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MODEL OF THE MAINTENANCE AND REPAIR SYSTEM IN SERVICE MAINTENANCE MANAGEMENT

Summary. The model of service maintenance and repair of passenger rolling stock is considered as a multi-channel system. The presented model is implemented on the queuing model basis. The service maintenance and passenger rolling stock system stipulates not only for the transition to a new level of the maintenance system as a type of activity but as a means boosting up the economic growth rate and living standards. As a result, we managed to resolve the problem of the optimum design for the service maintenance and repair model.

1. INTRODUCTION

The passenger railway transport is a complex industrial and economic system with its own territorial production and functional structure. Organizational changes in the passenger railway transport are brought about by high social importance of passenger transportation.

The project of the organization of high-speed traffic in the direction of Yekaterinburg-Chelyabinsk intends to connect the centers of two Ural cities with a million-population using a new railway line, with the help of which it will be possible to get from one city to another in 1 hour 10 minutes.

The implementation of the high-speed highway project will allow developing the social and economic structure of the region, and will also ensure the growth of population mobility. A new market for not only the companies carrying out rail transportation but also the maintenance and repair of high-speed passenger rolling stock will open.

Currently, the scientific support system for the maintenance and repair does not provide reasonably precise estimates. There is no possibility to forecast a level of the rolling stock readiness at the set funding limits, passenger rolling stock level and failure rate.

The choice of the maintenance and repair strategy is a significant basis for a rolling stock owner. To achieve a high efficiency of the action plan, one needs to build a certain strategy, introduce certain work organization rules and build up a maintenance center infrastructure.

Service maintenance of high-speed rolling stock is associated with the task to evaluate the capacity of service centers to ensure the operability of the rolling stock. We herein propose an analytical mass service system model. Statistical methods together with mathematical tools of waiting line theory have been widely used in rolling stock management.

2. LITERATURE REVIEW

The reorganization of the transport system and, in particular, the federal railroad (in Russia) triggered significant changes in the structure of transport services, such as increase in the number of carriers including those having their own rolling stock. The key freight and passenger market trend consists of higher requirements set up by the clients towards the quality of transport services [1].

The Spanish scientists [2] briefly describe the process and a number of stages to be implemented for maintenance management (main system and auxiliary structure). Concerning the maintenance management process, the authors present a general model suggested for maintenance management which unites other models set forth in the studies by Pintelon and Gelders; Gelders, Mannaerts and Maes; and Tsang, Jardine, and Kolodny [3-5]. They regard maintenance planning as a basis for increase in the efficiency and performance. The planning model depends on the time component (plant capacity planning, spare parts procurement, maintenance and repair frequency setting, etc.).

Shenoy and Bhadury [6] found out that the queuing theory models provide better results, which is especially true for the models reducing the self-cost of equipment use and labour to their minimum values. Similarly, Monte-Carlo simulations are widely used [7, 8].

The papers of Pierskalla and Voelker [9], Osaki and Nakagawa [10], Sherif and Smith [11], Valdez-Flores and Feldman [12], and Cho and Parlar [13] are aimed at the determination of optimum resources for maintenance and finding the economic life cycle. They identify traditional methods of the problem solution through linear and dynamic programming, stochastic models and current values analysis. These research studies have a mathematical interest as well as present the structure of created models.

Campbell [14] claims there is no proper maintenance structure, as only strategies can provide for the efficient use of the resources in the given situations. In any case, maintenance and repair organization shall be flexible.

At the moment, the implementation of the service maintenance and repair model in Russia implies a number of problems:

1. High cost of the project implementation in terms of the necessary infrastructure building.
2. The new maintenance and repair structure of a high-speed rolling stock.
3. The developed model for the existing railroad infrastructure facilities will involve the revision of a number of regulatory documents relating to passenger rolling stock maintenance and repair.

To overcome these difficulties, the authors are developing an optimization model of service maintenance and repair that will allow for the adaptation of the existing and high-speed passenger rolling stock maintenance and repair.

3. MODELLING OF TECHNOLOGICAL PROCESSES OF SERVICE MAINTENANCE OF RAIL PASSENGER TRAINS BASED ON GRAPH THEORY

The process of service maintenance and repairs organization of passenger carriages can be presented on the basis of graph theory. During their operation, the passenger rolling stock can be in failure, non-operable or limit state. The carriage condition in the system of service maintenance is presented in the form of a graph (Fig. 1).

The passenger carriage can have following conditions:

S_0 – failure-free operable state;
S_1 – failed but operable state;
S_2 – failed non-operable state;
S_3 – limit state, which can be restored by current repairs;
S_4 – limit state, which can be restored by roundhouse or capital repairs;
S_5 – limit non-restorable state;
P_i – probability of carriage states;
λ – failure rate,
μ – repair rate.

Transfer of carriage from one state into another occurs under the influence of certain operational factors.

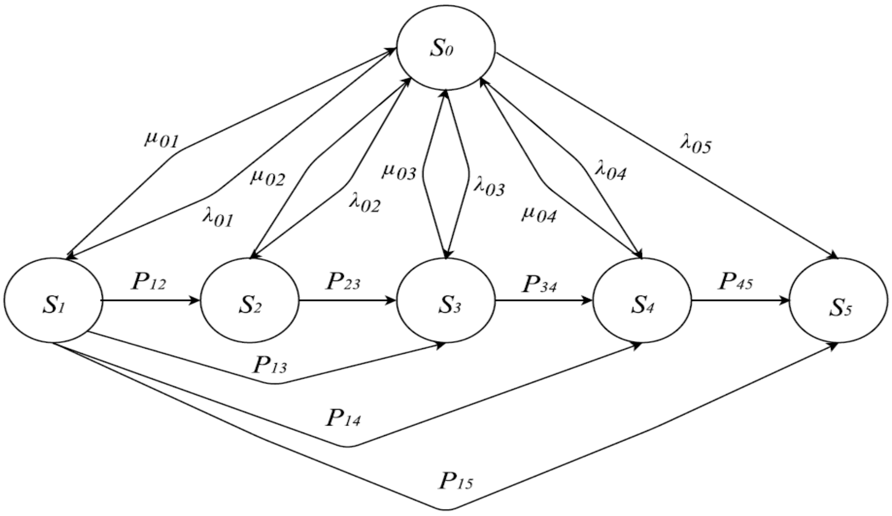

Fig. 1. Graph of carriage conditions in the system of technical maintenance and repairs

Failure rate of passenger rolling stock depends on the following factors:

- diagnostic results of rolling stock;
- service maintenance and repairs, conducted by the owner's company;
- service maintenance and repairs, conducted by the manufacturing company (operating company).

Let us introduce parameter α, which characterizes the proportion of rolling stock, repaired by the manufacturing company (operating company). In this case, the rate of failures to be repaired by the manufacturing company will look as follows:

$$\lambda_S = (1 - \alpha)\cdot\lambda \tag{1}$$

where λ – general failure rate.

The flow of rolling stock to be repaired by the manufacturing company is complex and contains two separate flows:

(1) flow, defined by failures, and

(2) flow of passenger rolling stock subject to repairs upon expiration of inter-repair time.

According to this, the rate function is a delta-shaped or impulse function with parameters η and τ.

$$\eta\cdot\delta(t-k\tau) \tag{2}$$

where η is the proportion of passenger rolling stock subject to capital repairs by the manufacturing (operating) company), τ is the periodicity of capital repairs of passenger carriages, and $\delta(t-k\tau)$ is the impulse periodical delta-function.

Moreover, the flow rate of passenger rolling stock is defined as follows:

$$\lambda_S(t) = \alpha\cdot\lambda + \eta\cdot\delta(t - k\tau) \tag{3}$$

$$(k=1,2,\ldots)$$

Let us compile the system of equations for an average number of passenger carriages in different states in accordance with the graph of state.

The system of equations (7) does not have absorbing states as well as in-flows of intensity from exterior sources. Therefore, the determined system, in which the overall number of passenger carriages $N(t)$ are in different states, is a constant.

We further present the system of differential equations (4) in the form of discreet process with discretization interval Δt, which is posed on condition of given accuracy.

Considering, that the minimal period of financial statements of railway car repair organizations is equal to 1 month, it is reasonable to set Δt = 1 month (t = 1,2,…T).

$$\begin{cases} \dfrac{dn_0(t)}{dt} = -\lambda_{01}n_0(t) + \mu_{10}n_0(t) - \lambda_{02}n_0(t) + \mu_{20}n_2(t) - \\ -\lambda_{03}n_0(t) + \mu_{30}n_3(t) - \lambda_{04}n_0(t) + \mu_{40}n_4(t) - \lambda_{05}n_0(t); \\ \dfrac{dn_1(t)}{dt} = \lambda_{01}n_0(t) - \mu_{10}n_1(t); n_1(0) = N_1; \\ \dfrac{dn_2(t)}{dt} = \lambda_{02}n_0(t) - \mu_{20}n_2(t); n_2(0) = N_2; \\ \dfrac{dn_3(t)}{dt} = \lambda_{03}n_0(t) - \mu_{30}n_3(t); n_3(0) = N_3; \\ \dfrac{dn_4(t)}{dt} = \lambda_{04}n_0(t) - \mu_{40}n_4(t); n_4(0) = N_4; \\ \dfrac{dn_5(t)}{dt} = \lambda_{05}n_0(t); n_5(0) = N_5; \\ n_0(t) + n_1(t) + n_2(t) + n_3(t) + n_4(t) + n_5(t) = N(t). \end{cases} \tag{4}$$

$$\frac{dn(t)}{dt} = n(t) - n(t-1) \tag{5}$$

$$\lambda = \frac{n(t) - n(t-1)}{N - n(t-1)} \tag{6}$$

Since the passenger rolling stock is quite numerous and failures belong to frequent accidents, it is reasonable to apply the waiting line model. On the one hand, this model describes the process of operation; on the other hand, its parameters can be defined according to statistical data.

The current method is an efficient means of planning and management, being at the same time accessible and quite simple.

4. SINGLE-CHANNEL MAINTENANCE AND REPAIR SYSTEM

To maintain passenger rolling stock in a serviceable and usable condition, one shall implement a range of measures including maintenance works. To achieve a high efficiency of such measures, one needs to build a certain strategy, introduce certain work organization rules, create an infrastructure of maintenance centers, and determine the scope of works performed by such centers.

As a part of the new high-speed passenger rolling stock maintenance and repair system, we present a new diagram for the cooperation of manufacturers, owners, and service centers (Fig. 2).

The establishment of service centers is characterized by the opportunity to organize various repair levels for various types of rolling stock, capacity, technical and economic indices of maintenance and repair performance.

The repair system of a service center is represented as a mass service system that has a limited number of working channels and a storage of unprocessed orders. The queuing system is characterized by incoming (failure rate) and outgoing (repair rate) flows. Each channel represents a repair subdivision. The channel input receives the repair requests with the failure rate *λ(t)* corresponding to a routine maintenance of high-speed rolling stock. The channel is able to service only a current request. Repair is performed with the repair rate *μ(t)*. Unprocessed repair requests for the period of *μ(t)* are forwarded to the storage facility which can contain a limited number of waiting spaces.

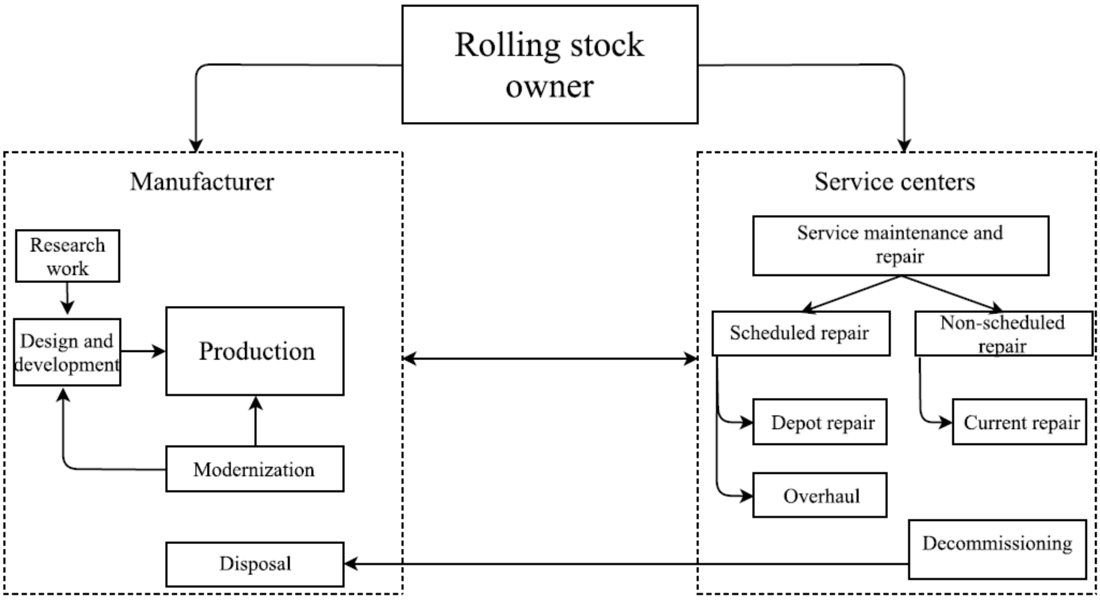

Fig. 2. Cooperation Diagram

The rate of defective car delivery depends on the following factors: rolling stock diagnostics results, maintenance and repair performed by an owner company, and maintenance and repair performed by a manufacturer (operator).

Figure 3 shows the graph of a mass service system with n working service channels and a storage with s slots.

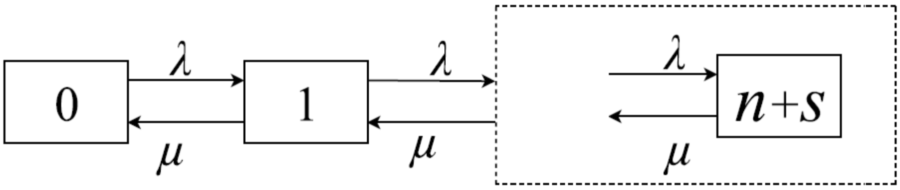

Fig. 3. Single-channel mass service system with a storage

The graph uses the follow notation: 0 stands for an idle service channel, 1 stands for a busy service channel, n+1 means the storage has one order in the queue, and n+s means the storage has s orders.

The probability dynamics $P_k(t)$ of the mass service system states is described by a system of differential equations [15].

$$\begin{cases} \dfrac{dP_k}{dt} = -(\bar{\lambda} + k\mu)P_k + \bar{\lambda}P_{k-1} + (k+1)\mu P_{k+1} \\ \qquad 0 \le k \le n \\ \dfrac{dP_k}{dt} = -(\bar{\lambda} + k\mu)P_k + \bar{\lambda}P_{k-1} + n\mu P_{k+1} \\ \qquad 0 \le k \le s \end{cases} \tag{7}$$

In this case, the recovery intensity is a discontinuous function (Fig. 4). The probability of service is an impulse periodical delta-function (Fig. 5). In this case, the servicing process is non-homogeneous and oscillatory in nature, which to a great extent affects the service performance.

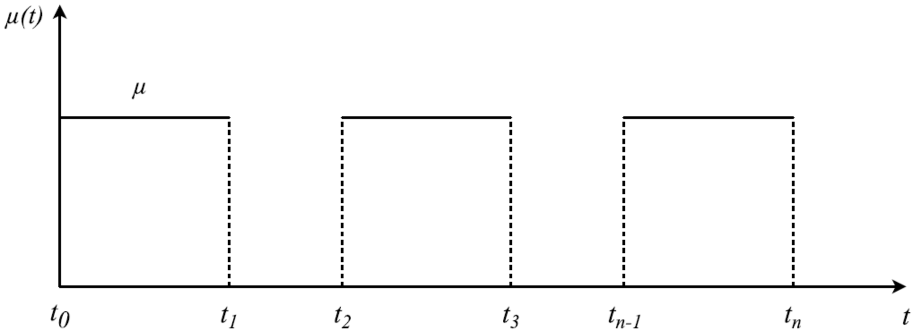

Fig. 4. Plot of the pulse recovery intensity function

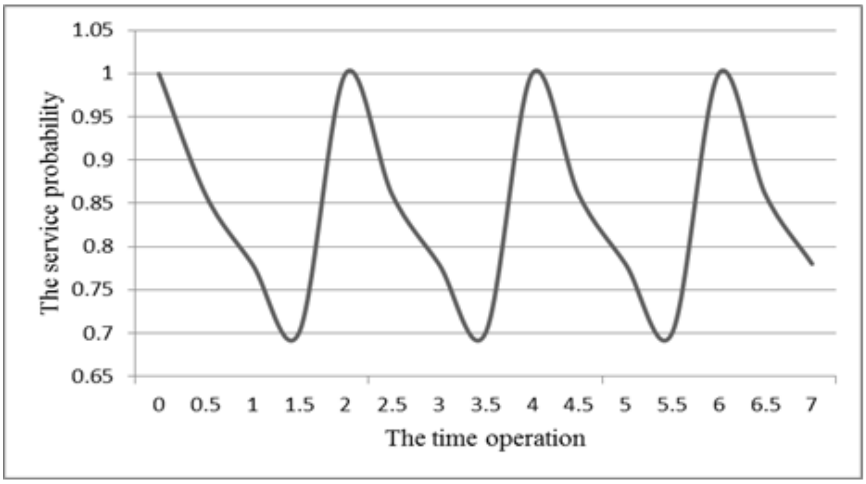

Fig. 5. Plot of the service probability

The intensity function is written as follows:

$$\mu(t) = \begin{cases} \dfrac{\beta}{T_p} \\ t > t_{\min} \end{cases} \tag{8}$$

where t_{min} is the minimum type-specific repair time, T_p is the mean repair time, and β is the recovery intensity increase factor ($\beta \geq 1$).

Minimum repair time depends on the type of rolling stock failure. The recovery intensity increase factor depends on both the type of failure and the conditions of high-speed rolling stock repair works.

To calculate non-homogeneous flows, the failure intensity and the recovery intensity are averaged at the time interval T which describes the external conditions of the mass service system. In this case, the system of differential equations (1) uses mean failure intensity and recovery intensity values.

$$\bar{\lambda} = \frac{1}{T}\int_0^T \lambda(t)dt \tag{9}$$

$$\bar{\mu} = \frac{1}{T}\int_0^T \mu(t)dt \tag{10}$$

The presented model is interesting in that it has a homogeneous solution for the system of differential equations (7).

The maintenance and repair model with a single-channel system allows one to model a process with any plant capacity analyzing the operation dynamics.

5. MULTI-CHANNEL TECHNICAL MAINTENANCE AND REPAIR SYSTEM

Consider the efficiency of using multiple single-channel maintenance and repair systems that perform repair operations simultaneously and independently (Fig. 6).

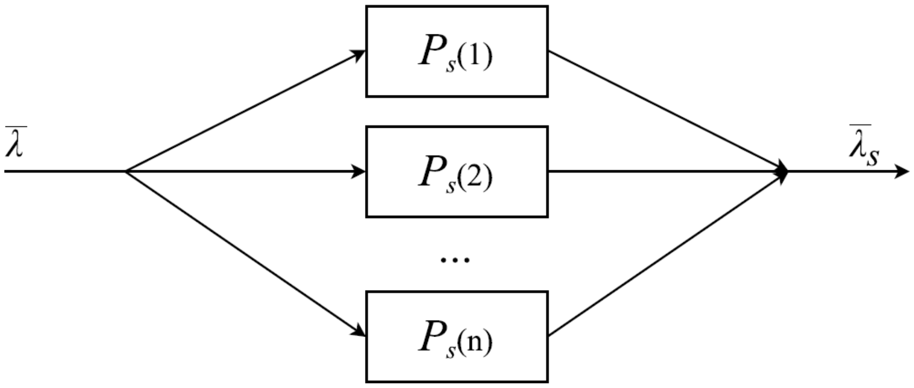

Fig. 6. Multi-channel mass maintenance diagram

The total failure intensity flow $\overline{\lambda}$ comes to each channel of the system. In this case, each subsystem services the orders with the same probability:

$$P_s(1) = \frac{1}{1 + \frac{\overline{\lambda}}{\mu}} \tag{11}$$

The probability of services a repair order n equals:

$$P_s(n) = 1 - \left(1 - P_s(1)\right)^n \tag{12}$$

By making calculations $P_s(n)$ for various n, we confirm that a multi-channel mass service system is more efficient. This is achieved by storing orders in the storage when all the service systems are busy. The ability to distribute repair orders among idle channels maximizes the effect of high-speed rolling stock maintenance operations performed in a complex system. The opportunity to distribute the requests between free channels provides for a synergistic effect implemented in a complex system.

The efficiency of such a multi-channel system increases as the applied failure intensity increases whereby the number of channels is raised to 5 (up from 1).

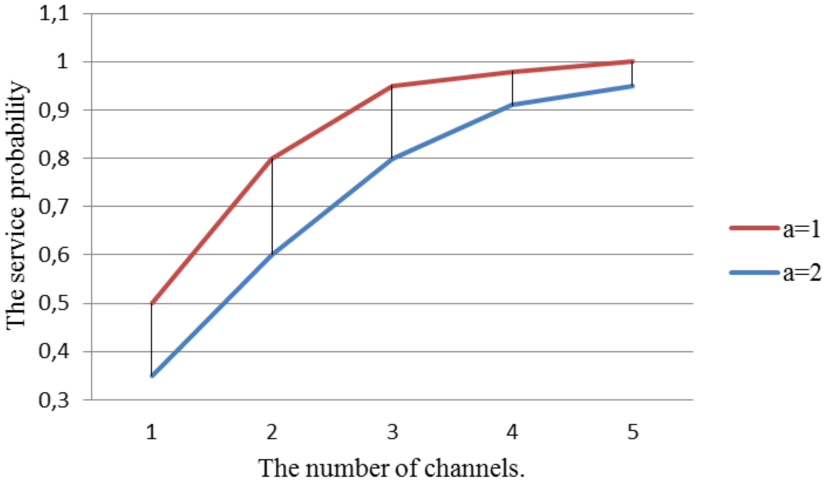

Fig. 7. Dependency of the service probability on the number of channels

The regressional dependence of a number of single-channel systems equivalent in terms of the efficiency of multi-channel queuing system servicing takes the form of $y=0.9814x^{1.19}$; the diagram of which is provided below (Fig. 8).

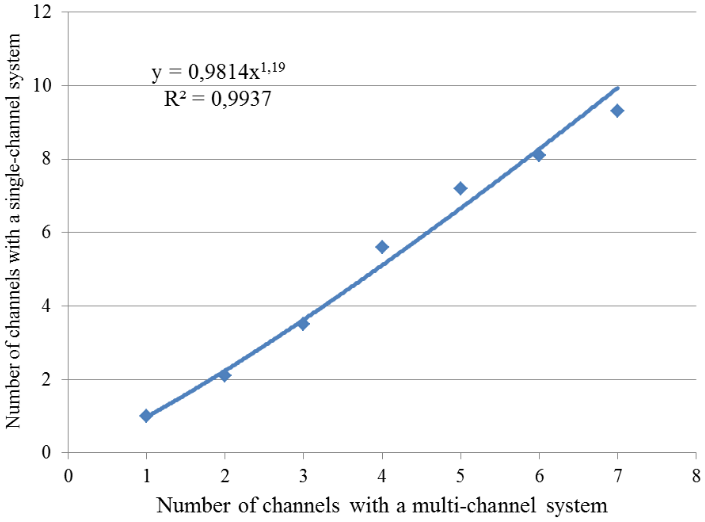

Fig. 8. Regressional dependence of systems

6. SYSTEM COMPARISON

The choice of a single-channel or a multi-channel system depends on the calculated plant capacity, transmission capacity and the type of the repaired rolling stock.

The data necessary for system calculation and modeling can be obtained on the basis of statistical data on the rolling stock failure rate. However, such data cannot allow for modeling a whole real plant. Both models shall be subject to performance analysis with the use of artificial data in a mathematical model.

The mathematical modeling of technical processes sets a goal to obtain the data on the process "quality" without time-consuming experimental research by means of a trial-and-error method under bulk experiment conditions. The most important part of a mathematical model is the availability of the conditions that shall be met in the process of problem resolving [16].

With regard to the conducted comparison, the choice of a single-channel system is preferable for the areas with a low passenger traffic as there is a necessity to service only a small number of passenger rolling stock. Besides, there is no necessity to invest large funds into material and technical resources.

In its turn, the multi-channel system choice is preferable for the areas with a high passenger traffic and, as a result, with the enlarged train schedule. A mathematical model apparatus allows for a reasonable determination of the work scope and the optimum number of repair channels.

Maintenance and repair are exposed to the influence of numerous internal and external factors influencing the efficiency of operation. The establishment of service centers is characterized by the opportunity to organize various repair levels for various types of rolling stock, capacity, technical and economic indices of maintenance and repair performance.

7. CONCLUSION

The considered approach for modeling a service center of high-speed rolling stock service maintenance will provide for a comprehensive assessment of manufacturing capabilities for the model implementation, reasonable planning and repair system organization.

Therefore, building multi-channel systems for high-speed rolling stock service maintenance and repair is the preferable option in terms of its efficiency. However, a multi-channel system will require for a more complex infrastructure in its turn.

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