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Article

Combinatorial Optimization of Shunting Operations for Industrial Sidings Adjacent to Railway Stations

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Abstract

The main objective of the study is to reduce the dwell time of wagons at stations and to improve the efficiency of shunting locomotive utilization. The problem has a combinatorial nature, since an increase in the number of loading and unloading fronts leads to a sharp growth in the number of feasible service variants. During the research, a mathematical model describing the servicing process of industrial sidings was developed. The study addressed the problem of determining the optimal sequence of wagon deliveries and the optimal distribution of workload among shunting locomotives. Under conditions where two or more shunting locomotives are used, an optimization method based on the indicator of wagon-hours reduction (σ) was proposed for allocating loading and unloading fronts. Using combinatorial properties, it was shown that many possible allocation variants are symmetric, which allowed the development of a mathematical solution that simplifies the search for an optimal solution. Computational results demonstrated that, at the hypothetical railway station "N-1", applying the optimal service sequence reduces wagon dwell time by 21% compared with an arbitrary sequence. At the hypothetical station "N-2", distributing wagon groups between two shunting locomotives improves the efficiency of the servicing process by 26% compared with using a single locomotive. Based on the proposed mathematical model and algorithm, a practical software tool was developed that enables the automatic determination of service sequences for loading and unloading fronts. The software allows the identification of optimal servicing orders, analysis of alternative variants, and evaluation of the efficiency of shunting locomotive utilization.

Keywords: industrial sidings; shunting operations; loading-unloading facilities; combinatorial optimization; mathematical modeling; multi-criteria optimization; optimization algorithm; decision-support software

1. Introduction

At present, railway transport is one of the key links in the freight transportation chain and plays an important role in ensuring the stable development of the national economy as well as the continuous operation of industry, agriculture, and logistics sectors. At the same time, due to increasing economic activity, the growing number of industrial enterprises, and the rise in freight flows, the volume of rail transportation has been increasing year by year. This trend leads to a significant growth of workload at railway stations, particularly due to the increase in operations associated with local wagons.

Practical analyses show that prolonged dwell times of local wagons are often caused not by technical deficiencies, but by insufficiently regulated servicing processes of industrial sidings. At many stations, the sequence of local operations is not planned in advance or is not adjusted to actual freight flows. As a result, wagons are subjected to repeated shunting movements.

This situation leads to excessive shunting operations of locomotives and prolongs the execution time of loading and unloading processes. Such conditions not only increase the turnaround time of wagons but also significantly reduce the efficiency of rolling stock utilization. Excessive shunting trips of locomotives result in higher fuel and energy consumption, which in turn increases operating costs and the load on railway infrastructure. Consequently, the processing capacity of the station decreases.

Therefore, selecting an optimal servicing sequence for loading and unloading facilities becomes particularly important. Implementing local operations according to a clearly defined and scientifically justified sequence makes it possible to significantly reduce the dwell time of wagons arriving at stations. This contributes to faster wagon turnover, ensures the continuity of freight transportation processes, and improves the overall efficiency of railway transport. Moreover, introducing an optimal servicing order helps prevent unnecessary shunting movements at stations and industrial sidings, promotes the rational use of rolling stock, reduces fuel and energy consumption, and lowers operating costs. This issue is especially critical for stations handling large freight flows and numerous industrial sidings, where solving it plays an important role in ensuring the stable functioning of the railway network.

2. Analysis of railway station infrastructure and wagon flow patterns: the case of JSC Uzbekistan railways

At railway stations operated by JSC Uzbekistan Railways, the efficiency of handling local freight largely depends on the infrastructure of industrial sidings adjacent to the stations and their operational capabilities, including the number of shunting locomotives available. Therefore, analyzing stations according to the number of sidings they serve makes it possible to assess the current state of local operations management.

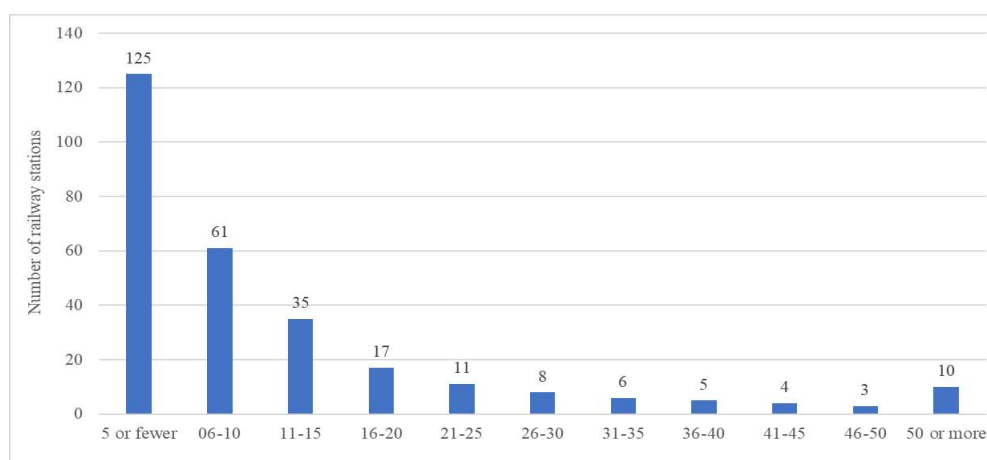


Figure 1. Distribution of railway stations operated by JSC Uzbekistan railways according to the number of industrial sidings served.

According to the analysis of statistical data presented in Figure 1, it can be observed that the majority of stations have a relatively small number of industrial sidings. In particular, stations with five or fewer sidings account for 68% of the total number of stations, representing the largest share. In contrast, large stations with more than twenty sidings are relatively few in number (Figure 1). This

indicates that the technical structure of stations across the railway network is heterogeneous and that local operations are performed under varying conditions.

The statistical data presented in Figure 2 indicate a significant disparity between the number of stations and the volume of freight operations they perform. In particular, despite their relatively small number, large stations with numerous industrial sidings handle the major share of daily loading and unloading operations. Conversely, although stations with a small number of sidings are more numerous, their share in freight operations remains comparatively low.

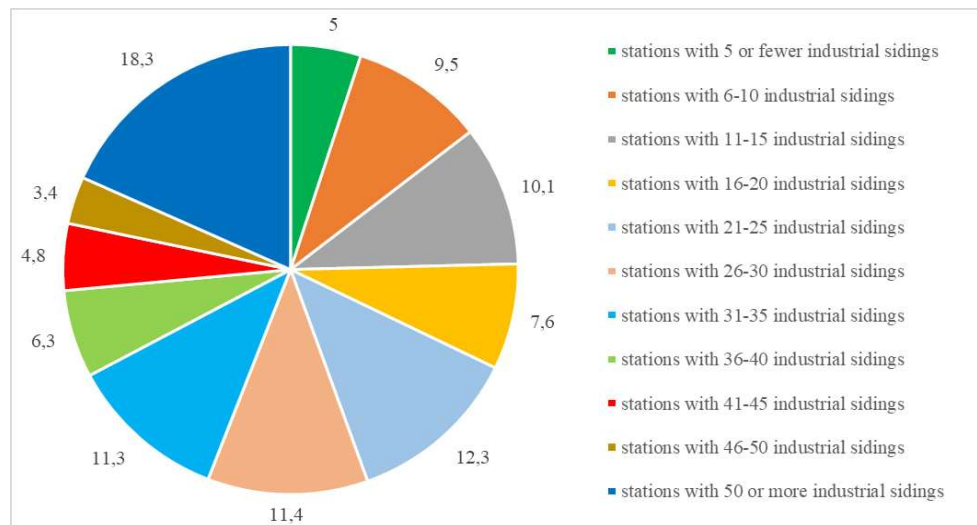


Figure 2. Distribution of JSC Uzbekistan railways stations by their share in average daily freight loading and unloading.

A comparison of the results of the two diagrams reveals a clear imbalance between the number of stations and the volume of loading and unloading operations they perform. For example, a relatively small number of stations with 50 or more industrial sidings account for 18.3% of the total daily volume of handled wagons. Similarly, stations with 31-35, 26-30, and 21-25 sidings also have a substantial share, accounting for 11.3%, 11.4%, and 12.5% of the total local wagon turnover, respectively.

At the same time, the numerous stations with five or fewer industrial sidings handle only about 5% of the total freight volume. This indicates that small stations, despite their numerical predominance, have a relatively low operational workload. Therefore, large stations with a greater number of sidings bear the main burden of handling local wagons.

The limited availability of shunting locomotive resources further increases the relevance of this issue. According to the data, 66% of stations are equipped with only one shunting locomotive. The share of stations with two and three shunting locomotives amounts to 16% and 14%, respectively, while stations with four or more shunting locomotives account for only 4%.

Under these conditions, determining the optimal servicing sequence through the digitalization of locomotive utilization processes, as well as developing methods for organizing local operations based on this sequence, acquires significant scientific and practical importance. This approach makes it possible to reduce wagon dwell time, decrease unnecessary shunting trips, improve the efficiency of locomotive and rolling stock utilization, and achieve savings in fuel and energy resources.

3. Literature review

Existing scientific literature related to the selection of servicing sequences for industrial sidings adjacent to railway stations was analyzed. The review shows that the studies in this field can be divided into four main groups, namely:

- traffic organization and control;

- rolling stock allocation;
- wagon delivery and removal operations;
- organization of loading and unloading processes.

This study primarily focuses on optimizing methods for solving problems related to wagon delivery to and removal from industrial sidings.

The problem of traffic organization and control constitutes a key component of the wagon delivery and removal process at industrial sidings and has been extensively studied over recent decades. Numerous variants with different characteristics have been proposed in this area, and a variety of mathematical models, heuristic approaches, and intelligent computational methods have been developed to address them.

In particular, the study by Jintang Sh. et al. [1] models the joint optimization of sorting operations and shunting processes at railway stations using a time-space network framework, where integer linear programming and the ADMM algorithm were applied to solve the problem. The results demonstrated a reduction in train dwell time and the number of shunting movements. In the work of P. Knops [2], shunting processes at a large classification yard were modeled based on real infrastructure and optimized using the Simulated Annealing algorithm, which showed improved wagon dispatching efficiency. Bing L. et al. [3] modeled the simultaneous delivery and removal of wagons at a railway terminal based on a hybrid siding infrastructure and applied a two-stage TSHOP algorithm. The results indicated a reduction in shunting locomotive working time and operating costs. In the article by Peiran H. et al. [4], the problem of train formation and resource planning was solved using mixed-integer linear programming, while the Logic-based Benders Decomposition algorithm enabled a reduction in the duration of shunting operations. The study by Nikola V. et al. [5] developed a real-time decision-support system based on operational data for managing disturbances at classification yards, enabling faster decision-making in shunting operations. Hongxiang Z. et al. [6] modeled wagon movements using a Markov decision process and applied a deep reinforcement learning approach based on graph neural networks, which significantly reduced wagon dwell time at stations. In the research of Nazhenov D. et al. [7], the influence of the number of shunting locomotives on the working fleet of freight wagons and performance indicators of the transportation process was analyzed. The results showed that selecting the optimal number of locomotives contributes to reducing wagon turnaround time and improving operational efficiency. The work of G. Chuijiang and L. Shengdong [8] optimized wagon delivery and removal processes at stations with industrial sidings using a mathematical model, where an improved Simulated Annealing algorithm reduced servicing time. Samuel D. et al. [9] systematically formalized shunting processes at stations, identified practical limitations of existing models and algorithms, and emphasized the lack of integrated approaches as a scientific challenge. Finally, the study by I.M. Vorobyev et al. [10] modeled freight service organization and route formation across the railway network using information systems and proposed a mechanism based on strictly scheduled operations.

In summary, although optimization of traffic organization and control processes has been widely addressed in studies within this field, in most cases the servicing of industrial sidings has not been fully integrated with the actual technological sequence of operations. In particular, the combinatorial complexity of servicing sequences arising from a large number of sidings has not been sufficiently considered. This situation justifies treating the servicing process of industrial sidings as a separate optimization object in the present study.

The allocation of rolling stock, including wagons and locomotives, to industrial sidings is one of the key factors determining the efficiency of freight transportation in railway systems. In recent years, research in this field has focused particularly on optimal resource allocation, locomotive scheduling, and the management of wagon flows. Various studies have proposed effective solutions based on mathematical models, heuristic and metaheuristic algorithms, as well as intelligent approaches.

In particular, the study by Tommaso B. et al. [11] models the allocation of rolling stock and the management of shunting processes at classification yards based on the “Shunt-In and Shunt-Out”

(SISO) concept. The problem was solved using a mixed-integer nonlinear programming model, and the results demonstrated the potential to reduce both shunting duration and operating costs. The research by Bing L. et al. [12] examined the organization of wagon delivery and removal processes within a siding network. A freight station model with a branch-shaped infrastructure was developed, and shunting processes were analyzed using simulation modeling. The results showed that comparing alternative servicing strategies can improve operational efficiency. In the article by Sh. Suyunbayev et al. [13], the issue of improving the efficiency of shunting locomotive utilization through station infrastructure enhancement was investigated. The impact of implementing electric interlocking on shunting operation duration was analyzed using technological schedules. The calculations showed that infrastructure modernization significantly reduces locomotive occupation time. The study by T.B. Suleimenov, T.T. Sultanov, G.M. Tlepiyeva, and Z.K. Sansyzybayeva [14] addressed the development of dry port logistics services within the Eurasian international transport corridors of the Republic of Kazakhstan. In the work of H. Falsafain and M. Tamannaei [15], the problem of minimizing the number of sorting tracks during train re-marshalling at railway stations was studied. The problem was formulated as the *Train Marshalling Problem*, and a dynamic programming-based algorithmic approach was proposed, demonstrating improved computational efficiency. The article by Y. Kim et al. [16] considered the locomotive allocation problem in railway networks. An integer optimization model based on a time-space network was developed for locomotive scheduling, and the results showed improved efficiency in locomotive fleet utilization. R. Zhao, J. Geunes, and X. Nie [17] investigated the optimization of shunting movements during outbound train formation. Wagon positioning and relocation were modeled using integer programming combined with a dynamic programming approach. Computational results indicated that the proposed method reduces shunting time and associated costs. In the research of S.N. Zhuravlev [18], the problem of automatic control of shunting locomotive speed during pushing operations on a classification hump was studied. An automatic control algorithm was developed to maintain stable locomotive speed, and experimental results demonstrated improved accuracy and stability of the pushing process. Finally, reports of the European Commission [19-20] analyzed the state and development challenges of the single wagonload (SWL) freight system. The findings showed that shunting and sorting operations constitute a significant portion of total costs, and their optimization is a key factor in improving SWL system efficiency.

The reviewed studies confirm that the allocation of rolling stock at railway stations directly affects the efficiency of freight transportation. Various mathematical and algorithmic approaches aimed at optimizing shunting processes, ensuring rational resource utilization, and reducing operating costs have been proposed in this field. However, in many existing studies, the processes are considered separately, while their interdependence within the station's technological system is not sufficiently taken into account. This indicates the need to develop integrated approaches in this area.

The processes of delivering wagons to and removing them from industrial sidings directly affect both the utilization of shunting locomotives and the dwell time of wagons at stations. Inefficient organization of these processes leads to an increase in the volume of shunting operations and higher operating costs. In recent years, research in this area has focused on determining optimal servicing sequences and optimizing shunting processes.

In particular, the study by S.B. Sattorov et al. [21] examined the problem of standardizing train dwell time on industrial sidings. The delivery and removal of wagons were modeled based on the sequence of technological operations, and the proposed approach demonstrated the potential to reduce excessive wagon dwell time on sidings. In the research of V.A. Tepikin, A.G. Kotenko, and I.A. Rolle [22], the improvement of the distribution process of train consists containing wagons not permitted for hump release was investigated. Various technological methods of shunting operations were developed, and their implementation was shown to increase the processing capacity of classification humps. The article by Sh.B. Jumayev et al. [23] addressed the improvement of local wagon flow organization. An optimization model aimed at reducing wagon dwell time was

developed, and computational results indicated a reduction in total dwell time and an increase in station processing capacity. In the work of A.A. Ananyeva [24], the legal regulation of empty wagon supply processes was analyzed, and the study demonstrated the expediency of formalizing such operations through special contractual arrangements. The research by Y.V. Dotsenko, A.I. Shekhovtsov, and Y.A. Shekhovtsova [25] modeled the interaction between stations and industrial sidings using Petri nets. The proposed models enable the formalization of wagon delivery and removal processes. In the article by V.A. Groshev [26], the issue of digitalizing real-time operational management at railway stations was considered. An information architecture and model-based approach enabling real-time control of station technological processes were proposed. The study by S.P. Vakulenko et al. [27] examined the placement of railway infrastructure within logistics centers. The results showed that coordinated functioning of sidings and station elements improves the efficiency of wagon delivery and removal operations. Finally, the research of A.V. Bauer and A.A. Harina [28] focused on improving interaction between freight stations and industrial sidings. The study demonstrated that optimizing technical and technological parameters can enhance the efficiency of wagon delivery and removal processes.

The analyzed studies confirm that the processes of delivering wagons to and removing them from industrial sidings directly affect the operational efficiency of railway stations. In existing works, the optimization of these processes has been addressed through technological, organizational, informational, and legal approaches. The obtained results demonstrate the potential to reduce both wagon dwell time at stations and the utilization time of shunting locomotives. However, the issue of comprehensively determining servicing sequences has not been sufficiently explored in the literature, which indicates the need to develop integrated approaches in this area.

Loading and unloading operations are among the key stages of freight transportation technology in railway systems, and their efficient organization directly affects wagon turnaround speed, the utilization level of loading fronts, and the overall efficiency of freight transportation. In recent years, research in this area has focused on planning loading and unloading processes, optimizing the use of equipment and handling machinery, and reducing servicing times.

In particular, the study by H. Chen et al. [29] investigated the planning of loading and unloading processes in automated container terminals. The results showed that a synchronized loading-unloading regime reduces working time and improves equipment utilization efficiency. The research by J. Wang et al. [30] addressed the optimization of loading and unloading operations at railway freight terminals. The interaction between loading fronts and technical equipment was analyzed using a mathematical model, demonstrating that the proposed approach can shorten the duration of handling operations. In the work of B. Sarsembekov et al. [31], it was noted that, similar to the technological solution proposed in the present study, the development of combinatorial optimization models for shunting services should consider operational and environmental criteria jointly. Regulatory documents of the International Union of Railways (UIC) [32] define technical requirements for loading and securing freight in wagons. These guidelines aim to ensure safe transportation and prevent failures during loading and unloading processes. The article by X. Li, A. Otto, and E. Pesch [33] examined the planning of loading and unloading operations at railway freight terminals with a single crane. The study showed that optimizing crane operations can minimize train dwell time at the terminal. In the research of S. Wang et al. [34], the planning of handling processes under limited loading-unloading resources at railway freight terminals was investigated. The results indicated that optimizing the processing sequence of cargo reduces the duration of handling operations. The article by A. Sewagegn and M. Dorda [35] modeled shunting processes at classification yards using queueing theory. A single-channel model with limited capacity was proposed, where secondary shunting movements were treated as system disturbances. Service and recovery times were represented using a hypoexponential distribution. The results allow evaluation of station load, wagon queues, and system stability. Finally, the study by D. Zhang et al. [36] examined the problem of improving traffic safety and energy efficiency during cargo placement in wagons. The combined center-of-gravity (CCOG) position of the load was optimized to model wagon

tilt and energy consumption, demonstrating that proper CCOG positioning can reduce energy use and enhance safety.

The reviewed studies demonstrate that loading and unloading operations directly influence the efficiency of freight transportation. In existing works, optimization of these processes has mainly been achieved through planning the operation of loading fronts and improving the utilization of technical equipment. At the same time, the issue of comprehensively integrating loading and unloading processes with station operations and shunting activities has not been sufficiently addressed.

4. Research Methodology

The results of the literature review indicate that most existing studies on improving freight transportation at railway stations primarily focus on developing technical infrastructure, increasing station capacity, and optimizing freight flows. However, the problem of optimizing the servicing sequence of industrial sidings and loading-unloading facilities adjacent to railway stations under conditions of limited shunting locomotive resources has not been sufficiently studied.

Currently, inefficient organization of operations involving local wagons leads to prolonged dwell times at stations. To address these problems, this study proposes a methodological approach aimed at determining the optimal servicing sequence for industrial sidings and loading-unloading facilities adjacent to railway stations. The proposed method is based on a comprehensive consideration of operational indicators of local wagons, the number of loading fronts served within a single network, and the availability of shunting locomotives.

4.1. Servicing technology for industrial sidings

In this section, the servicing technology of industrial sidings is considered using the example of a hypothetical railway station “N” and its infrastructure. Station “N” has several industrial sidings through which local wagon delivery and removal operations are performed (Figure 3). At the station, local operations are organized using a shunting locomotive.

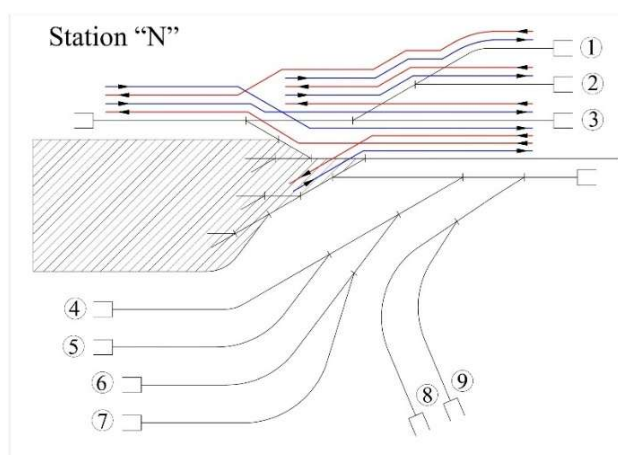


Figure 3. Routing scheme for shunting operations in an industrial siding network.

The interconnection scheme between industrial sidings and station tracks, their spatial arrangement, and the general directions of shunting movements play a crucial role in shaping the servicing technology. Therefore, the process of servicing industrial sidings at station “N” is described based on the technological scheme shown in Figure 3 [37-38].

In this scheme, routes for delivering wagons to industrial sidings are shown in blue, while removal routes are indicated in red. Figure 3 illustrates the routing of shunting operations using the

example of the upper network of sidings 1-3. In this context, the servicing technology and the logical sequence of shunting movements are taken as the basis.

Operation name	Operation duration (hours)				
	t	2t	3t	4t	5t
Coupling of the shunting locomotive with the wagon consist	t ₁				
Transfer of wagons to the siding network		t ₂			
Spotting wagons at the i-th loading-unloading point			t ₃		
Uncoupling wagons at the i-th loading-unloading point				t ₄	
$i = 1, 2, \dots, n$					⋮
Return of the shunting locomotive to station tracks					t ₅
Total duration	t _{tot}				

Figure 4. Technological schedule for servicing industrial sidings.

It should be noted that the same technological sequence is applied to the delivery and removal of wagons for the second network (sidings 4-7) and the third network (sidings 8-9). Although the routing of shunting operations in these networks differs in spatial configuration, the execution logic and servicing sequence remain identical.

Describing the servicing process of industrial sidings solely on the basis of their spatial layout is insufficient, since the operation of a shunting locomotive is closely related to the time factor. Therefore, a technological schedule is used to determine the sequence of servicing operations, the duration of shunting tasks, and their interrelations. The technological schedule reflects the operations performed by the shunting locomotive along the sidings in a time-ordered manner and makes it possible to identify the overall logical sequence of the servicing process (Figure 4).

Based on the technological schedule shown in Figure 4, it is possible to determine the total servicing time of an industrial siding by considering the sequence of shunting locomotive movements, including entry and exit operations as well as the coupling and uncoupling of wagons, while reflecting their interdependence [39-40]:

$$t_{tot} = t_1 + t_2 + \sum_{i=1}^n t_3 + \sum_{i=1}^n t_4 + t_5, \text{ hours} \quad (1)$$

This technological schedule is adopted as the basis for determining the logical sequence of the servicing process and serves as the initial framework for subsequent calculations.

4.2. Problem statement

This study considers the problem of optimally organizing the servicing process of industrial sidings located at the hypothetical small station "N-1" and large station "N-2" within the railway network.

The servicing sequence of industrial sidings can be organized in various ways, and an increase in the number of sidings leads to a rapid growth in the number of feasible variants. As a result, the problem has a combinatorial nature, making it difficult in practice to determine the optimal servicing order using conventional methods.

This situation necessitates the mathematical modeling of the servicing process and the development of a dedicated algorithm aimed at optimizing the movement sequence of the shunting locomotive. Therefore, in this study the servicing process is modeled based on the technological

schedule, and the minimization of the total wagon-hour indicator associated with excessive dwell time of local wagons at stations is considered the primary objective of the research.

4.3. Proposed solution method

This study is aimed at optimizing the servicing process of industrial sidings, where the combinatorial complexity associated with selecting the servicing sequence is considered the key factor shaping the problem. The servicing process and the order of operations directly depend on the spatial arrangement of sidings and the number of loading and unloading fronts.

In this study, the servicing process of industrial sidings is examined using the example of the hypothetical freight station "N-1" (Figure 5). The station infrastructure, the spatial arrangement of loading and unloading fronts, and the networks connecting them with station tracks determine the technological characteristics of the servicing process. Under these infrastructural conditions, the choice of the sequence for delivering wagons to loading and unloading locations directly affects servicing efficiency.

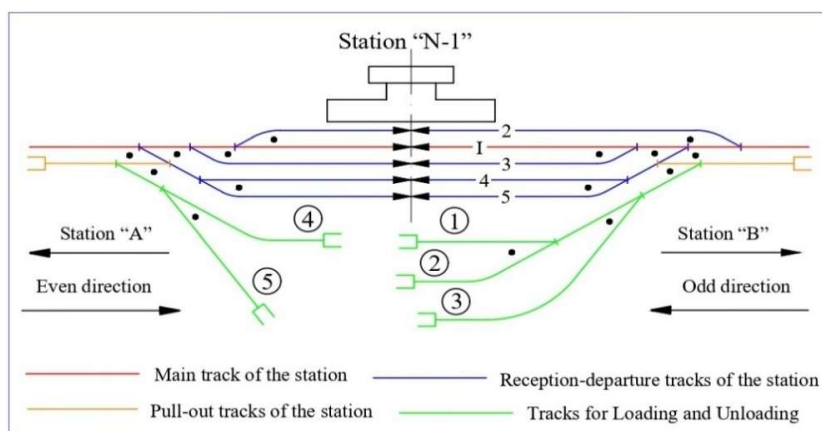


Figure 5. Scheme of the "N-1" railway station and its adjacent industrial siding network.

The large number of industrial sidings and their network-based arrangement lead to a rapid increase in the number of possible servicing sequences. Therefore, this process has a combinatorial nature, requiring the identification and evaluation of all feasible servicing sequences. The total number of possible servicing variants is determined using a combinatorial approach, and each variant is treated as a separate technological solution.

The number of possible sequences for delivering wagons to the loading and unloading fronts of industrial sidings adjacent to a railway station can be determined using a combinatorial approach according to the following formula [41-42].

$$k = n! \quad (2)$$

where: n number of serviced loading-unloading fronts

–

However, taking into account the spatial arrangement of industrial sidings and their connection network to the station, additional constraints can be introduced into Formula (2) based on sequential selection, allowing the number of variants to be expressed more precisely as follows:

$$k = f! \cdot (k_1 \cdot k_2 \cdot k_3 \cdot \dots \cdot k_n) = f! \cdot \prod_{i=1}^n k_i \quad (3)$$

where: f number of tracks connecting the station with loading and unloading locations

–

In turn, each element k_n of Formula (3) can be expressed as follows:

$$k_n = (C_p^m)! = \left(\frac{p!}{(p-m)!} \right)! \quad (4)$$

where: p – number of loading and unloading fronts that can be selected within each network connected to the station

m – number of facilities to which wagon delivery can be performed

$$k_n = (C_p^m)! = \left(\frac{p!}{(p-m)!} \right)! = \left(\frac{p!}{(p-1)!} \right)! = \left(\frac{p \cdot (p-1)!}{(p-1)!} \right)! = p! \quad (5)$$

For the infrastructure configuration of the considered station “N-1”, the number of possible variants for delivering wagons to loading and unloading locations can be expressed according to Formula (5) as follows:

$$k = f! \cdot (p_1! \cdot p_2! \cdot p_3! \cdot \dots \cdot p_n!) = f! \cdot \prod_{i=1}^n p_n! \quad (6)$$

For the infrastructure configuration and spatial arrangement of industrial sidings at the studied station “N-1”, the number of possible variants for delivering wagons to loading and unloading fronts amounts to 24:

$$k = 2! \cdot (2! \cdot 3!) = 24$$

Thus, since the five loading and unloading fronts are connected to the station by two linking tracks, the total number of feasible variants amounts to 24. Within these possible variants, the sequence of delivering wagons to the loading and unloading fronts is considered.

The identified variants are analyzed based on the wagon-hour indicators of the servicing process. In this analysis, the occupation time of the shunting locomotive, the waiting duration of wagons at the station and at loading-unloading locations, as well as the total time expenditure arising during the servicing process are calculated. The wagon-hour indicator is adopted as the main criterion for evaluating servicing efficiency.

Based on the obtained results, all servicing variants are compared, and the variant with the minimum wagon-hour indicator is selected as the optimal solution.

In the process of servicing industrial sidings, the main objective is to organize the delivery and removal of wagons to and from all loading and unloading locations in such a sequence that the wagon-hour indicator attains its minimum value.

To determine the servicing sequence, the following binary decision variable is introduced:

$$x_{ij} = \{1; 0\} \quad (7)$$

where i – loading-unloading fronts to be serviced ($i=1,2,3,\dots,n$);

j – loading-unloading fronts ($j=1,2,3,\dots,n$).

If loading-unloading location j is serviced in the i -th order – 1; otherwise – 0.

Decision variables are represented in the following matrix form:

$$X = \begin{bmatrix} x_{11} & x_{12} & x_{13} & \dots & x_{1n} \\ x_{21} & x_{22} & x_{23} & \dots & x_{2n} \\ x_{31} & x_{32} & x_{33} & \dots & x_{3n} \\ \dots & \dots & \dots & \dots & \dots \\ x_{n1} & x_{n2} & x_{n3} & \dots & x_{nn} \end{bmatrix} \quad (8)$$

In this matrix, each row represents a specific service order, and each column represents a particular loading-unloading front.

For practical use, it is convenient to represent it in the form of Table 1 with dimensions $n \times n$.

Table 1. Fragment representing a servicing variant for industrial sidings. n .

q_i	servicing time t_i , (hours)					variant
	t_1	t_2	t_3	...	t_i	

1	u_1	+	-	-	...	-	1
2	u_2	+	+	-	...	-	2
3	u_3	+	+	+	...	-	3
...
n_i	u_i	+	+	+	...	+	n

he technological time parameters t_i are calculated, where t_i is the technological time required to service loading-unloading location j (hours), including shunting movements, coupling and uncoupling of wagons, and their delivery to the front.

Due to the servicing sequence, the start time for servicing at position i is determined as follows:

$$T_i = \sum_{k=1}^i \sum_{j=1}^n t_j x_{kj}, \text{ hours.} \quad (9)$$

That is, servicing of front i begins only after all preceding operations have been completed.

The wagon-hour indicator is taken as the objective function and is expressed as follows, taking into account the cumulative effect of the servicing sequence:

$$B = \sum_{i=1}^k q_i \cdot T_i = \sum_{i=1}^k q_i \cdot \sum_{k=1}^i \sum_{j=1}^n t_j x_{kj} \rightarrow \min, \text{ wagon- hours.} \quad (10)$$

Thus, this function is aimed at minimizing the wagon-hour indicator associated with the total waiting time of wagons at the station.

The application of this function is subject to the following constraints:

1. Each loading-unloading location is serviced only once:

$$\sum_{j=1}^n x_{ij} = 1, \forall j \quad (11)$$

2. At each service step, only one loading-unloading location is serviced:

$$\sum_{j=1}^n x_{ij} = 1, \forall i \quad (12)$$

3. Number of wagons that can be delivered to each loading-unloading location:

$$0 < q_i \leq q_{\max}^{fr}; \quad (13)$$

4. Time required to deliver wagons to each loading-unloading front:

$$t_{\min}^{fr} \leq t_i \leq t_{\max}^{fr}, \quad (14)$$

where: q_{\max}^{fr} – maximum number of wagons that can be delivered to loading-unloading fronts in a single transfer, wagons:

$t_{\min}^{fr}, t_{\max}^{fr}$ – minimum and maximum time for delivering wagons to the loading-unloading fronts, respectively, hours.

5. Variable domain:

$$x_{ij} \in \{0,1\} \quad (15)$$

With the given constraints, the final optimization model can be expressed as follows:

$$B = \sum_{i=1}^k q_i \cdot T_i = \sum_{i=1}^k q_i \cdot \sum_{k=1}^i \sum_{j=1}^n t_j x_{kj} \rightarrow \min. \quad (16)$$

$$\sum_{j=1}^n x_{ij} = 1, \forall j$$

$$\sum_{j=1}^n x_{ij} = 1, \forall i$$

$$x_{ij} \in \{0,1\}$$

The proposed model solves the problem of selecting the servicing sequence for industrial sidings by reducing it to the minimization of cumulative waiting time (Table 2). The model accounts for the fact that, as the servicing order is delayed, the number of waiting wagons increases, which fully corresponds to the technological logic of real shunting processes.

Table 2. Representation of a servicing variant for the industrial sidings of station "N-1". n .

	q_i	servicing time t_i , (hours)					variant
		1.2	1.6	2.4	1.8	2.2	
1	3	+	-	-	-	-	1
2	4	+	+	-	-	-	2
3	2	+	+	+	-	-	3
4	3	+	+	+	+	-	4
5	5	+	+	+	+	+	5

For this servicing sequence, the wagon-hour indicator for delivering wagons to the loading-unloading locations is calculated as follows:

$$B = q_1 t_1 + q_2 (t_1 + t_2) + q_3 (t_1 + t_2 + t_3) + \dots + q_5 (t_1 + \dots + t_5), \text{ wagon-hours} \quad (17)$$

By substituting the parameter values, the value of B is calculated as follows:

$$B = 3 \cdot 1, 2 + 4 \cdot (1, 2 + 1, 6) + \dots + 5 \cdot (1, 2 + \dots + 2, 2) = 84, 6 \text{ wagon-hours}$$

This procedure is sufficient only for calculating the wagon-hour indicator for the sequence 1→2→3→4→5. For comparison purposes, it is necessary to determine the servicing sequence and calculate the wagon-hour indicator for the remaining 23 variants as well.

First, all possible servicing sequences are identified (Table 3).

Table 3. Servicing variants for the industrial sidings of station "N-1". Variant.

	Servicing sequence
1-variant	1→2→3→4→5
2-variant	1→2→3→5→4
3-variant	1→3→2→4→5
4-variant	1→3→2→5→4
5-variant	2→1→3→4→5
6-variant	2→1→3→5→4
7-variant	2→3→1→4→5
8-variant	2→3→1→5→4
Variant	Servicing sequence
9-variant	3→1→2→4→5
10-variant	3→1→2→5→4
11-variant	3→2→1→4→5
12-variant	4→5→2→1→3
13-variant	3→2→1→5→4
14-variant	5→4→1→2→3
15-variant	4→5→1→3→2
16-variant	5→4→1→3→2
Variant	Servicing sequence
17-variant	4→5→1→2→3
18-variant	5→4→2→1→3
19-variant	4→5→2→3→1
20-variant	5→4→2→3→1
21-variant	4→5→3→1→2

22-variant	5→4→3→1→2
23-variant	4→5→3→2→1
24-variant	5→4→3→2→1

All values of the wagon-hour indicator for these variants can be observed and compared in Figure 6.

The calculation results showed that among the 24 possible servicing variants, Variant 13 corresponding to the sequence 4→5→2→1→3 was selected as optimal. This order ensures the minimum value of the wagon-hour indicator.

In this sequence, priority is given at the initial stages of servicing to loading-unloading fronts with a relatively large number of wagons, which slows the growth of cumulative waiting time. As a result, the objective function attains its lowest value, and this variant is therefore selected as the optimal solution.

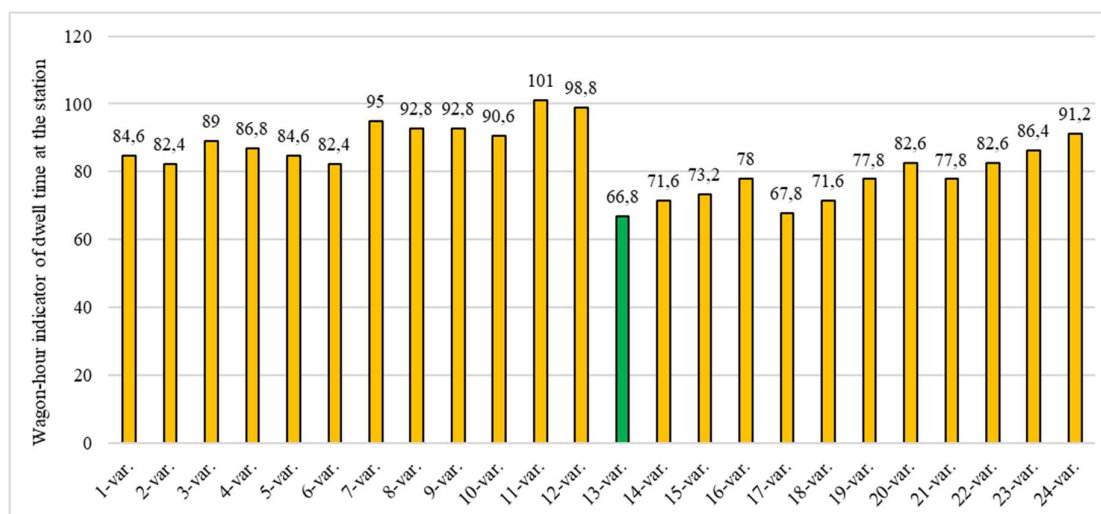


Figure 6. Wagon-hour dwell indicators for servicing variants of the industrial sidings at station “N-1”.

The proposed mathematical model makes it possible to formally represent the combinatorial complexity arising from an increase in the number of industrial sidings and serves as a foundation for developing algorithmic approaches in the subsequent stage.

4.4. Algorithmic approach and software development

For each servicing variant, it is necessary to calculate separately the movement time of the shunting locomotive, the duration of wagon coupling and uncoupling operations, the transfer time between station necks, and the duration of loading and unloading processes. When the servicing sequence changes, these time parameters must be recalculated, which further complicates the computational process.

Therefore, manual calculation of all possible variants is practically infeasible, which necessitates the use of an algorithmic approach to determine the optimal servicing sequence. The algorithmic approach enables the formalization of the servicing process, the systematic evaluation of all variants, and the scientifically grounded selection of the optimal solution.

The proposed algorithm represents the computational mechanism for solving the optimization problem formulated in the mathematical model. The algorithm generates all possible servicing sequences based on permutations and calculates the wagon-hour indicator of the objective function for each variant. In this way, the algorithm translates the optimization problem defined in the

mathematical model into a direct computational procedure, ensuring a close linkage between the theoretical model and the practical calculation process.

The algorithm consists of the following main stages:

1. Input of initial data parameters.
2. Generation of all possible servicing sequences.
3. Calculation of the objective function for each sequence.
4. Comparison of the obtained values and identification of the optimal solution with the minimum wagon-hour value.

The logical sequence of the algorithm is illustrated in Figure 7.

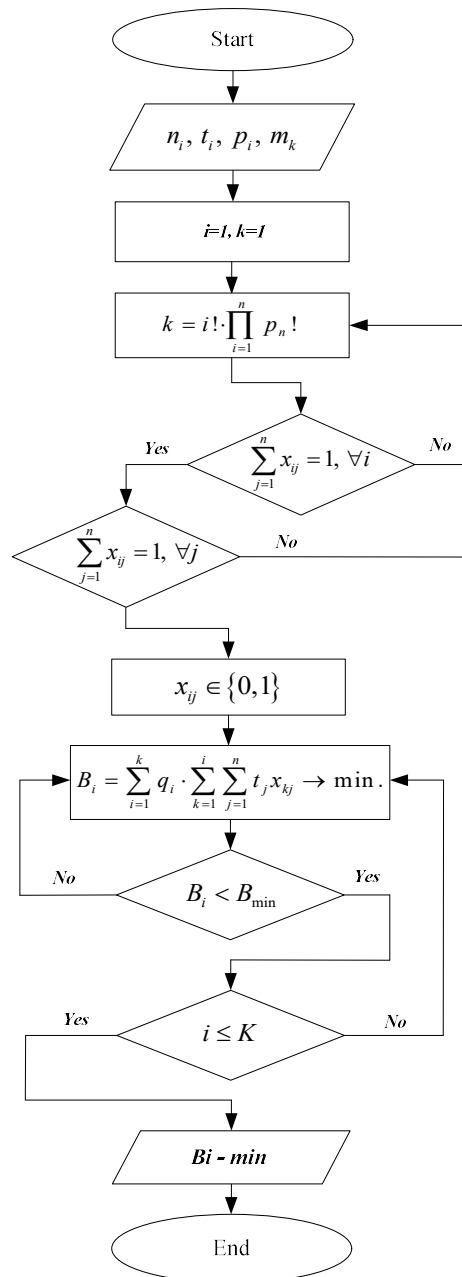


Figure 7. Algorithm for Selecting the Servicing Sequence of Industrial Sidings.

The algorithm begins with the input of initial parameters. Based on these parameters, all possible servicing sequences are generated. For each sequence, the duration of the servicing process and the waiting time of wagons are taken into account, and the total wagon-hour indicator is calculated.

During the computation process, the value of the objective function obtained for each sequence is compared with the previously recorded minimum value. If the current value is smaller than the minimum, it is accepted as the new optimal solution. This procedure continues until all possible variants have been evaluated.

As a result, the servicing sequence that minimizes the wagon-hour indicator is identified as the optimal solution.

Based on the proposed algorithm, software was developed to automate the servicing process. The program allows the user to enter initial parameters through a user-friendly interface, automatically perform the calculations, and obtain the results in a visual form.

The software was developed to fully reflect the logical sequence of the algorithm, thereby reducing the influence of the human factor in calculations and improving the reliability of the results. The program's initial data input interface is shown in Figure 8.

OPTIMAL SERVICING OF INDUSTRIAL SIDINGS

Enter initial data ⌵

Number of connecting tracks:
2 ⌵

Number of fronts on connecting track 1:
3 ⌵

Data for front 1:
 Number of wagons: 3 ⌵ Servicing time: 1,20 ⌵

Data for front 2:
 Number of wagons: 4 ⌵ Servicing time: 1,60 ⌵

Data for front 3:
 Number of wagons: 2 ⌵ Servicing time: 2,40 ⌵

Number of fronts on connecting track 2:
2 ⌵

Data for front 4:
 Number of wagons: 3 ⌵ Servicing time: 1,80 ⌵

Figure 8. Program interface for entering initial parameters.

The use of the developed software makes it possible to efficiently determine the optimal sequence for delivering wagons to loading-unloading locations (Figure 8). Applying the optimal sequence ensures minimization of the total wagon-hour indicator and consequently reduces wagon dwell time and the number of shunting operations. The calculation results obtained by the program can be viewed in the software interface shown in Figure 9. The consistency between the calculated wagon-hour indicators of the servicing variants presented in Figure 6 and the results obtained through the program shown in Figure 9 confirms the reliability of the proposed method.

Data fo front 5:

Number of wagons: 5 Servicing time: 2.20

CALCULATE

CALCULATION RESULTS

Total number of fronts: 5
 Number of feasible variants: 24
 Minimum wagon idle time B=66.8 wagon-hours
 Optimal servicing sequence:
 1. 4 – front
 2. 5 – front
 3. 2 – front
 4. 1 – front
 5. 3 – front

Figure 9. Program Interface for Displaying Calculation Results.

The developed software has the following main capabilities:

- Interactive input of the initial parameters required for the servicing process;
- Flexible configuration of parameters related to loading-unloading fronts;
- Automatic analysis of all possible servicing variants;
- Determination of the optimal servicing sequence;
- Calculation of the total process time, wagon-hours, and other operational indicators;

The developed software can be used as a decision-support tool for planning loading and unloading operations.

Thus, the practical infeasibility of manually determining the servicing sequence justifies the need for an algorithmic approach. The proposed algorithm makes it possible to determine the optimal solution on a scientific basis. The software developed on the basis of the algorithm automates the computational process and improves the efficiency of decision-making. As a result, a practically convenient tool for planning loading and unloading operations has been created. The developed method is specialized for conditions where industrial sidings are served by a single locomotive; therefore, further refinement of the method is required for situations involving multiple locomotives.

4.5. *Selecting the optimal servicing sequence under multiple shunting locomotive conditions*

If, in the single-locomotive case, the servicing sequence played the key role, then under conditions of using two or more shunting locomotives, the allocation of wagon groups among locomotives becomes decisive.

In practice, at large railway stations the servicing of loading and unloading locations is often carried out with the participation of several shunting locomotives. This helps increase the station's

processing capacity and reduce excessive wagon dwell time. At the same time, the parallel operation of multiple locomotives significantly increases the complexity of the servicing process.

Since two shunting locomotives use the same station throat and common track sections, their movements must be coordinated. As a result, the problem of selecting the servicing order is not limited to determining the sequence alone but also requires consideration of the technological interdependencies between locomotives. Therefore, this situation necessitates the development of an extended mathematical model and a corresponding algorithmic approach compared with the single-locomotive system.

When two shunting locomotives are used, the servicing plan consists of allocating wagon groups between the locomotives and determining the order of their execution. In this process, the wagon-hour amount associated with waiting during servicing is considered the main operational indicator.

The objective of the problem is to minimize the total number of wagon-hours under conditions where two shunting locomotives are used.

The following parameters are adopted in the model. In particular, t_i denotes the technological time required to service group i , and n denotes the number of industrial sidings to be serviced;

The following binary variables are introduced to represent the allocation of wagons among locomotives:

$$x_{il} = \{1; 0\} \quad (18)$$

where x_{il} indicator of assignment of group i to locomotive l

i – front index to be serviced ($i=1,2,3,\dots,n$);

l – number of shunting locomotives

If loading-unloading location i is serviced in the l -th order 1; otherwise 0. This variable determines to which locomotive each wagon group is assigned.

If loading-unloading location i is assigned to locomotive l , the start time of its servicing depends on the technological times of the groups previously handled by that locomotive:

$$T_{il} = \sum_{j \in P_l(i)} t_j \text{ hours} \quad (19)$$

where $P_l(i)$ – l is the set of groups processed by locomotive l before group i .

Since the main indicator for evaluating wagon waiting time is the minimization of the wagon-hours of dwell, the objective function is expressed as follows:

$$B = \sum_{l=1}^m \sum_{i=1}^n q_i T_{il} x_{il} \rightarrow \min \quad (20)$$

where q_i – number of wagons in group i ;

T_{il} – service start time.

The reduction in the wagon-hour waiting indicator resulting from assigning loading-unloading location 1 to shunting locomotive 2 can be expressed as follows:

$$\sigma_1 = (q_1 + q_2 + q_3 + \dots + q_n) \cdot t_1 \quad (21)$$

The reduction in the wagon-hour waiting indicator resulting from assigning loading-unloading location 2 to shunting locomotive 2 can be expressed as follows:

$$\sigma_2 = q_2 \cdot t_1 + (q_3 + q_4 + q_5 + \dots + q_n) \cdot t_2 \quad (22)$$

The reduction in the wagon-hour waiting indicator resulting from assigning loading-unloading location 3 to shunting locomotive 2 can be expressed as follows:

$$\sigma_3 = q_3 \cdot (t_1 + t_2) + (q_4 + q_5 + q_6 + \dots + q_n) \cdot t_3, \text{ wagon-hours} \quad (23)$$

The reduction in the wagon-hour waiting indicator resulting from assigning an arbitrary loading-unloading location k to shunting locomotive 2 can be expressed as follows:

$$\sigma_k = q_k \cdot \sum_{i=1}^{k-1} t_i + \sum_{i=k+1}^n q_i \cdot t_k, \text{ wagon-hours} \quad (24)$$

Here, the first term represents the gain in the wagon-hour indicator from servicing loading-unloading location k , while the second term represents the gain from servicing the subsequent loading-unloading locations.

If any two loading-unloading locations i and j ($i < j$) at the station are assigned to the second locomotive, the reduction in wagon-hours is:

$$\sigma_{ij} = \sigma_i + \sigma_j - (q_i t_j + q_j t_i), \text{ wagon-hours} \quad (25)$$

where σ_i and σ_j – the gain in the wagon-hour indicator obtained by allocating each loading-unloading location to the second shunting locomotive;
 $q_i t_j + q_j t_i$ – the wagon-hour contribution of waiting in the overlapping part of the two loading-unloading locations.

If any three loading-unloading locations i, j , and k ($i < j < k$) at the station are assigned to the second locomotive, the reduction in wagon-hours is:

$$\sigma_{ijk} = \sigma_i + \sigma_j + \sigma_k - (q_i t_j + q_i t_k + q_j t_i + q_j t_k + q_k t_i + q_k t_j), \text{ wagon-hours} \quad (26)$$

These formulas represent classical recurrence relations and are calculated based on Table 5.

If any g loading-unloading locations at the station are assigned to the second locomotive, the reduction in wagon-hours is:

$$G = \{i_1, i_2, i_3, \dots, i_g\}; i_1 < i_2 < i_3 < \dots < i_g \quad (27)$$

In this case, the total reduction for the variables in Formula (27) is:

$$\sigma(G) = \sum_{r=1}^g \sigma_{i(r)} - \sum_{1 \leq r < s \leq g} (q_{i(r)} t_{i(s)} + q_{i(s)} t_{i(r)}), \text{ wagon-hours} \quad (28)$$

In the problem of using two shunting locomotives, the allocation of loading-unloading fronts between locomotives possesses a symmetric property. In particular, distributions such as 1/17 and 17/1, 2/16 and 16/2, 3/15 and 15/3 are equivalent in terms of the total wagon-hours, differing only by the interchange of locomotives, while the servicing efficiency remains unchanged. Therefore, when determining the optimal allocation for 18 fronts, it is sufficient to consider only nine asymmetric cases from 1/17 to 9/9. This significantly reduces the computational complexity without losing the optimal solution.

At this stage, the problem reduces to determining the optimal proportion in which loading-unloading fronts should be distributed between two shunting locomotives. In other words, it is necessary to determine which division of the 18 fronts such as 8/10, 6/12, 9/9, and similar splits results in the minimum total wagon-hours. For this purpose, the reduction in wagon-hours $\sigma(G)$ is calculated for each allocation variant, and the case with the maximum value is accepted as optimal.

The number of possible variants for distributing the servicing of n loading-unloading locations at the station between two shunting locomotives can be expressed as 2^n .

Excluding the two trivial allocation cases, namely $0/n$ and $n/0$, the number of feasible variants can be expressed as $2^n - 2$

Taking into account that all existing variants are symmetric, i.e., each allocation has an equivalent counterpart,

$$\frac{2^n - 2}{2} = \frac{2 \cdot (2^{n-1} - 1)}{2} = 2^{n-1} - 1 \quad (29)$$

For the case considered in this study, there are 131 071 possible variants for servicing the 18 loading-unloading locations.

The efficiency achieved when two shunting locomotives are used is determined as follows:

$$B_1 - B = \sigma, \text{ wagon-hours} \quad (30)$$

The objective of the problem is to maximize the reduction in wagon-hours, i.e.:

$$\sigma \rightarrow \max \quad (31)$$

The objective of the problem is to maximize the reduction in wagon-hours, i.e.:

It is appropriate to impose the following constraints on the objective function:

1. Each wagon group must be serviced by only one shunting locomotive:

$$\sum_{i=1}^m x_{il} = 1, \forall i \quad (32)$$

This constraint excludes the possibility of two or more locomotives servicing the same group simultaneously.

2. Nature of the variables: the decision variables are binary:

$$x_{il} \in \{1; 0\}, \forall i, l \quad (33)$$

3. Constraint on locomotive movements within the station throat.

4. Two shunting locomotives are not allowed to operate simultaneously within the same station throat. If servicing two groups requires the use of the throat, then a time gap of at least δ must be maintained between their servicing times.

$$|T_{i1} - T_{j2}| \geq \delta, \forall i, j \in G. \quad (34)$$

where G – set of groups requiring the use of the station throat for servicing.

This constraint prevents technological conflicts between locomotives.

Thus, when two or more shunting locomotives are used, the servicing plan is reduced to the following optimization problem:

$$\begin{aligned} B &= \sum_{l=1}^m \sum_{i=1}^n q_i T_{il} x_{il} \rightarrow \min \\ B_1 - \sum_{l=1}^m \sum_{i=1}^n q_i T_{il} x_{il} &= \sigma \\ \sigma(G) &= \sum_{r=1}^g \sigma_{i(r)} - \sum_{1 \leq r < s \leq g} (q_{i(r)} t_{i(s)} + q_{i(s)} t_{i(r)}) \\ \sigma &\rightarrow \max \\ \sum_{i=1}^m x_{il} &= 1, \forall i \\ |T_{i1} - T_{j2}| &\geq \delta, \forall i, j \in G \\ x_{il} &\in \{1; 0\}, \forall i, l. \end{aligned} \quad (35)$$

The presented mathematical model formalizes the process of servicing loading-unloading fronts using two or more shunting locomotives. The model is based on evaluation through the wagon waiting indicator (B) and the saved wagon-hours criterion (σ), making it suitable for optimizing the servicing order and for subsequent algorithmic and software implementation.

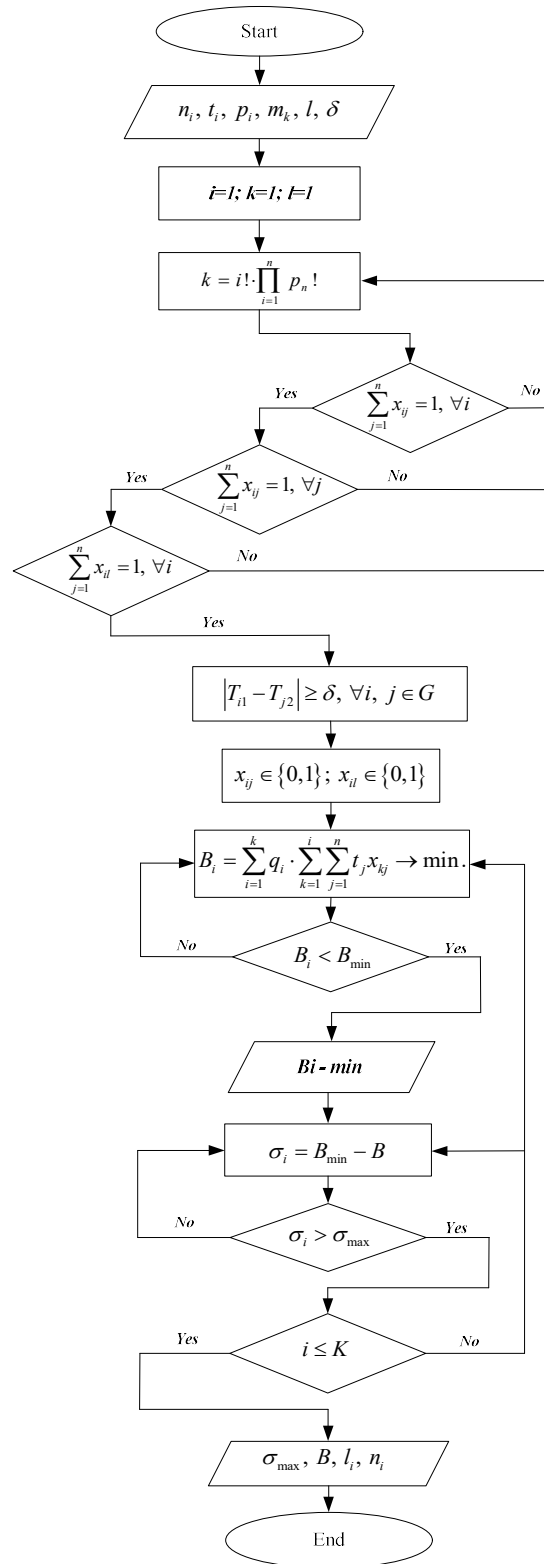


Figure 10. Algorithm for Selecting the Servicing Sequence for Industrial Sidings under Multiple Shunting Locomotive Operation.

This process was formalized using a mathematical model. The model incorporates the allocation of wagon groups among locomotives, the servicing sequence, and constraint conditions reflecting the impossibility of simultaneous operation within the station throat. The objective function is defined



as the minimization of the total wagon-hours (B), or equivalently, the maximization of the efficiency (σ) obtained from using two locomotives.

To apply the developed mathematical model in practical calculations, it was transformed into an algorithmic form. The proposed algorithm is based on examining all possible servicing variants, calculating the wagon-hours for each variant, verifying compliance with technological constraints, and identifying the optimal option. The overall logical structure and main stages of the algorithm are presented in Figure 10.

In this section, an algorithm was developed for the operation of two shunting locomotives within a single station infrastructure, and its logical structure was presented in the form of a flowchart. The algorithm fully corresponds to the decision variables, constraint conditions, and objective function introduced in the mathematical model and takes into account all major technological characteristics of the servicing process. Thus, the developed algorithm can be analogously applied under conditions where industrial sidings at a railway station are serviced by multiple shunting locomotives.

To evaluate the practical efficiency of the proposed algorithm, it was applied to a computational problem close to real station conditions. For this purpose, the initial parameters were formed based on the number of loading-unloading fronts, the composition of wagon groups, technological times, and constraints related to the station throat. The algorithm examines all possible servicing variants, calculates the wagon-hours for each variant, and determines the optimal servicing sequence. In this way, the operation of the algorithm was demonstrated using a practical example, and its applicability under real station conditions was assessed. The calculation results and their analysis are presented below.

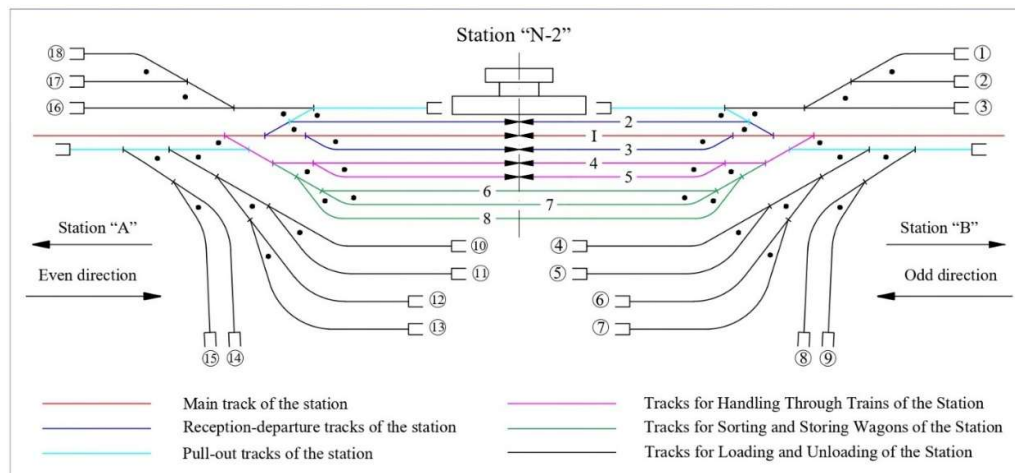


Figure 11. Layout of the “N-2” Railway Station and Its Adjacent Industrial Siding Network.

To analyze the simultaneous operation of two shunting locomotives, a scheme reflecting the spatial structure of the station is used (Figure 11). This scheme shows the main tracks, arrival-departure tracks, classification and loading-unloading tracks, as well as shunting movements performed through the station throats, which makes it possible to coordinate locomotive movements and to organize the servicing process in a technologically sound manner.

This scheme serves as a basis for identifying technological constraints associated with the use of common track sections by two locomotives, coordinating their movements, and evaluating the most efficient servicing sequence.

As initial parameters for the loading-unloading fronts available at the station, the number of wagons q_i for each front and the servicing time t_i for that front are specified. These data are presented in tabular form for loading fronts numbered 1-18 and serve as the basis for subsequent calculations.

To perform calculations for the case of using two shunting locomotives, the developed software allows the user to input station parameters, the number of connecting tracks, the number of shunting locomotives, and the initial data for each loading-unloading front (Figure 12). This demonstrates the

universality of the program compared with the single-locomotive case, as the number of shunting locomotives can be freely adjusted. Based on these data, calculations for optimizing the servicing process are carried out.

OPTIMAL SERVICING OF INDUSTRIAL SIDINGS

Enter initial data ⌵

Number of connecting tracks:
6 ⌵

Number of shunting locomotives:
2 ⌵

Number of fronts on connecting track 1:
3 ⌵

Data for front 1:
 Number of wagons: 3 ⌵ Servicing time: 2,40 ⌵

Data for front 2:
 Number of wagons: 4 ⌵ Servicing time: 1,70 ⌵

Data for Front 3:
 Number of wagons: 2 ⌵ Servicing time: 2,10 ⌵

Figure 12. Software Interface for Entering Initial Parameters When Using Multiple Locomotives.

Using these initial parameters, Table 5 is formed to represent the optimal servicing sequence for the loading-unloading fronts under the single shunting locomotive condition. Table 5 plays a key role in calculating the wagon-hours for the base case and in determining the σ values required for evaluating the efficiency of using multiple shunting locomotives in subsequent analysis.

Thus, the values q_i and t_i serve as the initial information for constructing Table 5 (Table 4) and form the mathematical basis of the entire optimization process.

Table 4. Data on the Number of Wagons Delivered to Industrial Sidings and the Servicing Time at Railway Station "N-2".

N	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
q_i	3	4	2	3	2	3	1	2	6	2	2	3	4	1	2	3	4	2
t_i	2.4	1.7	2.1	1.3	2.8	1.9	2.5	1.1	2.0	1.6	1.7	1.4	2.2	1.8	1.6	1.2	2.3	1.5

For the loading-unloading fronts of railway station "N-2", the values of the number of wagons q_i and the servicing time t_i for each front are presented in the table. Based on entering these initial

parameters into the program, the optimization problem for the case of using a single shunting locomotive was solved.

During the calculation process, all possible servicing sequences were examined, and the minimum wagon-hour value as well as the optimal servicing order were determined. The obtained results are presented in Figure 13.

Data for Front 18:

Vagonlar soni: Servicing time:

CALCULATION RESULTS

Total number of fronts: 18
 Number of feasible variants: 59 719 680
 Minimum wagon idle time for one locomotive: B=749,9 wag.-hours
 Optimal servicing sequence:

1. 15 – front
2. 14 – front
3. 4 – front
4. 6 – front
5. 5 – front
6. 7 – front
7. 2 – front
8. 1 – front
9. 3 – front
10. 12 – front
11. 13 – front
12. 10 – front
13. 11 – front
14. 16 – front
15. 17 – front
16. 18 – front
17. 9 – front
18. 8 – front

Figure 13. Program Interface Showing the Calculation Results and Optimal Servicing Sequence for Station “N-2” under the Single-Locomotive Case.

These results serve as the basis for analyzing the case of using two shunting locomotives. The minimum wagon-hour value determined for the single-locomotive scenario is taken as the reference criterion for comparison in the next stage. On this basis, the possibilities for reducing total wagon-hours by distributing loading-unloading fronts between locomotives are investigated. Considering the increase in the number of combinatorial variants in the two-locomotive case, the proposed mathematical model and algorithm are applied to determine the optimal allocation. As a result, an improvement in the efficiency of the servicing process and in the overall productivity of station operations is expected.

Based on the optimal sequence identified in Figure 13, the total wagon-hour indicator for delivering wagons to the loading-unloading locations is calculated. In this formula, the number of wagons q_i for each front and their cumulative servicing times are taken into account sequentially. By substituting the parameter values presented in the table into the variables of Formula (36), the total value is obtained. The obtained result makes it possible to quantitatively evaluate the efficiency of the selected servicing sequence and serves as a basis for comparison with multi-locomotive scenarios in the subsequent stage. Thus, the calculated indicator is accepted as an important criterion for determining the practical effectiveness of the optimal sequence. For this servicing order, the wagon-hour indicator for delivering wagons to the loading-unloading locations is calculated as follows:

$$B_1 = u_1 t_1 + u_2 (t_1 + t_2) + u_3 (t_1 + t_2 + t_3) + \dots + u_{18} (t_1 + \dots + t_{18}), \text{ wagon-hours} \quad (36)$$

By substituting the parameter values into the variables of Formula (36), the value of B is determined as follows:

$$B_1 = 3 \cdot 2,4 + 4 \cdot 4(2,4 + 1,7) + 2(2,4 + 1,7 + 2,1) + \dots + 2(2,4 + \dots + 1,5) = 749,9 \text{ wagon-hours}$$

Table 5. Matrix of the Optimal Servicing Sequence for the Single-Locomotive Case at Railway Station "N-2".

N	q	servicing time t_i , (hours)																va				
		i	2.	1.	1.	1.	1.	2.	2.	2.	1.	1.	1.	2.	1.	1.	2.		1.	1.	r.	
			5	9	1	7	3	1	8	3	2	7	4	0	6	7	4	2	8	6		
7	2	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	
6	1	+	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2	
8	6	+	+	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	3	
2	2	+	+	+	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	4	
4	2	+	+	+	+	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	5	
3	3	+	+	+	+	+	+	-	-	-	-	-	-	-	-	-	-	-	-	-	6	
5	3	+	+	+	+	+	+	+	-	-	-	-	-	-	-	-	-	-	-	-	7	
1	2	+	+	+	+	+	+	+	+	-	-	-	-	-	-	-	-	-	-	-	8	
7																						
1	4	+	+	+	+	+	+	+	+	+	-	-	-	-	-	-	-	-	-	-	9	
6																						
1	3	+	+	+	+	+	+	+	+	+	+	-	-	-	-	-	-	-	-	-	10	
1																						
1	4	+	+	+	+	+	+	+	+	+	+	+	-	-	-	-	-	-	-	-	11	
2																						
9	2	+	+	+	+	+	+	+	+	+	+	+	+	-	-	-	-	-	-	-	12	
1	2	+	+	+	+	+	+	+	+	+	+	+	+	+	-	-	-	-	-	-	13	
0																						
2	4	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	-	-	-	-	14	
1	3	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	-	-	-	15	
1	1	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	-	16	
3																						
1	2	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	-	17
4																						
1	3	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	18
5																						

For the case of using a single shunting locomotive, the optimal servicing variant for the loading-unloading fronts was determined. According to the fronts, this order formed the sequence 15→14→4→6→5→7→2→1→3→12→13→10→11→16→17→18→9→8 This sequence ensures the minimum wagon-hour value for the single-locomotive case and serves as a reference for subsequent comparisons. The problem then proceeds to distributing the servicing of the fronts between two shunting locomotives. In this stage, the loading-unloading fronts are divided into two groups using a combinatorial approach, and a separate servicing sequence is formed for each locomotive. The evaluation results of the two-locomotive allocation variants are presented in Table 5.

After determining the total wagon-hours B_1 for the case of using a single shunting locomotive, the next step is to calculate the values of σ , which characterize the reduction in wagon-hours



resulting from distributing the loading-unloading fronts between two locomotives (Table 6). The σ values obtained for each possible allocation variant are compared, and the case with the maximum σ is accepted as optimal. This is because in this variant the total wagon-hours $B_1 - \sigma$ reach their minimum value. This approach makes it possible to balance the workload of each locomotive, reduce excessive waiting times, and shorten the overall duration of the servicing process. Thus, it is substantiated that the two-locomotive servicing mode is technologically superior to the single-locomotive case.

Table 6. Matrix of σ Values Describing the Distribution of Loading-unloading Fronts between Two Locomotives at Railway Station “N-2”.

N	q	Servicing time t_i , (hours)																va		
		2.	1.	1.	1.	1.	2.	2.	2.	1.	1.	1.	2.	1.	1.	2.	2.		1.	1.	r.
	i	5	9	1	7	3	1	8	3	2	7	4	0	6	7	4	2	8	6	
7	2	σ	σ	σ	...	...	...	...	...	...	...	...	...	...	...	...	...	σ_1	σ_1	1
		1	12	13														17	18	
6	1	+	σ	σ	...	...	...	...	...	...	...	...	...	...	...	...	...	σ_2	σ_2	2
			2	23														17	18	
8	6	+	+	σ	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	3
				3																
2	2	+	+	+	σ	...	...	...	...	...	...	...	...	...	...	...	...	...	...	4
				4																
4	2	+	+	+	+	σ	...	...	...	...	...	...	...	...	...	...	...	...	...	5
				5																
3	3	+	+	+	+	+	σ	...	...	...	...	...	...	...	...	...	...	...	...	6
				6																
5	3	+	+	+	+	+	+	σ	...	...	...	...	...	...	...	...	...	...	...	7
				7																
17	2	+	+	+	+	+	+	+	σ	...	...	...	...	...	...	...	...	...	...	8
				8																
16	4	+	+	+	+	+	+	+	+	σ	...	...	...	...	...	...	...	...	...	9
				9																
11	3	+	+	+	+	+	+	+	+	+	σ	...	...	...	...	...	...	...	...	10
				10																
12	4	+	+	+	+	+	+	+	+	+	+	σ	...	...	...	...	...	...	...	11
				11																
9	2	+	+	+	+	+	+	+	+	+	+	+	σ	...	...	...	...	...	...	12
				12																
10	2	+	+	+	+	+	+	+	+	+	+	+	+	σ	...	...	...	...	...	13
				13																
2	4	+	+	+	+	+	+	+	+	+	+	+	+	+	σ	...	...	...	...	14
				14																
1	3	+	+	+	+	+	+	+	+	+	+	+	+	+	+	σ	...	...	...	15
				15																
13	1	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	σ	...	...	16
				16																

14	2	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	σ_1	...	17
15	3	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	σ_1		18

Based on the initial data presented in Table 4 and the performed calculations, the developed algorithm was implemented in a software environment. Using the program, the optimal allocation of loading-unloading fronts between two shunting locomotives was determined, and the results are presented in Figure 14. The matrix in Table 5, formed using the values of q_i and t_i given in Table 6, together with the calculated σ values, was analyzed by the algorithm, and the optimal allocation minimizing the total wagon-hours was selected.

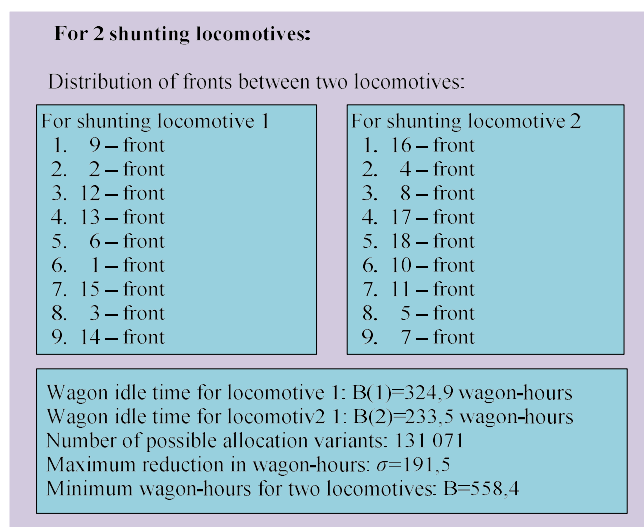


Figure 14. Program Interface Showing Calculation Results for the Multi-Locomotive Case at Railway Station “N-2”.

As a result of the performed calculations, the optimal allocation of loading-unloading fronts between two shunting locomotives was determined. The calculations showed that when nine loading-unloading fronts are assigned to each locomotive, the total wagon-hours reach their minimum value. In this case, the wagon-hours amount to 324.9 for the first locomotive and 233.5 for the second locomotive.

As a result, when two shunting locomotives are used, the total wagon-hours amount to 558.4 wagon-hours. Compared with the single-locomotive case, this represents a saving of 191.5 wagon-hours. The obtained results confirm that the proposed mathematical model and algorithm enable the efficient organization of shunting operations at large freight stations.

6. Results and Discussion

To evaluate the effectiveness of the proposed mathematical model, algorithm, and software approach, computational experiments were conducted. During the study, various servicing variants for loading-unloading fronts were examined, and their impact on the total wagon-hours was analyzed. The calculations were performed separately for the cases of using one locomotive and two or more shunting locomotives, and the obtained results were compared. The results demonstrated that optimizing the servicing sequence and properly allocating fronts between locomotives significantly improves the overall efficiency of station operations.

6.1. Results

To evaluate the effectiveness of the proposed mathematical model and algorithmic approach, computational experiments were carried out using the data of the hypothetical railway station "N-1". In the study, a real technological scenario with five loading-unloading fronts was first considered. For each front, the servicing duration and the number of wagons to be handled were taken as initial parameters.

First, the case of using a single shunting locomotive was analyzed. Under this condition, the servicing sequence for all loading-unloading fronts was determined based on the mathematical model, and the total wagon-hours representing the cumulative waiting time of wagons were calculated. The results showed that when only one locomotive is used, the overall duration of the servicing process is relatively long and the time wagons spend idle at the station increases significantly.

In particular, Table 7 shows that the optimal servicing sequence 3-2-1-5-4 for the loading-unloading locations performs 21% better than the arbitrarily selected sequence 1-2-3-4-5. At the same time, the optimal servicing order reduces the average wagon idle time by up to 20%.

Table 7. Comparative Analysis of Calculation Results for Servicing Loading - Unloading Fronts.

<i>Arbitrary sequence</i>	<i>Average case</i>	<i>Optimal sequence</i>
1→2→3→4→5	24 possible variants	3→2→1→5→4
84.6 wagon-hours	83.7 wagon-hours	66.8 wagon-hours

In the next stage, the servicing process was analyzed under the condition of using two or more shunting locomotives. In this case, different allocation ratios of loading-unloading fronts between locomotives were examined. The theoretical analysis showed that the allocation variants possess a symmetric property. Therefore, instead of considering all possible variants for 18 fronts, it was sufficient to analyze only the asymmetric distributions, i.e., those ranging from 1/17 to 9/9. This approach significantly reduced the computational complexity.

The optimal sequence determined for the single-locomotive case 15→14→4→6→5→7→2→3→12→13→10→11→16→17→18→9→8 was divided into two optimal subsequences for two shunting locomotives as follows: 9→2→12→13→6→1→15→3→14 and 16→4→8→17→18→10→11→5→7. Under this allocation, the wagon-hours for each locomotive amounted to 324.9 and 233.5 wagon-hours, respectively.

For each allocation variant, the indicator $\sigma(G)$, representing the reduction in wagon-hours, was calculated. The results showed that a relatively balanced distribution of loading-unloading fronts between locomotives leads to higher servicing efficiency. In particular, for the 9/9 allocation variant, the value of $\sigma(G)$ was maximal, and the total wagon-hours reached their minimum value.

The obtained results showed that the use of multiple shunting locomotives increases the overall efficiency of the servicing process and reduces the wagon-hour waiting indicator by up to 26%. According to the calculations, engaging a second locomotive resulted in a saving of 191.5 wagon-hours in total waiting time. This makes it possible to reduce wagon idle time at the station, decrease the number of shunting operations, and improve the efficiency of locomotive utilization.

6.2. Discussion

To assess the robustness of the proposed optimization model and the influence of its parameters, a sensitivity analysis was conducted. During this analysis, the impact of variations in the main input parameters on the total wagon-hour indicator (B) and on the optimal servicing sequence was examined. In particular, changes in servicing times at loading-unloading fronts, the number of wagons, and the number of locomotives were found to have a significant influence on the model results.

The analysis demonstrated that the model remains stable under different operating conditions, while the optimal solution is preserved within certain ranges of parameter variation. This confirms the high practical applicability of the proposed approach.

Two types of parameters were considered in the sensitivity analysis:

1. The servicing time (t_i) was varied within a range of $\pm 50\%$;
2. The number of wagons (q_i) was varied within a range of ± 5 units.

In each experiment, only one parameter was varied while the others were kept constant. The main objective of the analysis was to determine the stability of the optimal sequence and to identify the threshold values at which a change in the servicing order occurs.

First, it is necessary to evaluate the effect of parameter variations related to the servicing time (t_i) at the industrial sidings. Table 8 presents the results of increasing the servicing time from 0% to +50%. The results show that the total wagon-hour indicator B increases proportionally with changes in servicing time. The value of $\Delta B(\%)$ is equal to $\Delta t(\%)$, indicating that the system exhibits a linear behavior and that the elasticity coefficient is approximately equal to 1.

Moreover, for all increases of up to +50%, the optimal servicing sequence (4→5→1→3→2) remained unchanged. This confirms that the model is structurally stable with respect to increases in servicing time.

Table 8. Results of Increasing the Servicing Time of Industrial Sidings from 0% to +50%.

$q=const$	t_0	$+\Delta t (\%)$	$B(t_0)$	$B(t)$	$tartib$	$\Delta B(\%)$
6/8/7/9/8	1.5/1.2/1.4/1.8/1.6	0	165.50	165.50	4→5→1→3→2	0
6/8/7/9/8	1.5/1.2/1.4/1.8/1.6	10	165.50	182.05	4→5→1→3→2	10
6/8/7/9/8	1.5/1.2/1.4/1.8/1.6	20	165.50	198.60	4→5→1→3→2	20
6/8/7/9/8	1.5/1.2/1.4/1.8/1.6	30	165.50	215.15	4→5→1→3→2	30
6/8/7/9/8	1.5/1.2/1.4/1.8/1.6	40	165.50	231.70	4→5→1→3→2	40
6/8/7/9/8	1.5/1.2/1.4/1.8/1.6	50	165.50	248.25	4→5→1→3→2	50

Table 9 presents the results of reducing the servicing time by up to -50%. The results indicate that the total wagon-hour indicator decreases proportionally with the reduction in servicing time. The system exhibits a symmetric response to both positive and negative changes. For all considered values, the optimal sequence remained unchanged. This demonstrates that the model is stable over a wide range of variations in the servicing time parameter.

Table 9. Results of Reducing the Servicing Time at Industrial Sidings from 0% to -50%.

$q=const$	t_0	$-\Delta t (\%)$	$B(t_0)$	$B(t)$	$tartib$	$\Delta B(\%)$
6/8/7/9/8	1.5/1.2/1.4/1.8/1.6	0	165.50	165.50	4→5→1→3→2	0
6/8/7/9/8	1.5/1.2/1.4/1.8/1.6	10	165.50	148.95	4→5→1→3→2	10
6/8/7/9/8	1.5/1.2/1.4/1.8/1.6	20	165.50	132.40	4→5→1→3→2	20
6/8/7/9/8	1.5/1.2/1.4/1.8/1.6	30	165.50	115.85	4→5→1→3→2	30
6/8/7/9/8	1.5/1.2/1.4/1.8/1.6	40	165.50	99.30	4→5→1→3→2	40
6/8/7/9/8	1.5/1.2/1.4/1.8/1.6	50	165.50	82.75	4→5→1→3→2	50

Next, the effect of parameter variations related to the number of wagons (q_i) in the servicing process is evaluated. Table 10 presents the results of the stepwise increase in the number of wagons. According to the results, each additional wagon leads to a noticeable increase in the total wagon-hour indicator. However, unlike servicing time, an increase in the number of wagons affects the structural stability of the model.

It was found that when the number of wagons increases by three units, the optimal servicing sequence changes. This indicates the presence of a threshold value in the model and shows that priorities are redistributed as the freight volume increases.

Table 10. Results of Increasing the Number of Wagons from 1 to 5 in Servicing Industrial Sidings.

$t=const$	q_0	$+\Delta q$	$B(q_0)$	$B(q)$	$tartib$	$\Delta B(\%)$
1.5/1.2/1.4/1.8/1.6	6/8/7/9/8	0	165.50	165.50	4→5→1→3→2	0
1.5/1.2/1.4/1.8/1.6	6/8/7/9/8	1	165.50	186.60	4→5→1→3→2	12.75
1.5/1.2/1.4/1.8/1.6	6/8/7/9/8	2	165.50	207.70	4→5→1→3→2	25.50
1.5/1.2/1.4/1.8/1.6	6/8/7/9/8	3	165.50	228.80	5→4→3→1→2	38.25
1.5/1.2/1.4/1.8/1.6	6/8/7/9/8	4	165.50	249.90	5→4→3→1→2	51.00
1.5/1.2/1.4/1.8/1.6	6/8/7/9/8	5	165.50	271.00	5→4→3→1→2	63.75

Table 11 presents the results of decreasing the number of wagons. The analysis showed that when the number of wagons decreases by two units, the optimal sequence changes. This indicates that the system is more sensitive to reductions in freight volume. Thus, a decrease in freight volume produces an asymmetric response in the model, and the decision structure is reorganized more rapidly.

Table 11. Results of Decreasing the Number of Wagons by 1 to 5 Units in Servicing Industrial Sidings.

$t=const$	q_0	$-\Delta q$	$B(q_0)$	$B(q)$	$tartib$	$\Delta B(\%)$
1.5/1.2/1.4/1.8/1.6	6/8/7/9/8	0	165.50	165.50	4→5→1→3→2	0
1.5/1.2/1.4/1.8/1.6	6/8/7/9/8	1	165.50	143.90	4→5→1→3→2	13.05
1.5/1.2/1.4/1.8/1.6	6/8/7/9/8	2	165.50	120.60	4→5→1→3→2	27.13
1.5/1.2/1.4/1.8/1.6	6/8/7/9/8	3	165.50	97.30	1→3→2→5→4	41.21
1.5/1.2/1.4/1.8/1.6	6/8/7/9/8	4	165.50	74.00	1→3→2→5→4	55.29
1.5/1.2/1.4/1.8/1.6	6/8/7/9/8	5	165.50	50.70	1→3→2→5→4	69.37

The conducted sensitivity analysis allows the following conclusions to be drawn:

1. The model is highly stable with respect to the servicing time parameter, and the optimal sequence remains unchanged within a $\pm 50\%$ range.
2. The system is more sensitive to the number of wagons parameter, with structural changes observed when it varies by +3 or -3 units.

Overall, the proposed optimization model is stable with respect to variations in servicing time, but moderately sensitive to changes in the number of wagons. These results confirm the applicability of the model in practical conditions and indicate that the parameter representing the number of wagons to be serviced requires particular attention in the decision-making process.

The research results showed that, in optimizing the servicing process, it is essential to take into account the technological time parameters of loading-unloading fronts and the number of wagons. If the servicing sequence is formed based on these parameters, the cumulative waiting time of wagons decreases and the overall efficiency of station operations improves.

The proposed algorithm made it possible to systematically analyze all feasible servicing variants. The software developed on the basis of the algorithm enables automation of the calculation process, rapid obtaining of results, and determination of the optimal servicing sequence. This significantly simplifies the decision-making process in practical operating conditions.

The obtained results indicate that the developed mathematical model, algorithm, and software can be effectively applied in planning the servicing of loading-unloading fronts. The proposed approach contributes to improving the efficiency of shunting locomotive utilization at large freight stations and to reducing wagon idle time.

7. Conclusions

In this study, the problem of optimizing the servicing of loading-unloading fronts was investigated, and a mathematical model was developed to ensure the efficient organization of this

process. During the research, a method for determining the servicing sequence under the condition of a single shunting locomotive and for minimizing the total wagon-hours was substantiated. Due to the rapid growth in the number of combinatorial variants, it was shown that manual evaluation of all variants is practically infeasible, and therefore an algorithmic approach was proposed to solve this problem.

Under the condition of using multiple shunting locomotives, the problem of optimal allocation of loading-unloading fronts was analyzed based on the σ indicator. Taking into account the symmetry of allocation variants made it possible to simplify the computation process and quickly identify the optimal solution. Computational experiments were carried out using the example of a station with 18 loading-unloading fronts. According to the results, in the single-locomotive case the total wagon-hours amounted to 749.9 wagon-hours. When two shunting locomotives were used, the optimal allocation reduced this indicator to 558.4 wagon-hours.

As a result, a saving of 191.5 wagon-hours, or approximately a 35% increase in efficiency, was achieved in the servicing process. The obtained results demonstrate that a balanced distribution of loading-unloading fronts between locomotives significantly improves the overall efficiency of station operations.

The conducted sensitivity analysis showed that the model is highly stable with respect to the servicing time parameter, since the optimal sequence remained unchanged for variations of the servicing time (t_i) within $\pm 50\%$. At the same time, it was found that changes in the number of wagons by certain units lead to a redistribution of the servicing sequence. This indicates that the system is sensitive to the number of wagons.

A mathematical model based on the criterion of minimizing the total waiting time of wagons was developed to optimize the servicing process of loading-unloading fronts. This model makes it possible to comprehensively account for the servicing time of fronts and the number of wagons when determining the servicing sequence, and it provides a theoretical basis for identifying the optimal servicing order under the condition of a single shunting locomotive.

For the case of using two or more shunting locomotives, an optimization approach based on the σ indicator, which characterizes the reduction in wagon-hours, was proposed to solve the problem of allocating loading-unloading fronts. This approach revealed the symmetry of allocation variants between locomotives. As a result, the number of variants to be examined in the search for the optimal solution is significantly reduced. The approach enables an assessment of servicing efficiency and the identification of the optimal allocation, while, unlike existing methods, it takes into account the balance of workload between locomotives.

Based on the proposed mathematical model and algorithm, software was developed that enables automation of the servicing process for loading-unloading fronts. The program can be used to determine the optimal servicing sequence, rapidly analyze alternative variants, evaluate the efficiency of shunting locomotive utilization, and support decision-making.

The research results confirm that the optimized technology for servicing industrial sidings, based on the developed mathematical model, algorithm, and software approach, can be effectively applied in planning and managing shunting operations at railway stations.

8. Patents

1. "Selection of the sequence for delivering wagons to loading and unloading fronts using a single locomotive" Certificate of official registration of a computer program, Ministry of Justice of the Republic of Uzbekistan, No. DGU 52271, 2025. Authors: Ogabek Tohirov, Alisher Baqoyev, Boburjon Rustamjonov, Munira Polatova.

2. "Program for selecting the sequence of wagon delivery using several shunting locomotives at a railway station" Certificate of official registration of a computer program, Ministry of Justice of the Republic of Uzbekistan, No. DGU 55519, 2025. Authors: Ogabek Tohirov, Alisher Baqoyev, Boburjon Rustamjonov, Mafratkhon Tokhtakhodjayeva.

3. “Program for evaluating the influence of the number of shunting locomotives on the working fleet of freight wagons and other performance indicators of railway transport operation” Certificate of official registration of a computer program, Ministry of Justice of the Republic of Uzbekistan, No. DGU 42742, 2024. Authors: Alisher Baqoyev, Dautbay Najenov, Shinsolat Suyunbayev.

4. “Program for optimizing the process of servicing local wagons at railway stations and determining time standards” Certificate of official registration of a computer program, Ministry of Justice of the Republic of Uzbekistan, No. DGU 55517, 2025. Authors: Alisher Baqoyev, Ogabek Tohirov, Boburjon Rustamjonov, Munira Polatova.

Supplementary Materials: The following supporting information can be downloaded at: https://drive.google.com/file/d/1h0b_CG-IVomfqdPeDgum4ZfyCs2Z0DLO/view

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