Planning of Rational Terms of the Construction Equipment Replacement

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Abstract. Construction organizations (contractors) perform works using process equipment subject to significant physical wear. This study report results of developing and using an analytical model and a computer tool used to plan the rational times for construction equipment replacement. Physical wear and breakdowns of construction equipment disrupt production processes and cause unexpected production pauses leading to loss of contractor's profit. In the article, the algorithm of equipment replacement planning is described. Computer model for a decision-making on the rational times for construction equipment replacement is developed using Visual Basic for Applications (VBA). The offered algorithm for decision-making on construction equipment replacement is based on the following assumptions: decision on equipment replacement is made at the end of the year; the amount of expenses for the general period is calculated by adding the expenses of each year. If during the relevant year the equipment is not replaced, the amount is composed only of loss of profit (depending on the equipment age). If during the year the equipment is replaced, the amount, in addition to the loss of profit for the current year, includes the cost of new equipment, reduced by the value of the liquidation value of the used equipment. The offered VBA macro for Excel has a benefit of showing several options. Decision-makers can consider the best options and choose one of them. A benefit of the offered algorithm implies obtaining several alternative plans of the rational times for equipment replacement. The use of this algorithm and the computer model is justified if the effect of the decisions made is higher than the additional expenses related to information collection (on the loss of contractor's profit and market value of the new and worn equipment).

1. Introduction

Construction organizations (contractors) perform works using process equipment subject to significant physical wear. It is caused by complicated operating conditions: the equipment is used to cut pieces of metal and mix solid and granular compounds of mortars exerting a heavy load on the working parts. Such equipment includes parting shears, welding units, electric saws, bulldozers, excavators, concrete mixers, lifting screws and belt conveyors, concrete pumps, etc. (figure 1).

Some equipment is placed in cold shops and at construction sites in the open air, which makes it rather susceptible to weather conditions (frost, heat, moisture, wind, dust, etc.) causing failure to comply...
with the construction works schedule [1]. Physical wear and breakdowns disrupt production processes and cause unexpected production pauses leading to loss of profit. Regular maintenance can prevent many problems [2]. The older the equipment, the higher the expenses for keeping it serviceable. Therefore, it is important to make a reasonable decision on equipment replacement and take into account both the cost of new equipment and the loss of profit from the old equipment use by the contractors.

![Example of construction equipment](image)

**Figure 1.** Example of construction equipment.

The circumstances mentioned above create a problem of planning rational terms for replacing the worn equipment. At that, one shall compare the cost of replacement (purchase of new equipment) and the benefits of such a replacement (reducing the loss of profit caused by unexpected pauses and equipment repair expenses).

2. **Recent research and publications analysis**

The stated problem was studied by a lot of scientists. For example, they considered improved concrete equipment maintenance, planning of regular equipment repair, making a decision on the time of its replacement [3], and financial feasibility of construction equipment replacement. In particular, they indicated that contractors set several replacement alternatives that they evaluate by using a set of various qualitative (contractors’ business objectives, employee safety and morale, and, contractors’ image in the industry) and quantitative (inflation, downtime, obsolescence, salvage value, and depreciation) factors [4]. A monograph Applied Mathematical Modeling of Engineering Problems reveals the approaches to solving the issue of replacing engineering equipment. Authors of the monograph [5] considered both traditional approaches (in particular, Age-Specific Models of Equipment Replacement, Statistical Models of Equipment Renewal) and the approaches taking into account cutting-edge developments (in particular, Aggregated Model with Endogenous Useful Life of Equipment, Disaggregated Integral Model of Equipment Replacement) and qualitative indicators (so-called “turnpike properties” for the optimal lifetime of equipment). In their latest article [6], they draw a conclusion that the expected asset lifetimes appear to be different for sequential replacement cycles and depend on the future cost evolution. Apart from theoretical researches, the scientists focused on specific practical aspects of equipment replacement for certain types of production processes. David Zvipore et al. studied the issue of a rational term for conveyor belt replacement [7]. Mohammad Hejazian et al. in their article applied two models (Cumulative Cost Model and Cost Minimization Model) to determine the life cycle of
woodworking equipment [8]. However, it is important not only to describe analytical models but also to develop a universal set of computer tools to be used to plan the rational terms for equipment replacement. In early 90’s, some models for PC were developed, e.g., the ECON system was written in BASIC language, it runs on IBM PC compatible computers [9]. However, this system encompassed two models and was aimed at construction project managers. It is reasonable to develop a universal set of tools compatible with modern computers. In our article, we aim at describing the algorithm of equipment replacement planning and describe the application of the developed computer model for a specific example of decision-making on the rational terms for construction equipment replacement.

3. Description of the approach to problem solving
Making a decision on equipment change is complex in its essence. It is related to the fact that loss of profit by maintaining and repairing the old equipment depends on its age. As an example, we used data from an article describing an approach for determining the construction equipment operating time prior to replacement comparing the “accounting and economic rate of return” [10]. This approach has a drawback: the decision made depends on the method for accrual of depreciation. We offer another basis for decision-making in construction equipment replacement. It uses data about three values:

1) cost of new equipment;
2) liquidation value of the equipment which served for a certain number of years (revenue from the used equipment sale);
3) loss of profit by operating the old equipment.

Table 1 provides for data from the mentioned article used to illustrate the offered approach. Cost of new equipment described in this example totals UAH 100,000.

| Equipment age, years | Liquidation value of the equipment at the end of the year, UAH | Incoming cash flows from equipment use, UAH | Loss of profit, UAH |
|----------------------|---------------------------------------------------------------|---------------------------------------------|---------------------|
| 1                    | 90900                                                         | 40141                                       | 0                   |
| 2                    | 82600                                                         | 39372                                       | 769                 |
| 3                    | 75100                                                         | 38619                                       | 1522                |
| 4                    | 68300                                                         | 37881                                       | 2260                |
| 5                    | 62100                                                         | 37156                                       | 2985                |
| 6                    | 56400                                                         | 36446                                       | 3695                |
| 7                    | 51300                                                         | 35750                                       | 4391                |
| 8                    | 46700                                                         | 35067                                       | 5074                |
| 9                    | 42400                                                         | 34399                                       | 5742                |
| 10                   | 38600                                                         | 33743                                       | 6398                |

For a certain period, in particular ten years, a comprehensive decision to replace the equipment is comprised of intermediary decisions. There can be two options each year: to replace the equipment or to continue using it. Next year’s expenses depend on the option chosen last year. In general, if “equipment replacement” is 1 and “continued equipment use” is 0, one can form a comprehensive decision “tree” set out on figure 2 for an analyzed period of three years

A separate comprehensive decision is assigned to one route on the “tree” and a certain amount of expenses. The route can be described by a sequence of binary numbers made up from the elements according to the number of years in the period. For example, sequence (0;1;0) means that the equipment is replaced in the second year of operation (the relevant route on figure 2 is shown by wide arrows).

The offered algorithm for decision-making on construction equipment replacement is based on the following assumptions:

1. Decision on equipment replacement is made at the end of the year.
2. The amount of expenses for the general period is calculated by adding the expenses of each year defined taking into account the following:
   a) if during the relevant year the equipment is not replaced, the amount is comprised only of loss of profit (depending on the equipment age);
   b) if during the relevant year the equipment is replaced, the amount, in addition to the loss of profit for the current year, includes the cost of new equipment, reduced by the value of the liquidation value of the used equipment.

![Figure 2. Equipment replacement comprehensive decision “tree”](image)

The algorithms analyses all the possible variants. The calculations can be made very fast using a computer regardless of the fact that the variants for the term of \(N = 10\) years are numerous, specifically, \(P = 2^N = 1,024\). Decision at the end of \(t\)-th year is \(x_t\). If \(x_t = 0\), the equipment is not subject to replacement at year end and if \(x_t = 1\), replacement is conducted. As the planned period duration is \(N\), the sequence of binary numbers (zero and one) \(x_1, x_2, ..., x_N\) will describe the comprehensive decision encompassing the \(N\) of intermediary decisions. In fact, the purchase of new equipment is unreasonable at the end of last year, so \(x_N = 0\). According to our example, after the end of the planned period the equipment is no longer necessary and is subject to sale at a liquidation value depending on its age. Thus, one may consider \(N-1\) years, hence, \(P = 2^{N-1} = 512\) variants. Equipment liquidation value at the end of \(N\)-th year shall be subtracted from the total expenses during \(N-1\) years, then adding a loss of profit of the same year (both loss of profit and liquidation value depend on equipment age at the time).

Objective function in the algorithm is represented by total cash costs \(Z\) which shall be minimal. They are comprised of the expenses of each year, which, it its turn, is the amount of loss of profit and expenses for new equipment less the revenue gained from the sale of old equipment. The last two components (the expenses for new equipment and the revenue gained from the sale of old equipment) occur during the years of equipment replacement decision-making. The following symbols are used to describe the \(Z\) expenses:
- \(t\) is year number;
- \(Y_t\) is equipment age at the end of the \(t\)-th year;
- \(V_t\) is the cost of new equipment expected to be available on the relevant technical market at the end of the \(t\)-th year;
- \(V_0\) is the cost of new equipment bought at the beginning of the planned period;
- \(E_j\) is annual loss of profit due to using the equipment aged \(j\) years;
- \(L_j\) is the expected liquidation value of the equipment operated for \(j\) years.

Total costs (for each of \(P = 512\) variants of the comprehensive solution) may have the following formula:

\[
Z = V_0 + S_1 + S_2 + ... + S_{N-1} + E_t - L_t
\]
Here, $S_t$ stands for expenses in the $t$-th year. They are determined as follows:

$$S_t = V_t + E_t - L_t$$  \hfill (2)

If a decision was made not to replace the equipment during a certain year, in this year $V_t = 0$ and $L_t = 0$.

To calculate $Z$, one shall find the sum of $S_t$ for $N-1$ years in each comprehensive solution. As a matter of fact, the developed algorithm allows considering different cost of new equipment each year. Input data is entered into the Excel spreadsheet and the results are displayed there. In particular, data on the cost of new equipment is recorded in the range P5:P15 and data on the liquidation value and loss of profit is recorded in the range Q6:R6. The results are produced below the 36th line (number of lines depends on the input data). The thirty-sixth line offers the expenses for a basic variant implying refusal from equipment replacement for $N$ years. The lines below correspond to the decision variants improving (lowering) the value of the objective function $Z$. The relevant algorithm is presented as a computer macro developed using VBA (Visual Basic for Applications). Macro listing is provided below:

Sub Alg()
    Dim A0(), A1(), d(), L(), E() As Currency
    Dim X(), Y() As Integer
    Dim p As Long
    Dim Vo, Vr, Lr As Currency
    Vo = Cells(5, 16).Value
    n = Cells(2, 1).Value ' duration of planning period
    ReDim X(n)
    ReDim Y(n)
    ReDim L(n)
    ReDim E(n)
    ReDim v(n)
    ReDim A0(n)
    ReDim A1(n)
    ReDim d(n)
    p = 1 ' number of combinations
    For i = 1 To n
        A0(i) = 0
        X(i) = 0
        A1(i) = 1
        d(i) = 1 ' step
        p = p * 2
    Next i
    p = 0.5 * p ' in the last year X=0 no X=1
    Zmin = Vo
    For t = 1 To n - 1
        v(t) = Cells(5 + t, 16).Value
        Zmin = Zmin + v(t) ' first must be big number
    Next t
    For t = 1 To n
        L(t) = Cells(5 + t, 17).Value
        E(t) = Cells(5 + t, 18).Value
    Next t
    kk = 0
    k = 1
    3:    Z = Vo
t = 0
2:
   If t = n Then
   GoTo 1
End If
   t = t + 1
   If t = 1 Then
      Y(t) = 1
      Vr = 0
      Lr = 0
      GoTo 6
End If
   If X(t - 1) = 0 Then
      Y(t) = Y(t - 1) + 1
      Vr = 0
      Lr = 0
      GoTo 6
   End If
   Y(t) = 1
   Vr = v(t - 1)
   Lr = L(Y(t - 1))
6:
   Z = Z + Vr - Lr + E(Y(t))
   GoTo 2
1:
   Z = Z - L(Y(t))
   If Z <= Zmin Then
      Zmin = Z
      kk = kk + 1
      Cells(35 + kk, 1) = kk
      For j = 1 To n
         Cells(35 + kk, j + 2) = X(j)
      Next j
      Cells(35 + kk, 2) = Zmin
   End If
   If (k = p) Then
      GoTo 5
   End If
   k = k + 1
   X(1) = X(1) + d(1)
   If (Not X(1) > A1(1)) Then
      GoTo 3
   End If
   X(1) = A0(1)
   i = 1
4:
   If i = n Then
      GoTo 3
   End If
   i = i + 1
   X(i) = X(i) + d(i)
If Not X(i) > A1(i) Then
  GoTo 3
End If
X(i) = A0(i)
GoTo 4

5:
  Cells(35 + kk, 2).Select
End Sub

4. Developed algorithm application results

Having applied the provided algorithm for specific tasks in table 1, we obtained several alternative
decision variants regarding the term for construction equipment replacement. Figure 3 shows an Excel
spreadsheet screenshot with the list of variants (Variant column). Column Z provides for the objective
function values which become ever less during the algorithm action.

![Excel spreadsheet screenshot with results](image)

**Figure. 3.** Fragment of an Excel spreadsheet with the results of algorithm for terms of construction
equipment replacement

The last three variants (11, 12 and 13) are equal: they are more efficient in the amount of UAH 3.603
compared to the basic variant (UAH 94.236–90.633). In particular, in the last variant, the equipment
replacement is planned in the 4th and 7th year. The offered VBA macro algorithm for Excel has a benefit
of showing several options. Decision-makers can consider the best options and choose one of them.

Special attention should be paid to a situation when at the beginning of the planned period not only
new but also the old equipment (several years of age) is operated. In this case, the algorithm demands
the initial equipment age. In addition, the initial data shall contain additional information on the
liquidation value and loss of profit for the equipment with the age exceeding the planned period. A
hypothetical variant of no equipment replacement assumes that the equipment age during the last year
will be equal to the sum of the planned period duration and equipment age at the beginning. Figure 4
shows an Excel spreadsheet screenshot with the results of algorithm for the case if the equipment was
aged 2 at the beginning of the planned period.

The last variant (12) is more efficient compared to the basic variant (1) in the amount of UAH 7.847
(UAH 15.831–7.984). In particular, in this variant, the equipment replacement is planned in the 2nd and
6th year.
5. Conclusions
The benefit of the offered approach implies automated analysis of all the possible equipment replacement variants. Total amount of expenses for a certain variant is calculated by adding the expenses of each year. If during the relevant year the equipment is not replaced, the amount is comprised only of loss of contractor's profit depending on the equipment age. If during the relevant year the equipment is replaced, the amount also includes the cost of new equipment less liquidation value of the worn equipment. During the last year, the amount decreases by the liquidation value of the equipment according to its age at the time. A benefit of the offered algorithm implies obtaining several alternative plans of the rational terms for equipment replacement. The use of this algorithm and the computer model is justified if the effect of the decisions made is higher than the additional expenses related to information collection (on the loss of contractor's profit and market value of the new and worn equipment). To apply this approach, one shall possess information on the contractor expenses related to each type of construction equipment.

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