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IMPROVING THE OPERATION OF A SURFACE WATER INTAKE WITH EXCEEDED REDUNDANT CAPACITY USING RELIABILITY ANALYSIS AND LIFE CYCLE COSTING

Integrated procedures of analysis have been presented combining both reliability and economical aspects of operation of a water supply system (WSS). The method presented is a practical application of the reliability analysis and life-cycle costing which is a part of a decision support system (DSS) for WSS. It focuses on undisturbed operation of systems with exceeded redundant capacity minding system's reliable and lower possible operational costs. The proposed analytical approach is shown on the example of the surface water intake which is the first subsystem of WSS influencing operation of a whole system. As a part of the study, reliability and economic assessments of various variants of future operation of water intake have been carried out as a basis for choosing most advantageous solution. The authors indicate how exceeded redundant capacity affects applied maintenance method of the system. All calculations of the reliability indicators are based on operating data contained in exploitation logs (2001–2012). The costs have been estimated based on the obtained financial documentation.

1. INTRODUCTION

Since the beginning of the 90s, when market economy principles were introduced in the Polish water supply and sanitation sector, there has been a continuous decrease in water consumption. This is mainly related to the reduction of water consumed by industrial plants through the implementation of water-saving technologies and the introduction of closed water circuits. In addition, the demand for water in the household sector has been also decreasing, due to widespread water meters installation, changes in tariff price structure (i.e. higher water prices) and changes in consumption patterns [1, 2].

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Furthermore, the modernization of WSS resulted in a significant reduction in water leakages, as well as reducing the number of illegal water connections. It should be emphasized that water demand reduction is being observed in all member countries of the European Union and the European Commission has stated that they expect the demand to continue to fall [2].

The biggest Polish drinking water treatment plants (DWTP) supplying cities such as Warsaw, Cracow, Wrocław or Katowice have been designed, built, and often expanded when the general assumption was, that there would be a continuous increase in water demand [3, 4]. Minding the fact that lower water consumption is now observed, mentioned technical systems have significant redundant (underutilized) capacity. In other words, water companies have to purify and supply much smaller volumes of water than their dispositional capacity can provide. Such operational conditions for WSS, create new opportunities for the application of reliability analysis, including the technological (process), technical and economic aspects of operating DWTP [3–5].

Maintaining system with exceeded redundant capacity also affects management of the DWTP infrastructure. High probability to achieve the proper operation of the system (i.e. providing water of the required volume, quality and pressure) is mainly due to the high reserve capacity of most of the equipment. With this in mind, the system's operator often uses reactive and/or preventive technique, for the key process elements [6, 7]. The implementation of predictive maintenance strategies is exceptional. Choice of the maintenance method is often based on an intuitive operator's approach and not on measurable indicators.

Many authors [3, 4, 8] indicate that the results of technical, economic and reliability analysis can support the decision making process regarding the maintenance strategy of WSS with exceeded redundant capacity.

In order to meet the real needs of a water intake operation which includes dynamically changing internal and external conditions, this paper presents an application of the reliability theory and life cycle costing (LCC) method for surface water intake of one of the biggest DWTPs in Southern Poland. The goal of the paper is to present the method of improving the operation of water intake, which has underutilized capacity, without incurring costs associated with the modernization of the system. All calculations are based on actual recorded data.

2. RELIABILITY AND THE LIFE CYCLE COSTING MODEL

From the reliability theory point of view, water intake is a renewable technical facility with long operation time, in which the average working time between failures is much shorter than its durability. Every intake device during its life cycle is in one of the following operational states: state of operational stoppage, process stoppage, renewal, repair or waiting for repair [8]. These states can be defined as stationary processes with lack of memory [3, 8]. In this study, for reliability evaluation of the water intake, the two parameter method has been applied. It is based on the analysis of readiness indicator K_g and the average operating time between failures (average working time) T_p.

Based on the exploitation logs (01.01.2001–30.06.2012), the authors have created worksheets for each device of the water intake. Every worksheet includes information such as date of failure, renewal or inspections occurrence and date of its closure. Based on verified set of random variables, describing working times and renewal times, the values of the basic reliability indicators for each element have been calculated [8], i.e.:

- average operating time between failures T_p [h]

$$T_p = \frac{1}{n_p}\left(T - \sum_{i=1}^{n_o} t_{ni}\right) \tag{1}$$

- average renewal time T_o [h]

$$T_o = \frac{1}{n_o}\sum_{i=1}^{n_o} t_{ni} \tag{2}$$

- readiness indicator K_g

$$K = \frac{T_p}{T_p + T_o} \tag{3}$$

where: n_p is the number of segments of working periods in analysed period, n_o is the number of renewals in the analysed period, t_{ni} is the duration of i renewal, T is the total observation time.

The authors have adopted required values of indicator K_g as given in literature [8] and based on research conducted on WSS. Depending on the size of the supplied city and its nature, e.g. industrial or urban-industrial, relevant values of K_g are given [8]. They are defined for 3 states of the system, described with volume of treated water Q and total water demand in the city – Q_n. The states are:

- state of full production capacity: $Q = Q_n$,
- state of reduced production capacity: $\alpha_{aw}Q_n \le Q \le Q_n$, $\alpha_{aw} = 0.7$ is the index of emergency water supply reduction,
- state of the border capacity reduction $\alpha_g Q_n < Q \le \alpha_{aw}Q_n$; $\alpha_g = 0.2–0.35$ is the index of limit water supply reduction.

Taking into consideration that water supply is equally important as water treatment, it is assumed that water distribution subsystem (WDS) and water purification subsystem

(WPS) including DWTP are serial connected. What is more, thanks to the decomposition method [3, 8] taking into account all parallel and serial connections between groups of elements, the required values of K_g indicator are established. For the water intake it equals 0.9954818 [3, 8].

Ensuring reliable operation of technical systems inevitably results in costs and expenses. Economic analysis for technical systems can involve by various analytical approaches. The most common is the cost benefit analysis method (CBA) based on analysis of the net present value (NPV) and/or internal rate of return (IRR) [11]. The aim of these analysis is to determine the profitability of the planned construction or modernization. This paper presents new approach to integrated economic and reliability analysis which make possible the numerical comparison of various variants of system operation. Due to the nature of systems with exceeded redundant capacity, the most advantageous option includes operation of less number of devices and/or changing the maintaining strategy. However, no new construction or modernization are analyzed. The authors implement other well-known cost analysis – LCC [3, 4, 9–12]. This method is based on the assumption that every object or technical device goes through several phases of life during which it generates specific costs, expenses and profits. These phases are: design, construction, usage and disposal. Therefore the cost of a life cycle equals [4, 9, 10]:

$$LCC = CF_d + CF_b + CF_u + CF_{di} \tag{4}$$

where; CF_d – cash flows of design phase, CF_b – cash flows of construction phase, CF_u – cash flows of usage phase, CF_{di} – cash flows of disposal phase.

From an economic point of view, during the lifetime of a device, cash circuits defined as cash flow (*CF*) can be observed. Thus, *CF* may occur in different time, so they must be discounted to include the change of money value over time. According to the EU guidelines [13], Polish discount rate is 0.05 and this value is used in the study.

Basing on numerous works presented in world literature [14–17], it can be seen that Woodward's model [10], being an extension of the life cycle costs concept together with activity based costing (*ABC*) by Cooper and Kaplan [9, 10], are most relevant in the economic studies of technical systems. The combination of these approaches is called activity based life cycle costing (AB-LCC) [4, 10]. The main advantage of the AB-LCC model is its ease of adaptation to various computing variants, as well as the universality of applications in other fields such as aviation, construction, transport [16] or power engineering.

In each LCC analysis, the time horizon must be defined. The intake has been operating for over 60 years and it still meets all technical requirements. Based on data provided by the operator, it is determined that the time horizon for pumps' further cost effective operation is 15 years. It is therefore adopted in the study, that the horizon analysis for the intake equals 15 year time.

3. DESCRIPTION OF THE OBJECT

The analyzed intake is a subsystem of a DWTP with an available daily capacity of 500 000 m^3/day. However, the maximum daily water demand over the period 2009–2014 was 271 410 m^3/day. The DWTP treats surface water from two independent sources (Fig. 1). This solution has been introduced in the 70's with the aim of increasing the capacity of the DWTP and diversifying water sources as the quality of water from source 1 was poor. There were also other significant economic issues taken into consideration, e.g. the intake pumps consume a significant amount of energy, and water from the source 2 is transported by gravity, what reduces the cost of the intake and transport. All of these factors contribute to the fact that the intake system has now exceeded the redundant capacity.

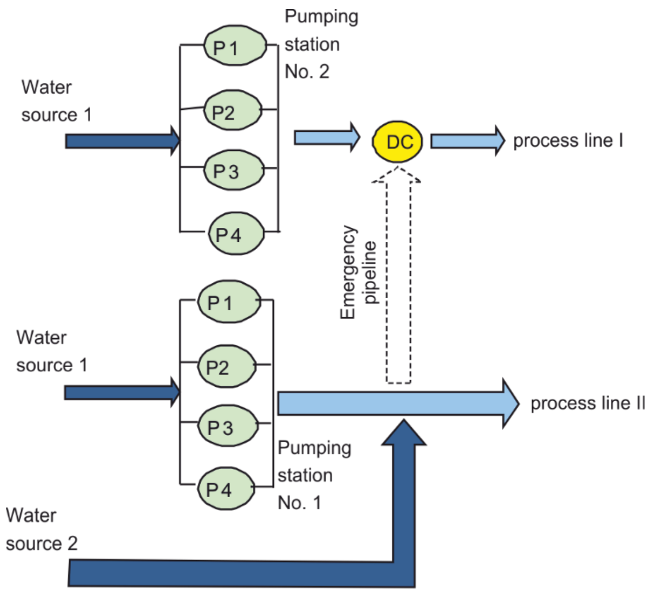

Fig. 1. Flow diagram; DC – distribution chamber

The analyzed intake is located on the shore of the dam reservoir. It consists of two independent first stage pumping stations. Each of them has 4 inlet channels equipped with steel bar screens and fine screens to prevent the entry of solid impurities to the pumps. In each inlet channel, one bar screen and one fine screen is provided.

In the pumping station No. 1, there are 4 pumps with the capacity of 138 200 m^3/day each. Their motor power equals 1000 kW each. Pumping station No. 2 is equipped with another 4 pumps with the capacity of 486 400 m^3/day each. Their motor power equals 1000 kW and 600 kW. Water is pumped from pumping station No. 2 to a distribution chamber (DC), from which it flows to process line I. Water from the pumping station

No. 1 is fed by gravity from the second reservoir, and it flows to the process line II. In exceptional situations, the process line II can be supplied by the process line I through the so-called emergency pipeline. The proportion of water volume subject to treating is determined by the water quality in the both sources.

4. RESULTS OF THE ANALYSIS

4.1. INTAKE PERFORMANCE IN THE ANALYZED PERIOD

As a part of the study, basic descriptive statistics related to the actual volume of intake water (2009–2014) have been determined (Table 1).

Table 1

Water intake efficency [m^3/day]

Average capacity	Media capacity	Minimum capacity	Maximum capacity
106 734	95 900	0	344 700

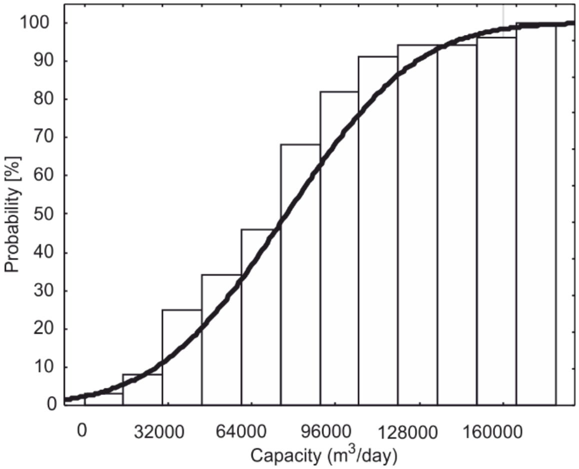

Fig. 2. Empirical cumulative distribution of the intake capacity

Lack of intaken water, which occurred during this period, was associated with poor water quality in source 1, and the maximum amount was related to water quality in source 2 which was lower than required. Based on the actual values of water volumes the empirical distribution function has been determined (Fig. 2).

In this study, a new concept – the maximum justified capacity is established. It seems necessary to show the distinction between the dispositional capacity and the actual volume of intaken water. The difference between these two parameters is referred to as the exceeded redundant capacity. The maximum justified capacity describes the daily capacity for which the occurrence probability is < 0.99. Thus the maximum justified capacity is 304 000 m^3/day, and the dispositional capacity equals 350 000 m^3/day.

4.2. RELIABILITY ANALYSIS

The reliability analysis is based on collected exploitation data. In order to ensure the most advantageous operation in accordance with the company procedures, steel bar screens and fine screens are regularly cleaned – the bar screens once every 6 months for 8 h, the fine screens once every 2 weeks for 1 working day (8 h). According to exploitation logs, the major renewal time for pumps are up to 12 months but the repair activities took approximately 2 weeks. Such a time difference is due to the need of disassembling the pump, transporting it to a subcontractor, formalities related to the ordering of spare parts and possible waiting time for them. This fact influences the values of reliability indicators.

The first stage of the analysis includes calculation of the reliability indicators (Eqs. (1)–(3)) for each device (Table 2). In accordance with the literature [3, 4], the authors calculated the readiness indicator to seven decimal places [3, 4, 8].

Table 2

Reliability indicators of the devices

Number of the pumping station	Element	T_p [h]	T_o [h]	K_g
No. 1	Bar screen	3867.38	8.00	0.9979357
	Fine screen	325.64	8.00	0.9760222
	Pump No. 1	679.59	30.14	0.9575308
	Pump No. 2	603.44	3.52	0.9941986
	Pump No. 3	614.65	3.48	0.9943677
	Pump No. 4	626.31	3.42	0.9945768
No. 2	Bar screen	3867.38	8.00	0.9979357
	Fine screen	325.64	8.00	0.9760222
	Pump No. 1	626.29	3.43	0.9945568
	Pump No. 2	630.23	3.46	0.9945466
	Pump No. 3	710.04	4.54	0.9936427
	Pump No. 4	657.03	14.75	0.9780409

Raw water flows into 8 independent inlet channels. Each of them is a serial connection of the bar screen, fine screen and pump. Therefore, the second study stage includes the calculation of basic reliability characteristics for each inlet channel (Table 3).

Table 3

Reliability indicators of each independent inlet channel

Number of pumping station	Number of inlet channel	Structure	T_p [h]	T_o [h]	K_g
1	1	3 of 3	208.29	15.04	0.9326421
	2		200.54	6.55	0.9683568
	3		201.76	6.56	0.9685216
	4		203.00	6.55	0.9687252
2	1		203.00	6.56	0.9687057
	2		203.41	6.57	0.9686958
	3		211.07	7.02	0.9678153
	4		206.12	10.25	0.9526190

The third stage of the reliability study is based on calculating reliability indicators describing the whole water intake subsystem. When identifying the operational structure of the intake system, the authors take under considerations the capacity of each pump. In the case of the maximum justified capacity of the intake, the operational structure is one of the followings scenarios, whose reliability indicators are given in Table 4:

- scenario 1: operate 2 pumps in pumping station No. 1 and 1 pump in pumping station No. 2,
- scenario 2: operate 1 pump in pumping station No. 1 and 2 pumps in pumping station No. 2,
- scenario 3: operate 3 pumps in pumping station No. 1,
- scenario 4: operate 4 pumps in the pumping station No. 2.

Table 4

Reliability indicators of the scenarios for the water intake subsystem

Name	T_p [h]	T_o [h]	K_g
Water intake subsystem	1.84×10^{10}	0.85	0.99999999995
Scenario 1	11 463.34	2.60	0.9997736
Scenario 2	14 347.76	2.45	0.9998290
Scenario 3	431.53	3.86	0.9911276
Scenario 4	51.46	8.02	0.8651493

Based on the obtained results, it can be stated that the present infrastructure management provides correct and reliable operation (the value of K_g equal to 0.999999999951 for the entire water intake is much higher than the value required – 0.9954818). Moreover, the current average working time (1.84×10^{10} h) is greater than the durability of the oldest water supply facilities. Such a situation is typical of systems with exceeded redundant capacity (with high reserve of device). Maintaining the reserve is directly responsible for the high level of system reliability; however it causes high maintenance costs [10, 14].

4.3. ANALYSIS OF THE LIFE CYCLE COSTING

LCC can be considered holistically (taking into account all phases of the life cycle) or, e.g. it may relate to the highest cost, the most common *CF* or the longest phase of the life. In the case of the water intake, the usage phase has been analysed, being the most representative and most important in LCC. The analysis takes into account the cash flows associated with:

- Cost of energy consumed by pump motors. As they are not equipped with inverters, the amount of energy consumed by a pump results from the motor power. Hence costs of energy are calculated basing on number of operating pumps, their motor power and unit price for 1 kWh.
- Cost of major renewals. Every 15 years each pump is subject to this type of renovation. Cost of spare parts, labour etc. are based on data obtained from the subcontractor who carries out the renewals.
- Cost of inspections carried out at regular intervals regardless of the number of the pump working hours. This cost is calculated based on management information such as duration of the action, number of workers employed, and their hourly wages including all overhead costs.
- Costs of inspections carried out every specified number of pump working hours. They include similar components as the costs of regular inspections.

The costs of the usage phases calculated after the analysis are given in Table 5.

Table 5

Costs of usage phase – current state

Name	Usage phase (15 years)
Scenario 1	73 585 151 PLN (18 744 943,70 $)
Scenario 2	62 420 341 PLN (15 900 840,89 $)
Scenario 3	84 749 961 PLN (21 589 046,52 $)
Scenario 4	90 370 987 PLN (23 020 936,16 $)

5. ANALYSIS OF FURTHER OPERATION OF WATER INTAKE

In order to improve the intake operation, the authors propose 4 variants of operation (Fig. 3):

- Variant I. Disabling the pump No. 1 in the pumping station No. 1.
- Variant II. Disabling the pump No. 1 in the pumping station No. 1 and pump No. 4 in pumping station No. 2.
- Variant III. Disabling the pumps Nos. 1 and 2 in thepumping station No. 1 and pumps Nos. 3 and 4 in the pumping station No. 2.
- Variant IV. Disabling the pumps Nos. 1, 2 and 3 in the pumping station No. 1 and pump No. 4 in the pumping station No. 2.

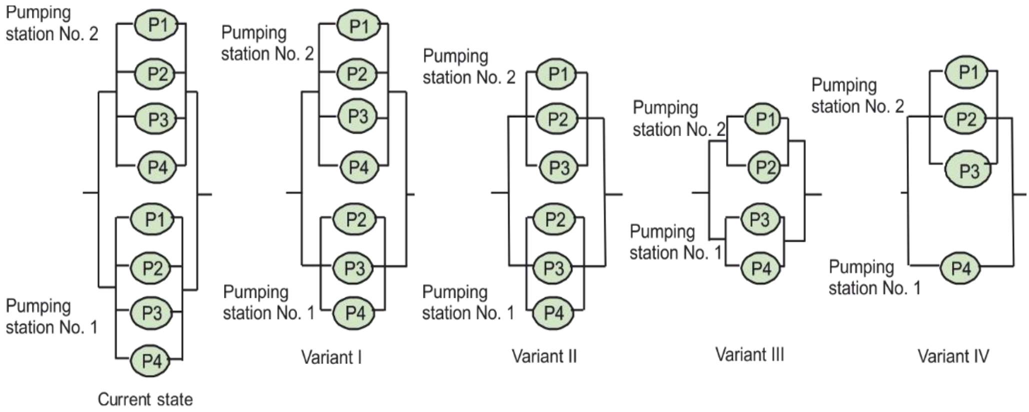

Fig. 3. Water intake diagrams – variants of operation

The first stage of improving operation procedures – proposing the variants is based on finding elements with the lowest readiness indicator K_g and the shorter operating time T_p. Then the costs of the usage phase are verified in order to disable devices generating higher LCC and the costs associated with the 15-year usage phase for each variant are calculated (cf. Table 6).

Table 6

Costs of the usage phases in variants 1–4

Scenario	Variant			
	I	II	III	IV
1	73 494 479 PLN (18 721 846 $)	73 403 807 PLN (18 698 748 $)	73 222 464 PLN (18 652 553 $)	–
2	62 329 669 PLN (15 877 743 $)	62 238 997 PLN (15 854 646 $)	62 057 654 PLN (15 808 450 $)	62 057 654 PLN (15 808 451 $)
3	84 659 289 PLN (21 565 949 $)	84 568 617 PLN (21 542 851 $)	–	–
4	90 280 315 PLN (22 997 839 $)	–	–	–

The readiness indicators calculated for variants 1–4 are given in Table 7.

Table 7

Readiness indicator K_g of each variant

Name	Variant			
	I	II	III	IV
Water intake system	0.99999999282	0.9999992	0.9960793	0.9658856
Scenario 1	0.9970906	0.9970607	0.9373121	–
Scenario 2	0.9997999	0.9970376	0.9374574	0.9658856
Scenario 3	0.9085426	0.9085426	–	–
Scenario 4	0.8651493	–	–	–

The calculations show that the operation in variant IV does not meet the basic criteria which is reliable operation defined by the acceptable level of failure rate. The readiness indicator K_g in this case is 0.9658856, while a minimum of 0.9954818 is required. It seems that that the variant III is the best solution as it fulfils the reliability condition (K_g = 0.9960793) and the cost of 15-year usage is the lowest among all other variants.

Based on the usage costs for the operational scenarios presented in Table 6, more economical way of operation may be obtained after implementation the variant III, scenario 2. In other words, the operation of 1 pump in pumping station No. 1 and 2 pumps in pumping station No. 2 (reliability structure 1 of 2 and 2 of 2), will result in greater savings associated with the intake usage than after implementation scenario 1.

6. CONCLUSIONS

- The obtained results allow identification of the best variant of operation of surface water intake. Implementation of variant III allows the operator to maintain system with the reliability level higher than required, and provides savings of 22 634 758 PLN (discounted value) over the next 15 years of operation of the system.
- The reduction of reserve devices requires change in approach to the maintenance of the pumps. The operator has to review the processes associated with inspections so as to be able to predict possible failures. Moreover, the duration of major renewals should also be optimized. Long intervals between the renewal and repair time result from operator's awareness of system's redundancy. However, to improve the economics of intake operation, all stages of the procedure must be reduced to a minimum.
- The proposed analysis is a comprehensive improvement method for technical operating conditions of systems with exceeded redundant capacity with simultaneous minimization of costs. Proposed actions related to maintenance of surface water intake do not generate additional financial outlays, only a change in the operation management is

required, this being based on measurable indicators. These conclusions provide guidance to DSS for rational management of technical facilities.

- The procedure described can be used not only for improving operation of DWTPs but also for any other manufacturing system with exceeded redundant capacity. What is more, it would be useful during designing or modernisation of such systems. It would help to find the best of considered operation variants.

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REFERENCES

[1] OLMSTEAD S.M., *The economics of managing scarce water resources*, Rev. Environ. Econ. Pol., 2010, 4 (2), 179.

[2] GRAFTON R.Q., WARD M.B., TO H., KOMPAS T., *Determinants of residential water consumption: evidence and analysis from a 10-country household survey*, Water Resour. Res., 2011, 47, W08537.

[3] ZIMOCH I., SZYMIK-GRALEWSKA J., *Risk assessment methods of water supply system in terms of reliability and operation cost*, [in:] S. Mambretti, C.A. Brebbia (Eds.), Urban Water II, WIT Press, Southampton 2014, 51.

[4] SZYMIK-GRALEWSKA J., ZIMOCH I., *Optimization of the drinking water coagulation and filtration system as a result of reliability analysis and life cycle costing*, [in:] T. Nowakowski, M. Młyńczak, A. Jodejko-Pietruczuk, S. Werbińska-Wojciechowska (Eds.), *Safety and Reliability Methodology and Applications*, Taylor and Francis Group, London 2015, 487.

[5] ZIMOCH I., SZYMIK-GRALEWSKA J., *Operational management of process water treatment systems based on the reliability and economic analysis*, Przem. Chem., 2015, 94 (8), 1000 (in Polish).

[6] LEGUTKO S., *Development trends in machines operation maintenance*, Maint. Rel., 2009, 2, 8.

[7] WANG Z., HUANG H., DU X., *Reliability-based design incorporating several maintenance policies*, Maint. Rel., 2009 (4), 37.

[8] WIECZYSTY A., *Reliability of water supply and sewage systems*. Vol. 1. *Theory of reliability and its application*, Part 1, Cracow University of Technology, Cracow 1990 (in Polish).

[9] KAUFMAN R., *Life cycle costing: a decision-making tool for capital equipment acquisition*, Cost Manage., 1970, March/April, 21.

[10] WOODWARD D., *Life cycle costing. Theory, information acquisition and application*, Int. J. Proj. Manage., 1997, 15 (6), 335.

[11] BARONE G., FRANGOPOL D.M., *Reliability, risk and lifetime distributions as performance indicators for life-cycle maintenance of deteriorating structures*, Rel. Eng. Syst. Safety, 2014, 123 (3), 21.

[12] PARRA C., CRESPO A.P., CORTES S., FYQUERO A., *On the consideration of reliability in the life cycle cost analysis (LCCA). A review of basic models. Safety and reliability for managing risk*, Taylor and Francis Group, London 2006.

[13] *Directorate-General. Regional Policy, Guide to cost-benefit analysis of investment projects*, European Commission, Brussels 2008.

[14] EMBLEMSVÅG J., *An activity-based life-cycle assessment method*, American Society of Mechanical Engineers (ASME), Design Engineering Technical Conference, Sacramento 1997.

[15] FABRYCKY W.J., *Evaluation in systems engineering*, [in:] A.P. Sage (Ed.), *Systems engineering and management for sustainable development*, EOLSS Publishers, Oxford 2008, 19.

[16] KAYRBEKOVA D., *Activity-Based Life-Cycle Cost Analysis Design, Operation and Maintenance in Arctic Environment*, Doct. Thesis, Department of Mechanical and Structural Engineering and Material Science, University of Stavanger, Stavanger 2011.

[17] KORPI E., ALA-RISKU T., *Life cycle costing. A review of published case studies*, Manage. Aud. J., 2008, 23 (3), 240.