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Transportation Research Procedia 63 (2022) 1307–1312

Transportation Research Procedia

www.elsevier.com/locate/procedia

X International Scientific Siberian Transport Forum

Cost optimization algorithm for spare parts reservation for transport machines

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Abstract

The algorithm of optimal reservation of spare parts is substantiated and tested depending on their resource, cost and distance of the consumer to an external source of spare parts (SP). The paper concretizes the procedure for implementing the methodological provisions for the optimal reservation of the SP, set out in Shilovsky et al, 2022, and is a continuation of this work. The criterion and goal of optimizing the SP reserve is the minimum amount of costs for eliminating failures of a geographically distributed fleet of transport and handling machines.

Keywords: Number of spare parts; optimization algorithm; cost minimization.

1. Introduction

Along with the work Shilovsky et al, 2022, the role of the supply and creation of a reserve fund of spare parts in the organization of cost-effective technical service and reduction of equipment downtime due to the lack of spare parts (SP) are considered in Shilovsky et al, 2021; Shilovsky et al, 2020. The consumption of the spare part depends on the resource of the machine elements.

Modeling of the operating time of machine parts to failure by the statistical method is considered in Law et al, 2004; Lyusterik et al, 1962.

The operating time of machine parts to failure $t_{i,j,l}$ can be modeled by the formula:

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10.1016/j.trpro.2022.06.140

$$t_{i,j,l} = \mu \times (-\frac{U_i}{2}), \quad (1)$$

where i – SP name ($i = \overline{1,P}$);
j – machine number ($j = \overline{1,N}$);
l – part number installed on the machine, if there is more than one ($l = \overline{1,L}$);
μ – mathematical expectation of the part resource (under the normal distribution law);
U_i – independent and uniformly distributed random numbers on the interval [0…1].

In order to achieve the required results in simulation modeling, it is necessary to use statistical methods for analyzing simulation runs presented in Shilovsky et al, 2022; Salivonik et al, 2014; Bulatov et al, 2001; Bykov et al, 2004; Henssmann, 1966; Ryzhikov, 2001.

2. Materials and Methods

2.1. Run Number Model

To obtain an estimate of the cost of eliminating machine failures C_{xi} with a given error, it is necessary to determine the number of repeated runs of the model according to the algorithm presented in Shilovsky et al, 2022:

1. We perform F=10 independent repeated runs of the multi-item reservation model of the SP, as a result of which we obtain ten values of independent estimates$(C_{xi})_f$ $(f = \overline{1,F})$.
2. Determine the sample mean of the estimate $\overline{C_{xi}}(F)$:

$$\overline{C_{xi}}(F) = \frac{\sum_{f=1}^{F}(C_{xi})_f}{F} \quad (2)$$

3. Determine the sample variance of the estimate $S^2(F)$:

$$S^2(F) = \frac{\sum_{f=1}^{F}\left[(C_{xi})_f - \overline{C_{xi}}(F)\right]^2}{F-1} \quad (3)$$

4. We set the relative error γ of the average estimate C_{xi} and the confidence level α.
5. We determine the corrected relative error γ necessary to obtain the specified relative error γ :

$$\gamma' = \frac{\gamma}{(1+\gamma)} \quad (4)$$

6. We determine the required number of repeated runs of the model F(γ) for the average estimate C_{xi} with a given relative error γ and a confidence level α using the following expression:

$$F(\gamma) = min\left\{ i \geq \left[10 - \left[\frac{t_{i-1.1-\alpha/2} - \sqrt{\frac{S^2(F)}{i}}}{\left|\overline{C_{xi}}(F)\right|} \right]^{-1} \right] \leq \gamma' \right\} \quad (5)$$

where $t_{i-1,1-\alpha/2}$ – Student's function quantile.

The number of repeated runs of the model $F(\gamma)$ is defined as the smallest integer i for which condition (5) is satisfied.

The general list of controlled and uncontrolled variables of the objective function according to Shilovsky et al, 2022 is presented in Table 1.

Table 1. General list of controlled and uncontrolled variables of the objective function.

No.	Objective function variables	Symbol	Dimension
1	2	3	4
	Controlled variables		
1	Number of reserved SPs of the i-th item	X_i	pcs.
	Uncontrolled variables		
1	The number of considered i-th names of parts	P	–
2	Type and indicators of the distribution law of the resource of the i-th name part		–
3	Design period	T	day
4	Number of cars	N	pcs
5	Number of parts installed on the machine	K	pcs
6	Average daily running hours of the machine	T_c	engine hours/day
7	The cost of SP of the i-th name at the time of delivery to the enterprise’s warehouse	C_{oi}	RUB
8	The cost of the same spare part in the dealer's warehouse	C_{odi}	RUB
9	Coefficient of specific increase in the cost of SP	C	h^{-1}
10	Unit cost of delivery of spare parts from the enterprise’s warehouse to the machine	Q	RUB/km
11	Unit cost of delivery of one SP of the i-th name from an external source (dealer's warehouse)	Q_i	RUB/km
12	Distance between the enterprise’s warehouse and the j-th machine	L_j	km
13	Distance between the enterprise’s warehouse and the dealer	L_i	km
14	Average vehicle speed for delivering SP within the enterprise	V_{av}	km/h
15	Average vehicle speed for delivering SP from an external source	V_{avi}	km/h
16	Economic losses from machine downtime	Z	RUB/h
17	Variable costs associated with saving resources when the machine is idle	Z_n	RUB/h
18	The number of terms of the objective function during one run of the model	F	–

The features of the mathematical model are:

- multi-nomenclature of the optimized reserve of SP;
- taking into account a complete set of controlled and uncontrolled variables in the model;
- the structure of the model built on the basis of discrete-event simulation.

2.2. Modeling Algorithm

To calculate the mathematical model of a multi-item reservation of the HR, the following algorithm is recommended for creating a calculation program on a computer:

1. Enter the initial data.
2. Calculate the set of intermediate values of the objective function elements for each *i*-th name of the SP:

- cost of delivering the SP to each *j*-th machine from the enterprise’s warehouse, $R_{dost,\,j}$;

- time of deliverying the SP to each *j*-th machine from the enterprise's warehouse, $t_{dost,\,j}$;
- cost of delivering the SP from the dealer's warehouse (external source) to the enterprise's warehouse, $R_{dost\,,i}$;
- delivery time of SP from the dealer's warehouse to the enterprise's warehouse, $t_{dost,\,i}$.

We assign the value $X_i = 0$ to the reserve value of the SP of the *i*-th name and the value $f = 0$ to the number of model runs.

3. We create a vector (U) with the number of members equal to the product of the number of machines (N) in the enterprise and the number of parts in the machine (L):
   $U = N \cdot L$ ($u = \overline{1, U}$) and assign zero values to each element of the vector $\bar{A} = \{0, 0 \ldots 0\}$.
4. Depending on the initial data of the problem, we change the values of each member of the vector $\bar{A}$ according to one of three options.

4.1. We do not replace (by default, we leave zero) $\bar{A} = \{0, 0 \ldots 0\}$;
4.2. We change the value of each vector $\bar{A}$ to the one taken from the initial data $\bar{A} = \{t_1, t_2, \ldots, t_u, \ldots t_U\}$;
4.3. We model the negative values of the terms of the vector $\bar{A}$ using the expression (1)
$\bar{A} = \{0 + y_1, 0{+}y_2, \ldots, 0 + y_u\}$.

5. We simulate random values of the part's time to failure (before replacement) $t_{otk,i,j,l}$.
6. To each member of the vector $\bar{A}$ we add independently simulated random values of the part's time between failures (before replacement) $\bar{A} = \{t_1 + t_{otk,i,1,1}, t_2 + t_{otk,i,1,2}, t_U + t_{otk,i,N,L}\}$.
7. We check the condition of non-exceeding of each member of the vector that changed the value $\bar{A} = \{t_1, t_2, \ldots, t_u, \ldots t_U\}$ of simulation period restrictions T.

If there is a member of the vector $\bar{A}$, which has a value greater than T, then we exclude this member from consideration and go to step 8.

If all members of the vector $\bar{A}$ have a value greater than T, then go to step 14.

8. From the remaining members of the vector $\bar{A}$ choose the smallest $t_u = min$ and remember its number u.
9. If the value of the HR reserve of the i-th item is $X_i > 0$, then go to step 10, otherwise go to step 11.
10. To the value $t_u = min$ we add the time for the delivery of the SP to the machine, calculated in paragraph 2, i.e. $t_u = t_u + t_{dost,\,j}$ and remember $t_{dost,\,j}$.

We calculate the costs of eliminating the failure of the *j*-th machine and remember their value:

$$C_{i,k} = (R_{dost,j} + (Z - Z_n) \times t_{dost,j} + c \times C_{oi} \times (t_u - t_{dost,j}))_k.$$

We make a decrease in the reserve of the SP of the i-th name $X_i - 1$, remember the new value of X_i and proceed to step 12.

11. To the value $t_u = min$ we add the time for delivery of the SP to the machine, calculated in paragraph 2, i.e. $t_u = t_u + t_{dost,j} + t_{dost,i}$ and remember the value $t_{dost,j} + t_{dost,i}$.

We calculate the costs of eliminating the failure of the *j*-th machine and remember their value:

$$C_{i,k} = (R_{dost,j} + R_{dost,i}(Z - Z_n) \times (t_{dost,j} + t_{dost,i}))_k.$$

We assign the reserve of the SP of the *i*-th name $X_i = 0$, remember the new value of X_i and proceed to step 12.

12. Add the newly generated MTBF of the new part $t_{otk,i,j,l}$ to the member of vector t_u with number u.
13. Proceed to step 7.
14. We sum up all the values $C_{i,k}$, $C_{xi} = \sum_{k=1}^{k} C_{i,k}$ and remember the value of C_{xi}. We assign the index f (number of model runs) a new value $f = f + 1$.
15. Compare the value of f. If $f < 10$, then go back to step 3 for a new run of the model, otherwise go to step 16.
16. We calculate the following quantities using expressions (2) – (4):

- sample mean, $\bar{C}_{xi}$ *($f = 10$)*;
- sample variance, S^2 *($f = 10$)*;
- corrected relative error, γ.

We determine the required number of repeated runs of the model *F(γ)* using the expression (5).

17. We carry out the modeling process from stage 3 to stage 15, taking into account the number of runs $f = F(\gamma)$, excluding calculation points 15 and 16, passing after step 14 immediately to step 17.
18. If during the second run of the model the number of runs – the value f has reached the value $f = F(\gamma)$, then we stop the modeling process, otherwise we return to step 17.
19. Determine the average costs $C_{xi}(X_i) = \sum_{k=1}^{F(\gamma)} C_{i,k}$ at X_i and remember the value $C_{xi}(X_i)$.
20. Compare the average values of $C_{xi}(X_i)$ with the previous value. If there is no previous value, go to step 21. If there is a previous value, check the condition $C_{xi}(X_i)_{new} > C_{xi}(X_i)_{prev}$; if the condition is met, then go to step 22 with the value $C_{xi}(X_i)_{prev}$, otherwise go to step 21.
21. We carry out a new calculation cycle from stage 3, taking into account the fact that $X_i = X_i + 1$.
22. We finish the calculations with the smallest cost result $C_{xi}(X_i)$ and the corresponding reserve (X_i).

In a similar way, we make calculations for other types of SP and their reservation values. The end result will be the total number of reserved SPs of the i-th names X_i and the expected costs $C_{xi}(X_i)$ for the design period T.

3. Results and Discussion

The results of testing the algorithm are presented in tables 2 and 3.

Table 2. The results of calculating the optimal number of reserved spare parts depending on their cost.

SP cost, rub.	Number of reserved SP, pcs.	Total costs of the enterprise, rub.
Part resource distribution law – normal (Lav = 1500 engine hours, σL = 750 engine hours); the number of parts on the machine K = 2, T = 100 days; distance to the external source of the SP – Li = 500 km		
Co = 1100 and Cod = 1000	14	19608.88
Co = 5100 and Cod = 5000	11	71101.70
Co = 31000 and Cod = 30000	6	379900.07

Table 3. The results of calculating the optimal number of reserved spare parts depending on the change in their resource.

Part resource indicators, engine hours	Number of reserved SP, pcs.	Total costs of the enterprise, rub.
Spare part: Co =1100 and Cod =1000; resource distribution law – normal K = 2, T = 100 days, Li = 500 km		
Lav = 500, σL = 250	60	163635.29
Lav = 1000, σL = 500	25	48914.65
Lav = 2000, σL = 1000	9	11853.96

4. Conclusion

Based on the substantiated mathematical model presented in Shilovsky et al, 2022, an algorithm for the optimal reservation of spare parts was developed and tested depending on their resource, cost and distance from the consumer to an external source of spare parts.

References

Bulatov, A.F. et al, 2001. Optimization in planning and managing enterprises of the regional timber industry complex. Petrozavodsk, PetrGU Publishing House, 227 p.

Bykov, A. et al, 2004. Inventory optimization based on simulation. Logistics 1, 19-21.

Henssmann, F., 1966. Application of mathematical methods in the management of production and stocks. M., Progress, 280 p.

Law, A.M. et al, 2004. Simulation modeling and Analysis. Classics CS. St. Petersburg, Peter, Kyiv, BHV Publishing Group, 847 p.

Lyusterik, L.A. et al, 1962. Method of statistical tests (Monte Carlo method). M., Fizmatgiz, 332 p.

Ryzhikov, Yu.I., 2001. Inventory management: Monograph. St. Petersburg, Peter, 384 p.

Salivonik, A.V., Pitukhin, A.V., Shilovsky, V.N., 2014. Improving the efficiency of logging machines by optimal reservation of spare parts and materials (using the example of John Deere machines). Petrozavodsk, PetrGU Publishing House, 80 p.

Shilovsky, V., Skobtsov, I., Pitukhin, E., 2022. Mathematical Model of Multi-item Spare Parts Reservation. Safety in Aviation and Space Technologies. Lecture Notes in Mechanical Engineering. Springer, Cham. https://doi.org/10.1007/978-3-030-85057-9_48.

Shilovsky, V.N. et al, 2020. Algorithm for the Development and Delivery of a Multi-Item Set of Spare Parts and Maintenance Supplies for Geographically Dispersed Consumers. International science and technology conference "FarEastCon-2019". IOP Conf. Series: Materials Science and Engineering 753, 1-12. https://iopscience.iop.org/article/10.1088/1757-899X/753/8/082031.

Shilovsky, V.N., Pitukhin, E.A., Skobtsov, I.G., 2021. Technique for Improving the Organization of Maintenance of Transport and Technological Vehicles. IOP Conference Series: Earth and Environmental Science International science and technology conference "Earth science" 666, 1-6. https://iopscience.iop.org/article/10.1088/1755-1315/666/6/062089.