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OPTIMUM DISTRIBUTION OF REPAIRS IN TS-8 OF ELECTRIC LOCOMOTIVES VL80^{C} BETWEEN REPAIR DEPOTS IN THE REPUBLIC OF KAZAKHSTAN

Summary. The article presents the solution for the problem of optimal distribution of electric locomotives in repair enterprises for carrying out repairs in the frame of technical service - 8 (TS-8) and increased technical service - 8 (ITS-8). The aim of the study is to improve the efficacy of a rolling stock with a simultaneous decrease in the total expenses connected with the repair of locomotives and their transportation in repair enterprises. This is possible due to a reduction in the requirement for repairs by optimization of a resource before change of wheel bandages in electric locomotives VL80C that promotes an increase in their between-repairs run.

1. INTRODUCTION

At present, in the Republic of Kazakhstan, repair enterprises are dispersed across several repair depots, which leads to a shortage of equipment and component parts, long idle times, poor-quality repair, and expensive repair processes. Further, in the Republic, there are practically no enterprises performing qualitative technical checkup (TC) and major repairs (MR) of locomotives, nor are there enterprises manufacturing the necessary spare parts and components.

In Kazakhstan, the scheme of alternation of repairs and between-repairs run of locomotives - the structure of a repair cycle - is regulated by the specifications of order №536-C from 8/19/1999 and №202-1 of the Ministry of transport and communications (MT&C) of the Republic of Kazakhstan. Thus, the basic system of maintenance service and repair of locomotives is one of scheduled preventive maintenance [1, 2].

2. THE ANALYSIS OF DISTRIBUTION OF LOCOMOTIVES IN RAILWAY REPAIR ENTERPRISES

An analysis of the railway transport system in the Republic of Kazakhstan has revealed the necessity for a scientific approach to define the optimum distribution of locomotives among railway repair enterprises.

As there is a lack of research on the optimum distribution of electric locomotives in railway repair enterprises, a study to determine the optimum distribution of electric locomotives VL80^{C}, and the subsequent application of results in the industry, was of both scientific and practical interest. This entailed generating certain mathematical models reflecting the technical and economic aspects of the investigation, correlation of communication between different elements and systems as a whole, and creating special programs and algorithms [3].

Thus, this study aimed to investigate the problem of optimum distribution of electric locomotives in railway repair enterprises in the Republic of Kazakhstan for carrying out repairs in volume technical service-8 (TS-8) and increased technical service-8 (ITS-8) depots in order to improve the efficacy of use of a rolling stock that leads to a decrease in the total expenses connected with the repair of locomotives and their transportation in repair enterprises, as well as a reduction in the requirement for repairs by optimizing a resource before change of bandages of wheel pairs of electric locomotives VL80^C that promotes an increase in their between-repairs run [4, 5].

Our analysis revealed the following:

1. Various aspects of the problem of development of a repair base has been investigated in many studies, wherein scientists and experts on railway transportation have studied the dilemma of optimum development and placement of enterprises for the repair of rolling stocks and its knots.
2. Optimum distribution of locomotives in railway repair enterprises was not researched. Therefore, the purpose of the present study was to find a solution to the dilemma of optimum distribution of electric locomotives VL80^C in railway repair enterprises in the Republic of Kazakhstan.

According to the joint-stock company "NC" KTZH data, there are two base repair enterprises, “Altyn Orda 2004” LLC and “Tulpar At” LLC, which are in the cities of Astana and Zhambyl, which carry out repairs of electric locomotives of series VL80^C in volume TS-8 and -9 operational depots (distances between which are presented in table 1).

Table 1

Distances between the repair enterprises carrying out repairs in TS-8 and operational depots, in km

Repair enterprises	Astana	Zhana-Yesil	Karaganda	Almaty	Shu	Zhambyl	Arys	Kostanai	Pavlodar
“Altyn Orda 2004” LLC	0	484	216	1335	1021	1253	1545	707	439
“Tulpar At” LLC	1253	1737	1037	546	232	0	292	1960	1692

The comparative analysis of Altyn Orda 2004” LLC and “Tulpar At” LLC carrying out repairs in volume TS-8 depots of electric locomotives VL80^C has shown that they differ in terms of repair technology, auxiliary configuration, and personnel qualification, which in turn was reflected in an idle time for electric locomotives under repair: 8, 5 and 7 days; therefore, the annual program of repairs of these enterprises is 60 and 72 electric locomotives (table 2).

The simplex method of linear programming was used to determine the optimum distribution of electric locomotives VL80^C in the repair enterprises undertaking repair in TS-8 [6-8]. As a criterion for optimizing the distribution of locomotives of operational depots between repair enterprises, the minimum of the objective function - the total cost of repairs with transport costs was chosen.

Table 2

The annual program of repairs of the enterprises carrying out repairs in volume TS-8 by order №536-C

Repair enterprises	Amount of repair positions C_{Pj}, units	Idle time on TS-8 t_{pj}, days	Annual program of repairs (power) b_j, un./year
“Altyn Orda 2004” LLC	2	8,5	60
“Tulapr At” LLC	2	7	72
Total	132		

3. APPLICATION OF THE SIMPLEX METHOD OF LINEAR PROGRAMMING DURING DEFINITION OF OPTIMUM DISTRIBUTION OF REPAIRS OF ELECTRIC LOCOMOTIVES VL80C IN RAILWAY REPAIR ENTERPRISES

The total cost of repair of the locomotive in volume TS-8, taking into account transport expenses, is defined as

$$c_{ij} = c_{rep} + c_{deliv\ ij}\,, \tag{1}$$

where c_{rep} is the cost of repair of 1 electric locomotive (45190 €) in volume TS-8, which is a set joint-stock company "Locomotive"; $c_{deliv\ ij}$ is the cost of delivery of the locomotive from i operational depot to repair enterprise j .

Expenses for electric locomotive delivery to the repair enterprise is defined as

$$c_{deliv} = l_{ij} \cdot c_{loc/km}\,, \tag{2}$$

where cost of 1 loc.-km. is 0.7 €; l_{ij} is the delivery distance of the locomotive from operational depot i to repair enterprise j in *km*.

The costs of delivery of electric locomotives calculated in (2) are related to repair enterprises in table 3.

Taking into account costs of delivery of electric locomotives in repair enterprises according to (1), expenses for repair and delivery of electric locomotives, c_{ij}, which are presented in table 4, are defined.

Table 3

Costs of delivery of electric locomotives in repair enterprises

Operational depot	Cost of delivery, €	
	“Altyn Orda 2004” LLC	“Tulpar At” LLC
Astana	0	864.4
Zhana-Yesil	333.8	1200
Karaganda	149	715.4
Almaty	914.9	370.5
Shu	704.4	160
Zhambyl	864.4	0
Arys	1 065.9	201.5
Kostanai	487.8	1 352.2
Pavlodar	4 303.8	1 167.3

Throughput of the repair enterprises is defined by the formula

$$M_{pj} = \frac{255 \cdot C_{pj}}{t_{pj}}\,, \tag{3}$$

where 255 is the number of working days per year; t_{pj} is the entertaining repair time position for this type of repair in days (table 2); C_{pj} is the quantity of repair positions in workshop TS-8 in repair enterprises “Altyn Orda 2004” LLC and “Tulpar At” LLC (table 4).

Table 4

Expenses for repair with delivery of electric locomotives in repair enterprises

Operational depot	Number i	Expenses for repair with delivery c_{ij}, €	
		“Altyn Orda 2004” LLC, $j=1$	“Tulpar At” LLC, $j=2$
Astana	1	45192,6	46057
Zhana-Yesil	2	45526.4	46391
Karaganda	3	45341.6	45908
Almaty	4	46507.4	45563
Shu	5	45896,9	45352.6
Zhambyl	6	46057	45192.6
Arys	7	46258.4	45394
Kostanai	8	45863	46544.8
Pavlodar	9	45495.5	46359.9

Throughput of repair enterprises “Altyn Orda 2004” LLC and “Tulpar At” LLC equals 60 and 72 units per year, respectively.

The annual program flow and major repairs of electric locomotives in operational depots is defined by the following formula:

$$N_K = \frac{S_{year}}{L_K} - \sum_{i>K} N_i \, , \qquad (4)$$

where S_{year} is the linear annual run of electric locomotives in km.; L_K is the run of electric locomotives before repair of K volume; $\sum_{i>K} N_i$ is the total number of repairs having great volumes.

Actual (calculated on the between-repairs run established by order №536-C) and planned annual requirements for repairs of electric locomotives for volume TS-8 operational depots are presented in table 5.

Table 5

The requirements for repairs in volume TS-8 - $a_i = N_{i(\text{TS-8})}$

Diesel Part	Dislocation	Linear annual run S_{year}, *thous.* km.	Planned according to the order №536-C, b_j, un.	Actual, a_j, un.
[DC 9]	Zhana-Yesil	2684	4	5
[DP 11]	Astana	10550	20	21
[DP 28]	Almaty	4980	9	10
[DP 30]	Shu	15754	30	31
[DP 31]	Zhambyl	9689	17	19
[DP 14]	Karaganda	14023	26	28
[DP 32]	Arys	8141	16	16
[DP 20]	Kostanai	2560	5	5
[DP 18]	Pavlodar	2930	5	6
Total:			132	141

The actual number of locomotives for TS-8 repair in all operational depots, calculated in (4), equals 141 units of electric locomotives; consequently, because of insufficient power of repair enterprises $\left(\sum_{j=1}^{2} b_j = 132\right)$, nine repairs in TS-8, which are accompanied by the rerun of electric locomotives annually, are not carried out, and it reduces the reliability of electric locomotives.

To find a solution for the problem of linear programming, the simplex method creates an algorithm for a choice of the plan for solving the problem [9].

For the practical calculation by a simplex method of optimization of criterion function at linear restrictions, it is necessary to know the repair cost, cost of delivery of an electric locomotive, requirement of repair operational depots undertaking repairs, and the power of repair enterprises (tables 3 and 4).

4. THE DEFINITION OF OPTIMUM DISTRIBUTION OF REPAIRS OF ELECTRIC LOCOMOTIVES VL80C

As the criterion of optimum distribution of electric locomotives between repair enterprises and operational depots, the minimum criterion function of total expenses for repair and transportation of electric locomotives with restrictions on annual requirement of depot for repairs in TS-8 of electric locomotives VL80^C and throughput (power) of repair enterprises is chosen.

Distribution of electric locomotives between the repair enterprises, set by the existing standard documentation - order №536-C, is presented in table 6.

Distribution of repairs of electric locomotives in the repair enterprises, set by order №536-C, is undertaken in the form of an order.

The optimum plan of distribution of electric locomotives VL80^C in repair enterprises is ascertained by the simplex method using the VBA program [1, 2].

In an existing system of repair, according to order №536-C, the between-repairs run in TS-8 is 350 thousand km. and requirements for repair on all nine operational depots is 132 units of electric locomotives corresponding to the annual program of repairs in TS-8 of two repair enterprises. The sum of demands for repair equals the annual programme of repairs of electric locomotives of repair enterprises, i.e.

$$\sum_{i=1}^{m} a_i = \sum_{j=1}^{n} b_j .$$

Criterion function in this case will become

$$F = \sum_{i=1}^{9} \sum_{j=1}^{2} c_{ij} x_{ij} \to \min \qquad (5)$$

Table 6

Distribution of electric locomotives between the repair shops, set by the existing standard documentation

Operational depot	The requirements in repair, set by order №536, units per year	Repair enterprises	
		"Altyn Orda 2004" LLC	"Tulpar At" LLC
		Distribution between RE, units per year	
Astana	20	20	0
Zhana-Yesil	4	4	0
Karaganda	26	26	0
Almaty	9	0	9
Shu	30	0	30
Zhambyl	17	0	17
Arys	16	0	16
Kostanai	5	5	0
Pavlodar	5	5	0
Total	**132**	**60**	**72**
The power of enterprises, units per year	**132**		

At restrictions

$$\begin{cases} \sum_{j=1}^{2} x_{ij} = a_i, i \in \{1,2...,9\} \\ \sum_{i=1}^{9} x_{ij} = b_j,\ j \in \{1,2\} \\ b_1 = 60, b_2 = 72 \\ x_{ij} \geq 0 \end{cases} \quad \ldots \quad (6)$$

Here, $c_{ij}\left(i = 1,2...,9;\ j = 1,2\right)$ is shown in table 4. Requirements for repairs in TS-8, established by order №536-C, are shown in the fourth column of table 5. Powers of the repair enterprises are $b_1 = 60$ and $b_2 = 72$ un./year.

On the basis of these parameters under the VBA program, the calculated optimum distribution of electric locomotives in repair enterprises agrees with order №536-C, presented in table 7.

From table 7, it is apparent that the requirements for repairs in TS-8 of electric locomotives VL80^C of all operational depots are satisfied, and the powers of repair enterprises are used 100%. The minimum total cost of repair with delivery in “Altyn Orda 2004” LLC and “Tulpar At” LLC is 5986 thousand €. As is apparent from tables 6 and 7, the distribution of electric locomotives set by the existing standard documentation and the calculated optimum distribution of electric locomotives in repair enterprises under the same entry conditions coincide, which testifies to the reliability of the results of the calculations performed.

Actual requirements for repairs in TS-8, calculated on the basis of the between-repairs run established by order №536-C, is 141 electric locomotives in a year. As the actual requirement for the repair of electric locomotives has exceeded the annual program of repairs in TS-8 of repair enterprises, a part of the electric locomotives cannot be repaired in “Altyn Orda 2004” LLC and “Tulpar At” LLC; i.e., $\sum_{i=1}^{m} a_i > \sum_{j=1}^{n} b_j$ the solution to the problem of optimum distribution of electric locomotives using the simplex method requires an additional fictitious repair enterprise with the annual program of repairs $b_0 = 9$ and cost of delivery and repair (c_{i0}) equal to zero.

Table 7

Optimum distribution of electric locomotives among repair enterprises

Operational depot	The requirements in repair, units per year	Repair enterprises	
		“Altyn Orda 2004” LLC	“Tulpar At” LLC
		Distribution between RE, units per year	
Astana	20	20	0
Zhana-Yesil	4	4	0
Karaganda	26	26	0
Almaty	9	0	9
Shu	30	0	30
Zhambyl	17	0	17
Arys	16	0	16
Kostanai	5	5	0
Pavlodar	5	5	0
Total	**132**	**60**	**72**
The power of enterprises, units per year	**132**		

After introduction of a fictitious repair enterprise the problem of linear programming accepts the balanced (closed) type. In this case, the criterion function becomes

$$F = \sum_{i=1}^{9}\sum_{j=0}^{2} c_{ij}x_{ij} \rightarrow \min \qquad (7)$$

$$\text{at restrictions} \begin{cases} \sum_{j=0}^{2} x_{ij} = a_i,\ i \in \{1,2...,9\} \\ \sum_{i=1}^{9} x_{ij} = b_j,\ j \in \{0,1,2\} \\ x_{ij} \geq 0 \end{cases}. \qquad (8)$$

The optimum distribution of electric locomotives on repair enterprises, taking into account actual requirements of operational depots, is presented in table 8.

The calculation of optimum distribution of repairs of electric locomotives VL80C has shown that at realization of the between-repairs run established by order №536-Ц, the repair enterprises “Altyn Orda 2004” LLC and “Tulpar At” LLC cannot cope with the number of actual electric locomotives under repair; therefore, annually there are 9 electric locomotives not repaired. Thus, the minimum total cost of repairs with delivery of electric locomotives is 5986 thousand €.

The operational depots of Almaty and Kostanai are at a great distance from the repair enterprises “Altyn Orda 2004” LLC and “Tulpar At” LLC. As the expenses for repair after delivery of electric locomotives from these depots are high from the point of view of the economy, it is possible that 4 and 5 repairs of electric locomotives in the operational depots of Almaty and Kostanaj were not carried out. From a practical point of view, this distribution of electric locomotives isn’t entirely acceptable, but from the mathematical point of view it is the most optimal option. Therefore, due to inadequate power to repair, the optimum distribution of electric locomotives in repair shops needs to be calculated further to exclude a situation in which in one or several operational depots, the most remote from repair enterprises, most, or even all, electric locomotives needing repair remain unrepaired; i.e., it is necessary to distribute the unrepaired electric locomotives between all operational depots at more regular intervals, as presently required in the Kazakhstan railway system.

Carrying out a repair in TS-8 is dictated by the necessity for the repair of wheel pairs by changing the worn out bandages, which between-repairs resource defines as the run before repair in TS-8. Therefore, a major problem is the maintenance of wheel-pairs Locomotive Park in good condition and planning repairs in a timely and rational manner.

Table 8

Optimum distribution of electric locomotives on repair enterprises taking into account actual requirements of operational depots

Operational depot	The requirements in repair, units per year	Repair enterprises		
		“Altyn Orda 2004” LLC	“Tulpar At” LLC	Number is not repaired locomotives
		Distribution between RE, units per year		
Astana	21	21	0	0
Zhana-Yesil	5	5	0	0
Karaganda	28	28	0	0
Almaty	10	0	6	4
Shu	31	0	31	0
Zhambyl	19	0	19	0
Arys	16	0	16	0
Kostanai	5	0	0	5
Pavlodar	6	6	0	0
Total	**141**	**60**	**72**	**9**
The power of enterprises, units per year		**132 plus 9 aren’t repaired locomotives**		

The calculations made have shown that at a between-repairs run of 350 thousand km, established by order №536-C, the thickness of bandages of wheel pairs in depots at Zhambyl, Karaganda, Astana, and Almaty average 60 – 65 mm. As the minimum admissible thickness for change of bandages for a wheel is 45 mm, it is obvious that the resource of wheel pair will be underused. Therefore, it is necessary to study whether it is really mandatory for the between-repairs run to objectively reflect actual requirements, or whether there is a possibility to increase the between-repairs run and, by that, reductions in the requirement for repairs.

Results [2] of the calculation of optimum run before repairs with change of bandages of wheel-pairs of electric locomotives $VL80^C$ for 4 operational depots are shown in table 9.

Table 9

Results of calculation of optimum run before repairs with change of bandages of wheel pairs of electric locomotives $VL80^C$ for 4 operational depots

The change of bandages	i	L_O, thousand km
Depot Zhambyl	1	554
Depot Karaganda	2	432
Depot Astana	3	441
Depot Almaty	4	464

The optimum terms for the change of bandages of wheel pairs received as a result of calculations for the same value of factor of a parity of expenses for planned and unplanned repairs differ. It means that service conditions considerably influence the thickness of bandages of wheel pair electric locomotives $VL80^C$ [7, 11, 12]. Therefore, terms for carrying out TS-8 repairs are necessary to be defined, considering the actual technical condition of wheel pairs CE (composition of electric).

Offered schemes of formation of a repair cycle at optimum between-repairs run of electric locomotives in 4 operational depots are presented in Picture 1.

Under formula (4), requirements for repairs in TS-8 operational depots of Zhambyl, Karaganda, Astana, and Almaty are defined at an optimum between-repairs run of 550 thousand km., 430 thousand km., 440 thousand km. and 460 thousand km., respectively.

The received results of calculation of requirement for repairs in specified TS-8 operational depots are presented in table 10.

Thus, thanks to the application of an optimum between-repairs run in operational depots at Zhambyl, Karaganda, Astana, and Almaty, it was possible to lower the requirements for repairs in TS-8 on 20 units of electric locomotives in a year. As the requirement for locomotives under repair in 4 operational depots changed, the optimum distribution of repairs of electric locomotives of all 9 considered depots will also have to be changed.

Table 10

The results of the calculation of the requirement for repairs in TS-8 for the specified operational depots

Operational depot	The requirements in repair, units per year	
	Existing on the basis of order №536-C	Optimum
Zhambyl	17	9
Karaganda	26	22
Astana	20	16
Almaty	9	5
Total:	**72**	**52**

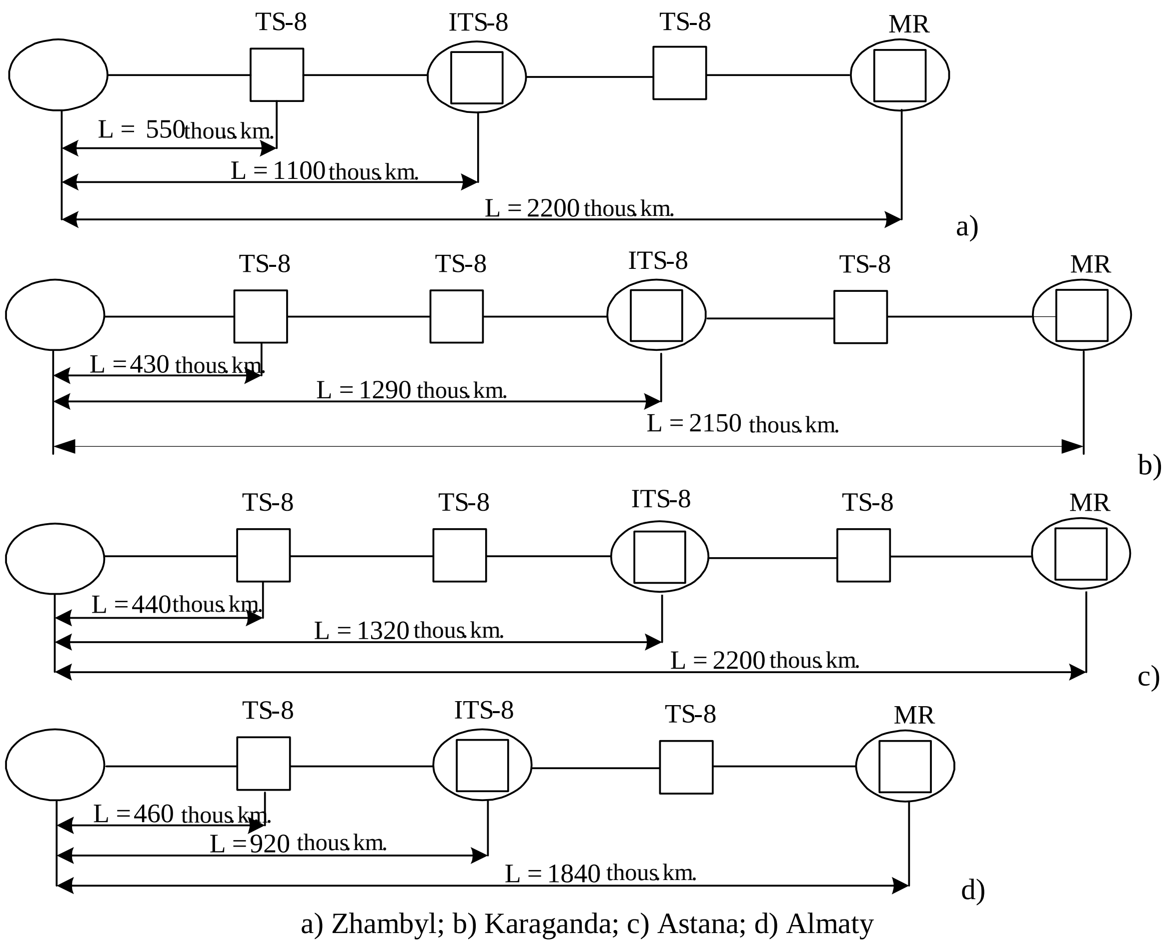
For the distribution of electric locomotives in repair enterprises, requirements for the repairs, calculated on the basis of the optimum between-repairs run in operational depots at Zhambyl, Karaganda, Astana, and Almaty (table 11), are used. For other operational depots – Zhana-Yesil, Shu, Arys, Kostanai, and Pavlodar - the actual requirements are presented in table 5. The total requirement for repairs is shown in table 11.

The total annual requirement is 112 units of electrical locomotives for repair, which doesn't correspond to the annual program of TS-8 repair of two repair enterprises. The sum of demands for repair is less than the annual program of repairs of electric locomotives of repair enterprises, i.e. $\sum_{i=1}^{m} a_i < \sum_{j=1}^{n} b_j$.

Table 11

Total requirement under repair electric locomotives

Operational depot	The requirements in repair, units per year
Astana	16
Zhana-Yesil	4
Karaganda	22
Almaty	5
Shu	30
Zhambyl	9
Arys	16
Kostanai	5
Pavlodar	5
Total	**112**



a) Zhambyl; b) Karaganda; c) Astana; d) Almaty

Fig. 1. Offered schemes of formation of a repair cycle at optimum between-repairs run of electric locomotives in 4 operational depots

For solving the linear programming problem, an additional fictitious operational depot was added with the need for repairs $a_0 = 20$ which will send on repair electric locomotives with cost of their repair and delivery c_{0j} equal to zero is entered [13, 14].

In this case, criterion function becomes

$$F = \sum_{i=0}^{9}\sum_{j=1}^{2} c_{ij}x_{ij} \to \min, \tag{9}$$

at restrictions

$$\begin{cases} \sum_{j=1}^{2} x_{ij} = a_i,\ i \in \{0,1,2,...,9\} \\ \sum_{i=0}^{9} x_{ij} = b_j,\ j \in \{1,2\} \\ x_{ij} \ge 0 \end{cases} \tag{10}$$

Optimum distribution of electric locomotives in repair enterprises at an optimum between-repairs run of 4 depots is presented in table 12.

Table 12

Optimum distribution of electric locomotives in repair shops at an optimum between-repairs run of 4 depots

Operational depot	The requirements in repair, units per year	Repair enterprises	
		"Altyn Orda 2004" LLC	
		Distribution between RE, units per year	
Astana	16	16	0
Zhana-Yesil	4	4	0
Karaganda	22	22	0
Almaty	5	0	5
Shu	30	0	30
Zhambyl	9	0	9
Arys	16	0	16
Kostanai	5	5	0
Pavlodar	5	5	0
Total	**112**	**52**	**60**
The power of enterprises, units per year	**112 plus 20 repairs of locomotives in reserves of enterprises**		

With an increase in the between-repairs run of electric locomotives of 4 depots, the requirement under repair decreases and 20 repairs of electric locomotives are in a reserve of repair enterprises: "Altyn Orda 2004" LLC - 8 and "Tulpar At" LLC - 12 repairs of electric locomotives in a year.

The total cost of repair with delivery in a case when the additional fictitious operational depot has been entered, and the requirements are balanced, equals 5080 thousand €.

5. CONCLUSIONS

According to investigations and calculations performed, the following points are defined:

1. With the help of the simplex method, an optimal variant of the VL-80 locomotive distribution in repair enterprises is defined.
2. Schemes of composition of the repair cycle with optimal mileages of locomotives in concrete operation depots are made.

3. As a consequence of the implementation of optimal inter-repair mileages in 4 operation depots, the need for TO-8 repair is reduced by 20 locomotives per year.
4. The annual economy from the application of an optimum between-repairs run in the operational depots of Zhambyl, Karaganda, Astana, and Almaty, at the expense of a decrease in requirement for repairs of electric locomotives, has made 906 thousand €.

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