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Organization of operation, repair and maintenance of locomotives in the railroad operating domain

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Abstract. The methods that are widely used today to determine the required locomotive fleet, the corresponding maintenance and repair system consider the locomotive as a whole, without taking into account the technical condition of its individual units, which have a limited life cycle. Furthermore, the methods used today do not take into account the time spent on relocation from an operational locomotive depot to a service depot and back. The purpose of this study is to develop the methods for determining the number of locomotives based on the anticipated workloads for specific operational sections, the necessary accompanying maintenance and repair, the optimized repair cycle structure with due account of the available resources of the limiting units in the railroad operating domain which are capable of taking into account the technical condition of equipment (failures, repair costs, and time spent on relocation from one depot to another). A model for organization of repair of gas turbine locomotives assigned to operational locomotive depots while undergoing repair in service locomotive depots is proposed. Using this model, it is possible to develop a software product for distributing routine locomotive repairs among service providers, thus optimizing the workload of the latter.

1 Introduction

Development of the Far North regions is an important economic problem for the Russian Federation. Creation of the Northern Latitudinal Railway railroad operating domain will solve the following important problems: 1) provide access to Dudinka and Igarka ports to gain access to the Northern Sea Route connecting the Urals with European Russia and the Far East; 2) develop Russkoye and Zapolyarnoye oil and gas fields and the corresponding infrastructure; 3) create a stable transport connection with the city of Norilsk; 4) create an alternative railroad connection from the Yamalo-Nenets Autonomous District to the North-Western Region, as well as provide transportation support, infrastructure development, and operation of oil and gas fields of the Yamalo-Nenets Autonomous District and the Lower Angara Region; 5) link the Northern and Sverdlovsk railroads; 6) reduce the load on the Trans-Siberian Railway; 7) connect the Yamal peninsula with the country's transportation infrastructure.

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Within the framework of the “Strategy for Developing Rail Transport in the Russian Federation up to 2030” approved by the Government of the Russian Federation, the Northern Latitudinal Railway, railroad lines in the sections Obskaya–Salekhard (54 km long), Salekhard—Nadym (355 km), Nadym—Pangody (111 km) will be built. Provisions are made for reconstruction of the sections Pangody—Noviy Urengoy (113 km long), Noviy Urengoy—Korotchaevo (74 km), with a further planned extension of Korotchaevo—Russkoye (Yuzhno-Russkoye oil and gas field, 122 km long), Russkoye—Igarka (482 km), Igarka—Norilsk (285 km).

Since the railroad lines of the Northern Latitudinal Railway will not be electrified, a promising rolling stock includes locomotives with a gas turbine engine (LGTE) running on liquefied natural gas (LNG), i.e. mainline gas turbine locomotives GT1h, which showed good performance results during experimental operation on the Sverdlovsk railway.

The Russian railroad network has many converter stations for electric and diesel traction. Since a diesel locomotive is much less powerful than an electric locomotive, the trains at such stations need to be broken up and hauled in parts. To move away from this, starting 2005, RZD OJSC launched a complex of research and development works to create a locomotive with a gas turbine engine (LGTE) operating on liquefied natural gas (LNG). The LGTE is more powerful compared to both the electric or diesel locomotives, it is more cost-effective and environmentally friendly, and the LGTE can haul a train weighing more than 6,000 tons and deliver it to the destination without reconfiguration. In 2007, GT1h-001, a novel mainline gas turbine locomotive based on VL15 electric locomotive, was built, and in 2013, a second gas turbine locomotive (GT1h-002) based on TEM7A diesel locomotive was manufactured [1, 2]. In February 2017, GT1h-002 was consigned to RZD OJSC to the Sverdlovsk railway for operation. Currently, the gas turbine locomotive (GTL) is serviced by STM-Service LLC in Artyomovsky service locomotive depot (SLD); the GTL is operated by crews of Egorshino operational locomotive depot.

Because of its more complex structure (compared to a diesel locomotive), the problem of organizing operation, maintenance and repair for a modern GTL in the railroad operating domain Korotchaevo—Voynovka of the Sverdlovsk railway has arisen. This section is not electrified, it is included in the centralized traffic control. Section length is 1,331 km, there are way stations and junctions along the train line.

However, there are no methods that take into account the required number of locomotives based on the anticipated workloads for specific operational sections, the necessary accompanying maintenance and repair, the optimized repair cycle structure with due account of the available resources of the limiting units in the railroad operating domain which are capable of taking into account the technical condition of equipment (failures, repair costs, and time spent on relocation from one depot to another), or such methods are not perfect [1–5].

2 Research Methods

To organize the repair and maintenance of gas turbine locomotives in a railroad operating domain, it is necessary to calculate their required number, and the corresponding repair and maintenance rates.

Service speed is determined by the given service speed coefficient:

$$V_s = 0.8 \cdot V_T \tag{1}$$

where 0.8 is the service speed coefficient.

Full turnover of locomotive:

$$T_1 = \frac{2L}{V_s} + t_m + t_{to} \quad (2)$$

where L is the length of the operational section, km; tm is downtime for technical inspection for one turnover cycle, hr; t_{to} is locomotive downtime in turnover point, hr.

Locomotive requirement ratio:

$$K_r = \frac{T_l}{24} \quad (3)$$

where T_l is locomotive turnover in the operational section, locomotive-·km.

The requirement ratio shows the number of locomotives required to serve one pair of trains per day.

Then the operated park of locomotives in the section will be:

$$N_o = K_r \cdot n \quad (4)$$

where n is the number of train pairs.

Based to the calculated number of locomotives in the section park, let us determine the repair program and the required operational resources.

Daily mileage is determined using the following equation:

$$S_d = 2 \cdot L \cdot n \quad (5)$$

where L is section length, km; n is the number of train pairs per day.

Annual and monthly locomotive mileage:

$$S_{year} = S_d \cdot 365 \quad (6)$$

$$S_M = S_d \cdot 30.4. \quad (7)$$

Average daily mileage for one locomotive is determined using the following equation:

$$S_{av.d} = 2 \cdot L \cdot \frac{n}{N_o} \quad (8)$$

where N_o is the operated park of GTL; L is section length, km; n is the number of train pairs.

The number of repair bays is determined by the annual program for locomotive repair in a service depot, their downtime in repair or maintenance, and the bay's production time. For repairs that take days (RR-2 (routine repair), RR-3, BR (basic repair), MR (major repair)), we use the following equation [6]:

$$C_{ri} = \frac{N_{ri} \cdot t_{ri}}{D} \quad (9)$$

where N_{ri} is the annual program for this type or repair; t_{ri} is repair downtime, days; D is the number of working days per year, D = 247 days.

For repairs and inspections that take hours (M-2 (maintenance), M-3, RR-1), the number of repair sites is determined using the following equation:

$$C_{ri} = \frac{N_{ri} \cdot t_{rdi} \cdot \mu}{D \cdot C \cdot T_{sh}} \quad (10)$$

where T_{sh} is the average duration of a shift; t_{rdi} is repair duration, hr; C is the number of shifts per day; μ is the coefficient accounting for nonuniformity of gas turbine locomotives arrival and docking for repairs M-2, M-3, RR-1, μ = 1.1.
Generally, the number of bay sites (bays) for inspection and repair of equipment during routine repair of locomotives depends on many factors (repair downtime, shift duration, the bay's production time, uniformity of docking for repair), and is determined using the following equation [7]:

$$C_r = \frac{N_r \cdot t_r}{K \cdot F \cdot t_{sh} \cdot n_{sh}} \cdot \psi, \tag{11}$$

where N_r is the number of routine repairs; t_r is the standard downtime for locomotive repair, hr; K is the converting factor for the number of locomotive sections; F is the bay's production time, days; t_{sh} is the duration of a shift, hr; n_{sh} is the number of shifts; ψ is the coefficient accounting for nonuniform docking, ψ = 1.1–1.2 [8].

The sequence of equipment failures in the course of locomotive operation can be presented in the form of the following model [9, 10]. Monitoring of the new (repaired) equipment starts at time $l = 0$ (Fig. 1).

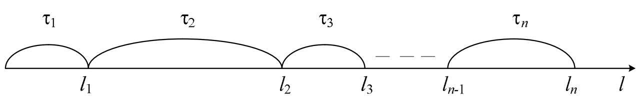

Fig. 1. Model of the repair process.

After operating for a certain time (running time) τ_1 a failure occurs, then, equipment is repaired or replaced with new equipment within a time period much shorter than running time to failure l_i. After running time τ_2 the equipment fails, it is repaired again or replaced with the similar functioning equipment. Then, this process continues in a similar fashion. Since all the failures occur due to the same factors, it is reasonable to assume that the times between failures $\tau_1, \tau_2, \ldots, \tau_i, \ldots, \tau_n$ τ_1, τ_2 have the same distribution law [11]:

$$F(l) = P\{\tau < l\}. \tag{12}$$

The probability of a failure-free operation is the probability that the time to failure τ of equipment will be no less than l [12]:

$$P(l) = P\{\tau \geq l\}. \tag{13}$$

Since failure and failure-free operation are complementary events, the probability of failure is:

$$Q(l) = P\{\tau < l\} = F(l) = 1 - P(l). \tag{14}$$

The problem of optimizing the organization of repair and maintenance of locomotives can be solved using the queuing theory [13]. In this case, the party requesting routine locomotive repair (RR) is an operational locomotive depot (OLD), while the contractor is a service locomotive depot (SLD). However, the classic methods of the theory of Markovian processes cannot produce an optimization solution for this problem, as there may be both several SLD and several OLD, with each OLD sending locomotives for RR to the SLD providing the highest quality of repair. Furthermore, the following should be noted: the temporal properties of the process obey the exponential distribution law only when

Markovian models are in place, which is far from being completely and always true. In this case, it would be useful to create a model of organization of locomotive repair and perform computer simulation modeling, with the result being the best distribution of specific RR of locomotives among SLD [14].

We need to choose an algorithm for selecting an SLD for repairing a specific locomotive assigned to a specific OLD. To this end, let us use a pseudorandom number generator with a range of 0 to 100 and a scale of 1, and for each OLD, we will set the probability (Fig. 2) of sending the locomotive to one SLD or another (α_1, α_2, α_3, …, α_N,).

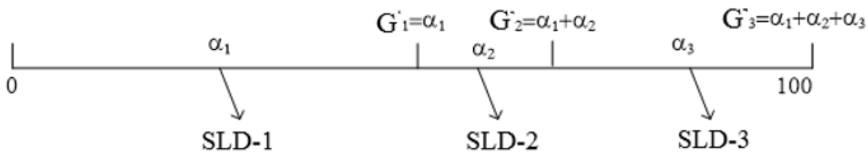

Fig. 2. Selecting an SLD for locomotive repair.

After generating a pseudorandom number with a computer and comparing it to the limit values (boundary values G_1, G_2, G_3, …, G_N), we determine where we are going to send the locomotive.

Thus, to solve this problem, we simply need to determine the best values of α_1, α_2, α_3, …, α_N for each OLD. Taking into account the nonuniformity of traffic, each locomotive, at certain time τ, enters the state of required RR. Correspondingly, GT1h are sent to SLD in the order of reaching such a state [15]. Using the algorithm for selecting an SLD for repair above, the SLD where GT1h is sent is determined. The locomotive arrives at the SLD after a certain fixed time t that is determined by dividing the distance between the OLD and the SLD by the speed of GT1h transportation to the SLD and back to the OLD. Upon the locomotive's arrival at the SLD, two variants are possible: 1) the SLD's repair sites are waiting for the locomotive's arrival, i.e. they are not busy, so RR of GT1h starts immediately after its transportation to the SLD. In this case, the total duration of locomotive downtime at repair sites ($T_{\sum rs}$) will increase by the difference between the time of GT1h arrival and the time the previous locomotive left the repair site, thus making it available [16]; 2) repair sites in SLD are busy repairing the locomotive that arrived earlier, the second GT1h is waiting for its turn, RR will be performed at the repair site that becomes available first, and the total duration of locomotive downtime awaiting RR ($T_{\sum GT1h}$) will increase by the difference between the time the repair site becomes available and the time of GT1h arrival.

After the operational repairs are completed, the locomotive is relocated to its OLD after a certain fixed time t. Upon arrival to the OLD, the locomotive starts hauling trains, and after a certain running time limit has elapsed, GT1h requires the next RR, and the entire process repeats. Let us consider the algorithm of functioning of the discussed model using a specific example (Fig. 3), which includes three OLD with assigned parks of gas turbine locomotives (N_i), two SLD (SLD-1 is equipped with one repair site, while SLD-2 has two sites). The random moments in time related to events occurring with the locomotives will be denoted as follows: $\tau_{A/B\text{-}C}$, where A is the number of the OLD, B is the number of the locomotive, C is the number of the moment in time; similar notation is used for the events related to SLD: $\theta_{A/B\text{-}C}$, where A is the number of the SLD, B is the number of the repair site, C is the number of the moment in time. The duration of transportation is denoted as $t_{A/B\text{-}C}$, where A is the number of the OLD, B is the number of the locomotive, C is the order number.

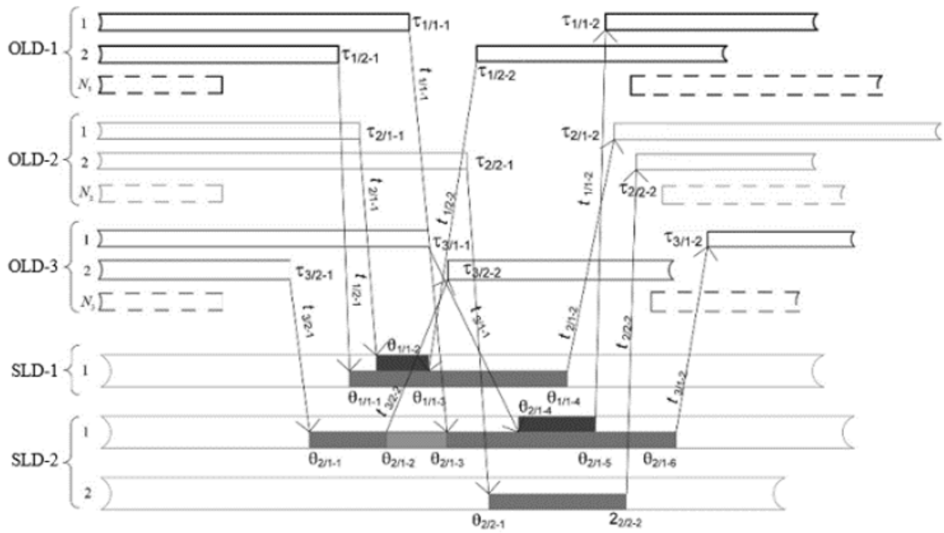

Fig. 3. Example of model functioning.

The first event that we consider in this example relates to the second locomotive from the park assigned to OLD-3 and consists in the necessity to perform RR. The random time of repair is $\tau_{3/2\text{-}1}$. Let us assume that, based on the used algorithm for selecting an SLD for repair of this locomotive, we decide to perform RR at SLD-2. Taking into account transportation, arrival time at SLD-2 will be: $\theta_{2/1\text{-}1} + t_{3/2\text{-}1}$. By this time, both repair sites at SLD-2 are no longer busy (are available), so GT1h repair starts immediately after docking onto one of the two repair sites. Completion of RR, and, correspondingly, freeing of the first repair site occurs at time $\theta_{2/1\text{-}2}$. Arrival of this locomotive at its OLD occurs at random time $\tau_{3/2\text{-}2} = \theta_{2/1\text{-}2} + t_{3/2\text{-}2}$. The total transportation time will be $T_{\Sigma\mathrm{rd}} = T_{\Sigma\mathrm{rr}} + (t_{3/2\text{-}1} + t_{3/2\text{-}2})$. For the second locomotive from OLD-1, RR has to be performed at random time $\tau_{1/2\text{-}1}$. If a decision is made to send it to SLD-1, it will be transported there by time $\theta_{1/1\text{-}1} = \tau_{1/2\text{-}1} + t_{1/2\text{-}1}$. At this time, the first repair site is available, correspondingly, RR of GT1h will start immediately after its arrival at SLD-1, and will be completed by time $\theta_{1/1\text{-}3}$. The locomotive will be delivered to its permanent station (OLD) at random time $\tau_{1/2\text{-}1} = \theta_{1/1\text{-}3} + t_{1/2\text{-}2}$. The total transportation time will be $T_{\Sigma\mathrm{rd}} = T_{\Sigma\mathrm{rr}} + (t_{1/2\text{-}1} + t_{1/2\text{-}2})$.

3 Experimental Data and Results

To organize maintenance of gas turbine locomotives at sections Obskaya—Korotchaevo, the relevant infrastructure is needed, and therefore, natural gas liquefaction complexes need to be constructed. We suggest deployment of gas supply infrastructure units (locomotive equipment shops) shown in Fig. 4.

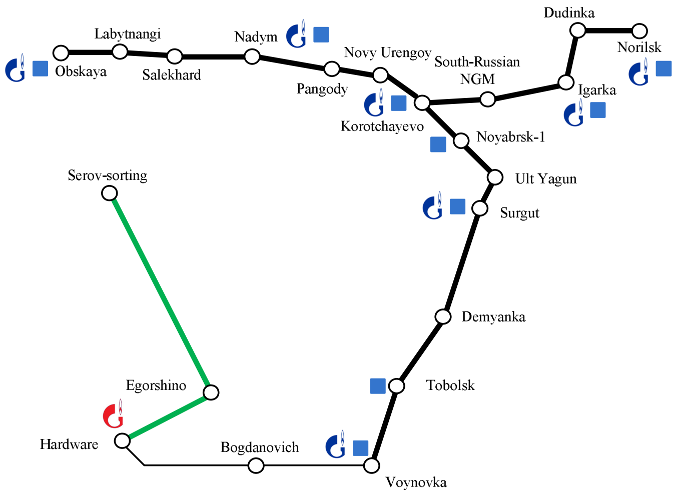

Fig. 4. Deployment of gas supply facilities: —the operating LNG production complex; —the required LNG production complex; —the equipment shop (ES).

Today, the only operating liquefied natural gas production complex is located at Apparatnaya station (city of Ekaterinburg). The authors in [6] proposed to deploy three additional complexes in the section Voynovka—Korotchaevo. Therefore, to ensure stable traffic in the section Obskaya—Korotchaevo, the deployment of two additional LNG production complexes at stations Nadym and Obskaya was proposed. This location will ensure timely refueling of locomotives along the route. Equipping is performed on specialized platforms [17].

We suggest launching into operation by 2030 seven LNG production complexes at stations Tobolsk, Demyanka, Surgut, Limbey, Korotchaevo, Nadym, and Obskaya, and seven equipment shops (complexes) for refueling gas turbine locomotives at the stations where LNG is produced (Fig. 5).

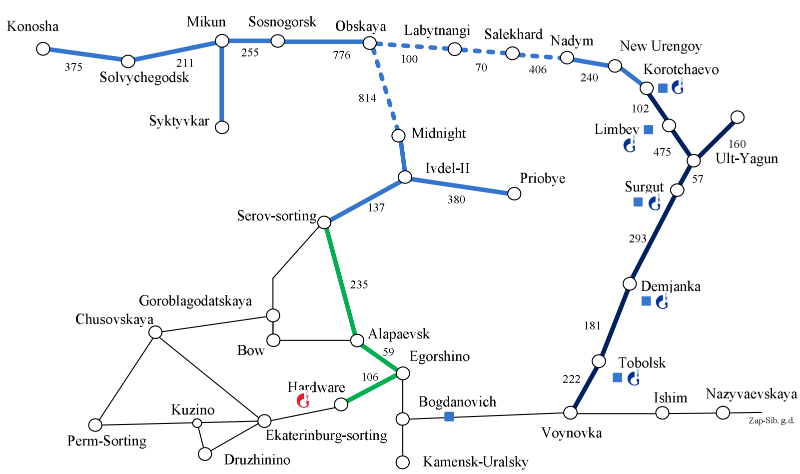

Fig. 5. Deployment of equipment shops for refueling gas turbine locomotives: —the operating LNG production complex; —the required LNG production complexes; —the LNG equipment shops.

Such deployment accounts for the specific features of working with cryogenic liquids, such as LNG, to which strict requirements as to their minimum supply level in storage tanks, mandatory to preserve the necessary temperature of tank walls, are applied.

A complete depletion of a cylinder or tank of a gas turbine locomotive would require a cooldown of the tank when refilling, during which the evaporated LNG exits the tank via drainage outlets, which results in LNG losses of 10–15% of the tank volume. Therefore, the number of draining and filling operations with LNG needs to be minimized. This can be done in two ways: 1) equipping gas turbine and gas engine locomotives directly from the loading and receiving rack of the LNG production facility and 2) using detachable tanks or tanks connected with a cryogenic pipeline for equipping gas turbine locomotives. From the point of view of organizing locomotive fueling, the most cost effective would be fueling locomotives directly at the equipping site integrated into the production facilities. This method allows employing production loading and receiving rack used for dispensing LNG into tank cars to fuel the locomotives. Integrated equipment shops will allow us to reduce the number of equipment infrastructure facilities, and thus, reduce capital and operating costs, as well as losses of commercial goods related to draining and filling operations and the ensuing evaporation of cryogenic liquids [5].

According to the program, RZD OJSC plans to increase by 2023 the park of mainline gas turbine locomotives and shunting gas engine locomotives operating on LNG from a total of 3 to 22 units [8].

To organize repair and maintenance of gas turbine locomotives in the Northern Latitudinal Railway railroad operating domain, it is necessary to calculate the repair and maintenance rates in sections Korotchaevo—Nadym, Nadym—Obskaya, Korotchaevo—Russkoye, Russkoye—Igarka, Igarka—Norilsk.

Let us consider the section Korotchaevo—Nadym (298 km), the number of train pairs is 6, to calculate the operational park of gas turbine locomotives, the operating speed in the section in even and odd directions is taken as 50 km/hr.

Similar results have also been obtained for sections Nadym—Obskaya, Korotchaevo—Russkoye, Russkoye—Igarka, Igarka—Norilsk. All the performed calculations for the considered sections, as well as for types of maintenance and repair are provided in Table 1.

Table 1. Annual program for GTL maintenance and repair, units.

Section	Types of Maintenance/Repair						
	M-2	M-3	RR-1	RR-2	RR-3	BR	MR
Korotchaevo—Nadym	365	104	13	7	3	1	1
Nadym—Obskaya	511	143	18	9	4	1	1
Korotchaevo—Russkoye	219	43	5	3	1	0	0
Russkoye—Igarka	511	169	21	11	5	2	1
Igarka—Norilsk	365	100	12	6	3	1	1
Total	1.971	559	69	36	16	5	4

The required number of operated gas turbine locomotives in the park in the section of the Northern Latitudinal Railway is shown in Table 2.

Table 2. Operated park of gas turbine locomotives in the section Korotchaevo—Obskaya.

Section	Number of Locomotives, Units
Korotchaevo—Nadym	5
Nadym—Obskaya	7
Korotchaevo—Russkoye	3
Russkoye—Igarka	7
Igarka—Norilsk	5
Total	27

To calculate the number of repair sites, we use downtime standard rates for gas turbine locomotives in maintenance and routine repair taken from [18], the standard rates are listed in Table 3.

Table 3. Downtime standard rates for gas turbine locomotives in maintenance (M) and routine repair (RR).

M-2	M-3	RR-1	RR-2	RR-3	BR
1.2 hr	12 hrs	36 hrs	4 days	6 days	6 days

The number of repair sites for gas turbine locomotives in the Northern Latitudinal Railway railroad operating domain is given in Table 4.

Table 4. Number of repair sites.

M-2	M-3	RR-1	RR-2	RR-3	BR
1	2	1	1	1	1

To solve the problem of optimization of the workload of each SLD for performing RR of gas turbine locomotives, a model can be built with a rather complex topology of interrelations between OLD and SLD, and a decision was made to develop a PC software to describe the model using visualization means. In an Integrated Development Environment for Microsoft Windows (Embarcadero Delphi) an executable file “NW.exe” was created, which, when run by a user, opens the window of the “Project Wizard” program. Information on project (model) properties is entered step by step to avoid errors in data input.

At the first step (Fig. 6), the user enters the “project name”, the number of both OLD and SLD, the cost of 1 hour of gas turbine locomotive downtime during RR and of 1 hour of GT1h transportation, the number of repair sites at SLD.

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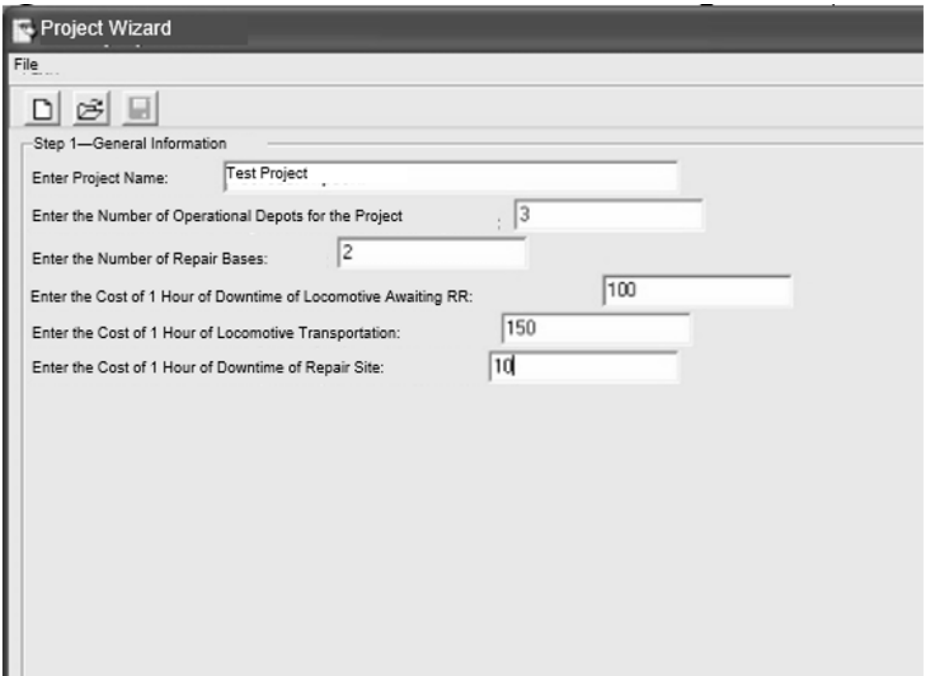

Fig. 6. Window of the “Project Wizard” software for entering initial data.

After distributing the locomotives among SLD based on the algorithm described above, the optimal model parameters can be determined and a unit cost diagram can be built (Fig. 7). The duration of the modeling period should be as long as possible (several dozens of years) to collect the required statistical data. Since modern high performance PCs can perform modeling in just several minutes, let us take the duration of the modeling period T_M = 1,000,000 hrs = 114.16 years. As can be seen from the produced unit cost diagrams for repair of gas turbine locomotives, before optimization the diagram has a falling shape with high costs, while after optimization the diagram assumes a more stable shape with minimal and stable costs. Thus, a conclusion can be drawn that optimization of repair in this area is rather promising.

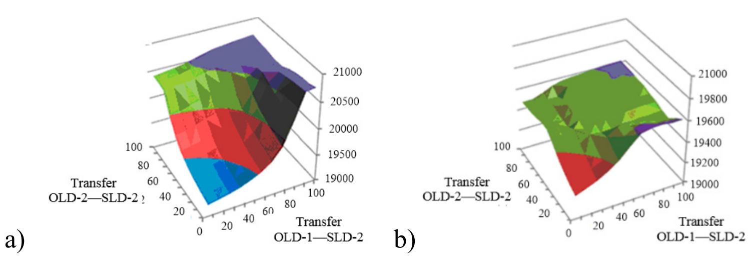

Fig. 6. Unit cost diagrams for repair of gas turbine locomotives before (*a*) and after (*b*) optimization.

To identify GTL equipment that is most prone to failure, in 2018, statistical data on defects in the units of GT1h-002 was collected at SLD Artyomovsky (Table 5).

Table 5. Classification of defects of units of GT1h-002 gas turbine locomotive.

Unit	Number of Defects	Accumulated Sum of Defects	Percent Fraction of Defects of the Total Number of Defects	Accumulated Percent Fraction
Fuel feed system	19	19	31.2	17.5
Mechanical equipment	14	33	23.0	54.2
Traction motor	11	44	18.1	72.3
Train-stop equipment	5	49	8.4	80.7
Auxiliary equipment	3	51	4.9	85.6
Power electric circuits, devices	2	53	3.2	88.8
Safety instruments	1	54	1.6	90.4
Control system	1	55	1.6	92.0
Traction generator	1	56	1.6	93.6
Signal and lighting devices	1	57	1.6	95.2
Alarm systems	1	58	1.6	96.8
Radio sets	1	59	1.6	98.4
Body	1	60	1.6	100
Gas turbine power unit NK-361	0	60	0	100
Total:	61	–	100	–

Based on the statistical data (Table 5), using the method of [19], a Pareto chart was plotted (Figure 8).

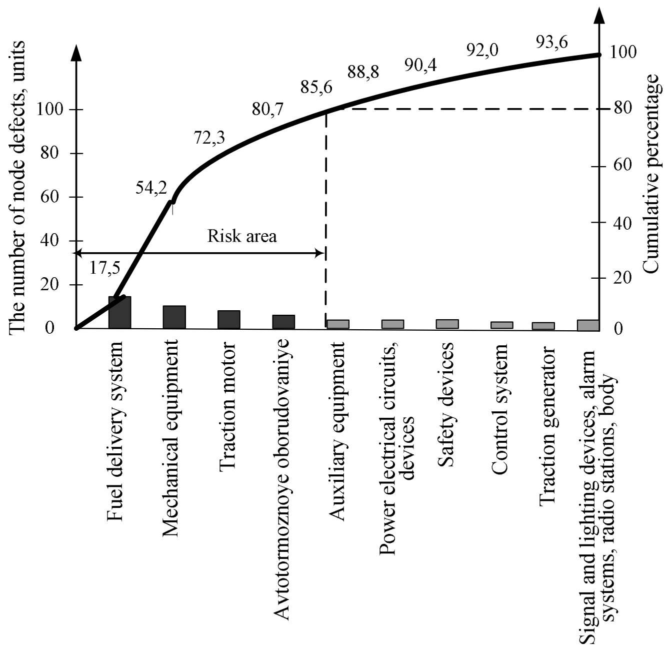

Fig. 7. Pareto chart for defects of gas turbine locomotive units.

From Fig. 8 we can see that the risk area includes such units as the fuel feed system, mechanical equipment, traction motor, and train-stop equipment, for a total of 80.7%. From Table 5 and Fig. 8 we can see that: gas turbine power unit NK-361 has a significant failure-free operation lifetime (no defects found during travels); there is a high risk that the claimed service life of the fuel feed system (cryogenic pump) manufactured in Switzerland will not be met; a weak spot is traction motor and train-stop equipment. The problem of failing traction motors manufactured in Ukraine (Kharkov) could not be solved. The issues related to failure-free operation of the braking system are currently being solved at USURT and UB AO VNIIZHT.

To reduce the number of defects and keep the locomotives in good operating condition, we need to develop methods to increase the reliability of the four units of GT1h-002 gas turbine locomotive. Together with AO VNIKTI and Lyudinovsky Diesel Locomotive Plant work on increasing the reliability of GT1h-002 gas turbine locomotive is underway, which has resulted in the technical availability coefficient (TAC) of 0.89 and intrinsic availability coefficient (IAC) of 0.95.

Based on the results of processing of statistical data using the developed method [20], a bar graph showing the probability of equipment failure for GT1h-002 gas turbine locomotive was built after routine repair RR-1 (Fig. 9).

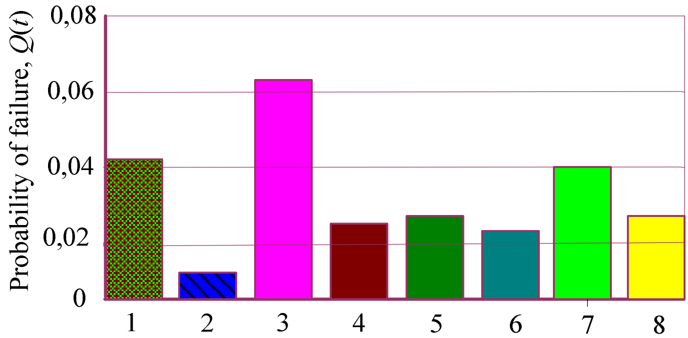

Fig. 8. Bar graph showing probability of equipment failure in 2018: 1—mechanical equipment; 2—safety instruments; 3—fuel feed system; 4—power electric circuits, devices; 5—train-stop equipment; 6—traction generator; 7—traction motor; 8—auxiliary equipment.

When performing calculations, the repair crew working time of 12 hours was taken into account. Three work variants were considered: 1) 24 hours per day, 7 days per week, F = 365 days; 2) 24 hours per day, with holidays off, F = 353 days; 3) 24 hours per day, with weekends and holidays off, F = 249 days.

In addition to bay sites for inspection and repair of GTL during routine repair, special bays for equipment diagnostics should also be provided. Such diagnostics bays are available, e.g., at SLD Sverdlovsk. The number of calculated bay sites required for diagnostics and routine repair RR-1 of GT1h gas turbine locomotive is listed in Table 6.

Table 6. Number of bay sites for routine repair RR-1.

Name	Bay's Production Time, Days		
	365	353	249
Number of bay sites for routine repair RR-1	1.36	1.40	2.24
Number of bay sites for diagnostics	0.68	0.70	0.99

Eventually, the number of bay sites may be reduced if the inspection of equipment in the bay can be completed within one 12-hour shift.

The developed computer program "Optimization of periodicity of locomotive repair in the railroad operating domain" [21] was used to calculate and optimize the structure of the repair cycle of GT1h-002 gas turbine locomotive . Fig. 10 *a* shows the structure of the repair cycle of a unit before optimization [22], and Fig. 10 *b* shows the optimized structure (with the number of failures of the fuel feed system, mechanical equipment, traction motors, and train-stop equipment reduced by half).

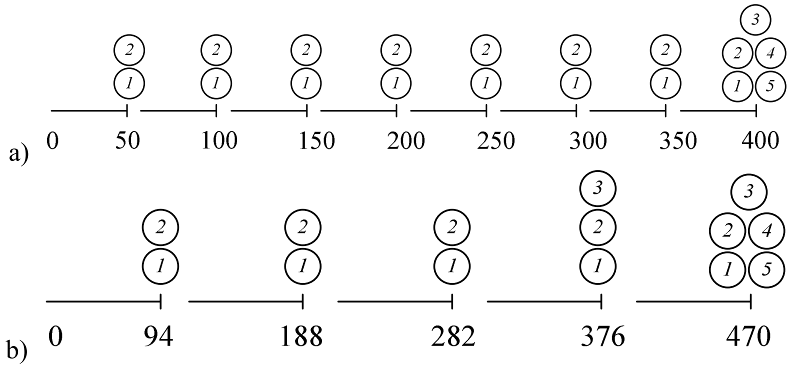

Fig. 9. Structure of the repair cycle before (*a*) and after (*b*) optimization: *1*—fuel feed system; *2*—mechanical equipment; *3*—traction motor; *4*—train-stop equipment; *5*—power electric circuits, devices.

The mileages between GTL maintenances and repairs after structure optimization are provided in Table 7.

Table 7. Standard Mileages for Locomotives between Repairs.

Locomotive Series	Periodicity by Repair Type, Thousand Km				
	RR-1	RR-2	RR-3	BR	MR
GT1h	94	282	470	1.410	2.820

The obtained optimized structure of the repair cycle was used to correct for an increase in inter-repair mileages [7] and reduce the volume of routine repairs for GT1h gas turbine locomotives.

4 Conclusions

1. The methods for calculating the number of locomotives based on the anticipated workloads for specific operational sections have been developed.
2. A method for determining the necessary maintenance and repair, the optimized repair cycle structure with due account of the available resources of the limiting units in the railroad operating domain which are capable of taking into account the technical condition of equipment (failures, repair costs, and time spent on relocation from one depot to another) is provided.
3. A model for organization of repair of gas turbine locomotives assigned to operational locomotive depots while undergoing repair in service locomotive depots was proposed. Using this model, we can develop a software product for distributing routine locomotive repairs among service providers, thus optimizing the workload of the latter.
4. As an example, the issues related to organization of operation of gas turbine locomotives operating on liquefied natural gas to implement the technology for hauling goods from the Far North regions of the Russian Federation were considered.
5. The locations of locomotive equipment shops, and the operating park of gas turbine locomotives to be used in the Northern Latitudinal Railway have been determined. The number of maintenances and repairs of gas turbine locomotives has been calculated, as well as the number of required repair sites according to the annual program for gas turbine locomotive repair taking into account downtime for maintenance and routine repair.
6. The use of gas turbine locomotives with high traction characteristics will allow us to solve several problems at once:

- organize heavytrain traffic in the Far East regions, in non-electrified sections of the railroad network such as the Northern Latitudinal Railway, providing increasing volumes of traffic with a reduced need for locomotives and locomotive crews;
- increase the carrying capacity and throughput of railroads in the existing railroad infrastructure;
- reduce the operational costs for freight transportation by using LNG instead of diesel fuel;
- reduce the detrimental environmental impact of railroad transport due to a reduction of locomotive emissions when using LNG.

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