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Interactions between port stations and ports: Models of dynamic prioritization of a digital twin

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ABSTRACT The purpose of the article is to increase the efficiency of interaction between port railway stations and ports by the aggregation of forecasting, optimization, and control systems with the use of dynamic prioritization methods and integration of a digital twin into the system. The study analyses the volume of container traffic on the railway network, presents an analytical report with averaged data on the number of containers transported on the railways of the Russian Federation, proposes ways to improve the methodology of interaction between ports and port stations, considers and proposes game-theoretic models for the system of interaction between port stations and ports, presents objective functions for each participant in the process, and reveals imperfections of the system. As a result of the research, the authors present a game-theoretic model of the system of interaction between port stations and ports and an operation algorithm, set an optimization task for integrating a digital twin into the system, and mathematically justify the use of this system. The practical significance of the study lies in the improvement of the interaction between port railway stations and ports in order to increase their handling and throughput capacities. Further research should consider the implementation of the method of interaction between port stations and ports including the operation of the system with an integrated digital twin using the example of a station of the October Railway.

KEYWORDS: port; port station; intelligent system; containers; digital twin; game-theoretic model; synthesis

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Научная статья

Взаимодействие припортовых станций и портов: модели динамической приоритизации цифрового двойника

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АННОТАЦИЯ Целью статьи является повышение эффективности взаимодействия припортовых станций и портов посредством комплексирования систем прогнозирования, оптимизации и управления с применением методов динамической приоритизации с интеграцией в систему цифрового двойника. Проведен анализ объема контейнерных перевозок на сети железных дорог, приведен усредненный аналитический отчет перевезенных контейнеров на железных дорогах Российской Федерации, представлено совершенствование методики взаимодействия портов и припортовых станций, рассмотрены и предложены теоретико-игровые модели для системы взаимодействия припортовых станций и портов, представлены целевые функции для каждого участника процесса, выявлены несовершенства данной системы. В результате исследования представлена теоретико-игровая модель системы взаимодействия припортовых станций и портов и алгоритм работы, поставлена оптимизационная задача для интеграции цифрового двойника в данную систему, математически обосновано использования данной системы. Практическая значимость исследования обусловлена совершенствованием взаимодействия припортовых станций и портов для повышения их перерабатывающей и пропускной способностей. В дальнейших научных исследованиях следует рассмотреть применение методики взаимодействия припортовых станций и портов с интегрированной системой цифрового двойника на примере станции Октябрьской железной дороги.

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КЛЮЧЕВЫЕ СЛОВА: порт; припортовая станция; интеллектуальная система; контейнеры; цифровой двойник; теоретико-игровая модель; синтез

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INTRODUCTION

Currently, the railway network handles an average of more than one million of loaded and empty con-

tainers per month, with over 500,000 of them being 40-foot containers (Table 1) [1]. Fig. 1 shows the volume of container traffic on the map of Russian railways¹.



Fig. 1. Container traffic volume on the map of Russian railways¹

Container transport management in port regions has been the subject of study in works by many authors, including V.L. Belozarov [2, 3], G.M. Groshev [2–4], A.V. Sugorovsky [4], N.V. Klimova [2–5], and others.

Methods of managing the container transport by rail were studied by E.A. Petrenova, A.A. Koroleva, I.A. Fartunin, P.Yu. Shevchenko, E.N. Smolyaninova, I.A. Golubeva, S.P. Pokhilko [6], A.S. Gapich [6], I.Yu. Mamontov [7], A.P. Shirokov [8], E.A. Eremenko [8], and others.

The paper by G.M. Groshev, V.L. Belozarov, and N.V. Klimov entitled “Choosing a method for delivering containers between an off-dock logistics terminal and a seaport” examines interactions between an off-dock logistics terminal and a seaport drawing on the case of Predportovaya Station; however, it fails to address the influence of the operating company on the efficiency of container transport management.

The paper by G.M. Groshev, N.V. Klimova, A.V. Sugorovsky, A.D. Manakov, and P.E. Bulavsky, entitled “Automation of information support for independent

participants in multimodal transport of containers to a seaport in a transport hub” considers information exchange between automated systems for managing container block trains, but does not discuss single wagon load transport as a method to manage container transport in a railway network.

The paper by S.P. Pokhilko and A.S. Gapich entitled “Analysis of the infrastructure of a port railway station and a seaport” studies interactions between a port railway station and a seaport, but does not highlight the issue of wagon idle time at a port station.

In Russia, the major portion of container traffic is accounted for by railway regions adjacent to ports [9]. Various automated systems are used to arrange operations and interactions of transport actors at port railway stations and ports [10]. For example, the following systems have been actively developed on railways: the new-generation unified automated damage claim and complaint handling system for departments of commercial operations in freight transport (EASAPR M NP)² [11], the automated complaint handling system in the premium

¹ Review of the Union of Railway Operators for 12 months of 2025 – URL: <https://railsovet.ru/upload/iblock/027/4dkrvovxvjklcifw5oj68204qfkgzqkd.pdf?ysclid=mquxll0i4a759443985> (accessed on June 15, 2026)

² New-generation unified automated damage claim and complaint handling system for departments of commercial operations in freight transport (EASAPR M NP) – URL: <https://reestr.digital.gov.ru/reestr/1307103/> (accessed on June 15, 2026).

transport service system (EASAPR SFTO)³, the new-generation automated system for operational control and analysis of commercial operations performance and safety of freight transport (ASKM NP)⁴, the new-generation automated system for centralized preparation and execution of shipping documents (AS ETRAN NP)⁵, the new-generation automated system for control of railway station operations (ASU ST NP)⁶, the automated system for operational control and analysis of commercial operations performance and safety of freight transport ASKM

Safety (ASKM Safety)⁷, the new-generation intelligent system for rail transport management (ISUZHT NP)⁸ [12], and the unified model of transport service data for field operations management (EMD PP UER)⁹. The EMD PP UER system is used indirectly to monitor certain functions of port stations and ports. Ports actively utilize the Terminal Operating System (TOS)¹⁰. The Automatic Identification System (AIS) is used to locate vessels¹¹; however, there is currently no dedicated system for interactions between port stations and ports.

Table 1

Average monthly consolidated data on container traffic on the railway network

Railway name	Loaded (general purpose) containers / Empty (general purpose) containers						
	Containers dispatched, physical units	Container gross/ tare weight, t	Average weight of loaded container / tare, kg	Containers arrived, physical units	Container turnover, thousand t/km	Container mileage, thousand container-km	Average container transport distance, km
October Railway	15,575 / 39,406	425,517 / 121,529	27,321 / 3,084	48,332 / 27,265	2,599,528	112,735 / 18,872	2,333 / 692
Kaliningrad Railway	37 / 12	354 / 36	9,563 / 2,962	49 / 36	971	126 / 17	2,579 / 484
Moscow Railway	17,674 / 32,713	372,971 / 121,679	21,103 / 3,720	81,111 / 4,388	8,392,190	494,099 / 4,725	6,092 / 1,077
Gorky Railway	5399 / 3,262	150,761 / 15,294	27,924 / 4,689	3,542 / 5,358	310,004	13,551 / 5,507	3,826 / 1,028
Northern Railway	16,434 / 2,168	459,119 / 8,011	27,937 / 3,695	2,745 / 16,756	209,280	6,968 / 17,115	2,538 / 1,021
North Caucasus Railway	1,516 / 9,591	38,356 / 27,905	25,301 / 2,910	14,403 / 1,124	1,059,943	43,088 / 1,586	2,992 / 1,411
South Eastern Railway	7,098 / 1,520	187,327 / 4,978	26,391 / 3,275	1,052 / 6,299	116,166	4,336 / 6,114	4,122 / 971
Privolzhskaya Railway	1,523 / 830	40,382 / 2,865	26,515 / 3,452	5,035 / 3,111	241,593	9,448 / 4,380	1,877 / 1,408
Kuybyshev Railway	8,545 / 5,257	244,023 / 21,038	28,557 / 4,002	6,023 / 8,654	409,116	17,371 / 10,232	2,884 / 1,182
Sverdlovsk Railway	17,663 / 5,705	49,156 / 21,205	27,830 / 3,717	10,076 / 14,303	971,127	46,271 / 26,775	4,592 / 1,872
South Urals Railway	10,492 / 1,229	329,723 / 4,083	31,426 / 3,322	16,027 / 10,315	585,749	23,330 / 15,498	1,456 / 1,502
West Siberian Railway	18,567 / 4,286	495,482 / 14,070	26,686 / 3,283	14,254 / 13,668	1,057,783	53,791 / 32,655	3,774 / 2,389
Krasnoyarsk Railway	5,532 / 2,350	153,593 / 7,925	27,764 / 3,372	4,621 / 5,680	346,037	16,507 / 15,121	3,572 / 2,662
Yakutian Railway	148 / 1,400	2,485 / 5,125	16,792 / 3,661	1,618 / 124	207,482	10,042 / 65	6,207 / 520
East Siberian Railway	13,886 / 7,210	391,841 / 26,220	28,218 / 3,637	16,343 / 13,650	1,312,073	53,256 / 34,467	3,259 / 2,525
Transbaikal Railway	11,665 / 966	213,561 / 2,840	18,308 / 2,940	19,072 / 316	2,540,705	92,288 / 480	4,839 / 1,519
Far Eastern Railway	57,144 / 5,841	1,086,134 / 16,605	19,007 / 2,843	35,338 / 2,283	5,984,751	236,580 / 2,688	6,695 / 1,177

IMPROVING THE METHOD FOR INTERACTION BETWEEN PORT STATIONS AND PORTS: A GAME-THEORETIC MODEL AND DIGITAL TWIN INTEGRATION

The studies [13, 14] raise the question of developing a method for interaction between port stations

and ports. At present, the method consists of a basic module and an auxiliary module [13, 14]. The method synthesizes planning, optimization and management systems by using the dynamic prioritization method. Fig. 2 shows a consolidated method for interaction between port stations and ports. New blocks supplementing the existing methodology are highlighted in orange.

³ New-generation automated complaint handling system in the premium transport service system (EASAPR SFTO NP) – URL: <https://reestr.digital.gov.ru/reestr/1307101/> (accessed on June 15, 2026).

⁴ New-generation automated system for operational control and analysis of commercial operations performance and safety of freight transport – URL: <https://reestr.digital.gov.ru/reestr/1043986/> (accessed on June 15, 2026).

⁵ AS ETRAN. New Platform. 2021 Phase. (AS ETRAN NP) – URL: https://reestr.digital.gov.ru/reestr/1149363/?sphrase_id=2769405 (accessed on June 15, 2026).

⁶ New-generation automated station control system – URL: <https://reestr.digital.gov.ru/reestr/1123393/> (accessed on June 15, 2026).

⁷ ASKM Safety – URL: <https://catalog.arppsoft.ru/product/6203322?ysclid=mquxwj35bi517373484> (accessed on June 15, 2026).

⁸ Unified intelligent system for rail transport business process management and automation (ISUZHT NP) – URL: <https://reestr.digital.gov.ru/reestr/3050507/> (accessed on June 15, 2026).

⁹ Unified model of transport process data (EMD PP) – URL: <https://reestr.digital.gov.ru/reestr/1273062/> (accessed on June 15, 2026).

¹⁰ TOS – URL: <https://marine-digital.com/ru/tpost/mj5hoy169i-funktsional-oblachnoi-tos?ysclid=mquy1hsbfg203424646> (accessed on June 15, 2026).

¹¹ AIS – URL: <https://www.midland-rus.ru/articles/navigacziionnaya-sistema-ais?ysclid=mquy35o1i1770530955> (accessed on June 15, 2026).



In this method, the system already has the dynamic prioritization and adaptive planning functionality, but it lacks a continuously updated digital copy of objects. Control is based on a statistical model of the system $G(h)$, which is updated discretely on the basis of average data. The system should be considered in terms of a game-theoretic model [15].

The model includes five participants: the Centre in the form of the existing system (where the elements are influenced by planning) and active elements: station dispatcher (AE1), port dispatcher (AE2), ship owner (AE3), and cargo owner (AE4). The hierarchical structure of the model of interaction between port stations and ports is shown in Fig. 3.

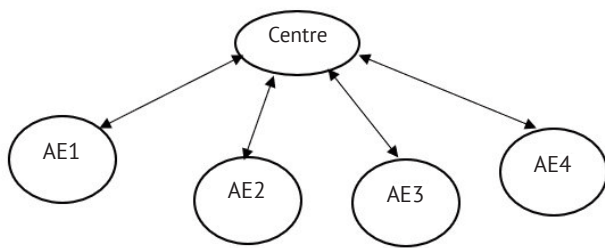


Fig. 3. Hierarchical structure of the model of interaction between port stations and ports

The Centre receives and processes information from each active element, makes forecasts and provides them to all agents, and develops recommendations for allocation of resources. The Centre does not change the objective functions of the active elements, but proposes plans that are aligned with their interests.

Strategies:

The Centre – Select planning $p(s)$;

AE1 (station dispatcher) – Select $y_1 \in A_1$ (priority, time);

AE2 (port operator) – Select $y_2 \in A_2$ (distribution of operations);

AE3 (ship owner) – Report $s_3 \in S_3$ (ship arrival time);

AE4 (cargo owner) – Report $s_4 \in S_4$ (cargo characteristics and priority).

Then, the objective functions for each of the participants will be as follows:

The Centre cannot directly choose y ; it can only propose a set x , and the active elements choose their actions y based on their objective functions.

The Centre's objective function is

$$F(x) = \max_{y \in Y(x)} F(y), \quad (1)$$

where $F(y)$ is the value of the function for different parameters y (priority and time for station dispatcher; distribution of operations for port operator).

The station dispatcher manages the delivery of wagons, their placement on tracks, and the marshalling of trains. Their objective function is to ensure

maximum capacity and timely distribute wagons by track and direction.

The station dispatcher's objective function (wagon/hour) is

$$f_1(y_1, r_1) = U_1(y_1, r_1) - \theta_1 \cdot D_1(y_1, r_1) \rightarrow \max, \quad (2)$$

where y_1 is the station dispatcher's actions (handling priority, time for delivery, tracks to be used); r_1 is the station type (technical capabilities); $U_1(y_1, r_1)$ is the station throughput capacity (number of wagons/trains handled per unit of time with given actions (wagons/hour)); $D_1(y_1, r_1)$ is the wagon delay time (deviation from the schedule (hours)) which the dispatcher wants to minimize; and $\theta_1 > 0$ – is the coefficient that reflects a “penalty” for delay, such as, for example, reprimands from the traffic management directorate; loss of coupons; downgrading the station's rating.

The port operator manages cranes, berths, and transhipments, and their costs have a direct impact on the financial performance of the port.

The port operator's objective function is

$$f_2(y_2, r_2) = c_2(y_2, r_2) \rightarrow \min, \quad (3)$$

where $c_2(y_2, r_2)$ are the port operator's costs on power and depreciation of cranes, personnel remuneration, ship demurrage charges, where provided for in contracts with ship owners.

The port operator minimizes their costs by choosing the most efficient allocation of resources.

The ship owner minimizes port fees and demurrage charges.

The ship owner's objective function is

$$f_3(y_3, r_3) = c_3(s_3, y_3, r_3) \rightarrow \min, \quad (4)$$

where s_3 is the ship arrival time report from the ship owner; y_3 is the ship owner's actions (actual speed, selection of the port call time); r_3 is the real arrival time only known to the ship owner; and c_3 is the ship owner's costs, including port fees, delay penalties, and fuel costs.

The ship owner can manipulate s_3 report in order to obtain a better plan, such as, for example, an earlier handling window. However, in the current system, the Centre cannot check s_3 and the ship owner can benefit from distortions.

The cargo owner minimizes the cost of delivery and lost costs:

The cargo owner's objective function is

$$f_4(s_4, r_4) = c_4(s_4, r_4) \rightarrow \min, \quad (5)$$

where s_4 is the report from the cargo owner (characteristics and priority of goods); r_4 is the true priority of goods (only known to the cargo owner); and c_4 is the cargo owner's costs, including transport costs, losses due to delays, and late delivery penalties.

The cargo owner can overstate the priority in order to obtain faster handling, even if goods are not a high

priority shipment. In the current system, the Centre cannot verify s_4 .

In the current system, the forecast is updated in the course of work and there is no possibility to adjust plans promptly. Therefore, improving the method of interaction between port stations and ports is a relevant scientific and practical task.

One of the solutions to the problem is to integrate a digital twin into the system of interaction between port stations and ports. A digital twin is a model of the controlled system $G(h, t)$ that is updated in real time. The model is expanded by introducing a dynamic information function.

In this case, the system operation status problem will look as follows:

Let $X(t) \in R^m$ be the status vector at time t , including coordinates and speed of ships, track and berth occupancy, statuses of wagons and handling equipment, and meteorological conditions.

Status dynamics are described by a stochastic differential equation:

$$dX(t) = F(X(t), u(t), t)dt + \sigma(X(t), t)dW(t), \quad (6)$$

where $dX(t)$ is an infinitesimal change in the state of the system over an infinitesimal interval; $F(X(t), u(t), t)$ is the function that defines deterministic dynamics, showing how the system status would evolve if there were no randomness; dt is the infinitesimal time step; $u(t)$ are control actions (plans, priorities); $dW(t)$ is the Wiener process; and $\sigma(X(t), t)$ is the diffusion coefficient that reflects random fluctuations.

Given the introduction a digital twin, there is a fuzzy information function $\tilde{P}(z, y)$, which will be updated in real time on the basis of data from the twin to take into account both probabilistic and fuzzy uncertainty.

In order to make trade-offs between throughput, costs, and waiting time, we should consider multi-criteria optimization including the construction of the Pareto frontier as follows:

$$\max_{u(\cdot)} \int_t^{t+T} e^{-p(s-t)} \Phi(X(s), u(s)) ds, \quad (7)$$

where $u(\cdot)$ is the vector function of control – the set of all decisions made by the Centre at each point of time, including plans for each active element, dynamic priorities, and other corrective actions; $e^{-p(s-t)}$ is the discount factor reflecting that earlier utilities have a greater weight compared to later ones; T is the duration of time interval; t is the current point of time; s is the time point within the interval $[t, t + T]$; $X(s)$ is the system status vector at time point s , which includes all variables required to describe the current situation (data from the cargo owner, ship owner, port operator, and station dispatcher); and ds is the variable of integration.

With a digital twin, the Centre solves the optimal control problem on a receding horizon without a fixed plan,

$$\max_{u(\cdot)} \int_t^{t+T} e^{-p(s-t)} \left[\alpha U(X(s), u(s)) - \beta C(X(s), u(s)) - rW(X(s), u(s)) \right] ds, \quad (8)$$

where α is the weighting factor for throughput capacity, which determines a degree to which increasing the throughput is important to the Centre compared to the other criteria; β is the weighting factor for operating costs; the higher this factor, the more the Centre aspires to reduce operating costs; r is the weighting factor for waiting time, reflecting a degree to which the Centre is impacted by the idle time of wagons and ships; $U(X(s), u(s))$ is the terminal's throughput at time point s (wagons/hour); $C(X(s), u(s))$ are operating costs at time point s (RUB/hour); and $W(X(s), u(s))$ is the average waiting time at time point s (hours).

With the following restrictions:

- status dynamics $\dot{X} = F(X, u)$ define how the status changes over time depending on parameters;
- restrictions on the use of resources.

Dynamic prioritization is introduced as a generalization of jump incentive schemes:

$$P_i(t) = \sum_{k=1}^5 w_k(t) \cdot f_{ik}(t), \quad (9)$$

where $P_i(t)$ is the final characteristic for status i at time t ; $w_k(t)$ is the active element's weight at time t ; and $f_{ik}(t)$ is the contribution of the active element to state i at time t .

Weighting factors $w_k(t)$ are adapted based on the twin data in real time.

Thus, with the integration of a digital twin $U(X(s), u(s))$, the terminal's throughput at time s increases due to the systematization of operations of all process participants, operating costs at time s $C(X(s), u(s))$ are reduced due to the review of port and port station operations in real time, and the average waiting time at time s $W(X(s), u(s))$ is reduced due to the systematic allocation of resources (Fig. 4).

CONCLUSION

With the integration of a digital twin into the existing management system, which already implements forecasting, dynamic prioritization, and real-time planning, the quality of control changes from statistical to dynamic, from discrete to continuous. This is ensured by continuous updating of the state model $X(t)$ through the digital twin, flexible recalculation of plans and priorities based on relevant forecasts, and theoretical guarantees of non-manipulability, consistency, and optimality as proven within the framework of the theory of active systems. Further studies should involve reviewing and considering the introduction of the developed system at the operating domain of the October Railway.

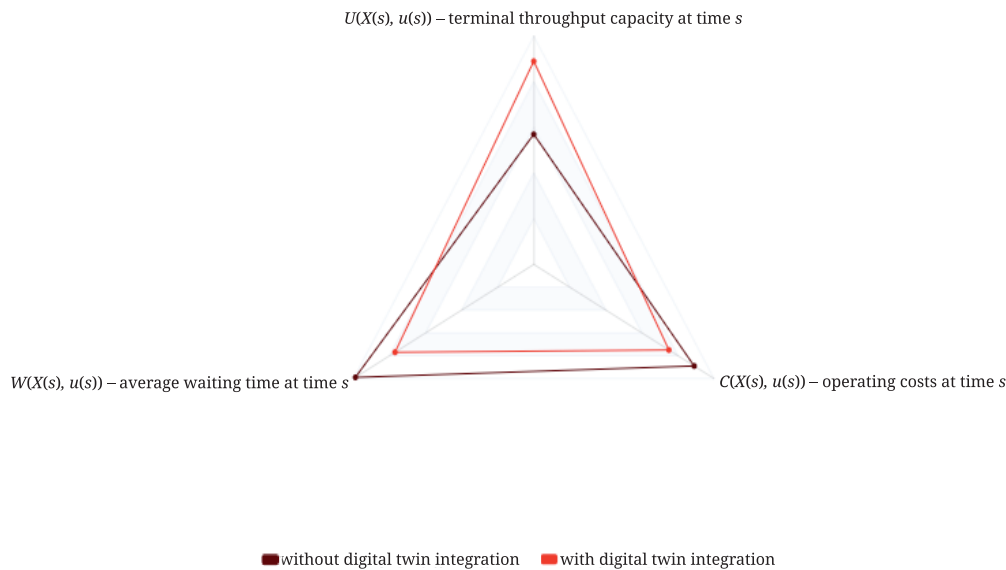


Fig. 4. Radar chart comparing the system performance with and without digital twin integration

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