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MULTICRITERIA EVALUATION OF OPERATIONAL EFFECTIVENESS OF FREIGHT DIESEL LOCOMOTIVES ON LITHUANIAN RAILWAYS

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Abstract. The paper analyses and assesses the operating expenses of freight Diesel locomotives 2M62, 2M62K, 2M62M and ER20CF, suggesting the ways of their reduction. Given the damages of the old locomotive M62 and the structure of its operating expenses, some methods of Diesel locomotives' upgrading are offered. Service life of new generation Diesel locomotives SIEMENS ER20CF and the locomotives 2M62K, 2M62M after the upgrade are determined. The taxes on air pollution by the exhaust gases of Diesel engines are calculated for the locomotives of each series. The effectiveness of operation of freight Diesel locomotives is calculated by three multicriteria evaluation methods and the most efficient freight Diesel locomotive for Lithuanian Railways is determined based on a set of criteria. Basic conclusions are also given.

Keywords: Diesel locomotives, the analysis of operating expenses, relative fuel consumption, multicriteria evaluation.

1. Introduction

Railway transport should provide safe transportation for freight and for passengers as well. Freight transportation accounts for about 90% of the income of the joint-stock company 'Lithuanian Railways' (AB „Lietuvos geležinkelai“ – LG).

Many scientists of various countries have made research works about the structure of railways costs (Bitzan 1999; Jonaitis 2007; Schach, Naumann 2007; Andersson 2008; Ludvigsen, Osland 2009; Sonmez, Ontepeli 2009; Jaržemskienė, Jaržemskis 2009; Butkevičius 2009; Dailydka 2010; Sivilevičius, Maskeliūnaitė 2010; Kreutzberger 2010). The overall financial performance, investments trends and expansion of Spain Railways were estimated by Campos (2008). Therefore, the economic policy of the Board Directors in Freight Transportation LG Company largely determines its overall profit. This means that the effective use of the available rolling stock is of paramount importance (Liudvinavičius, Lingaitis 2010; Bureika *et al.* 2009; Dailydka *et al.* 2008; Djukić *et al.* 2010; Bureika, Mikaliūnas 2008). Coelli and Perelman (1999) investigated technical efficiency in European railways.

Talking about Lithuania, should be noted that passenger transportation by railway is unprofitable here. It follows that the considered enterprise should at least have a sufficient amount of freight locomotives and

wagons to satisfy the needs of customers for the freight transportation (Vaičiūnas 2001). It is also important that traction locomotives should be in a good state. They should be reliable for the use and have the required engine power and tractive force of locomotives too (Bureika, Subačius 2002; Bureika 2008; Bureika *et al.* 2009; Liudvinavičius *et al.* 2009).

In the last decade, the state of the freight locomotives M62 and 2M62, which were mainly used for freight transportation by LG, caused serious problems for Lithuanian railways. The total depreciation of the LG freight locomotives reached 84%, implying that it was hardly reasonable to use four fifths of their Diesel locomotives. All of them had to be written off. In 2004, the situation with LG rolling stock had become critical. The locomotives were becoming unreliable and the expenses on their unscheduled repairs were constantly growing. Having studied the situation and the financial possibilities of purchasing new locomotives, LG managers saw that they could hardly renew the whole park of Diesel locomotives.

Therefore, in 2003, the company began the programme of renewing and upgrading freight locomotives. This included upgrading of locomotives by changing only their Diesel engines (upgrading programme M1) and upgrading by changing the engines as well as the main traction generators and auxiliary equipment

(upgrading programme M2). Until 2007, 22 locomotives of the series 2M62 and 16 locomotives of the series M62 were upgraded according to the programme M1, while 20 locomotives of the series 2M62 were upgraded according to the programme M2. This ensured continuous operation of the freight locomotives' park. The amount of the transported goods had increased by 20% every year. At the same time, the operating expenses, primarily associated with fuel and Diesel oil consumption, were decreasing (Bučinskas *et al.* 2006). Relative fuel consumption of the locomotives upgraded according to the programme M1 was reduced by 19%, while those locomotives upgraded according to the programme M2 were decreased even by 33%. Taking into account annual freight turnover by LG and the reduction of fuel consumption by freight locomotives, about 40 million litas could be saved annually. In addition, the upgraded locomotives were more powerful and could pull the trains of 5000 tons, which were by 20% heavier than those pulled by old locomotives. This has increased the carrying capacity as well as efficiency of Lithuanian railway by about 10%.

Given this experience, LG considered a possibility of purchasing new freight locomotives as another way of increasing the efficiency of freight transportation. Due to the use of new locomotives SIEMENS ER20CF generation, diesel oil consumption was reduced by 40–45% compared to that of not upgraded locomotives 2M62, while the train mass increased from 4200 tons to 6000 tons (Bureika 2008). Besides, the scope of the repair and maintenance work was reduced and the conditions of the engine-driver's operation as well as ergonomic conditions were largely improved.

LG was faced with the dilemma whether it would be better (from economic perspective) to upgrade the locomotives 2M62 or to purchase the last generation of SIEMENS ER20CF freight locomotives. The investigation based on the investments of upgrading the locomotives from the series M1 and M2, the cost and the repay time of new locomotives was performed. The author of the present paper attempts to determine the multicriteria evaluation methods (Brans, Vincke 1985; Sivilevičius *et al.* 2008; Šelih *et al.* 2008; Jakimavičius, Burinskienė 2009; Turskis *et al.* 2009; Sivilevičius, Maskeliūnaitė 2010; Edalat *et al.* 2010; Čokorilo *et al.* 2010; Vasilis Vasiliauskas *et al.* 2010) and which of the three types of the locomotives, stated above, would be the most suitable and effective for freight transportation on LG company.

2. Mathematical Modelling of Operating Expenses

General expenses of LG traction rolling stock consist of material (and other similar) expenses (60.0%), depreciation costs (8.5%), work payment (16.7%), taxes (9.8%), social insurance (5.0%) and environment protection payment (0.3%).

Material and similar expenses consist of the costs of diesel oil (85.0%), maintenance and structural materials and spare parts (7.0%), as well as repair (3.0%) and other

expenses (5.0%). The LG locomotives use about 97% of all fuel consumed by the LG company, while only 3% of fuel is used for production purposes.

General operating expenses of LG rolling stocks fleet may be expressed as follows:

$$I = I_{social} + I_{salary} + I_{taxes} + I_{amort} + I_{mater}, \quad (1)$$

where: I_{social} denotes social insurance expenses, rel. units; I_{salary} is work payment, rel. units; I_{taxes} denotes taxes, rel. units; I_{amort} means amortisation costs, rel. units; I_{mater} denotes material and similar expenses, rel. units.

Determining the priorities of the locomotives' use we should rely on economic criteria. These may be general operating expenses I_{gen} , expected for the planned service time of the locomotive. Operating expenses I_{loc} of the locomotive until its state reaches the critical point. It may be calculated by the formula:

$$I_{loc} = \sum_{i=1}^{i_{cr}} x_i \cdot R \cdot K_p \quad (2)$$

where: x_i is the planned service life of a locomotive, years; i_{cr} is the critical service life of a locomotive, years; R is the expected annual kilometrage of a locomotive, thous.km/year; K_p is the locomotive's operating expenses in the period from the first year of its operation till the end of its service life, €/thous. tkm.

When the critical point of the locomotive's service life has been reached, the increase of the locomotive's operating expenses ΔI_{loc} may be calculated by the formula:

$$\Delta I_{loc} = \sum_{i_{kr}}^n x_i \cdot R \cdot (K_p - K_{cr}), \quad (3)$$

where: K_p is the locomotive's operating expenses in the period after it has reached the critical point of its service life, €/thous. tkm; K_{cr} is the locomotive's expenses at the critical point of its service life, €/thous. tkm.

Given that the annual kilometrage of all LG locomotives of the series 2M62M is 3.34 million km, the dependence of the general operating expenses on the planned period of service x may be obtained. The sum calculated by formulas (2) and (3) shows the general operating expenses of the locomotives. A considerable increase of the locomotives' operating expenses may be observed in the period of operation after their critical age has been reached.

The above general operating expenses of the locomotives may be expressed by the formula:

$$I_{gen} = I_{loc} + \Delta I_{loc} = \\ \sum_{i=1}^{i_{cr}} x_i \cdot R \cdot K_p + \sum_{i_{kr}}^n x_i \cdot R \cdot (K_p - K_{cr}). \quad (4)$$

Conclusion. Further use of the locomotives which have reached the critical point of their service life is becoming unprofitable for the LG company, because the costs of scheduled and unscheduled repairs, work payment and fuel exceed the profit obtained from freight transportation.

3. Operating Expenses of the Locomotives Upgraded According to the Programmes M1 and M2 and the Locomotives of the Series ER20CF

The operating expenses of the locomotives from the series 2M62 upgraded according to the programmes M1 and M2 have changed. The calculation of operating

expenses and costs of the team's work hour for freight locomotives of the series 2M62, 2M62K, 2M62M and ER20CF are given in Table 1.

The distribution of the expenses of the locomotives of the series 2M62, 2M62K, 2M62M and ER20CF and their comparison are presented in Fig. 1.

Table 1. Generalized calculation results of operating expenses of freight Diesel locomotives 2M62, 2M62K, 2M62M and ER20CF

Criterion	Unit of measurement	Locomotives series			
		2M62	2M62K	2M62M	ER20CF
Locomotive depot expenses					
Direct expenses	million rel. units	0.480	0.899	1.558	1.783
Depreciation costs	million rel. units	0.000001	0.054	0.706	0.619
The initial cost of a locomotive	million rel. units	0.496	1.490	8.126	12.384
Repair costs	million rel. units	0.598	0.845	0.852	0.529
Indirect expenses	million rel. units	0.124	0.383	0.376	0.498
Production cost	million rel. units	0.604	0.937	1.596	1.832
Commercial service cost	rel. units/hour	73.60	108.37	183.55	210.55
Cost of the locomotive team's work hour					
Direct expenses	rel. units	213.13	196.15	178.20	247.22
Wages expenses	rel. units	34.50	27.71	27.71	20.84
Fuel costs	rel. units	319.20	150.53	134.40	212.28
Oil costs	rel. units	10.53	6.13	4.72	1.52
Locomotive servicing costs, 2.58% from the consumed fuel	rel. units	8.24	3.88	3.47	6.62
Indirect expenses	rel. units	35.93	29.14	29.14	23.57
Commercial cost	rel. units	260.90	234.80	216.85	275.73
Commercial cost of the locomotive operation and the locomotive team's work	rel. units/hour	335.5	343.17	400.40	486.28
Extra charges (10%)	rel. units	33.45	34.32	40.04	-
Commercial cost of the locomotive operation and the locomotive team's work	rel. units/hour	368.95	377.49	440.44	486.28

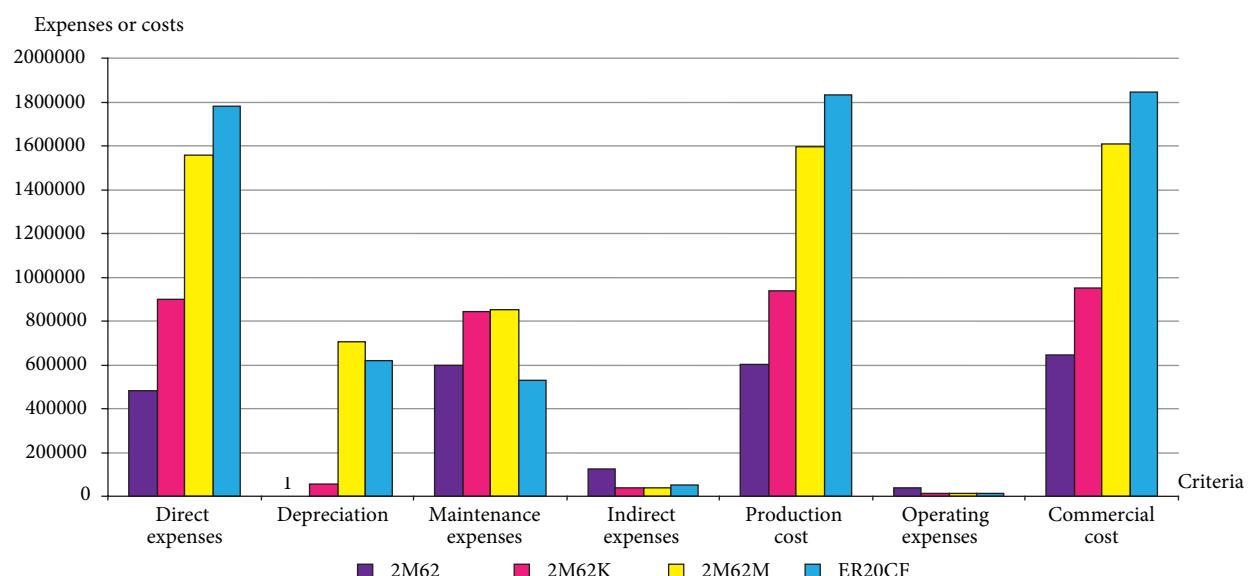


Fig. 1. Operating expenses of LG freight Diesels

The analysis of the data presented in Table 1 and Fig. 1 shows that direct expenses, as well as the production and commercial cost of the locomotive ER20CF, are the highest for freight Diesel locomotives. Other expenses (e.g. depreciation and repair costs) are the highest for the upgraded Diesel locomotive 2M62M. Direct expenses of the locomotive upgraded according to the programme M2 are three times higher than those of the locomotives 2M62 and 1.7 times higher than those of the locomotives 2M62K. However, they are 1.1 times lower than the expenses of the locomotives of the series ER20CF.

Depreciation costs for the locomotives from the series 2M62 reach only about 0.30 € due to their old age and long run, while for the locomotives from the series 2M62K, they make about 15.6 thous. €. For the locomotives 2M62M these expenses are 13 times higher than those of the above-mentioned locomotives, reaching about 205 thous. €, while those of the locomotive ER20CF are slightly smaller, reaching 180 thous. €.

The repair costs are also the highest for the locomotives of the series 2M62M, exceeding by 42%, 0.87% and 60% the respective costs for Diesel locomotives of the series 2M62, 2M62K and ER20CF.

Air pollution produced by the exhaust gases released by Diesel engines of the locomotives of the series 2M62 exceeds that of the locomotives 2M62K, 2M62M and ER20CF by about 66% (Lingaitis, Bureika 2005). However, it should be noted that the researchers of Dept of Railway Transport of Vilnius Gediminas Technical University tested the locomotives which use biological diesel oil as an alternative type of sustainable fuel (Lingaitis, Pukalskas 2007, 2008).

4. Multicriteria Evaluation of the Efficiency in Locomotives' Operation

4.1. Multicriteria Evaluation Methods

To determine the efficiency of multifaceted objects' performance, various multicriteria evaluation methods are used (Brans, Vincke 1985). These methods may be quantitative and qualitative. Qualitative evaluation methods determine the best or several best alternatives based on expert estimates. Quantitative multicriteria methods quantitatively evaluate a particular alternative determining the difference between the values of the alternatives considered. Each method has its advantages, focussing on some particular features of the alternatives analysed. Most methods use various types of normalisation or transformation of the initial data (the values of the criteria). Methods of quantitative evaluation are based on the matrix ($R = [i; j]; i = 1, \dots, m$ and $j = 1, \dots, n$; where m is the number of criteria, n is the number of compared objects (alternatives)) of statistical data or expert estimates of the criteria describing the compared objects. In fact, none of the methods could be directly applied. Each method has some specific features and advantages.

When using quantitative evaluation methods, one should determine the type of each evaluation criterion, which may be maximized or minimized. The best values

of maximized criteria are their largest values, while the smallest values are the best for minimized criteria. The considered methods use the specific types of normalization or transformation of the initial data (criterion values). The methods may also be complex or simple.

The present analysis is based on three multicriteria evaluation methods as follows:

- 1) Sum of Ranks, SR;
- 2) Simple Additive Weighting, SAW;
- 3) Geometrical Mean, GM.

4.2. The Sum of Ranks Method (SR)

The *Sum of Ranks* V_j may be obtained for each j -th object by the formula:

$$V_j = \sum_{i=1}^m m_{ij}, \quad (5)$$

where: m_{ij} is the rank of i -th criterion for j -th object ($1 \leq m_{ij} \leq m$).

As follows from formula (5), the best V_j value will be the smallest value. If several m_{ij} values are the same, every object is assigned to the same value (rank), which is the closest arithmetic mean. For example, if three research objects get the same rank according to the i -th criterion and they obtained the successive 4th, 5th and 6th ranks, then, they are assigned to the same value (rank) is 5.0. If, for example, the same values of the i -th criterion correspond to the 3rd and 4th ranks, the respective objects are assigned to the rank 3.5. The values of the criterion V_j do not depend either on the method of the initial data normalization, or the transformation of their scale or the values ($i = 1, \dots, m$) of the criterion significance ω_i . The main requirement to the application of the method is the determination of the maximized or minimized type of the criteria used. However, it should be noted that minimized criteria may be converted into the maximized ones by the formula:

$$r_{ij} = \frac{\min r_{ij}}{r_{ij}}, \quad (6)$$

where: r_{ij} is the value of the i -th criterion for j -th object. In this case, the smallest criterion value will become the largest value equal to unity.

The calculations show that the considered method (SR) is the simplest and should be used only for the initial rough assessment. However, in many cases, it yields the results slightly differing from those obtained by applying more complicated mathematical methods.

4.3. The Method of Simple Additive Weighting (SAW)

In this method, the sum of normalized criteria values S_j is found for each j -th object. It is obtained by the formula:

$$S_j = \sum_{i=1}^m \omega_i r_{ij}, \quad (7)$$

where: ω_i is the significance index of i -th criterion; r_{ij} is normalized value of i -th criterion for j -th object.

Normalization of the initial values is performed by the formula:

$$r'_{ij} = \frac{r'_{ij}}{\sum_{i=1}^n r'_{ij}}, \quad (8)$$

where: r'_{ij} is i -th criterion value for j -th object.

For approximate calculations, the values of all the criteria may be assumed to be equal, i.e. $\omega_i = \frac{1}{16} = 0.0625$. The best value of the criterion S_j is its largest value.

4.4. The Method of Geometrical Mean (GM)

The geometrical mean of normalized values of all the criteria Π_j (in the method GM) is obtained by the formula:

$$\prod_j = \sqrt[m]{\prod_{i=1}^m \omega_i r'_{ij}}. \quad (9)$$

The order of preference of the considered objects, determined by formula (8) does not depend on the criteria value ω_i , therefore, this value should not be used in this formula. The largest value of the criterion Π_j is the best value.

4.5. Calculating the Values of the Criteria Describing the Effectiveness of the Locomotive Operation

Five criteria describing LG freight locomotives, whose values are taken from Table 1, are used for evaluation:

- 1) the largest train mass carried, t;
- 2) relative fuel consumption, g/kWh;
- 3) cost of TP-3 upgrading programme, rel. units;

- 4) cost of ER-1 upgrading programme, rel. units;
- 5) relative air pollution, kg/t.

The following criteria significance indices r_y are assumed:

- 1) the largest train mass carried – 0.10;
- 2) relative fuel consumption – 0.30.

Other criteria are assigned to the same significance index – 0.20, i.e. these criteria are equally significant.

Evaluation criteria are presented in Table 2.

The locomotive series are denoted as the alternatives A_i : 2M62 – A_1 ; 2M62K – A_2 ; 2M62M – A_3 and ER-20CF – A_4 .

The evaluation criteria of the locomotives of various series are denoted by R_j : the largest train mass carried – R_1 ; relative fuel consumption – R_2 ; cost of TP-3 upgrading programme – R_3 ; cost of ER-1 upgrading programme – R_4 ; relative air pollution – R_5 . $R=1$ refers to the best criteria describing the LG freight locomotives (in this case, the criteria of the locomotive of the series ER20CF are the best). The data for calculation are taken from Table 1.

In the present evaluation, the efficiency function is as follows:

$$R_j \rightarrow 1.$$

The notation used for locomotives and criteria and their values are given in Table 3.

4.6. Calculating the Locomotive Effectiveness by the Sum of Ranks Method

The ranks assigned to the research objects are given in Table 4.

Table 2. Multicriteria evaluation criteria

Criteria	Locomotive series				r_y
	2M62	2M62K	2M62M	ER20CF	
The largest train mass carried, ton	3800	3800	5000	6000	0.10
Relative fuel consumption, g/kWh	233	226	206	201	0.30
Cost of TP-3 upgrading programme, rel. units	7959	6747	5821	3230	0.20
Cost of ER-1 upgrading programme, rel. units	17911	13690	12415	5860	0.20
Relative air pollution, kg/t	183	162	171	59	0.20

Table 3. The notation and values for criteria and locomotives (alternatives)

Criteria	Alternative				r_y
	A_1	A_2	A_3	A_4	
R_1	0.60	0.60	0.80	1.00	0.10
R_2	0.86	0.89	0.97	1.00	0.30
R_3	0.41	0.48	0.55	1.00	0.20
R_4	0.33	0.43	0.47	1.00	0.20
R_5	0.32	0.36	0.35	1.00	0.20

Table 4. Ranks of research objects (alternatives)

Criterion	Alternative				r_y
	A_1	A_2	A_3	A_4	
R_1	3.5	3.5	2	1	0.10
R_2	4	3	2	1	0.30
R_3	4	3	2	1	0.20
R_4	4	3	2	1	0.20
R_5	4	2	3	1	0.20

Then, the ranks of the objects given in Table 4 are summed up:

$$\begin{aligned} A1 &= A_1 R_1 + A_1 R_2 + A_1 R_3 + A_1 R_4 + A_1 R_5 = \\ &3.5 + 4 + 4 + 4 + 4 = 19.5; \\ A2 &= A_2 R_1 + A_2 R_2 + A_2 R_3 + A_2 R_4 + A_2 R_5 = \\ &3.5 + 3 + 3 + 3 + 2 = 14.5; \\ A3 &= A_3 R_1 + A_3 R_2 + A_3 R_3 + A_3 R_4 + A_3 R_5 = \\ &2 + 2 + 2 + 2 + 3 = 11; \\ A4 &= A_4 R_1 + A_4 R_2 + A_4 R_3 + A_4 R_4 + A_4 R_5 = \\ &1 + 1 + 1 + 1 + 1 = 5, \end{aligned}$$

where: $A_i R_y$ is the rank of an object; A_i is the criterion of a particular locomotive series; R_y is the locomotive series.

4.7. The Method of Geometrical Mean (GM)

The data for normalisation are taken from Table 4 and calculated by the formula:

$$N_{11} = \frac{A_1 R_1}{A_1 R_1 + A_2 R_1 + A_3 R_1 + A_4 R_1}, \quad (10)$$

where: N_{11} denotes normalisation data on the objects' ranks $A_1 R_1$.

$$\text{Then, } N_{11} = \frac{0.6}{0.6 + 0.6 + 0.8 + 1} = 0.2.$$

The evaluation data yielded by the GM method are given in Table 5.

The GM criterion is calculated by the formula:

$$G_1 = \sqrt[5]{A_1 R_1 \cdot A_1 R_2 \cdot A_1 R_3 \cdot A_1 R_4 \cdot A_1 R_5}. \quad (11)$$

Table 5. Evaluation results obtained by using the GM method

Criterion	Alternative				r_y
	A_1	A_2	A_3	A_4	
R_1	0.20	0.20	0.27	0.33	0.10
R_2	0.23	0.24	0.26	0.27	0.30
R_3	0.17	0.20	0.23	0.41	0.20
R_4	0.15	0.19	0.21	0.45	0.20
R_5	0.16	0.18	0.17	0.49	0.20

4.8. The Method of Simple Additive Weighting (SAW)

Normalised data are used in calculations. SAW criterion S_n is calculated by the formula:

$$\begin{aligned} S_1 &= N_{11} \cdot r_1 + N_{12} \cdot r_2 + \\ &N_{13} \cdot r_3 + N_{14} \cdot r_4 + N_{15} \cdot r_5. \end{aligned} \quad (12)$$

Summary Table 6 presents the results obtained by applying various evaluation methods.

5. Conclusions

1. The operating expenses of an upgraded locomotive from the series 2M62M (with a new CAT3512B engine) make only a half of the operating expenses of the old locomotive, being by 1.4 times smaller than those of the locomotive after modernisation M1. These Diesel locomotives are more powerful and reliable and a smaller number of them are needed for transporting the same mass of goods. It means that 29 upgraded Diesel locomotives from the series 2M62M can replace 50 old locomotives of the respective series. The upgraded Diesel locomotives can haul trains whose mass makes 1.8 times that of the trains hauled by re-engined locomotives.
2. The analysis shows that the upgrading costs of the locomotives from the series 2M62K and 2M62M differ considerably, however, the differences decrease in time because operating expenses of the locomotive after the modernisation M1 make 1.4 times those of the upgraded by programme M2 locomotives, though its service life is longer.
3. Based on the results obtained in multicriteria evaluation of the locomotives of the LG company by three various methods, SR, SAW and GM, it may be concluded that Diesel locomotives ER20CF are the most effective for freight transportation. The locomotives 2M62M are ranked second, 2M62K – third and the locomotives from the series 2M62 – fourth.
4. To make the analysis more comprehensive, some additional criteria describing the locomotives should be used, including wages expenses, fuel and oil expenses per hour and Diesel engine maintenance expenses.
5. The replacement of the old Diesel locomotives 2M62 by the locomotives from the series 2M62K, 2M62M and ER20CF allows fuel expenses to be reduced by 28%, 44% and 49%, respectively, while Diesel oil expenses may be reduced by 55%, 14% and 75%, re-

Table 6. The investigation results obtained by various multicriteria evaluation methods

Alternatives	Method						Average rank	Rank		
	SR		GM		SAW					
	Rank	Value	Rank	Value	Rank	Value				
A_1	4	19.5	3	0.18	4	0.182	3.67	4		
A_2	3	14.5	4	0.13	3	0.202	3.33	3		
A_3	2	11	2	0.22	2	0.228	2	2		
A_4	1	5	1	0.38	1	0.390	1	1		

- spectively. Maintenance expenses may be reduced by 11%, 60% and 66%, respectively. One train driver is enough to operate the locomotives 2M62M and ER20CF instead of a train driver and an assistant, thereby saving 41% and 35% of expenses on work payment, respectively.
6. Freight locomotives 2ER20CF may haul trains of the mass up to 6000 tons. This exceeds the train mass hauled by the old-type locomotives from the series 2M62 (3800 tons) by more than 1.6 times.
 7. Environmental pollution taxes of Diesel locomotives from the series 2M62 are by 66% higher than those of the locomotives from the series 2M62K, 2M62M and ER20CF. Moreover, lower tax correction coefficients are used for new Diesel locomotives because their new-generation internal combustion engines release considerably smaller amounts of pollutants, while their exhaust systems are provided with soot filters.

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