

Life Cycle Equivalent Annual Cost (*LCEAC*) as a Comparative Indicator in the Life Cycle Cost Analysis of Buildings with Different Lifetimes

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Abstract. The paper deals with the issue of the life cycle cost in the construction. It also focuses on the part of the model for the calculation of the life cycle cost of buildings with consideration of the risk that allows the calculation of the life cycle cost of buildings with different lifetimes. For the construction of this part of the model, the authors used the life cycle equivalent annual cost indicator (*LCEAC*). The operation of this part of the model was presented on the example of three scenarios of the life cycle of pneumatic sports halls for which the estimated service life of the building (*ESLB*) was ranged from 19 to 30 years.

1 Introduction

One of the issues directly related to the life cycle in the construction are the life cycle cost of buildings, mentioned by the authors of the publications: [1-7].

As defined in the work of Boussabaine and Kirkham [8], life cycle cost are expressed in monetary value of all significant costs that are related both to the initial cost of the construction and its subsequent operation, and to the final withdrawal. Estimation of the life cycle cost is a calculation. Therefore, the impact of the risk should be taken into account in the determined value. The ISO 15686-5:2008. "Buildings and constructed assets. Service life planning: Life cycle costing" [9] notes that there is no methodology for calculating the life cycle cost with consideration of the risk, which in the case of construction, would be based merely on the expert knowledge as in many over cases of risk management in construction [8, 10].

This study is a continuation of the research work of the authors on the construction of the model for the calculation of the life cycle cost of buildings with consideration of risk factors. The results of the research work on the model were presented by the authors in [6, 7] so far. The main aim of this study is to present a part of the model that allows the calculation of the life cycle cost of buildings with different lifetimes using the life cycle equivalent annual cost indicator (*LCEAC*). The operation of this part of the model is presented on the example of three scenarios of the life cycle of pneumatic sports halls for which the estimated service life of the building (*ESLB*) is different.

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2 The author's model for calculating the life cycle cost of buildings with consideration of risk factors

2.1 Algorithms and methods used in the construction of the model

The structure of the author's model for calculating the life cycle cost of buildings with consideration of risk factors is based on the possibility theory and fuzzy sets.

The fuzzy sets theory is combined here with the dynamic method used for economic efficiency analysis of construction projects based on discounted cash flows (*DCF*). This is the net present worth method (*NPW*) which will be used for the construction of the model in a fuzzy version (as a fuzzy *NPW* method).

The calculation procedure of the model is based on the following terms, methods and analysis:

- discounted cash flows analysis (*DCF*) at a given value of discount rate (r),
- net present worth method (*NPW*),
- term of a fuzzy number which makes it possible to express a value encumbered with measurable uncertainty (risk),
- decomposition theorem of a fuzzy set into α -cuts,
- principle of the fuzzy expansion of Zadeh.

The fuzzy *NPW* method calculation procedure requires the calculation to be carried out in accordance with the decomposition theorem of a fuzzy set and principle of the fuzzy expansion of Zadeh. Without these rules, the performing basic arithmetic operations on fuzzy numbers, i.e. addition, subtraction or multiplication would be impossible [11].

In addition, the calculation procedure of the model is complemented by the following methods and algorithms that the authors described in their publications [6, 7]. These are:

1. (*DSW*) algorithm developed first by the team of Dong, Shah and Wong [12], and later modified by the team of Givens and Tahani [13], involving the implementation of the principle of the fuzzy expansion of Zadeh in the context of performing basic arithmetic operations (addition, subtraction, multiplication and division) on two fuzzy numbers (marked as $[a, b]$ and $[c, d]$ in a given α -cut), it comes down to the use of appropriate mathematical formulas,
2. vertex method (*VM*) that eliminates errors that could occur during arithmetic operations on fuzzy numbers, in particular on their intervals after the decomposition of fuzzy sets into α -cuts [14],
3. centre of gravity method (*CoG*) used to sharpen the result.

2.2 Division and parametrization of the input data

The input data to the model for calculating the life cycle cost of buildings with consideration of risk factors are divided into the following parameters:

- time (global), i.e. the lifetime (T_i), which is equal to the estimated service life of the building (*ESLB*),
- time (local), namely, times (t_{ik}), (t_{im}), after which k -th periodic operating cost or m -th periodic benefit (revenue) is calculated, respectively,
- financial (global), in the form of a discount rate (r), which is necessary to calculate the present value of a given monetary amount based on its value determined in the future time,
- cost (understood as costs that may arise in the life cycle of a building), among which annual costs are distinguished – in particular, annual operating costs ($C_{opA,ij}$) and

periodic ones – initial costs ($C_{in,i}$), periodical operating costs ($C_{opNA,ik}$) and withdrawal costs ($C_{wd,i}$), respectively,

- cost (understood as revenues that may occur in the life cycle of a building), i.e. annual revenues ($I_{opA,il}$) and periodic - successively periodical revenues earned in the building operation phase ($I_{opNA,im}$) and revenues achieved in the decommissioning phase ($I_{wd,i}$).

The division of individual parameters according to their global or local character is related to the fact that the building's service life (T_i) or the discount rate (r) are accepted as permanent parameters, conditioning and valid throughout the entire life cycle of the building. The local character for the remaining time and cost parameters is connected with the necessity of taking them into consideration only after those years (during the period of building operation), in which their occurrence is expected.

To parameterize any inputs to the module for estimating the total cost of the building life, convex and normal fuzzy numbers will be used, and the following two cases are distinguished:

- if the parameter associated with discount rate, time, cost or income is not burdened with the influence of the impacting risk, the parameter will be modelled as a certain amount in the form of a fuzzy number with a singleton membership function with a degree of membership of 1.0 only for one particular value of the argument (x) (Figure 1a),
- if any of the parameters mentioned above take into account the impact of risk, then it will take the form of an uncertain amount, modelled as a fuzzy number, or shaped as a membership function as in Figure 1b (for time parameters or a discount rate), or as in Figure 1c i Figure 1d (for time or cost parameters).

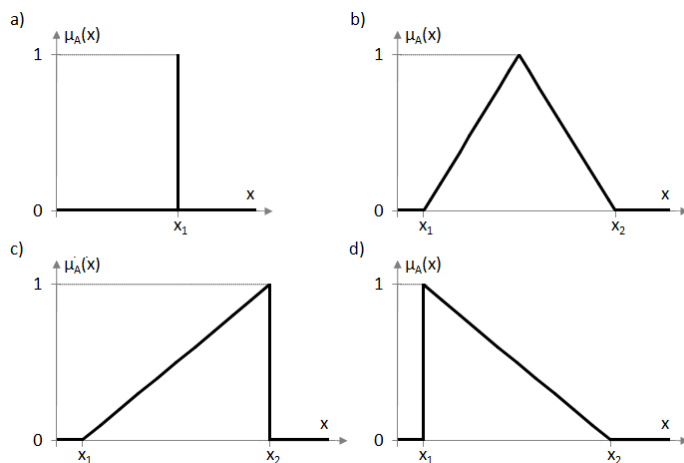


Fig. 1. Membership functions of fuzzy numbers used in a model for estimating the whole life cost of a building; source: own study

2.3 The calculation procedure of the part of the model that allows the calculation of the life cycle equivalent annual cost indicator (LCEAC)

The calculation algorithm for the model of estimating the total cost of living, especially considering the risk allowance in the life cycle of buildings, is presented in the publications of [6, 7, 15]. In these publications, the authors discussed in detail the parts of the model that concern life cycle cost analysis (LCCA) within the following scope:

- life cycle cost of buildings (LCC) if the investor does not record the benefits (revenues) during their life cycle,

- whole life cost of buildings (*WLC*) when, in addition to the costs incurred during the life cycle phases of the building, the investor also notices benefits (revenues),
- addition for risk in the life cycle of buildings (ΔR_{LCC}), which can be expressed in monetary units.

In this paper the authors discuss a part of the model that allows the calculation of the life cycle cost of buildings with different lifetimes using the life cycle equivalent annual cost indicator (*LCEAC*).

To be able to estimate the amount of the life-cycle cost of the *i*-th building (LCC_i) and the life cycle equivalent annual cost indicator ($LCEAC_i$), it is necessary to find a set of discounting factor values (*PWF*) which relate the future cost values to the present value, that is until the moment when a the life cycle cost analysis should be done. These coefficients are determined separately for initial, annual operational and periodical costs, as well as for decommissioning costs. Then, the fuzzy value of life cycle costs of the *i*-th building is calculated, $LCC_i = LCNPW_i^C$ according to the formula:

$$\overline{LCNPW_i^C} = \overline{C_{ln,i}} + \overline{PWF_{AC,i}} \cdot \sum_{j=1}^{n_{AC,i}} \overline{C_{opA,ij}} + \sum_{k=1}^{n_{NAC,i}} \overline{C_{opNA,ik}} \cdot \overline{PWF_{NAC,ik}} + \overline{PWF_{WD,i}} \cdot \overline{C_{wd,i}} \quad (1)$$

where: cost data (*C*) is as described in chapter 2.2; $\overline{PWF_{AC,i}}$ – present worth factor for annual costs of *i*-th building; $n_{AC,i}$ – number of annual costs of *i*-th building; $n_{NAC,i}$ – number of non-annual costs of *i*-th building; $\overline{PWF_{NAC,ik}}$ – present worth factor for non-annual costs of *i*-th building in *k*-th year; $\overline{PWF_{WD,i}}$ – present worth factor for withdrawal costs of *i*-th building.

When comparing buildings whose lifetimes are different, first the fuzzy values of the annual discount coefficient should be calculated ($\overline{AF_i}$), and then the fuzzy values for the equivalent annual costs of *i*-th building ($\overline{LCEAC_i}$). The following formulas serve this purpose:

$$\overline{AF_i} = \frac{\overline{r} \cdot (1 + \overline{r})^{\overline{T_i}}}{(1 + \overline{r})^{\overline{T_i}} - 1} \quad (2)$$

$$\overline{LCEAC_i} = \overline{LCNPW_i^C} \cdot \overline{AF_i} \quad (3)$$

where: *r* – discount rate; T_i – lifetime.

3 An example of calculating the life cycle equivalent annual cost indicator (*LCEAC*)

3.1 Subject of the analysis

The subject of the analysis of the the life cycle equivalent annual cost indicator of buildings (*LCEAC*) are three alternative life cycle scenarios of pneumatic sports halls used for roofing tennis courts, swimming pools, skate parks or football fields in the winter season (in Poland, usually up to 180 days a year). Sports facilities are often subject to cost analysis. This is discussed by such publications as [16-18].

Pneumatic halls are devoid of a heavy and expensive load-bearing structure, which means that the costs of their implementation are much lower than in the case of fixed-construction halls. The covering of a pneumatic hall maintains a structure in space thanks to the overpressure in the interior with a value of from 250 to 350 (*Pa*). This overpressure is generated by the warm air coming from a blower device. The value of the heat transfer coefficient for the covering of the pneumatic hall ranged from 2.5 to 2.9 (W/m^2K).

Figures 1 and 2 illustrate examples of pneumatic sports halls made in technologies of two-layer covers without rigging and three-layer covers with a protective mesh made of steel cables, respectively.



Fig. 2. Double-layer pneumatic hall without rigging; source: [19]



Fig. 3. Three-layer pneumatic hall with a protective mesh made of steel cables; source: [20]

3.2 Data assumed for the analysis

Individual scenarios of the pneumatic sports halls life cycle were built for halls 55 meters in length, 36 meters in width and 9 meters in height (a surface equal to the roof for 3 tennis courts). The halls are made in two-layer covering technologies (scenario: $[i = 1]$) and three-layer ones (scenarios: $[i = 2]$, and $[i = 3]$, the third scenario assumes the replacement of the outer foil every 5 years with a new one). These scenarios differ in the amount of the lifetime (T_i) which equals the estimated service life of building (*ESLB*). These differences result from the necessity to take into account the anticipated operating conditions for each hall separately.

To estimate the (*ESLB*) the methodology presented in the standard PN-ISO 15686-1:2005 “Buildings and constructed assets. Service life planning: General principles and framework” [21] was used.

According to the methodology, the estimated service life of building (*ESLB*) is equal to the product of the reference period of the use of the building (*RSLB*) and correction values for factors that may have negative (correction: $[f = 0.8]$), positive (correction: $[f = 1.2]$) or neutral (correction: $[f = 1.0]$) impact on (*RSLB*). As a model operation period for pneumatic halls, 30 (*years*) were adopted in accordance with the PN-EN standard 1990:2004 “Eurocode. Basis of structural design” [22], that is, as for category 3 of the design lifetime (agricultural constructions and similar).

The following factors have been identified that may have a negative impact on the durability of the hall structure. They include: external environment (destructive influence of weather conditions – correction: $[f_E = 0.8]$) and conditions of use (exposure of the pneumatic covers to acts of vandalism – correction: $[f_F = 0.8]$). For the remaining factors (f_A – the quality of the materials or components used, f_B – level of design, f_C – level of implementation, f_D – internal environment, f_G – level of maintenance), no impact was assumed ($f = 1.0$).

The risk related to the consideration of the abovementioned factors affecting the estimated service life of building (*ESLB*) included for each of the three life cycle scenarios for the pneumatic halls in the lifetime (T_i). Double-layer pneumatic hall (scenario: $[i = 1]$) does not have an additional outer film to protect against weather conditions and is exposed to vandalism. Possible incision of the hall's cover causes its tearing on a very long, progressive section (there is an emergency condition). Three-layer pneumatic halls

(scenarios: $[i = 2]$, and $[i = 3]$) are secured against breakdown resulting from an act of vandalism with a net of wire ropes, which limits the tear to a maximum of one grid field, and against weather factors, provided that the outer foil layer is replaced every 3-5 years.

Table 1 presents results of the analysis of lifetimes (T_i) taking into account the above-described factors affecting ($ESLB$).

Table 1. The results of the analysis of lifetimes (T_i); source: own study

Scenario	$RSLB_i$	f_A	f_B	f_C	f_D	f_E	f_F	f_G	$ESLB_i$
$i = 1$	30 (years)	1.0	1.0	1.0	1.0	0.8	0.8	1.0	19 (years)
$i = 2$	30 (years)	1.0	1.0	1.0	1.0	0.8	1.0	1.0	24 (years)
$i = 3$	30 (years)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	30 (years)

where description of: ($RSLB$), ($ESLB$) and factors from f_A to f_G is consistent with the description

In the case of cost data, the following types of costs were identified for all life cycle scenarios:

- initial costs (C_{in}) – purchase and assembly costs for pneumatic hall (including blowing installations and interior lighting),
- annual operating costs (C_{opA}) – costs of electricity and natural gas consumption as a source of heating of inflatable air, costs of servicing a technical worker and costs of seasonal assembly and disassembly of the hall,
- withdrawal costs (C_{wd}) – the costs of the disposal of a pneumatic hall components after the lifetime (after the time $[T_i]$).

Additionally for the third pneumatic hall (scenario: $[i = 3]$) the outer foil is planned to be replaced every 5 years with a new one in order to eliminate the negative influence of weather factors on the hall's covers. Therefore, periodical operating costs (C_{opNA}) is also included for this scenario which are calculated consecutively after 5, 10, 15, 20 and 25 years of operation (t_{ik}).

For all the types of costs listed above, the values were determined based on market data from the companies offering pneumatic halls in Poland, i.e. Grimar Katowice, Interhall Katowice, Plastbud Warszawa, and Sporthalls Wrocław. Decommissioning costs were assumed to be equal to 0.00 (PLN) due to the assumption of full recycling of all components.

Moreover, it was assumed that future market changes (one type of financial risk factors) were very probable during the lifetime of the building. Therefore, the life cycle cost analysis ($LCCA$) also involved changes in the discount rate by modelling it in the form of an interval of achievable values.

Table 2 presents the all cost, time and financial data assumed for the analysis.

Table 2. The data assumed for the analysis; source: own study

Parameter	Scenario ($i = 1$) double-layer hall	Scenario ($i = 2$) three-layer hall	Scenario ($i = 3$) three-layer hall
Lifetime ($T_i = ESLB_i$)	from 19 to 30 (years)	from 24 to 30 (years)	30 (years)
	triangular membership function (Figure 1d)		
Discount rate (r_i)	from 6 to 10 (%)	from 6 to 10 (%)	from 6 to 10 (%)
	triangular membership function (Fig. 1b)		
Initial costs ($C_{in,i}$)	551,300.00 (PLN)	399,750.00 (PLN)	467,400.00 (PLN)
Annual operating costs $C_{opA,ij}$	122,600.00 (PLN)	139,800.00 (PLN)	131,200.00 (PLN)
Periodical operating costs ($C_{opNA,ik}$) after (t_{ik}) = 5, 10, 15, 20, and 25 (years)	not applicable	not applicable	6,800.00 (PLN)

Withdrawal costs ($C_{wd,i}$) after ($T_i = ESLB_i$)	0.00 (PLN)	0.00 (PLN)	0.00 (PLN)
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3.3 Calculation results

For all three scenarios of life cycle of pneumatic sports hall, the life cycle cost (LCC) and the life cycle equivalent annual cost indicators ($LCEAC$) were calculated according to the calculation procedure presented in chapter 2.3. The resulting acute values representing the output fuzzy numbers for the life cycle cost (1,796,800.00 [PLN], 1,913,800.00 [PLN], and 1,979,100.00 [PLN], respectively) and the life cycle equivalent annual cost (268,300.00 [PLN], 256,600.00 [PLN], and 227,800.00 [PLN], respectively) were calculated with the use of the centre of gravity method (CoG) to sharpen the result.

Figure 4 illustrates an output membership function for the life cycle equivalent annual cost ($LCEAC$) for the three analysed scenarios of pneumatic sports halls.

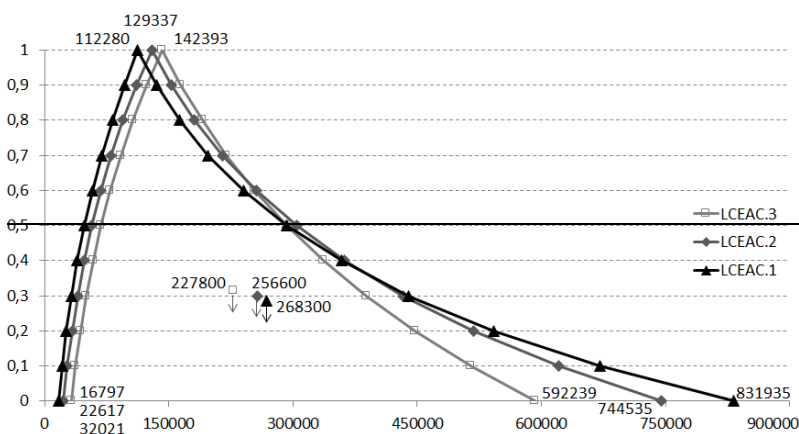


Fig. 4. The output membership function for the ($LCEAC$); source: own study

Table 3 illustrates the output values calculated for all scenarios of pneumatic sports hall in the chosen α -cut equal to 0.5.

Table 3. Values calculated within the α -cut equal to 0.5; source: own study

Values calculated	Scenario ($i = 1$)		Scenario ($i = 2$)		Scenario ($i = 3$)	
	0,5 (left boundary)	0,5 (right boundary)	0,5 (left boundary)	0,5 (right boundary)	0,5 (left boundary)	0,5 (right boundary)
LCC_i (PLN)	1,748,593.00	1,818,444.00	1,801,466.00	2,003,163.00	1,826,464.00	2,109,246.00
$LCEAC_i$ (PLN)	47,807.00	292,803.00	56,882.00	304,170.00	68,213.00	292,447.00

4 Conclusions

The results of the calculations presented in chapter 3.3 indicate that the most favourable solution for a pneumatic sports hall due to the life cycle cost of the building (LCC) is scenario ($i = 1$). The (LCC) amount is the smallest for a double-layer hall ($[LCC_i]$ and is equal to 1,796,800.00 [PLN]), but the scenario predicts that the lifetime of the hall is, however, the shortest of all three scenarios ($[T_i]$ ranges from 19 to 30 [years]).

On the basis of Figure 4 one can conclude that the most favorable solution for the planned investment is the implementation of scenario ($i = 3$) which generates the lowest value of the

life cycle equivalent annual cost (*LCEAC*) with, at the same time, the longest lifetime ($[T_3]$ is exactly 30 [years]).

Since the life cycle equivalent annual cost analysis (*LCEAC*) does not include the analysis of income that can be obtained by the investor in the life cycle of the building, in the calculation example for pneumatic sports halls, their simulations for renting tennis courts were not presented. Therefore, the whole life cost analysis was not performed.

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