

Rationing of the number of signals and interlockings in the operational stock of railway stations

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Abstract. The operational stock of signals and interlockings is necessary to ensure the uninterrupted operation of the electric interlocking systems in the event of their component failure. The existing standards for the composition and number of signals and interlockings available in the operational stock of railway stations are not mathematically based. It is considered the task of justifying the number of signals and interlockings in the operational stock of railway stations, and the factors affecting its quantity are indicated. It is proposed the mathematical model for rationing the amount of equipment necessary to ensure the uninterrupted operation of station signals and interlocking systems with a specified probability. The process of using and replenishment of reserve equipment is described using the the single-channel Markov queuing system model with a limited queue. The proposed probabilistic methodology approbation for the rationing of the amount of reserve equipment was carried out at the stations of the two Belarusian Railway divisions totaling to 58 stations equipped with relay and computer-based electric interlocking. It is shown the efficiency of the calculated amount of equipment in comparison with the existing values.

1 Problem statement

At railway stations, it is stored the stock of relay and other electronic equipment operated at a station (SPTA – spare parts, tools and accessories). This stock is needed to ensure uninterrupted operation of signals and interlocking systems in case of their component failure.

For stations equipped with relay electric interlocking (EL), there are no standards for the number of spare parts, and, in fact, their actual quantity was established historically and approved at a regulatory level. For stations equipped with computer-based interlocking (CBI), the number of SPTA, in accordance with the documents [1, 2], has to be at least 10% of the total amount of the used equipment of each type.

However, this standard incorrectly (only linearly) takes into account the amount of equipment in use and does not take into account:

- equipment failure rate;
- possibility and efficiency of stock replenishment.

For example, at a station there can be operated 10 impulse reed relays with a rectifier (plus 1 relay at stock) and 200 highly reliable neutral small-sized plug-in relays (plus 20 relays at stock).

Obviously, such a ratio of operated and spare relays is unjustified.

The most important thing is that the standard of the

number of signals and interlockings given in [1, 2] and available in the operational stock of the railway stations of Belarusian Railway is not justified on the basis of the predetermined probability of SPTA absence.

2 Mathematical model of rationing of the number of signals and interlockings

2.1 Model description

Let us consider the process of SPTA usage and replenishment at a railway station.

Suppose at the station it is operated N items of signals and interlockings of the same type with a failure rate of λ , and there are X more devices at stock (Figure 1, *a*).

In case one of N devices fails (with the total rate of $N \cdot \lambda$) it is replaced with one of X spare devices and is given for repair to a maintenance area (MA). After some time T_s , a similar device will be returned to the station (see Figure 1, *b*).

If during the stock replenishment period T_s , X devices will additionally fail (a total of $X + 1$), then the last of them cannot be replaced, and the transportation process will be disrupted due to SPTA absence (see Figure 1, *c*).

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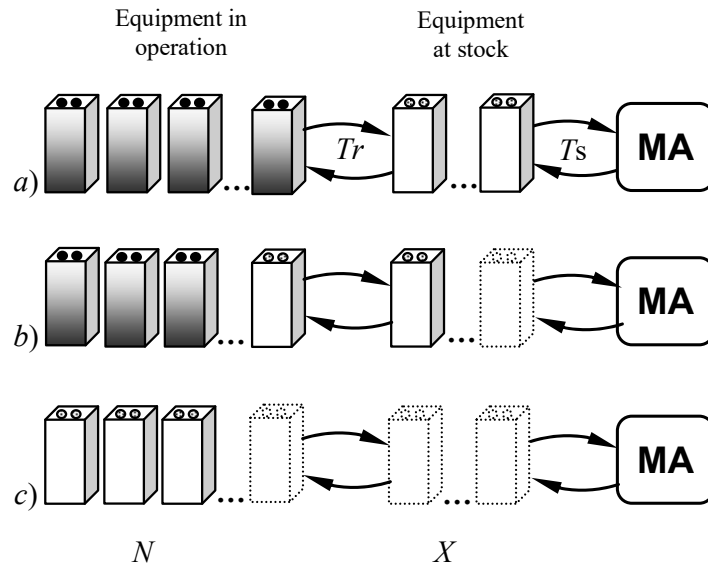


Fig. 1. Stock usage and replenishment chart [compiled by the authors]

The usage and replenishment process of a certain SPTA type can be described by a single-channel Markov queuing system (QS) model with a limited queue $M/M/1/(X-1)$ (Figure 2).

The incoming flow of requests is formed by the failure of X items of the same equipment type requiring replacement. The rack with N reserve equipment items is modeled by the servicing device (1 item) and the queue ($N-1$ items).

At the same time, the servicing device also performs the functions of personnel engaged in SPTA replenishment (transferring faulty equipment to a maintenance area and returning similar operative parts to the station).

A repair request (a failed signaling arrangement) that faces N requests in the queuing system is rejected due to the absence of SPTA (all N spare signal and interlocking equipment is already in operation).

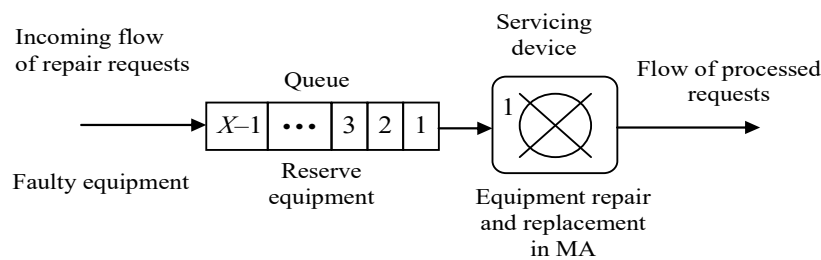


Fig. 2. Conceptual model of stock usage and replenishment
 Source: compiled by the authors based on [3]

2.2 Mathematical model assumptions

Let us consider the basic assumptions of the proposed mathematical model.

The failure flow of all equipment types is assumed to be the simplest, i.e.

- stationary (the flow for which the mathematical expectation of the equipment failure rate per unit of time does not change in time);
- ordinary (meaning the practical impossibility of two or more simultaneous equipment failure manifestations);

Thus, the task of SPTA rationing comes to determining (for each equipment type) the smallest value of N for which the actual probability of maintenance rejection Q_N would not exceed the standard probability P for given values of the equipment amount X and its failure rate λ [3].

$$Q_X = \rho^X \left(\sum_{i=0}^X \rho^i \right)^{-1} \quad (1)$$

where

$$\rho = \lambda \cdot N \cdot T_s,$$

T_s is stock replenishment average time.

- forgetful (means that the number of equipment failures in the past does not determine how many of them will occur in the future) [4].

This assumption is traditional when analyzing the reliability of electronic signal and interlocking systems. It is valid for systems operating in the period of normal use in which case component failures are practically independent [5-7].

It is assumed that stock replenishment time T_s is characterized by an exponential distribution.

Additional studies on the simulation model in the GPSS system [8-10] have shown a slight change in the probability of maintenance rejection when replacing the exponential distribution of service time with other distributions which, compared to the exponential law, have less variance with the same mean value.

It is assumed that SPTA replenishment is done gradually piece by piece (the Markov queuing system is single-channel).

In fact, several devices (and also of various types) can be delivered to / from a maintenance area at the same time. This assumption, obviously, overestimates the standard values of the number of SPTA.

The proposed model of stock usage and replenishment assumes the availability of at least one item at stock which is consistent with a number of Belarusian Railway's governing documents.

As a source of data on the equipment failure rate, in practice, it is used guaranteed estimations (by means of upper confidence regions) that exceed the true values.

2.3 Probability substantiation P of the absence of a certain SPTA type

One of the important criteria for rationing the number of SPTA is the probability P of the lack of stocks, a reduction in which leads to an increase in the number of spare parts. Until now, the probability of the lack of signal and interlocking stocks P has not been specified and normalized [11-13]. The following approach is proposed for P specification.

The average non-failure operating time of station signal and interlocking systems (for an average railway station), as a rule, does not exceed 2000 hours (about 2.8 months), and their average recovery time is at least 1 hour. Consequently, the signal and interlocking system (SI) stationary availability (A) [11, 14] at an average railway station usually does not exceed the following:

$$K_A^{SI} < \frac{5000}{5000+1} = 0,9998.$$

Note. In the standard [15] (p.18) it is indicated that the normative value of the availability factor of devices and railway automation systems should not be less than 0.98.

Consequently, the unavailability factor (UN) of the signal and interlocking system (SI) is:

$$K_{UN}^{SI} = 1 - K_A^{SI} > 5,00 \cdot 10^{-4}. \quad (2)$$

There is no much sense in the lack of stock probability provision P which would be significantly less than the railway automation and telemechanics unavailability factor. Therefore, it is proposed to specify the absence probability P of each SPTA type at

$$P = 0,5 \cdot K_{UN}^{SI} = 2,50 \cdot 10^{-4}, \quad (3)$$

so that the influence of the «lack of SPTA» factor on the reliability of the signal and interlocking system is relatively small (at 50%) as compared to the influence of

the «automation and telemechanics failure» factor.

On the other hand, for unreliable equipment, the requirements for the probability P of SPTA absence should be specified not at 50% of the signal and interlocking system unavailability factor, but of the unavailability factor of the very equipment of a particular type.

As a result, the absence probability P of i -type spare equipment should be chosen as the greatest out of two numbers

$$P = \max \{2,5 \cdot 10^{-4}; 0,5 \cdot K_{UN}^i\}, \quad (4)$$

where K_{UN}^i is the unavailability factor of i -type equipment [14] defined by the expression:

$$K_{UN}^i = 1 - \frac{(N\lambda)^{-1}}{(N\lambda)^{-1} + T_r}, \quad (5)$$

where N is the amount of i -type equipment operated at a station; λ is the failure rate of i -type equipment, 1 / hour; T_r is the average time of equipment recovery, hours.

3 Methodology approbation

3.1 Obtained results

For some typical source data in Table 1, we give the proposed methodology recommendations and compare them with the existing computer-based interlocking standard [1].

Here X_1 is the quantity of spare equipment according to the existing standard;

T_s is the stock replenishment average time (delivery of similar signal and interlocking equipment from the maintenance area), hour;

X_2 is the amount of spare equipment according to the proposed mathematical model.

Table 1. Standards of SPTA quantity

No	N	X_1	λ	T_s	X_2
1	20	2	10^{-6}	24	2
2	20	2	10^{-6}	12	1
3	20	2	10^{-7}	24	1
4	500	50	10^{-7}	120	2
5	10	1	10^{-6}	48	2

Source: compiled by the authors based on [3]

Note. In the standard [16] it is indicated that the failure rate of neutral small-sized plug-in relays is $1,1 \cdot 10^{-7}$ 1 / hour.

It can be seen that for the source data in the first line, the results of the existing and stochastic approach are identical ($X_1 = X_2$).

In case when average stock replenishment time T_s may be reduced from 24 to 12 hours (see line 2, table 1),

the operational equipment stock could be narrowed down from 2 to 1 item.

Besides, the operational equipment stock can be reduced to 1 item for highly reliable equipment (with the failure rate of no more than 10^{-7} 1 / hour, see line 3, table 1).

The stochastic model provides the greatest benefits for massively operated highly reliable equipment ($N = 500$, $X_2 = 2 \ll X_1 = 50$, see line 4).

For small equipment of a low or medium level of reliability, the stochastic model can suggest a larger stock (see line 5) than it is stipulated by the existing standard [2].

The proposed stochastic methodology of the stock rationing has the following advantages over the existing approach:

- objectively takes into account (and nonlinearly) the amount of operated equipment;
- makes allowance for the equipment failure rate;
- takes into account the efficiency of SPTA replenishment;
- includes the requirements for the probability of SPTA absence.

The implementation of the proposed stochastic methodology of operational stock rationing is characterized by the following practical importance:

- a general increase in the reliability of railway automation and telemechanics systems during their operation due to an increase in SPTA number at stations where its quantity is insufficient;
- as an objective, reasonable tool for calculating the volume of SPTA. It is planned to introduce automation into the calculation of operational stock standards in automatic signal and interlocking control system (a subsystem of a maintenance area) which is a road-level information system;
- minimization of the operational stock of signals and interlockings by reducing the number of SPTA where it is redundant;
- minimization of the cost of introduced railway automation and telemechanics (including imported items) due to equipment operational stock optimization included in the delivery set (a manufacturer / supplier is interested in increasing the scope of delivery).

The dependence of the automation and telemechanics availability factor (indeed, the equipment of each individual type) on the SPTA number is of an exponential nature (Figure 3). SPTA reduction (where it is redundant) results in a slight decrease in the availability factor of equipment of the type under consideration.

Where the amount of spare equipment is not enough an increase in SPTA by one item results in a significant availability factor increment.

Thus, in Figure 3, the standard value of the availability factor requires two pieces of equipment of a certain type. An increase in the number of SPTA from one to two items entails a considerable availability factor increment.

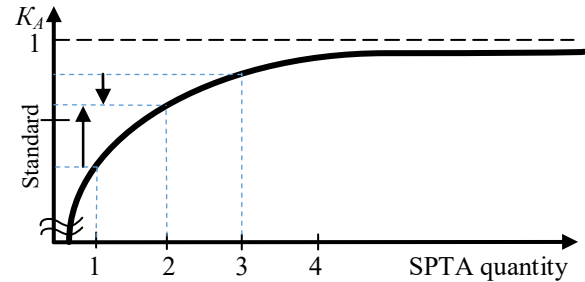


Fig. 3. Dependence of the equipment availability factor on the SPTA number [compiled by the authors based on [5, 14]]

A reduction in the number of SPTA from three items to two implies an insignificant decrease in the availability factor.

As a result, the redistribution of SPTA equipment among signals and interlocking divisions is accompanied by a release of a certain amount of equipment.

This equipment can be used to eliminate the need for the purchase of a new signal and interlocking equipment.

Thus, in the course of the preliminary approbation of the stochastic methodology of SPTA rationing using the example of signals and interlocking division 1 (Minsk) of Belarusian railway, it has been established that the release of a certain SPTA amount can result in:

- more than 30 thousand rubles as a lump sum (on a one-off basis, due to the refusal to purchase similar equipment in the reporting period);
- more than 1.5 thousand rubles annually (due to cuts in expenditures on transportation and periodic inspection of SPTA in signal and interlocking maintenance areas).

3.2 Methodology realization

For engineering calculation of the number of SPTA equipment of each type at the station in accordance with the proposed methodology, the document [1] is proposed to be supplemented with an appendix where for typical values of failure rates λ (in columns) and the amount of operated equipment X (in rows), in the form of a two-dimensional table, it will be specified the required amount of spare parts. For the following typical values of average stock replenishment time $T_s = 24, 48, 72, 120$ hours and average recovery time $T_r = 0.5, 1, 1.5, 2$ hours, a separate table is filled in.

For equipment with known failure rate characteristics and stock replenishment time, as well as in case of non-standard values of these characteristics, an individual calculation of the number of SPTA is possible.

3.3 Specifying information on the equipment failure rate

The developed methodology involves the use of a known failure rate value of the equipment type under examination.

The most reliable statistical estimates of signals and interlocking reliability factors are those obtained during operation in real conditions on the basis of statistics on failures and total operating time.

The priorities in obtaining initial information on the reliability (intensity) of signals and interlockings are as follows:

- 1) statistical methods for estimating failure rates according to operating results;
- 2) manufacturer's data;
- 3) literary sources;
- 4) reliability manuals.

However, for a number of railway automation and telemechanics devices, the information on their failure rate may be missing. In this case, it is proposed the approach when the equipment failure rate is set indirectly based on the known maintenance interval of signal and interlocking equipment in a maintenance area.

Based on the comparison of information on maintenance intervals and known equipment failure rates, it has been found that the probability of failure during the period between inspections of various equipment types is mostly about 0.001-0.05. Moreover, for neutral small-sized plug-in relays 1, this probability does not exceed 0.0144. This value is selected as a reference one in determining the equipment failure rate based on the frequency of maintenance.

3.4 Approbation results

The approbation of the proposed stochastic methodology of SPTA rationing was carried out at a number of Belarusian Railway's stations equipped with relay electric and computer-based interlocking. In the approbation process it was revealed the following:

- at stations equipped with electric interlocking, the actual number of SPTA is established by decrees of the division head. These values were formed “historically” in the process of more than 20 years of operating the equipment. At the same time, they practically coincide with the values proposed by the stochastic methodology;
- at stations equipped with computer-based interlocking, the number of spare equipment significantly exceeds the standard of 10%, which is largely due to the lack of objective information on the reliability of new equipment and the desire of staff to minimize the risks of SPTA shortage;
- the number of recorded failures of relay signals and interlockings is several times less than the real value, due to the existing approach of material incentives and punishment of division workers. It is almost impossible to hide computer-based interlocking equipment failures because of the automatic event documentation, and the fact that the repair of such an equipment type is usually performed by a manufacturer.

4 Conclusions

As compared with the existing deterministic approach, the proposed stochastic technique objectively takes into account the intensity of equipment failures and stock replenishment efficiency, as well as the likelihood of its absence (due to remote maintenance).

For the majority of signals and interlockings operated at stations (taking into account failure rates), the new

approach justifies a reduction in the operational stock. It would make it possible to:

- 1) eliminate the need for the purchase of new equipment;
- 2) reduce the cost of SPTA storage.

For stations that are already in operation, the new standard would allow for clarifying and «legalizing» the existing number of SPTA.

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