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Substantiation of Passenger Elevators Maintenance Intervals Based on Studies of Modes and Conditions of Their Operation

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Abstract

Introduction. Maintenance is one of the factors of elevator systems safe operation. In regulatory documents, the influence of the loading mode of elevators on the frequency of maintenance is not taken into account and is assumed to be the same for objects operating in disparate conditions. This suggests the need to determine rational intervals between maintenance to ensure safe and economically feasible operation of the equipment in question. The work objective is to substantiate the required maintenance frequency of passenger elevators based on comprehensive assessments of their technical condition.

Materials and Methods. The domestic and foreign experience of choosing the maintenance frequency of elevator units is considered. The paper evaluates the possibilities of substantiating the required maintenance intervals on the basis of established comprehensive assessments of technical condition, taking into account the conditions and operating modes. Since the problem has no direct analytical solution, an alternative approach is proposed. It is based on the hypothesis of the interrelation between the regulatory resource characteristics of assemblies and the modes and conditions of their operation. The authors obtained the necessary indicators through measurements in high-rise apartment buildings in Rostov-on-Don, experiments and adequate simulation modelling.

Results. A structural and logical model has been developed to solve this problem. It consists of procedures that can be described in detail and clarified. A method for adjusting the maintenance frequency of elevators is proposed and tested. The standards of the system resource in terms of time and number of work cycles for the control time are summarized and tabulated. In this light, the gearbox, electric motor, brake, door drive and elevator ropes in 9-storey buildings are described at a cabin speed of ≤ 1 m/s. For example, the paper provides the calculated normative indicators:

– $K_{m\text{ср норм}}$ — coefficient of net machine time (NMT);

– $n_{\text{ср норм}}$ — specific number of switching-on of the main drive and the door mechanism.

According to the calculation results, $K_{m\text{ср норм}}$ for the electric motor is 0.228; $n_{\text{ср норм}}$ for the brake is 1.065 per NMT minute. To assess the overall load level, the resulting technical condition of the elevator and its main components, a single generalized indicator is proposed — the load index W_{Σ}. It is calculated as the sum of coefficients reflecting the relative level of load on the elevator assembly. It is established that as the resource is being depleted, while maintaining the value of time and power indicators, the estimated maintenance frequency will decrease. The recommended change threshold is 15–20 %.

Discussion and Conclusion. The developed methodology for assessing the technical condition of the elevator unit allows us to develop a complex index by which we can judge the need to revise the regulatory intervals of the elevator unit assemblies. The proposed procedures are applicable to existing, installed and designed elevators. Simulation modeling in a specially developed computer program determines the main indicators of the technical condition of the power units of the elevator: the coefficient of net machine time, switching-on specific number, the power load and the share of the expired service life. Simulation modelling also takes into account the parameters of the building: population density and random external and internal influences. The method of adjusting the maintenance frequency allows you to quickly plan and optimize the costs of operating elevator equipment without losing the level of reliability and safety.

Keywords: passenger elevator, simulation modeling, operating mode, technical condition, workload indicators, maintenance frequency, adjustment of the repair interval, net machine time coefficient, switching-on specific number, power load, share of the expired service life.

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Introduction. Passenger elevators safety and operating costs depend on their technical condition. Each cycle of operation of the elevator system is accompanied by multiple efforts to start and brake it. Passenger elevators operate in the mode of random impacts on the duration, magnitude and frequency of loads. Simulation modeling (SM) methods are widely used to study the functioning of such machines. This allows us to obtain reliable results at significantly lower costs and time of research. For passenger elevators, the established frequency of maintenance does not depend on the operating conditions and modes. It is determined by regulatory documents[1, 2] and operating manuals[3], and is assumed to be the same for all elevators and does not depend on the number of floors of the building, the occupation rate, the parameters of the elevator unit (load capacity, speed), as well as the current technical condition of the object.

For a comprehensive assessment of the current technical condition of the elevator unit in a specific period, the following time indicators are used: net machine time (NMT), switching-on frequency, load and level of resource development [1]. It is advisable to express them in terms of dimensionless values: K_m — NMT coefficient; n — specific number of switching-on of the main drive and the door mechanism, per minute of NMT; $\lambda_{экв}$ — relative value of the power load; K_{RO} — share of the of regulatory resource development.

The authors of this work used two methods to establish the listed indicators formed during the operation of the object as a result of a sequence of random cyclic impacts:

– regular observations —machines in operation [2];

– IM — for the designed elevator installations [3, 4].

Depending on the combination of the values of these random indicators, the rates of equipment wear, the frequency and severity of failures change. Therefore, it makes sense to sometimes adjust the maintenance frequency (in particular, repair and maintenance work). However, as noted above, the regulations do not provide for the variability of

[1] GOST R 55964-2014. Lifts. General safety requirements in service. Technical Committee for Standardization TC 209. Moscow: Standartinform, 2019. 30 p. (In Russ.).

[2] GOST 34303-2017. Lifts. General requirements for maintenance lifts instruction. Technical Committee for Standardization TC 209. Moscow: Standartinform, 2019. 12 p. (In Russ.).

[3] Operation manual. 0621EM.00.00.000 RE. Passenger elevator. OAO "MEL". Available from: https://www.burmistr.ru/upload/forum/fc5/fc50d9b45781d2c11cafb3b2651567f7 (accessed 14.11.2022). (In Russ.)

the maintenance schedule[4]. Perhaps, in some cases, this leads to a higher than necessary frequency of maintenance and, accordingly, to costs that could have been avoided. A more significant objective of adjustments is to exclude an unreasonable increase in the intervals between maintenance, which is associated with the risks of premature loss of performance and a decrease in the level of safety.

A. I. Antonevich, P. V. Arkhangelskiy, D. P. Volkov, N. A. Lobov, A. V. Mechiev[5], P. I. Chutchikov[6], N. A. Shpet and others studied the dynamics of elevator equipment and the improvement of its reliability [1, 5–10].

In some publications [1, 6] and regulatory documents, it is noted that the intervals between the scheduled maintenance should take into account such characteristics of objects as the number of floors of the building, lifting height, load capacity, occupation rate. At the same time, it is not reported exactly how they should be taken into account, and the examples are not given.

The work objective is to substantiate the required frequency of maintenance of passenger elevators on the basis of the established comprehensive assessments of technical condition, taking into account the conditions and modes of their operation.

Materials and Methods. To realize the work objective, it is necessary, firstly, to scientifically substantiate the relationship of conditions, modes of operation of elevator units with the maintenance frequency. Then, based on the data obtained, it is necessary to develop methods for determining the appropriate maintenance frequency, which will ensure the maintenance of the necessary technical condition of the passenger elevator.

Domestic and foreign authors proposed analytical methods for solving the problem of optimizing the frequency of maintenance of machines, including elevator units. Fundamental developments were carried out at the Institute of Mechanical Engineering of the USSR Academy of Sciences[7, 8]. The authors of this article propose to be guided by the scheme presented in Fig. 1.

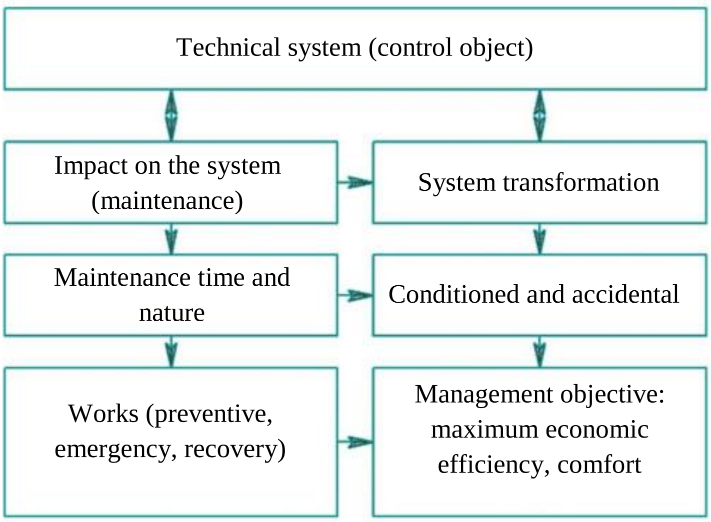

Fig. 1. Block diagram of the analytical solution to the problem of establishing the optimal maintenance frequency of elevator equipment

[4] Ob organizatsii bezopasnogo ispol'zovaniya i soderzhaniya liftov, pod"emnykh platform dlya invalidov, passazhirskikh konveierov (dvizhushchikhsya peshekhodnykh dorozhek), eskalatorov, za isklyucheniem eskalatorov v metropolitenakh. Government of the Russian Federation. Available from: https://base.garant.ru/71707662/ (accessed 03.09.2022). (In Russ.).
[5] Mechiev A. V. Razrabotka putei obespecheniya bezopasnoi ekspluatatsii liftov. Author's abstract. Moscow, 2018. 18 p. (In Russ.).
[6] Chutchikov P. I. Issledovanie passazhirskikh liftov s tsel'yu povysheniya ikh ekspluatatsionnoi nadezhnosti. Author's abstract. Moscow, 1973. 148 p. (In Russ.).
[7] Gnedenko B. V. (Ed.) Matematicheskie metody v teorii nadezhnosti i effektivnosti. Nadezhnost' i effektivnost' v tekhnike: spravochnik. In 10 vol. Vol. 2. Moscow: Mashinostroenie, 1987. S. 165–180. (In Russ.).
[8] Kuznetsov V. I. (Ed.), Barzilovich E. Yu. (Ed.) Ekspluatatsiya i remont. Nadezhnost' i effektivnost' v tekhnike: spravochnik. In 10 vol. Vol. 8. Moscow: Mashinostroenie, 1990. P. 112–146. (In Russ.).

Analytical decisions on the justification of the maintenance intervals are based on the idea of a specific function of the evolution of the system over time. Conditional transformations are possible — $x(t)$ or random ones — $\xi(t)$. Solving the problem based on such an algorithm requires detailed formalized representations of the behavior of a technical system in time, which is described by a random function $\xi(t)$. These data are unknown if we are talking about elevator units.

In the last 10–15 years, the problem of optimizing the maintenance frequency of elevators has been actively discussed in the People's Republic of China [11–14]. The solution involves changing the system failure rate function by introducing an adjustment coefficient depending on the failure rate. As an objective function, a mathematical model of maintaining the technical condition of the equipment is used, built with respect to the repair costs and losses from the elevator equipment downtime.

The above brief analysis allows us to assert that the task of frequency substantiating does not have a direct analytical solution, because the elevator functions cyclically, in the mode of stochastic changes in external and internal influences. Therefore, the resulting time and power indicators of the elevator characterizing its technical condition are random variables with previously unknown distribution laws.

As an alternative to the direct use of reliability indicators to determine the required intervals, the hypothesis of the relationship between the normative resource indicators of individual assemblies and the entire unit with the probabilistic characteristics of modes and operating conditions is adopted in this work. The authors integrated this information with the analysis of experimental data and adequate to them SM results [3, 4]. This approach made it possible to determine the characteristics of the load and operating conditions of elevators, as well as to develop methods and SM programs for their reproduction[9]. This makes it possible to formulate the task of adjusting the regulatory maintenance intervals. It is based on the statement that the mentioned probabilistic indicators of the elevator load determine its technical condition. For specific conditions, the solution of the problem of the necessary periodicity will take into account the data of regulatory documents, the results of observations or SM (Fig. 2).

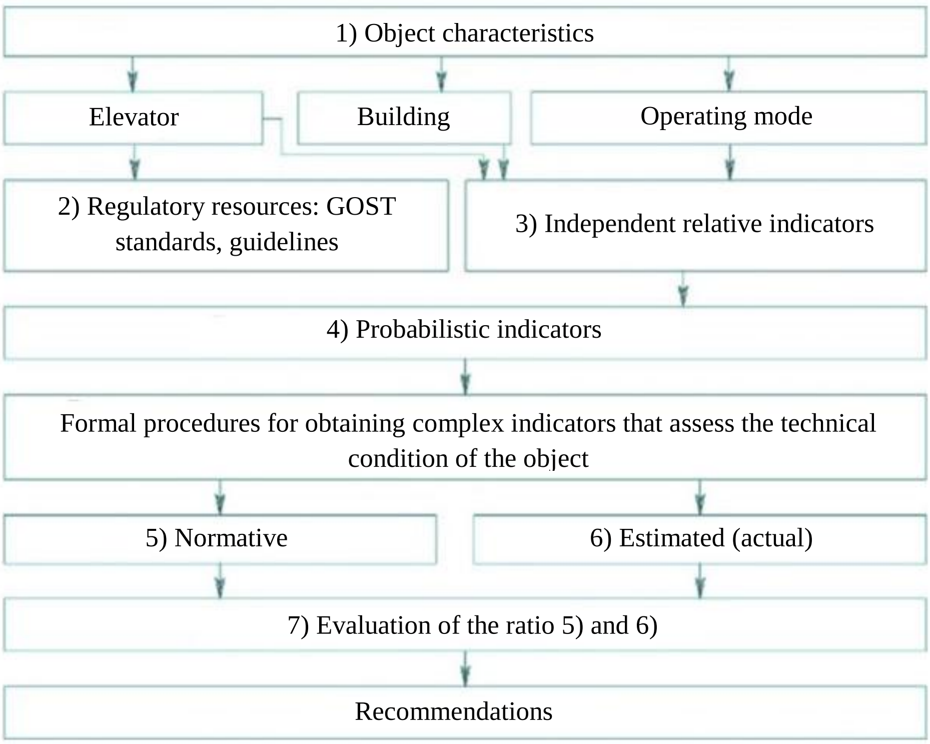

Fig. 2. Block diagram of an approximate solution to the problem of correcting the elevator units maintenance intervals based on probabilistic indicators of their technical condition

Figure 2 shows the necessary procedures to solve the problem of establishing the elevator unit maintenance frequency based on complex indicators of the technical condition of the object. Here is a brief description of them.

1) A description of the object, conditions and operating mode to assess its technical condition and adjust the

[9] Otrokov A. V., Khazanovich G. Sh., Apryshkin D. S. Imitatsionnoe modelirovanie rezhimnykh kharakteristik passazhirskikh liftov. Computer Program State Registration Certificate No. 202661811. Russian Federation. Don State Technical University, 2022. (In Russ.).

maintenance frequency. We are talking about an elevator unit with the following parameters: R, $Q_{п}$, v, $N_{дв}$, $i_{ред}$, $r_{КВШ}$ (load capacity, weight of the counterweight, cabin speed, engine power, gear ratio of the gearbox, radius of the traction sheave), etc. in a residential building with the parameters H, N, $h_{эт}$, Z (lifting height, number of floors, interfloor distance, number of residents). Operating mode: time of day, alternation of cycles by type, cab loading function, etc.

2) Determination of the regulatory resources of the units in accordance with GOST and other regulatory documents: by net operating time (τ), by the switching-on number (n), by nominal long-term load (M), by service life before overhaul or replacement — T (for engine, gearbox, brakes, doors, ropes and other units).

3) Justification of the nomenclature and the number of independent relative indicators for assessing the technical condition of the object (K_i).

4) Determination of probabilistic indicators to assess the estimated (actual) technical condition of the object based on SM or regular observations ($K_{mф}$, $n_{ф}$, $\lambda_{ф}$).

5) Justification of formal procedures to determine a complex indicator assessing the normative technical condition of the object — $W_{\Sigma.норм}$.

6) Justification of formal procedures to determine a complex indicator-index that evaluates the estimated (actual) technical condition of the object — $W_{\Sigma расч}$.

7) Evaluation of the ratio of normative and actual indicators of the technical condition of the main components of the elevator unit.

The results of these procedures allow us to formulate recommendations for adjusting the maintenance frequency ($K_{кор}$).

The main indicators characterizing the operability and durability of the object and its individual components are the standards established by the manufacturer or the specialized documents. In general, the following maximum resource characteristics should be given for each elevator unit before major repairs or replacement: net operating time τ, switching-on number (starts-brakes) n, nominal long-term load M, service life T. The nomenclature of resource indicators may be different for units operating in different conditions.

According to the regulatory documents[10] the actual technical condition is assessed based on the results of direct control, diagnostics and monitoring of the facility based on a comparison of the recorded indicators with those stated in the regulatory and technical documentation. A different approach is needed to select indirect indicators of the technical condition of the elevator and its components. Main requirements: indirect indicators should be independent and should characterize the technical condition of the object more fully. In our case, this is the net machine time coefficient, the specific number of switching-on of the main drive and the door mechanism, the level of power load and the degree of development of the normative resource, that is, K_m, n, $\lambda_{экв}$ and K_{RO}. All of them are determined by direct observation of a group of elevators or based on SM These indicators are accepted as basic according to the results of the analysis of their mutual independence and sufficiency for an indirect assessment of the technical condition of the elevator. They describe the main characteristics of the loading of the object. Each of them can be correlated with an analogue recorded in the elevator passport or regulatory document and presented in a different form, dimension. So, for example, GOST provides the standard indicators for electric motors: net operating time is 30 thousand hours, service life is 15 years. The conditional normative coefficient of the machine time of the electric motor is determined by calculation.

Results. The authors justified the approach to solving the issue of adjusting the elevators maintenance intervals. The methodology is based on four indicators: K_m, n, $\lambda_{экв}$ and K_{RO}.

According to the sequence of procedures (see Fig. 2) first, the regulatory resources of the main elevator assemblies are specified. These data are used to determine the corresponding values of time parameters: $K_{m\ норм}$, $n_{норм}$. According to GOST R 55964-2014[11] the elevator should serve for 25 years. Its components and mechanisms should serve from 5 to 15 years.

The dimensions of the resource indicator of the assembly can be:

– duration of equipment operation in hours (NMT);

– the number of switching-on per unit of time or for the entire period of operation.

[10] GOST 27.002–2015. Dependability in technics. Terms and definitions. Interstate Council for Standardization, Metrology and Certification. Moscow: Standartinform, 2016. 31 p. (In Russ.).

[11] GOST R 55964-2014. Lifts. General safety requirements in service. Technical Committee for Standardization TC 209. Moscow: Standartinform, 2019. 30 p. (In Russ.).

So, for example, according to GOST 31592-2012[12] for worm gearboxes used in elevator equipment, the resource before major repairs is at least 10 thousand hours. This value can be taken as the minimum regulatory resource that must be provided for the entire established service life of the gearbox (12.5 years). For electric motors, a service life of 15 years is set. At the same time, according to paragraph 5.1.4 of GOST 31606-2012[13] the resource before major repairs is at least 30 thousand hours.

Another source for determining the normative switching-on number is GOST 59155-2020[14]. So, for elevators in 9-storey buildings with a nominal speed of 0.67–1.0 m/s, the switching-on number $n_{норм}$ should not exceed 120 hour^{-1} or 2 min^{-1}. The switching-on of the elevator engine and all kinematically related components: gearbox, brakes, traction sheave (TS), ropes — occur only during machine time, therefore, the requirement of $n_{норм} \leq 2$ on/min should apply to NMT. That is, for all these units in the elevators of 9-storey buildings, the basic value of the switching-on number for the engine, brake, gearbox, TS should be taken $n_{норм} = 2$ on/(min NMT).

Table 1 summarizes the resource standards for time, number of cycles of units and aggregates for a certain control period of time. On the basis of these indicators, the normative power and time parameters of the operation of assemblies of the elevator unit are calculated. For example, the calculated normative indicators $K_{mср\ норм}$ and $n_{ср\ норм}$ of elevators of 9-storey buildings with a cabin speed of ≤ 1 m/s are given.

Table 1

Normative resources and time parameters of the elevator unit assemblies operation

No.	Elevator unit or assembly	Standard (indicator /for the period)		Calculated normative time parameters		Nominal load
		In NMT hours	In switching-on number	$K_{m\ ср\ норм}$	$n_{ср.\ норм}$	$M_{ном}$, H·м or $P_{ном}$, H
1	Gearbox	10^4/12,5 years	–	0.09	2	According to the equipment passport
2	Electric motor	$3\cdot10^4$/15 years	–	0.23	2	
3	Brake	–	7×10^6/12,5 years	0.77	1.07	
4	Brake	–	400/1 hours	28.2	6.7	
			2/1(min NMT)	0.47	4	
5	Ropes	–	6×10^5/1 years	0.3	1.14	According to 56943-2016

The control period of time is set in regulatory documents and technical passports of equipment. This can be:

– the full service life before replacement or overhaul;

– a specific value (year, hour, minute).

The calculated normative parameter $K_{mср\ норм}$ is determined as the quotient of dividing the net annual operating time of the unit by the number of hours per year. For example, for an electric motor:

$$K_{mср\ норм} = (30\cdot10^3/15)/(365\cdot24) = 0.228.$$

Similarly, the standard switching-on number is determined — 1/(min NMT). As an example, we will give switching-on per minute for the brake, NMT:

$$n_{ср\ норм} = (7\cdot10^6/12.5)/(365\cdot24\cdot60) = 1.065.$$

For door drive $n_{ср.норм}$ is chosen the minimum one of two options:

1) according to the elevator passport — at least 400 1/h or 6,7 1/(min NMT);

2) min NMT — 2 1/(min NMT).

For one switching-on of the elevator drive, there are two switching-on of the door drive, so $n_{ср\ норм} = 4$ 1/(min NMT). For ropes, the standard annual switching-on number (600 1/year) is given in the instructions

[12] GOST 31592-2012. Machine reducers. General specifications. Federal Agency for Technical Regulation and Metrology. Moscow: Standartinform, 2014. 22 p. (In Russ.).

[13] GOST 31606-2012. Rotating electrical machines. Asynchronous motors of power from 0,12 to 400 kW inclusive. General technical requirements. Federal Agency for Technical Regulation and Metrology. Moscow: Standartinform, 2013. 22 p. (In Russ.).

[14] GOST R 59155-2020. Lifts. Specifications. Technical Committee for Standardization TC 209, 2020. 15 p. (In Russ.).

for the maintenance of steel ropes[15].

Let us find the coefficients reflecting the relative level of load on the elevator assembly. They are determined as relationships:

– calculated or experimental values of time and power indicators to the normative ones;

– the spent resource to the full normative resource.

$$K_1 = \frac{K_{m.ср.мод}}{K_{m.ср.норм}}, K_2 = \frac{n_{ср.мод}}{n_{ср.норм}}, K_3 = \frac{M_{экв}}{M_{ном}} = \lambda_{экв}, K_{RO} = \frac{P_{отр.р}}{P_{норм.р}}.$$

For each power unit, it is necessary to calculate a combination of four coefficients: K_1, K_2, K_3, K_4. This is necessary for a comparative assessment of the load levels of units or elevators. If such data is not available in regulatory documents, then it is necessary to take as basic the values corresponding to the average values of a group of elevators with similar parameters operating in similar conditions.

Summing up the relative coefficients of the influence of various mode and time factors and the state of resource development suggests, that the final result is considered according to the principle: the lower the value W_Σ is, the less stressful the operating mode of this unit of the elevator installation will be. According to the method of summation of K_1, K_2, K_3 and K_{RO} the normal, not overloaded technical condition of the elevator should be considered such that the sum of the coefficients does not exceed 4.

Elevator assemblies are divided into groups:

1) working continuously during the NMT (motor, gearbox, TS and ropes);

2) pulse-operated, for example elevator doors.

For the 1st group, the calculation of W_Σ must be carried out by the sum of 4 coefficients, for the 2nd one — 2 coefficients, excluding K_m and $M_{экв}$. Accordingly, the normative sum W_Σ will also change: for the first group$W_\Sigma = 4$, for the second group $W_\Sigma = 2$. The option $W_\Sigma = 3$, is also possible, which takes into account the load of two types and the level of resource development.

Figure 3 shows a block diagram of the methodology for determining the adjusted maintenance frequency of elevator equipment based on regulatory documents, the results of their power and time performance indicators.

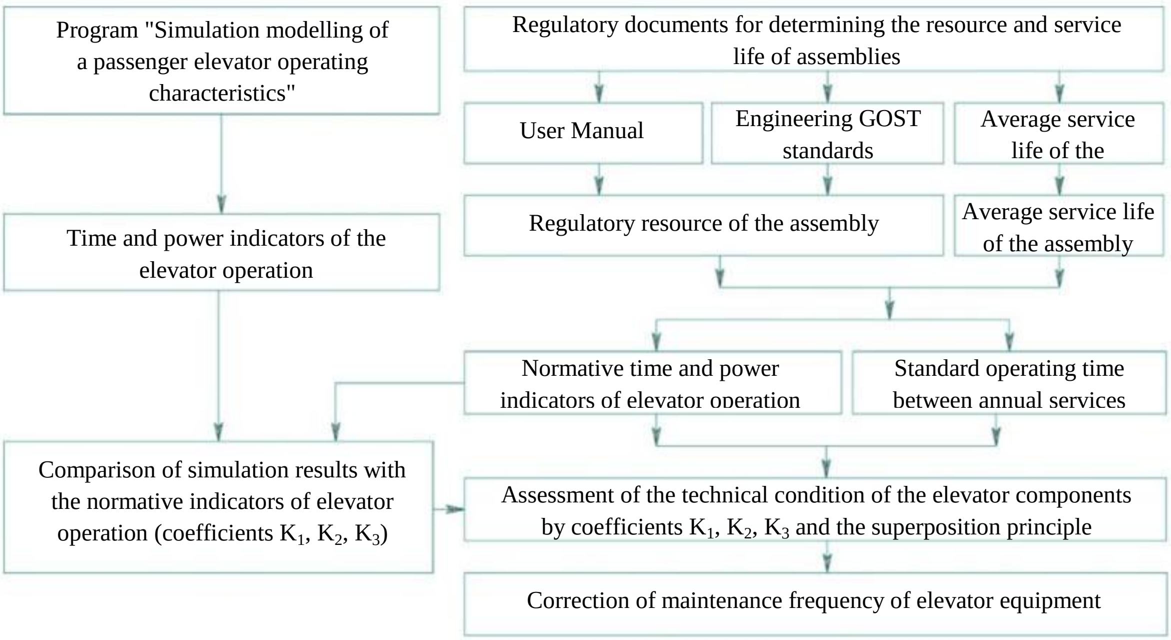

Fig. 3. Block diagram of decision-making on the adjustment of the maintenance frequency of elevator equipment

For example, Table 2 shows the results of a comparative assessment of the loading of units and the coefficients of adjustment of maintenance frequency performed in accordance with the stated methodological provisions for elevators that have worked for 5 years.

[15] Stal'nye kanaty Gustav Wolf. Instruktsiya po ekspluatatsii. Revator. Available from: https://revator.ru/upload/docs/Rope_inst_GW_v4.pdf (accessed 03.09 2022). (In Russ.).

Table 2

Results of the study of elevator units in two 9-storey buildings in Rostov-on-Don: assessment of the loading of units and adjustment of maintenance frequency *

Assembly	$K_{m/мод}$/ $K_{m.норм}$	K_1	$n_{мод}/n_{норм}$, inc./min NMT	K_2	Load, $M_{мод}$/ $M_{ном}$, Н·м* or $P_{мод}/P_{ном}$, Н**	K_3	$P_{RO\ расч}$/ $P_{RO.норм}$, years	K_{RO}	$W_{\Sigma расч}$	КТО = $W_{\Sigma расч}$/ $W_{\Sigma норм}$
14, Kapustina str.										
Engine	0.187/0.23	0.81	2.89/2	1.46	16.73/30.172*	0.55	5/15	0.33	3.15	0.79
Gearbox	0.187/0.09	2.07	2.89/2	1.46	216.3/1114*	0.19	5/12.5	0.4	4.12	1.03
Brake	0.813/0.77	1.06	2.89/1.07	2.7	478/960*	0.5	5/12.5	0.4	4.66	1.17
Ropes	0.187/0.30	0.62	2.89/1.14	2.54	11.70/30.17**	0.4	5/5	1	4.56	1.14
Door	0.337/0.47	0.72	2.89/4	0.72	2.2/2.2*	1	5/6	0.83	3.27	0.82
68, Orbitalnaya str.										
Engine	0.05/0.23	0.22	2.96/2	1.48	16.73/30.17*	0.55	5/15	0.33	2.58	0.65
Gearbox	0.05/0.09	0.06	2.96/2	1.48	216.3/1114*	0.19	5/12.5	0.4	2.13	0.53
Brake	0.95/0.77	1.23	2.96/1.07	2.8	478/960*	0.5	5/12.5	0.4	4.47	1.12
Ropes	0.05/0.30	0.17	2.96/1.14	2.6	11.70/30.17**	0.4	5/5	1	4.17	1.04
Door	0.345/0.47	0.73	2.96/4	0.74	2.2/2.2*	1	5/6	0.83	3.30	0.83
KTO — the coefficients of maintenance frequency adjustment. At 0.95 ≤ KTO ≤ 1.05 no adjustment is required. When KTO < 0.95 — the frequency is adjusted downward by 1 KTO. When KTO > 1.05 the frequency is adjusted upward by 1 KTO.										

As the resource is being worked out, while maintaining the values of time and power indicators, the estimated maintenance frequency will be reduced to ensure the necessary level of technical condition of the equipment. Let us consider, for example, an elevator speed reduction gear in a building on 14, Kapustina. We should take into account that $W_{\Sigma норм} = 4$. If K_{RO} increases from 0.4 to 0.9, then the ratio $W_{\Sigma\ расч}/W_{\Sigma\ норм}$ will increase from 1.03 to 1.15. The final decision on changing the maintenance intervals of the elevator, depending on the increment, is made by the service organization. The recommended threshold for changing KTO is 15–20 %.

Discussion and Conclusion. The programs developed by SM for operation modes of passenger elevators and the methodology for adjusting the maintenance frequency make it possible to predict the real load of elevator units over a long period of operation, taking into account the number of floors, the population density of the building and the technical characteristics of the elevator. This makes it possible to set the forecast speed of working out the normative resource of each elevator unit and determine the service intervals for it that ensure the maintenance of the elevator units in working condition throughout the entire service life.

The applied value of the results of scientific research described in the article is due to the fact that regulatory documents, requiring the stated frequency of maintenance, do not take into account the modes and operating conditions of elevator units.

The characteristics of the modes and operating conditions for elevator units are determined by the data obtained on the basis of SM and checked for adequacy during dispatching monitoring. We are talking about such indicators as the net machine operating time, the switching-on specific number, the level of the power load of the drive and kinematically related assemblies, as well as the amount of the determined resource development. Before the elevator is put into operation, it is possible to build a maintenance schedule in the program created by the authors "SM of operating characteristics of a passenger elevator".

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Conflict of interest statement

The authors do not have any conflict of interest.

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