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Quantification of the risk addition in life cycle cost of a building object

Kwantyfikacja dodatku za ryzyko w kosztach cyklu życia obiektu budowlanego

Abstract

This paper focuses on the estimation of life cycle cost of buildings taking into account the influence of risk. The authors present a original model for the estimation of the life cycle cost of a building object which allows quantifying the degree of cost increase arising from the incurred and assessed risks. The operation of the model is demonstrated by a relevant example.

Keywords: risk, building object, life cycle, life cycle cost, fuzzy sets

Streszczenie

W niniejszym artykule zwrócono uwagę na kwestie szacowania kosztów cyklu życia z uwzględnieniem wpływu ryzyka na ich wielkość. W pracy przedstawiono autorską koncepcję modelu szacowania kosztów cyklu życia obiektu budowlanego, dzięki któremu będzie można skwantyfikować wielkość dodatku za zaistniałe i ocenione ryzyko. Działanie modelu zobrazowano przykładem.

Słowa kluczowe: ryzyko, obiekt budowlany, cykl życia, koszty cyklu życia, zbiory rozmyte

1. Introduction

One of the issues directly related to the concept of life cycle in the building industry is life cycle cost (*LCC*).

As defined in ISO 15686-5:2008: "Buildings and constructed assets. Service life planning: life cycle costing" [1], life cycle cost are the sum of all the significant costs arising during the life cycle of a building object, expressed in monetary units, including the costs influencing both accessibility and the reliable and safe operation of a building in the analysis period (for instance, until the withdrawal of the building by its demolition).

The impact of occurrent risk is required to be taken into account whilst estimating the life cycle cost of a building. This vital aspect is highlighted in the ISO norm described above [1], which states that although there exist models involving the influence of identified risk factors on the sum of the life cycle cost of a building, none of them define or express the influence as the addition for the risk.

Therefore, the authors decided to define addition for the risk as a difference expressed in monetary units between the sum of a building life-cycle cost which involves the impact of risk, and the sum of the building life cycle cost which excludes risk.

The main aim of this paper is the presentation of the authors' model of estimating life cycle cost of a building object including risk in the form of a quantified amount of addition for the occurrent risk, which may become one of the possible comparative criteria for the investor during the selection of the most advantageous solution for the planned construction project.

2. Models of life cycle cost estimation for a building object

The estimation of the life cycle cost of building objects is the subject of research in Poland and other countries. To date, as a result of studies and analyses, a number of novel methods have been developed – the application of these depends on the type of object under analysis, the scope of the analysis and the country in which the analysis is to be conducted.

The LCC analysis may be conducted using either simple or complex methods. Simple methods are used for uncomplicated comparisons. Their basic features involve calculations which do not take into account changes in the value of money over time and changes in energy prices. The basis for the calculation of the value of life cycle cost is a formula which sums purchase costs C_{pur} (understood as the cost of study analysis, design and construction) and the product of the planned lifetime of a building in years *SL* (service life) and the annual energy cost C_{en}. Complex methods, on the other hand, are based on mathematical economic models which do take into account changes in the value of money over time.

An example of a complex method is the analysis of the effectiveness of investments based on discounted cash flow taking into account environmental issues *LCNPV*, which is calculated according to the following formula [2]:

$$LCNPV = \sum_{i=0}^{n} \frac{CF_i}{(1+r)^i} \tag{1}$$

where: CF_i – cash flow in *i-th* year; n – number of years involved in a life cycle; i – subsequent year; r – discount rate.

This method may serve, for example, to estimate life cycle cost of a building object, but without taking into account the possibility of the simultaneous occurrence of risk factors.

There are rather few existing complex mathematical models designed for the estimation of life cycle cost in the construction industry which include the possibility of risk in each phase of the life cycle.

Table 1 presents a selection of complex mathematical models designed for the estimation of the life cycle cost of building objects in which the authors performed an analysis of the simultaneous occurrence of risk factors.

Table 1. Selected models of life cycle cost estimation involving the analysis of the impact of risk
Source: own study based on [3, 4, 5]

AUTHORS AND YEAR OF PUBLICATION	CASES ANALYSED	TYPE OF APPROACH
Frangopol, Lin, Estes 1997	Concrete bridge girders	Combining strategic planning (event trees) with probabilistic techniques, as well as deterministic economic account for the purposes of optimisation
Sobanjo 1999	Building objects	Using fuzzy sets theory and expert knowledge
Fuller, Boyles 2000	Heat pumps	Based on probabilistic techniques used in conditions of uncertainty

As the literature review shows, complex mathematical models exist which involve the influence of identified risk factors on the sum of life cycle cost of a building object; however, they never quantify this influence as an addition for the risk. Thus, the statement sourced from ISO 15686-5:2008 [1], expressed in the introduction, is maintained.

3. Authors' proposed model for the estimation of life cycle cost of a building object with risk factored in

The costs identified in the individual stages of the building life cycle are divided into initial costs (associated with land purchase and construction), operating costs (related to the maintenance of the building) and withdrawal costs (linked to the demolition of the object). The structure of each of these costs should include environmental costs, as is required by ISO 15686-5:2008 [1].

In the individual stages of implementation, maintenance and withdrawal of the building object, one can identify profits (incomes) expressed in monetary units (for instance, from the sale or the lease of living or business space or the resale of furnishings). In this case (when there are profits identified in the life cycle), the ISO standard [1] relates to the concept of whole life cost (*WLC*).

Due to the fact that the life cycle of a building involves not only costs, but also possible profits, one needs to distinguish the following two cases of cost analyses for which the model is designed:

1) life cycle cost analysis (*LCCA*),
2) whole life cost analysis (*WLCA*).

3.1. Algorithms and methods used in the development of the model

Risk is connected to the so-called quantified uncertainty which translates into the parameters necessary to, for example, perform an appraisal of the economic efficiency of a planned investment [6]. At present, two types of quantified uncertainty descriptions are used for performing such appraisals, these are probability distribution and possibility distribution – probability distribution being the most commonly used method, possibility distribution employs fuzzy numbers for this purpose [7].

The structure of the authors' model for estimating the life cycle cost of a building object which takes risk into account is based on the possibility theory and fuzzy sets.

Fuzzy logic is combined with the most common, dynamic method used for the economic efficiency analyses of a construction project based on discounted cash flows – this is the net present worth method (*NPW*).

The *NPW* fuzzy method is founded on the decomposition theorem of fuzzy sets – it allows the presentation of any fuzzy set *A* contained in space *X* as the sum (understood as set-theoretical) of fuzzy sets generated by the so-called α-sections, which may also be referred to as α-significance level sets [8].

The calculation procedure of the model is complemented by the following methods:

1) the *DSW* algorithm – first developed by the team of Dong, Shah & Wong [9], later modified by the team of Givens & Tahani [10], which involves the implementation of the principle of fuzzy expansion in the context of performing basic arithmetic operations (addition, subtraction, multiplication and division);
2) the vertex method (*VM*), which eliminates errors that could occur during arithmetic operations on fuzzy numbers, particularly on their intervals after the decomposition of fuzzy sets;
3) one of the universal defuzzification methods, which can be effectively used regardless of the shape of the membership function of the resulting fuzzy set, that is, either the centre of gravity method (*CoG*) or the area compensation method (*AC*), in which the acute resulting value representing the fuzzy output set is the arithmetic average of the surface (A_l i A_r) appointed by vertical axis $\mu(x)$ and left or right curve limiting the resulting fuzzy set, respectively.

Since all the costs, profits, time, discount rates and discount factors may be presented as positive values, which means as non-zero ones, the application of the methods mentioned above in performing addition, subtraction, multiplication or division operations is fully justified.

3.2. The calculation procedure of the model

The method involves the description of parameters exclusively by means of convex and normal fuzzy sets (of a maximum degree of membership of 1.0) for which membership functions are continuous intervals. This requirement stems mainly from the use of the decomposition theorem of fuzzy sets, the *DSW* algorithm and the centre of gravity method as one of the ways of defuzzification the resulting values.

If the parameter associated with the discount rate, time, cost or income does not involve the impact of risk, it will be modelled as a certain value in the form of a fuzzy number of a singleton membership function with a degree of membership of 1.0 exclusively for one certain value (Fig. 1a).

On the other hand, if any one of the parameters mentioned above involves the influence of risk, it will assume the form of an uncertain value modelled as a triangular fuzzy number or as one shaped as a membership function, as in Fig. 1b (for time parameters and a discount rate), or as in Fig. 1c (for costs and incomes).

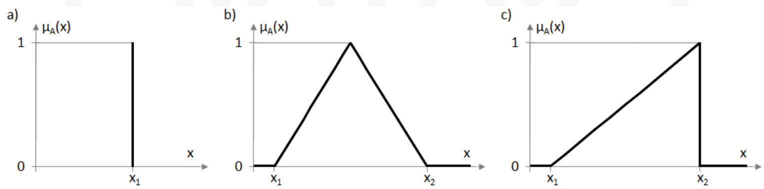

Fig. 1. Membership functions of fuzzy numbers used in a model for estimating whole life cost of a building object; source: own study

To enable the calculation of the value of life cycle cost LCC_i or the whole life cost $WLCC_i$ of the *i-th* building object variant, it is necessary to designate the value of discounting factors which make it possible to refer the value of the future costs or profits to the present value, that is the moment when the analysis is performed. The values of the factors can be calculated using the following rules (the description of the relevant terms in the text):

- for operating costs and profits calculated on an annual basis:

$$\overline{PWF_{AC,i}} = \overline{PWF_{AI,i}} = \frac{1}{\bar{r}} \cdot \left(1 - \left(1 + \bar{r}\right)^{-\bar{T}}\right) \tag{2}$$

- for operating costs calculated periodically after *k-th* time t_{ik}:

$$\overline{PWF_{NAC,ik}} = \frac{1 - \left(1 + \bar{r}\right)^{-\overline{t_{ik}}}}{\left(1 + \bar{r}\right)^{\overline{t_{ik}}} - 1} \tag{3}$$

- for operating profits calculated periodically after *m-th* time t_{im}:

$$\overline{PWF_{NAI,im}} = \frac{1-\left(1+\bar{r}\right)^{-\overline{t_{im}}}}{\left(1+\bar{r}\right)^{\overline{t_{im}}}-1} \tag{4}$$

- for costs and profits related to the withdrawal of the *i-th* building object by its demolition after its maintenance time finishes (after $ESLB_i$):

$$\overline{PWF_{WDC,i}} = \overline{PWF_{WD,i}} = \left(1+\bar{r}\right)^{-\bar{T}} \tag{5}$$

In order to determine the recurring fuzzy value of LCC_i or $WLCC_i$ of the *i-th* variant of the building object, one needs to use the following equations:

- for the fuzzy value $LCC_i = LCNPW_i^C$:

$$\overline{LCNPW_i^C} = \overline{C_{in,i}} + \overline{PWF_{AC,i}} \cdot \sum_{j=1}^{n_{AC,i}} \overline{C_{opA,ij}} + \sum_{k=1}^{n_{NAC,i}} \overline{C_{opNA,ik}} \cdot \overline{PWF_{NAC,ik}} + \overline{PWF_{WD,i}} \cdot \overline{C_{wd,i}} \tag{6}$$

- for the fuzzy value $ILCC_i$:

$$\overline{ILCC_i} = \overline{PWF_{AI,i}} \cdot \sum_{l=1}^{n_{AI,i}} \overline{I_{opA,il}} + \sum_{m=1}^{n_{NAI,i}} \overline{I_{opNA,im}} \cdot \overline{PWF_{NAI,im}} + \overline{PWF_{WDI,i}} \cdot \overline{I_{wd,i}} \tag{7}$$

- for the fuzzy value $WLCC_i = LCNPW_i^I$:

$$\overline{LCNPW_i^I} = \overline{ILCC_i} - \overline{LCNPW_i^C} \tag{8}$$

The process of cost estimation or the estimation of the whole life cost of the *i-th* variant of a building object is divided into the following stages:

1) expressing of global input variables using fuzzy numbers (concerns the value of life cycle $T_i = ESLB_i$ and discount rate r_i);
2) expressing of global input variables using fuzzy numbers (concerning the value of the duration of calculating the periodic costs and incomes t_{ik}, t_{im});
3) using fuzzy numbers to express input variables related to the costs incurred during the life cycle of a building (where: $C_{in,i}$ – initial costs, $C_{opA,ij}$ – annual operating costs, $C_{opNA,ik}$ – periodic operating costs, $C_{wd,i}$ – withdrawal costs);
4) using fuzzy numbers to express input variables related to incomes in the life cycle of a building (where: $I_{opA,il}$ – annual operating costs, $I_{opNA,im}$ – periodic operating costs, $I_{wd,i}$ – income related to the withdrawal of a building object);*
5) selecting sections $\alpha \in$ <0; 0.1; …; 1.0>;
6) determining the values of factors discounting the values of costs $PWF_{AC,i}$, $PWF_{NAC,ik}$, $PWF_{WDC,i}$ by means of formulas (2), (3), (5) for the boundary elements in each section α;
7) determining the values of factors discounting the values of incomes $PWF_{AI,i}$, $PWF_{NAI,im}$, $PWF_{WDI,i}$ by means of formulas (2), (4), (5) for the boundary elements in each section α;*

8) calculating discounted component values of the costs modelled for uncertain values (affected by the influence of risk) and summing them up to the fuzzy value LCC_i on the basis of formula (6) on $LCNPW_i^C$ for the boundary elements in each section α;
9) calculating the discounted values of income components and summing them up to a fuzzy value $ILCC_i$ on the basis of formula (7) for the boundary elements in each section α;*
10) calculating the value of the difference between fuzzy values $ILCC_i$ and LCC_i, that is the fuzzy value of the whole life cost $WLCC_i$ on the basis of formula (8) on $LCNPW_i^I$ for the boundary elements in each section α;*
11) performing defuzzification of the fuzzy value LCC_i to an acute value;
12) performing defuzzification of the fuzzy value $WLCC_i$ to an acute value;*
13) calculating discounted values of cost components modelled for certain values (not affected by the influence of risk) and summing them up to a fuzzy value LCC_i on the basis of formula (6) on $LCNPW_i^C$ for the boundary elements in each section α;**
14) calculating the value of the difference between the values LCC_i in points 8 and 13, that is the fuzzy value of the cost addition for the identified and evaluated risk $\Delta R_{LCC,i}$ for the boundary elements in each section α;**
15) interpreting the results obtained for the fuzzy value $\Delta R_{LCC,I}$;**
16) repetition of the calculation stages from 1 to 15 for the remaining *i-th* variants of solutions to the planned investment;
17) arranging (ranking) the *i-th* variants of solutions to the planned investment in accordance to the criterion of life cycle cost or the whole life cost, or addition for risk in the life cycle of a building object.

where: * means the need to perform calculations in the case of the identification of incomes in the life cycle of a building; ** means the need to perform calculations when it is necessary to estimate the value of the addition relating to the incurred risk.

3.3. An example operation of the model

The operation of the fuzzy model estimating the whole life cost of a building object whilst factoring in risk is illustrated using the example of a multifamily residential building with a separate service area and garages in the basement for which three variants of a solution (i = <1, 2, 3>) was prepared. The reason for this lies is the need to include the impact of the technological risk factor which was identified and assessed with the use of the fuzzy risk assessment module on life cycle cost entitled 'incorrect assumptions about materials and structure' [11] for the range of works related to the building facade.

For each variant, costs and incomes that could occur in the life cycle were identified. A type of reaction to an identified and assessed risk factor was proposed. It was assumed, that future market changes were very probable during the maintenance period of the building. Therefore, the analysis of life cycle cost also involved changes in the discount rate by modelling it in the form of an interval of achievable values.

Table 2 presents the values of parameters adopted for the analysis for each scenario of the life cycle a building. For the modelling of the majority of the parameters included in the table, a singleton membership function presented in Fig. 1a. with the exception of these parameters which had information about the membership functions applied added into their cell.

Table 2. Data assumed for analysis; source: own study

PARAMETER		SCENARIO $i = 1$	SCENARIO $i = 2$	SCENARIO $i = 3$
The type of reaction to risk		Lack of reaction to risk (allowing a solution from the original design concept)	Allocation of risk in initial costs (a more expensive exchangeable solution applied at the stage of object implementation)	Transfer of risk to the maintenance stage (a more expensive exchangeable solution applied at the stage of general renovation)
Life cycle $T_i = ESLB_i$		50 years	50 years	50 years
Discount rate r_i		from 6 to 10 % (triangular membership function, Fig. 1b)	from 6 to 10 % (triangular membership function, Fig. 1b)	from 6 to 10 % (triangular membership function, Fig. 1b)
Initial costs $C_{in,i}$		13 445 333 PLN	max. 13 856 694 PLN (triangular membership function Fig. 1c)	13 445 333 PLN
Annual operating costs $C_{opA,ij}$		210 374 PLN	210 374 PLN	210 374 PLN
Periodical operating costs $C_{opNA,ik}$ after $t_{ik} = \ldots$	10	513 470 PLN	513 470 PLN	513 470 PLN
	20	513 470 PLN	513 470 PLN	513 470 PLN
	30	2 053 881 PLN	2 053 881 PLN	max. 2 460 865 PLN (triangular membership function, Fig. 1c)
	40	513 470 PLN	513 470 PLN	513 470 PLN
Withdrawal costs $C_{wd,i}$ after $T_i = ESLB_i$		1 105 566 PLN	1 105 566 PLN	1 105 566 PLN
Annual income $I_{opA,il}$		371 908 PLN	371 908 PLN	371 908 PLN
Periodic operating income $I_{opNA,im}$ after $t_{im} = \ldots$ (sales of apartments and garages)	1	16 664 356 PLN	16 664 356 PLN	16 664 356 PLN
	2	5 127 494 PLN	5 127 494 PLN	5 127 494 PLN
	3	2 563 747 PLN	2 563 747 PLN	2 563 747 PLN
	4	1 025 499 PLN	1 025 499 PLN	1 025 499 PLN
	5	256 375 PLN	256 375 PLN	256 375 PLN
Income $I_{wd,i}$ from the sale of a building plot after $T_i = ESLB_i$		3 132 000 PLN	3 132 000 PLN	3 132 000 PLN

Figure 2 a–c presents the successively adopted fuzzy distributions for the values of the discount rate r_i (for all variants) of the values of initial costs $C_{in,2}$ (scenario 2) and the periodical operating costs $C_{opNA,330}$ related to the general renovation of the building after the thirtieth year of maintenance (for scenario 3). The whole membership equal 1.0 is assigned to average values, also known as expected ones.

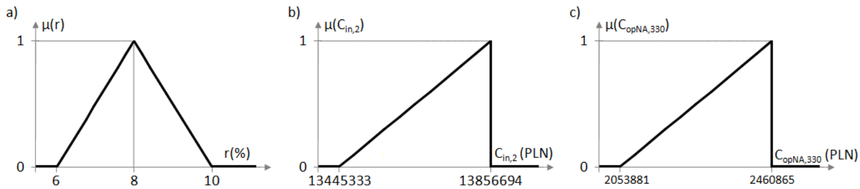

Fig. 2. Membership functions for parameters under the influence of risk; source: own study

Figure 3 illustrates an output membership function for the addition of risk $\Delta R_{LCC,i}$ for the three analysed variants of building object implementation. The resulting acute values representing the output fuzzy sets (95 700 PLN 369 400 PLN and 118 500 PLN respectively) were calculated with the use of the centre of gravity method.

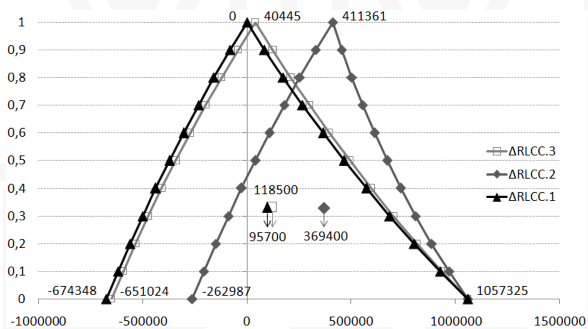

Fig. 3. The output membership function for the $\Delta R_{LCC,i}$ criterion; source: own study

Table 3 illustrates the output values calculated for all scenarios in the chosen section α equal to 0.5.

Table 3. Values calculated within the section α = 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]	16 245 919	17 083 997	16 657 280	17 289 678	16 276 594	17 110 730
$ILCC_i$ [PLN]	26 595 766	28 349 570	26 595 766	28 349 570	26 595 766	28 349 570
$WLCC_i$ [PLN]	9 511 769	12 103 651	9 306 088	11 692 290	9 485 037	12 072 976
$\Delta R_{LCC,i}$ [PLN]	- 372 337	465 740	39 024	671 421	- 341 663	492 473

4. Conclusions

On the basis of Fig. 3, one may conclude that the most advantageous solution for the planned investment is the implementation of scenario 1 – this generates the lowest value of the addition for risk; however, it needs to be emphasised that in the case of this scenario for the life cycle of a building object, only the addition relating to financial risk was accounted for.

If one choses to consider scenarios 2 and 3 which include the addition for both types of risk (financial and technological), the more reasonable solution for the planned construction investment would be the implementation of scenario 3 – this assumes the transfer of technological risk to the maintenance stage and bearing higher costs for the general renovation of the building object after the thirtieth year of its use. Another argument for this solution is the fact that the difference between acute output values of additions for risk in scenarios 1 and 3 of the building life cycle is merely 22,800 PLN.

It is also worth mentioning, that the resulting fuzzy distributions for the addition of risk (Fig. 3) indicate that during the life cycle of the implemented building object (with a reasonably large probability for scenarios 1 and 2), there may occur such circumstances, which due to the existing risk, will not constitute a loss for the investor, but will generate a profit (when $\Delta R_{LCC,i} < 0$).

In future work on the model developing, the authors especially plan to focus on the diversity of the impact of risk in the different phases of the life cycle of a building with different categories of risk factors, i.e. technological, relating to the construction process, financial, political, environmental or legal.

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