor running costs as these are more uncertain and subject to discounting. Building materials of high quality, imposing low maintenance costs and solar PV system that provides low energy costs is according to this study a profitable solution. Furthermore, wooden-based building materials illustrate significantly low embodied carbon emissions and are considered as relatively expensive solutions. Material prices are subject to change in the future, so only the predictions could be considered.

In our calculations, the LCC results for 50 years lifespan present 36 261 SEK/m², corresponding to ~3 588 €/m² including taxes, taking into account 7% discount rate and an inflation rate of 2%. In a similar case study investigated in Sweden for Väla Gård, the total LCC excluding taxes was 2 352 €/m². They used the same economic parameters for a 40-year lifespan [30]. In the study, material costs including labor costs represent the largest share of total LCC. Moreover, in a similar study, Sterner [27] has also highlighted initial construction costs as the main contributors to total LCC. It can be observed that construction costs in the building industry in Sweden are significantly higher than running costs.

5.1. Uncertainties in LCC and How to Reduce Them

The LCC analysis represents the calculation and estimation of the future costs and therefore includes many uncertainties. The accurate cost calculation depends on data quality as well as future trends of economic indicators, which influence the total life cycle outcomes. Future predictions of a discount rate, inflation rate and energy rate in a long term can also reduce the risk assessment. One way to decrease the uncertainty level is to investigate different alternatives. Uncertainties in the LCC analysis that are related to the prediction of future costs can be reduced by the selection of different discount

rates. Discount rates have been used to equate future costs to the present value, excluding inflation. Due to the high uncertainty of predicting future costs, the LCC approach has not been completely explored in the building sector [27,45]. Furthermore, investigation of the service life of different components of a building and the lifespan of the whole building can influence the results. As the future economic parameters are unpredictable, sensitivity analysis is the most commonly used way to lower the risk of misleading LCC calculations. Data collection is an intensive process for gathering costs due to the complexity of building components. If there is a lack of real data regarding any building component, the forecasts are usually based on generic (average) data, as this takes less time during the calculation process. The challenge in data collection regarding specific data is to find the most appropriate material from databases as the EPDs show low compatibility and are not yet fully standardized. For instance, there are international and national EPDs that include different LCA modules. Future research should put the emphasis on making more transparent and comparable EPDs in order to increase clarity in LCI methods that are also in correlation with cost estimation. In order to decrease uncertainties regarding data collection, the emphasis should be on life cycle inventory (LCI) methods as a part of LCA. A review study by Crawford et al. [46] provide an overview of different hybrid LCI methods and highlight the need for researchers to increase the clarity of each method.

It is believed that wooden-based houses in Sweden often last for at least hundred years. Thus, during the lifespan of a building, after at least 50 years lifespan, many changes in the operational phase (energy use, maintenance and replacement of building materials and installations, water consumption, waste processing) will have a significant impact on the cost evaluation. This could lead decision-makers to establish cost-effective solutions with aim to reduce total costs of buildings by finding a potential balance between construction costs and running costs, with the right choice of lifespan for building components and the building itself. Considering that the electricity costs in Sweden are low in comparison to many other countries, it is recommended to put the emphasis on selection of the right choice of profitable building materials and installations, in order to decrease the LCC.

In previous case studies, especially for multi-family buildings, the emphasis was on electricity costs during the use phase of buildings. In Sweden, the electricity costs can differ depending on the national, regional and local levels, in terms of fixed or variable price. Estimating energy costs is a challenge in a long term due to high risk and uncertainty level. The accuracy of electricity costs will increase if the energy data are calculated from monthly energy bills on annual basis. Thus, for future predictions of operational energy costs, it is recommended to identify the difference between measured and assumed energy calculations for the house and utilize the annual average electricity price. Using actual energy prices at the building site, rather than regional or national average prices, will provide more realistic calculations. Other factors that should be considered to achieve appropriate results are summer and winter costs for a specific building.

A significant difference in price is noticed also within materials, especially regarding insulation materials. However, average-based prices may vary broadly. The software One Click LCA used for LCC calculations provides costs for different insulation materials with different technical properties including average and specific (EPDs) data. The most commonly used insulation materials in the building industry are glass wool and stone wool installed for external and internal walls, and in roofs. However, in this case study cellulose insulation was used as an organic insulation material for external walls and the roof. From an environmental perspective, cellulose insulation shows the lowest environmental impact compared with the other two materials. However, from an economic point of view, cellulose is not the most cost-effective option, having at least two times higher price than glass or stone wool insulation [37]. Thus, in this case, ecological material does not lead to reduced costs. The fundamental issue is to find a balance between cost-effective solutions and environmental-friendly materials during decision-making process. However, Bolek and Hanák [47] presented a method for LCC estimation of building materials that provides a choice of different solutions by taking into account investor preferences.

5.2. Limitations

In the study, some limitations regarding the accuracy and availability of data in the LCC calculations can be found. The long-time perspective with varying different parameters and unknown or limited data could lead to high uncertainties. For example, the use, maintenance and repair costs (B1-B3) are given as a lump sum in the LCC calculations without the possibility to separate them and having more available and transparent data. Therefore, we used average costs per square meter based on Swedish conditions. The reliability of maintenance costs is overall a big challenge to predict in the long term and mostly depends on occupants' preferences and the nature of building materials. Regarding the accuracy of different cost solutions presented in the LCC analysis, there are slight updates in the building materials input data and possible errors through estimations of different systems that suit technical characteristics in the software. The issue is negligible, as it does not change the results and main conclusions of the study.

Some previous studies have included maintenance costs, particularly for renovation purposes of multi-family buildings. Overall, there are insufficient data to demonstrate average costs as they can vary from building to building. Despite unavailable studies about maintenance and repair costs for single-family houses, some predictions could be taken into consideration. Farahani and Dalenbäck [48] proposed a systematic approach by using the modified 'Schroeder' method to simulate the maintenance effect for building components for Swedish residential buildings. This method can be used for single or combination of buildings by using different energy-efficient measures. The results demonstrate great savings, up to 30% by using a proper maintenance regime taking into account customer perspective and existing limitations. Estimated costs in the study [48] can help property managers in predicting maintenance and renovation costs on the available budget and possible limitations. However, considering buildings, every project is individual and specially adapted to its conditions.

5.3. Possible Relations with LCA

The relationship between costs and emissions is still considered as a complex issue. In our case study, we found costs and emissions partly interrelated. However, the purpose was to integrate them in the same framework and rise the understanding between different life cycle stages relevant in the decision-making process. Previous studies were mostly focused on analyzing LCA and LCC methods separately and faced challenge in integrating them in a single model. For example, in the study by Fregonara et al. [49], they discussed the combination of both environmental and economic indicators in a single unit with a focus on the end-of-life phase of a building. Furthermore, in the study by Fawcett et al. [50], the evaluation of costs and emissions were combined in the same framework with an emphasis on differences and their role in decision-making.

This case study has been performed for discovering long-term costs based on the same life cycle inventory data used for LCA. Thus, the entire single-family house Dalarnas Villa was investigated from both the environmental and the economic point of view. The use phase during the entire life cycle has shown the highest contribution of total CO₂e emissions [44]. However, different cost solutions investigated in this study highlight the construction costs as the major contribution to total costs considering discounting approach. Despite following the same life cycle perspective from "cradle to grave", there are found more differences than similarities with previous studies. The methodologies are different, as the LCA uses environmental impacts as outcomes, while LCC uses costs. Thus, there is the possibility to analyze them systematically and discuss relations for decision-making purposes. Another observation while using the software outcomes, which is not presented in this study, is to take into account undiscounted costs. Costs without considering discount rate is not common approach among previous studies, but making correlation between emissions and costs would provide possible explanations. Schmidt et al. [51] demonstrated an economic assessment of GHG emissions. They used the discount cash flow method to evaluate the present value of GHG emissions. The method considers all positive and

negative emissions and discounted them to the present value. The second method in integrating economic and environmental assessments is to apply capitalization approach by multiplying GHG emissions with the market price for carbon. They pointed out that there is a need for further investigation to explore discount rates in both methods and sensitivity analysis of inflation measures used in discounting scheme.

5.4. Future Investigations in the Building Sector

A sustainable built environment strives for combining economic and environmental assessment of buildings. Decision-makers in the building industry are interested in investigating the best solutions in the early design of a project. Despite a complex process of life cycle approach, it is possible to systematically present the relation between costs and environmental impacts. Besides, the LCC approach could help decision-makers in deciding on different solutions for end-of-life of construction. Calculating and estimating costs that occur during reusing, recovering and recycling building materials have a great role in the future for achieving a resilient built environment. We assume that the cost for disassembling will be higher than demolition costs. On the other hand, there will be both environmental and economic savings as parts from the building can be reused in other buildings or for other purposes. Following this idea, it would also be interesting to explore how to use secondary materials during the construction of the building. This could bring investment costs down, unless it will cost more labor, and also from an environmental point of view it will be advantageous as the carbon footprint for such materials will be less.

There is a trend that the building industry in Sweden tends to use more sustainable building materials in the construction sector by investing in the early stage of a building where designers, planners and architects have a major role. Their aim is to choose “greener” building materials that are cost-effective and carbon-neutral. One challenge for future construction is to analyze the relationship between end-of-life costs and impacts that occur during the demolition of a building, and how the circularity process can improve the length of the service life of building materials.

This study has briefly explored the impact of the escalated energy rate on LCC result. Although energy price is relatively stable in Sweden over the past years, it can be a potential challenge for building industry during the large-scale urban energy system transition. For instance, energy prices will be more and more localized and dynamic on the energy market with higher penetration of renewable energy. Accordingly, energy prices could potentially vary a lot during the transition. A wider range in escalated energy rate should be considered in a future study. In addition, as observed in the LCC study, PV panels have a great positive impact on the LCC results, which means more PV panels could significantly reduce the long-term operational costs. On the other hand, PV panels with high environmental impact from the production process can increase the total CO₂ emissions according to the previous LCA study [44]. A case study regarding the optimal capacity of PV panels in such a single-family house is necessary to carry out in the future while considering both LCC and LCA results.

6. Conclusions

The LCC results of Dalarnas Villa case study are strongly affected by the selected economic parameters, such as different discount rates, inflation rate, the forecast of energy prices, and variations in lifespan. Findings in calculations demonstrate that the future costs will increase when the discount rate decreases. The construction costs (A0–A5) remained as the major contributors to the total LCC with labor costs taking half of them. Further, among running costs, the maintenance and replacement of materials have a larger contribution to the total costs than energy, water and end-of-life costs. According to systematically analysed LCA and LCC results, a full correlation was not found, but a partial relationship was investigated. Due to high uncertainty, it is not possible to predict the discount rates, inflation rates and energy prices in a long term. Therefore, to evaluate LCC, different alternatives with assumed variable discount rates and price rates are necessary

to investigate when performing a sensitivity analysis. In fact, predicting future costs is less accurate with increasing the lifetime of a building. When the lifespan of a building is very long, it is hard to assume the service life of building materials and installations as well. The main uncertainties investigated in the LCC calculations are related to the forecast of economic parameters, life cycle length, and reliability of data collection. Owners could invest more time in an early stage of a building by discovering various economic parameters for choosing the most cost-effective solution in the long term. Due to the lack of LCC analysis of single-family houses as a whole concept in Scandinavia, this case study can be used as a general overview and help clients and building professionals in understanding and making choices for long-term cost analysis. This paper presents commonly used LCC parameters, their outcomes, and potential limitations. Hence, this study includes specific input parameters based on reliable data and provides different cost solutions for decision-makers in the building industry. Additionally, the study can be adopted for other single-family houses built with similar technical properties and climate conditions.

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