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To cite this article: A Kowalski and M Blichtarski 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **679** 012015

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The method of determining the optimal life cycle of the mining machine

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Abstract. One of the significant components of production costs are the purchase and operating costs of machinery and equipment; according to Sandvik Coromant, they can account for approx. 30% of manufacturing costs. In the mining industry, the share of purchase and operation costs of machinery and equipment in the mining cost is certainly even greater. Such a large share of machine and tooling costs in manufacturing costs determines the significance of the issue of minimizing these costs, which is connected with the problem of determining the moment when further operation of a worn machine becomes unprofitable. One of the currently available ways to determine the length of the operation lifecycle is to register and compare the total costs of machine maintenance and its annual maintenance costs. This method is easy to apply, unfortunately it is not possible to use it at the machine purchase planning stage and thus it does not allow for prior determination of a viable life cycle length. The aim of the article is to propose a method for determining a profitable life cycle of a mining machine, taking into account the economic factors of macroenvironment. The costs related to operation, including failure costs, were also considered. Determining the duration of the operation cycle is based on determining the payback time of investment for the purchase of a new machine or on minimizing the average cost of monthly use and purchase of the machine in several operating cycles for a longer period of operation. The differences in operating costs between used and new machines are taken into account in calculating the payback period. Sample calculations were carried out using the example of the self-propelled Getman S330 scaler.

1. Introduction

One of the criteria that can be used to estimate the profitability of an investment may be its payback period. This parameter is widely used to evaluate investments [1, 2]. It defines the time which is necessary for the costs incurred for the investment to be paid back. It plays a special role when financial liquidity is the key factor for the company [3]. The calculated investment payback period parameter can be a key factor in choosing between two investments. An investment with a shorter payback is considered a less risky investment. If there is no need to choose between two projects, the payback period should be referred to the reference payback period set by the company [4].



The payback period is calculated as:

$$PBP = \frac{\text{The cost of investment}}{\text{Annual income from investment}} \quad (1)$$

where: PBP – the payback period [5].

The use of the payback period parameter according to formula 1 has the following advantages:

- ease of using the payback period parameter,
- it enables comparison of projects in terms of liquidity risk,
- low-cost method calculations affect low analysis costs.

In the case of a new machine purchase, the proceeds from the investment will not have a fixed value, therefore it is impossible to apply the formula 1 in its current form. The proceeds from the investment will be determined as the difference in the costs incurred in relation to the maintenance of the machines. The payback period will be determined as the moment when profits from the purchase of a new machine exceed its cost.

1.1. Life Cycle Cost Analysis

By definition, the life cycle cost analysis (LCC - Life Cycle Cost) is a process aimed at determining the sum of costs related to a product or a project, including costs of acquisition, installation, operation, repairs and utilization. It is a tool for estimating the total costs that appear during the life cycle. The LCC method was developed by the Department of Defence of the United States in the mid-1960s and was used in large infrastructure projects like military centres and refineries. In later years, different variations of the method were developed, such as the Environmental Life Cycle Cost (ELCC). The main purpose of the LCC method is to compare the total life cycle costs for different products or alternative processes. It is a method to identify the most cost-effective variant in order to facilitate the decision-making process.

In the life cycle cost analysis method, you can distinguish the following four steps:

- cost structure analysis – this step is to identify all elements affecting costs in the life cycle and determine the limits of the application of the analysis. This is the most important step because its correct implementation prevents overlooking or double-counting of specific costs,
- cost estimation – the process of determining the approximate value of costs based on known values, values predicted based on empirical data or based on expert opinions,
- discounting – this is the process of calculating the value of a given amount of money based on its value in the future. If the value of the discount rate is high, it means that the money currently held is more important, if it is lower, more important is the money held in the future. If the discount rate is zero, it means that there is no difference between the value of same amount of money at different times. The value of the discount rate depends on many factors, such as inflation, investment opportunities, preferences and should be determined when consulting an expert.
- inclusion of inflation – inclusion of price changes in the considerations [6].

However, it is difficult to decide whether to end the use of the machine or the device based on the payback period parameter or to seek an answer to this question directly in the LCC method.

2. Main factors affecting the economic aspects of machine operation

The most important factors occurring regardless of the type of machine used were selected. They include:

- the purchase cost of a new machine or a device,
- operating costs,
- repair costs,
- influence of inflation.

These factors will have a decisive impact on the method proposed in the following chapters to determine the optimal life cycle of the machine.

2.1. Operating and repair costs

One of the types of costs that change during the operation of the machine are the costs of repairs and operation [7]. Many factors affect such costs, including the environment of exploitation, care for the machine and its equipment. Two groups of processes that influence the evolution of the machine state can be distinguished:

- physical aging,
- machine wear.

Physical aging is a term used for physical processes that lead to irreversible changes of properties of the operated object. They occur as a result of both external and internal extortion, starting from machine production and leading to gradual loss of physical properties.

Machine wear means permanent, undesirable changes occurring during its operation. They are related to the forces occurring in interacting kinematic pairs during the transformation of energy into mechanical work. Variable mechanical stresses created during operation are responsible for the wear processes. There are three phases that can be distinguished in the course of wear (Figure 1):

- Phase I – called also the break-in period. It is a short-term period, and its duration is not clearly definable. During it, a significant intensity of wear caused by material defects and production errors is observed. Wear in this phase is not harmful and leads to the transformation of the state of layers of cooperating elements to a state characterized by higher wear resistance;
- Phase II – it is characterized by a constant intensity of wear. This phase is responsible for the period of proper cooperation of elements;
- Phase III – the period of accelerated wear. This is the period during which the intensity of wear increases. This is related to the increased clearance between the cooperating elements and the associated occurrence of additional dynamic loads. They result in larger deformations of elements leading to change of tribological conditions and increase of material losses [8, 9].

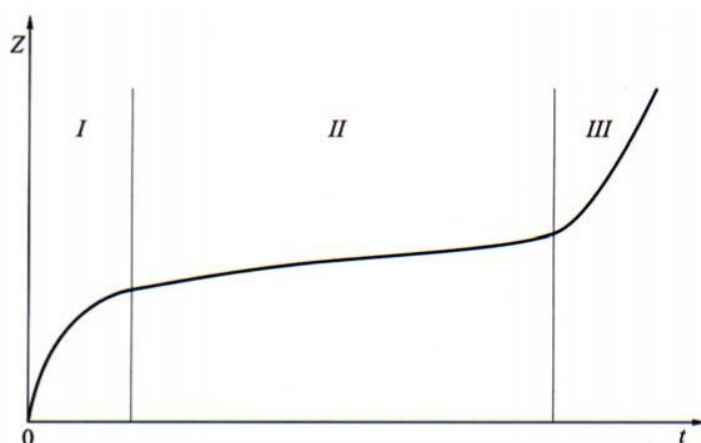


Figure 1. Empirical wear curve according to Lorenz, where: Z – wear, t – time [8].

The mathematical model that can be used in estimating the costs of repairs and operation can be formula 2 used in the studies of Markus Lips and Frank Burose [10]:

$$y = \beta_0 \prod_{i=1}^n x_i^{\beta_i} \quad (2)$$

where: y – annual cost of repairs and operation expressed as a part of the machine price, x_i – factors affecting the costs of repairs and operation, β_i – coefficients.

The annual use of the machine and its age are the factors that most strongly affect the costs of repairs and operation. At the same time, they were the only universal factors (used for each type of the machines considered in the study). There is a relationship between the degree of use of the machine and the total cost of repairs and operation, assuming a constant total working time. In the case of longer service cycles, the total costs of repairs and operation may be in extreme cases 3 ÷ 4 times higher than in short ones. This indicates that the costs of repairs and operation will be the smallest with short operating cycles [11]. Similar conclusions can be drawn by analysing data on the costs of repair and maintenance of agricultural tractors. They show the relationship between the costs of using the machine and the age of the tractor. On this basis, it can be stated that these costs at a certain point in the operating cycle may be 4 ÷ 5 times higher than at the beginning [12].

There is also a group of methods – indirectly helpful in deciding on the end of machine operation – for calculations of profitability of overhaul (e.g. balance account [13], maximum limit cost method [14]) and optimization of machine replacement period [15], developed in 70's and 80's of the 20th century. They enable determining the economic limit of outlays for overhaul, based on the analysis of costs incurred during the actual operation of the machine. However, it is impossible or difficult to use these methods at the stage of planning the machine purchase.

2.2. Inflation

In the case of long-term considerations, it is necessary to take into account the prices that are changing on the market. Not only the costs of machines, but also the costs of consumables change over time, which results in an increase in operating costs.

One of the price change indicators commonly used in the world is PPI - Producer Price Index. This is the oldest of this type of indexes. It was introduced in the United States, where its calculation and publication is dealt with by the Bureau of Labour Statistics as part of the US Department of Labour. In Poland, PPI takes the form of the price index of production sold in the industry, and its calculation and publication of results is handled by the Central Statistical Office. The price index of production goods for the European Union, the eurozone and individual Community countries is published by Eurostat.

The PPI index is usually calculated as the ratio of prices in a given year to prices in the base year. The US Labour Statistics Office in the calculation of PPI covers all branches of industry excluding imports.

3. Description of the machine subject to analysis – Getman S330

The subject of the analysis is the life cycle of the Getman S330 mining machine (Figure 2); this device is used to secure excavations by removing loose rocks hanging from the ceiling or side walls. Such a treatment is necessary to ensure the safety of people as well as to protect the equipment from damage caused by the detachment and fall of rocks, which could cause not only an accident, damage to property, but also halt the mining [16].

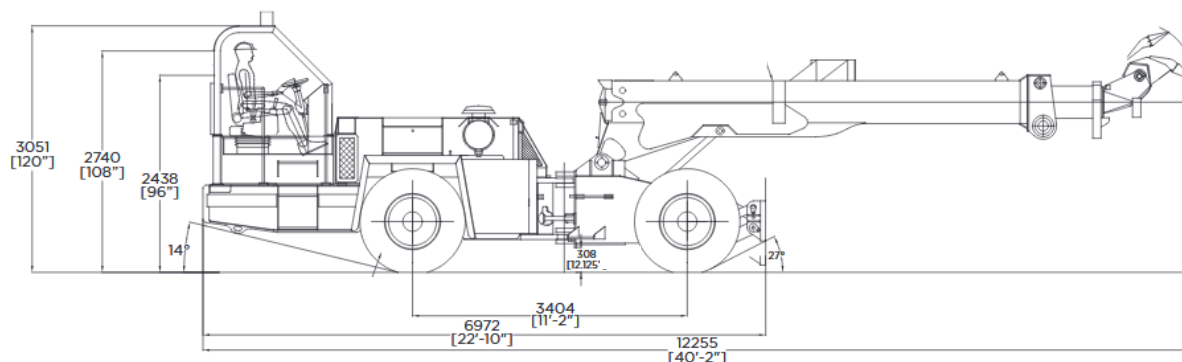


Figure 2. Mining machine Getman S330, main dimensions in mm [16].

The Getman S330 machine is equipped with a 4-cylinder engine with 173 horsepower, and its reach enables works at a height of up to 9 meters. The estimated cost of the machine is PLN 2 900 thousand (€ 680 thousand). In the considered case of the mining plant, the device was set up in a 2-shift system for 250 days a year. It was assumed, based on historical data, that the average annual use of the machine is 56%. This data is necessary to calculate the hourly use of the machine during the year.

4. Algorithm of the method for determining the optimal time of machine operation cycle

Figure 3 shows the algorithm of the proposed method for determining the optimal cycle time of the machine. The method has the following steps:

1. selection of coefficients and calculation of the machine usage rate,
2. construction of a table of repair costs, repair costs including inflation, accumulated repair and operating costs, and machine prices including inflation.

The next steps of the method depend on the adopted optimization criterion. The method assumes a choice between minimizing the average costs of operating cycles per unit of operating time and optimization based on the payback period. The payback period criterion should be chosen if the priority is to ensure financial liquidity. In situations where the investment does not have a significant impact on the financial liquidity of the enterprise, the criterion of average costs of operating cycles should be selected.

For the criterion of average costs of operating cycles, it is necessary to take the following steps:

- 3a. building a table of machine purchase moments,
- 4a. building a table of machine purchase costs,
- 5a. building a table of cumulative repair and operating costs,
- 6a. calculation of the sum of costs and average costs of operating cycles per unit of operating time, finding the minimum.

For the criterion of the payback period, the subsequent steps take the following form:

- 3b. defining the target payback period based on investment plans and the company's investment strategy,
- 4b. calculation of monthly profits resulting from lower costs of repair and operation of a new machine,
- 5b. calculation of the sum of profits since the purchase of a new machine,
- 6b. finding the payback period for each moment of purchase,
- 7b. finding the optimal purchase moment based on the target payback period.

Step 1 – selection of coefficients and calculation of the machine usage rate

The first step of the method is the selection of coefficients and the calculation of the hourly use of the machine. Coefficients should be selected depending on the machine type according to the literature data, manufacturer's recommendations or actual data on the operating costs of the machine already in use. The hourly usage of the machine can be calculated according to the formula 3:

$$W_h = l_z l_d W_{\%} \quad (3)$$

where: W_h – hourly use of the machine during the year [h], l_z – number of shifts, l_d – number of working days per year, $W_{\%}$ – machine usage [%].

At this stage, it is also necessary to specify the time of operation under consideration (it was assumed that $t_e = 600$ [month]) and inflation indicators.

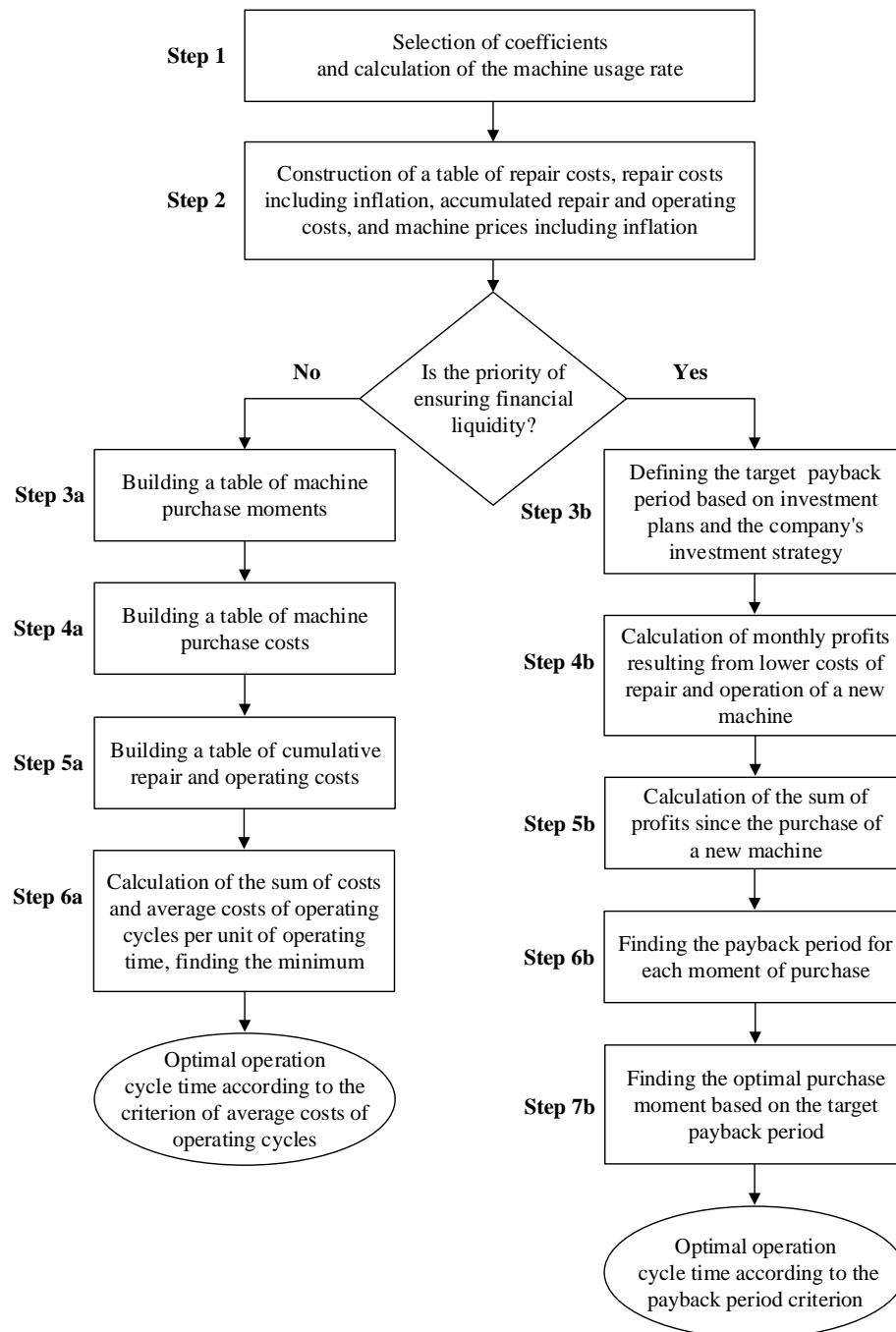


Figure 3. The algorithm of the method for determining the optimal time of the machine's operating cycle.

Step 2 – construction of a table of repair costs, repair costs including inflation, accumulated repair and operating costs, and machine prices including inflation

In order to calculate the costs of repairs, repair costs including inflation, cumulative repair and operating costs, and machine prices including inflation, formulas 4 to 7 are needed. Formula 4 is used to determine the costs of repairs and exploitation in the i -th month of machine operation:

$$K_{nie_i} = \frac{c_m \beta_0 \left(\frac{i}{12}\right)^{\beta_1} W_h^{\beta_2}}{12} \quad (4)$$

where: i – month of operation, K_{nie_i} – costs of repairs and operation in a given month [PLN], C_m – machine cost [PLN], $\beta_0, \beta_1, \beta_2$ – coefficients influencing the costs of repairs and operation, W_h – [h hourly use of machines during the year [h].

Formula 5 is used to calculate the costs of repairs and operation including inflation. These costs are calculated on the basis of the formula for compound interest:

$$K_{nie(I)_i} = K_{nie_i} (1 + I_{nie})^{\frac{i}{12}} \quad (5)$$

where: $K_{nie(I)_i}$ – costs of repairs and operation including inflation in the i -th month [PLN], I_{nie} – inflation coefficient for repair and operating costs.

Formula 6 enables calculation of cumulative repair and operating costs. The cumulative cost of repairs and operation is the sum of the costs of repairs and operation, taking into account inflation, from the beginning of the machine's use until the i -th month:

$$K_{nie(skum)_i} = \sum_{k=1}^i K_{nie(I)_k} \quad (6)$$

where: $K_{nie(skum)_i}$ – the cumulative cost of repairs and operation for the i -th month [PLN].

Formula 7 allows you to calculate the cost of purchasing a new machine in the i -th month, including inflation:

$$C_{m(I)_i} = (C_m - W_m(i))(1 + I_m)^{\frac{i}{12}} \quad (7)$$

where: $C_{m(I)_i}$ – the cost of purchasing a new machine, regarding inflation [PLN], I_m – inflation coefficient for the price of the machine, $W_m(i)$ – the value of the worn-out machine as a function of its age [PLN].

4.1. The algorithm of the method for the criterion of average lifecycle costs

Step 3a – building a table of machine purchase moments

To build the table of the machine purchase moments, it is necessary to use formulas 8 and 9. Formula 8 is used to determine the end of machine use. This is the month of withdrawal from use of a given type of machine, assuming a full number of operating cycles of the length of i months, hence the result is rounded up:

$$T_{ei} = \left\lceil \frac{t_e}{i} \right\rceil i \quad (8)$$

where: T_{ei} – end of machine operation, t_e – assumed last month of machine operation, i – length of the operating cycle.

Formula 9 is used to determine the purchase moments of a new machine. For every length of the operation cycle, the first purchase of the machine will be made at the very beginning of the cycle, i.e. in the zero month. The next purchase of a new machine will take place in a month being a multiple of the life cycle length, shorter than the last month of machine operation:

$$M_{z_{ij}} = i(j - 1), j: j \in N \wedge j \leq \frac{T_{ei}}{i}, i: i \in N \wedge i \leq t_e \quad (9)$$

where: $M_{z_{ij}}$ – j -th moment of purchase of a new machine for the length of the operation cycle i .

Step 4a – building a table of machine purchase costs

The construction of the machine purchase cost table was based on the formula 10. This expression was used to determine the purchase costs of the machine in the j -th operating cycle for the cycle length i . This cost is equal to the purchase cost of the machine at the corresponding purchase moment $M_{z_{ij}}$:

$$C_{m(I)_{ij}} = C_{m(I)_{M_{z_{ij}}}} \quad (10)$$

Step 5a – building a table of cumulative repair and operating costs

To build a table of cumulative repair and operating costs, it is necessary to use formulas 11 and 12. Formula 11 is used to determine the cumulated costs of repairs and operation of the machine in the j -th operation cycle for the cycle length i . This cost is equal to the cumulative cost of repairs and operation of the machine with length cycle i and taking into account inflation:

$$K_{nie(skum)_{i,j}} = K_{nie(skum)_i} (1 + I_{nie})^{\frac{Mz_{i,j}}{12}} \quad (11)$$

where: $K_{nie(skum)_{i,j}}$ – the cumulative cost of repairs and operation of the machine from the j -th operating cycle of length i [PLN].

Formula 12 makes it possible to determine the total repairs and operation costs incurred for j operating cycles of length i . This cost is equal to the sum of accumulated costs of repairs and operation of machines with cycle length i :

$$K_{niec(skum)_i} = \sum K_{nie(skum)_{i,j}} \quad (12)$$

where: $K_{niec(skum)_i}$ – total repair and operating costs for the cycle length i [PLN].

Step 6a – calculation of the sum of costs and average costs of operating cycles per unit of operating time, finding the minimum

The formulas 13 and 14 are needed to complete the table of total costs and average costs per unit of operation time. Formula 13 defines the total costs incurred for the operation cycle of the length i . This cost is equal to the sum of the costs of repairs and operation and the purchase costs of machines:

$$K_{c_i} = K_{niec(skum)_i} + C_{mc(I)_i} \quad (13)$$

where: K_{c_i} – total costs for the exploitation cycle of length i [PLN].

Formula 14 is used to determine the average costs of operating cycles per unit of operation time:

$$K_{c\acute{s}_i} = \frac{K_{c_i}}{T_{e_i}} \quad (14)$$

where: $K_{c\acute{s}_i}$ – average costs of operating cycles per unit of operation time [PLN].

After calculating the average costs of operating cycles per unit of operating time, it is possible to determine the optimum cycle time $t_{c_{opt}}$. This is the time of cycle i for which the average costs of operating cycles will be the smallest (Formula 15):

$$t_{c_{opt}} = \{i: K_{c\acute{s}_i} = \min\{K_{c\acute{s}}\}\}. \quad (15)$$

4.2. The algorithm of the method for the payback period criterion

Step 3b – defining the target payback period based on investment plans and the company's investment strategy

As a result of this step, the optimal payback period PBP_{opt} is determined.

Step 4b – calculation of monthly profits resulting from lower costs of repair and operation of a new machine.

Formula 16 is used to determine the profits resulting from the lower costs of repair and operation of a new machine in the i -th month of its use. Profit is the difference between the costs of repairs and exploitation of a worn out machine and the repair and operation costs of a new machine:

$$Z_{i,j} = K_{nie_{i+j}} - K_{nie_i} \quad (16)$$

where: $Z_{i,j}$ – profit resulting from lower costs of repairs and operation in the i -th month of use of the machine purchased after the j -th month of operation of the machine that has been depleted [PLN].

Step 5b – calculation of the sum of profits since the purchase of a new machine

Formula 17 made it possible to calculate the total profits resulting from the lower repair and operating costs of a new machine in the i -th month of its use. This is the sum of profits until the i -th month of use of the machine.

$$Z_{i,j} = K_{nie_{i+j}} - K_{nie_i} \quad (17)$$

where: $Z_{i,j}$ –total profits resulting from lower repair and operating costs [PLN].

Step 6b – finding the payback period for each moment of purchase

Formula 18 allows you to set a payback period when purchasing a new machine after j months of using a worn out machine. The payback period is the minimum time in a month, after which the profits will be at least equal to the costs of purchasing a new machine, reduced by the value of a worn-out machine.

$$PBP_j = \min\{i: Z_{i,j} \geq C_m - W(j)\} \quad (18)$$

where: PBP_j – the payback period for the purchase of a new machine after j months of use of a worn out machine.

Step 7b – finding the optimal purchase moment based on the target payback period

The optimal operation cycle time determined on the basis of the payback period is equal to the smallest month of purchase of a new machine, for which the payback period is equal to the optimal one:

$$t_{c_{opt}} = \min\{j: PBP_j = PBP_{opt}\} \quad (19)$$

where: $t_{c_{opt}}$ – optimal operation cycle time.

5. Presentation of calculation results on the example of Getman S330

In order to apply the algorithm for sample calculations, the above formulas were included in the MS Excel spreadsheet. Missing coefficients were selected based on literature data; they were collected in Table 1.

Table 1. Selected values of coefficients.

Name	Symbol	Unit	Value
The price of the machine	C_m	thousands PLN	2 900
The value of the worn-out machine	$W_m(i)$	thousands PLN	580
Assumed operating time	t_e	month	600
Coefficient β_0	β_0	%	5
Coefficient β_1	β_1	–	1.4
Coefficient β_2	β_2	–	0.07
Number of shifts	l_z	–	2
The number of days of the machine usage	l_d	–	250
Machine usage rate	$W_{\%}$	%	56
Inflation rate for the price of the machine	I_m	%	3.5
Inflation rate for repair and operating costs	I_{nie}	%	2.35
Optimum payback period	PBP_{opt}	month	12

5.1. Calculation results for the criterion of average costs of operating cycles.

The final results of the algorithm are presented in Figures 4 and 5. These charts show the average costs of operating cycles per unit of operating time in connection with the purchase of machines and their repair and operating costs for the total number of operating cycles with length i in operating time

greater than or equal to the assumed. There are noticeable large disparities between average costs, especially in the case of very short and very long operating cycles (Figure 4). The smallest costs occur in the range of operating cycles up to 100 months.

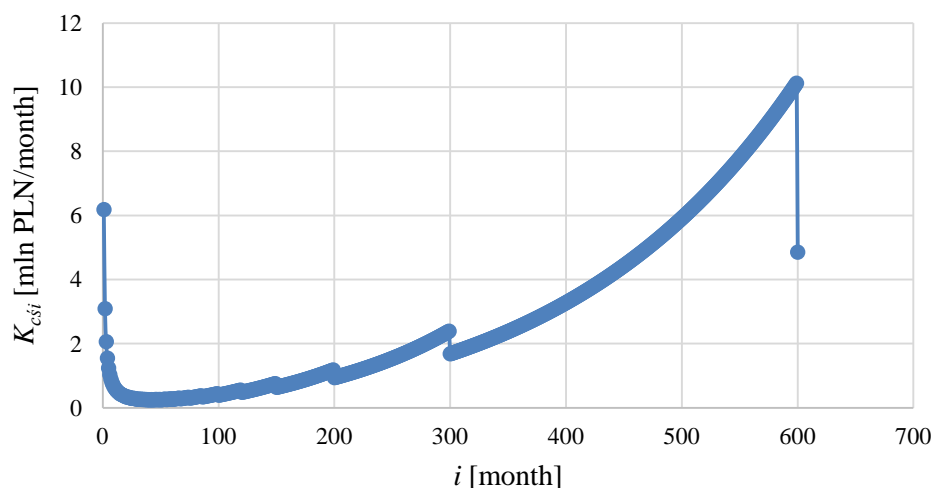


Figure 4. The chart of average costs of operating cycles.

Due to the insufficiently accurate scale to read the minimum, an additional chart was prepared (Figure 5), presenting a section of data near the minimum of the global chart. The chart also shows the total costs of machinery purchase and the total costs of repairs and operation.

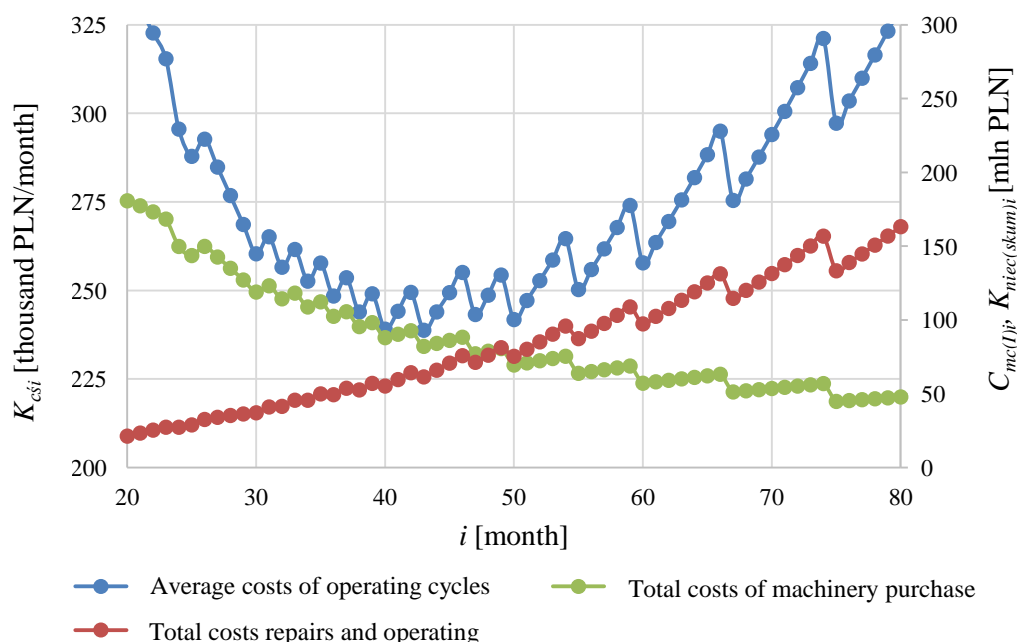


Figure 5. The chart of average costs of operating cycles, total costs of machinery purchase and total repairs and operating costs.

The minimum readout has been achieved for the cycle length $i = 43$ months and is equal 239 thousand PLN/month. The smallest values of average costs of operating cycles are in the range in

which the total purchase costs of machines and the total costs of repairs and operation reach similar values. Significantly, the global minimum of average life-cycle costs has not been achieved for the intersection of operating costs curves and the purchase of new machines. Therefore, for the criterion of average costs of operating cycles, $t_{c_{opt}} = 43$ months is the optimum cycle time.

5.2. Calculation results for the payback period criterion

The vector of payback period PBP_j is presented in Figures 6 and 7. The payback period reaches the highest values for the shortest operating times i (for $100 \div 400$ months).

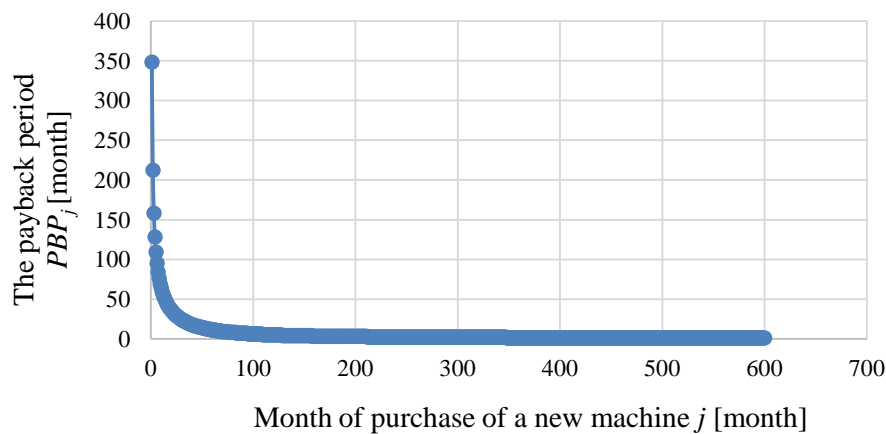


Figure 6. The payback period PBP_j .

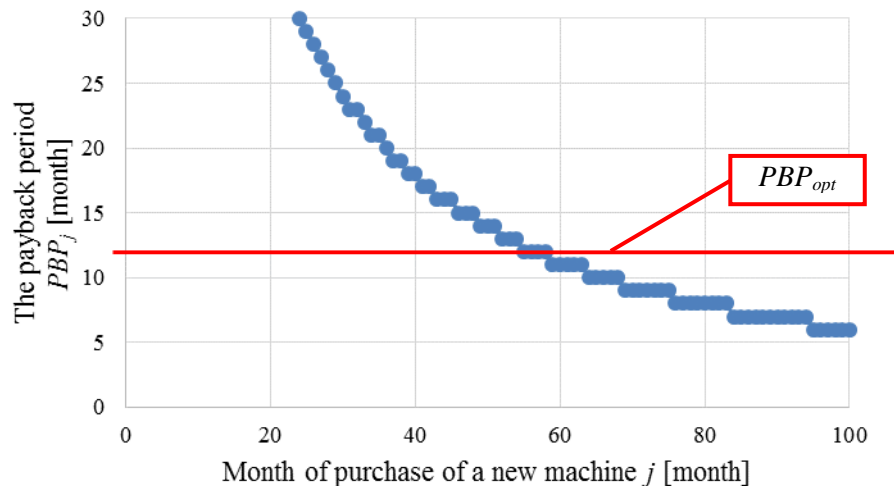


Figure 7. The payback period PBP_j , intersection point.

The values of the PBP_j vector are arranged in non-incremental order. The red line in Figure 7 indicates the assumed optimal payback period. The optimal operation cycle time $t_{c_{opt}}$ determined for this criterion is 55 months.

6. Summary

Methods for computational optimization of the machine life cycle length, developed mostly in the 60s, 70s and 80s of the twentieth century, are difficult to access or are not popularized. These methods, used to determine the profitability limit of overhauls, focus on the analysis of costs incurred during the

actual operation of the machine. This approach makes it impossible to use these methods when planning a machine purchase.

A significant share of machine and tooling costs in manufacturing costs indicates the importance of this issue. The selection of the length of time of the machine operation cycle at the planning stage can have a significant impact on the profitability assessment and making investment decisions. The proposed method has the following advantages:

- the possibility of using the method already at the stage of planning the purchase of the machine,
- takes into account the costs of using the machine at different lengths of operating cycles,
- inclusion of purchase, operation and repair costs as well as economic factors of macroenvironment.

The general nature of the method means that it can be applied to most machines and devices. The presented formulas can be extended with further factors in special cases affecting the operating costs.

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