Automation of operational management of wagon flows in the technological cycle of IART

Gulshan Ibragimova a), MafratkhonTokhtakhodjayeva

*Tashkent State Transport University, Tashkent, Uzbekistan*

*a) Corresponding author:* [*ibragimova.gulshana@mail.ru*](mailto:ibragimova.gulshana@mail.ru)

Abstract. This article investigates the improvement of railway operational efficiency through the automation of train traffic management and shunting processes. The study focuses on the key role of station operators in coordinating wagon distribution and highlights the limitations associated with subjective decision-making and the absence of standardized regulatory procedures. To address these challenges, a mathematical optimization model based on set theory and combinatorial analysis is proposed. The model enables the formalization of wagon allocation tasks and supports the minimization of total idle time within the railway operational cycle. The developed approach provides automated generation of optimal wagon delivery sequences, facilitates integration with digital traffic control systems, and allows real-time adjustment of operational plans under changing conditions. Moreover, the model is suitable for processing large datasets and can be synchronized with enterprise resource planning (ERP) systems, ensuring consistency across different levels of railway logistics management. The results demonstrate that algorithmic optimization significantly reduces human-related operational errors, improves transparency in decision-making, and enhances the reliability and responsiveness of railway transport systems. The findings confirm the substantial potential of digital automation and mathematical modeling tools for strengthening operational efficiency and supporting the sustainable development of the railway sector amid increasing traffic volumes and rising competitive pressures.

**INTRODUCTION**

At the global level, throughout all stages of the development of the world economic system, considerable attention has been devoted to the improvement of transport as one of the key factors ensuring the functioning of the economy and society as a whole [1]. The acceleration of interaction among all sectors of the economy predetermines the need for continuous development and modernization of the transport sector [2].

The growth of industrial production and international trade requires transformations in the global transport sector, which itself has become one of the main drivers of globalization [3]. The creation of a unified information space, largely driven by advances in computer technologies, has formed the basis for a number of global trends – among which one of the most important is the globalization of goods markets [4].

This process poses a significant challenge for any national production structure and its crucial component – the transport and logistics system [5]. Under these conditions, it is evident that the competitiveness of manufacturers depends not only on the balance of price, quality, and product characteristics but also on the efficiency of transportation and distribution methods, as well as on the time required to reach the market [6]. At the same time, an increase in cargo delivery time has a negative impact on the competitiveness of producers and on the national economy as a whole [7].

The quality of railway transportation not only determines the customer satisfaction index but also has a direct impact on the economy of the entire country. Recognition and elimination of deficiencies in the existing system of technical regulation can serve as a foundation for achieving higher performance in the field of transportation, which, in turn, contributes to increasing the competitiveness of railway transport and ensures its sustainable development in the future [8].

The efficiency of railway operations directly depends on the quality of transport process organization and the level of technical standardization. At the same time, the need to increase wagon movement speed, improve conditions for minimizing non-productive downtime, and implement innovative management methods becomes particularly relevant. Under conditions of intensified competition and rising customer expectations, the importance of fulfilling transport commitments and ensuring timely cargo delivery acquires paramount significance.

The issues related to the automation of complex industrial enterprises have been studied in the works of [9-14], as well as in the studies of foreign authors such as Jin Guo and Pei-yan Yun [15], Joon-Young Ko and Jae-Young Park [16].

The problems of coordinating the operation of junction stations and private railway tracks in the context of improving criteria for selecting the optimal service sequence of freight facilities, as well as developing algorithms for determining the rational order of servicing private tracks, are examined in detail in study [17].

Research devoted to solving problems related to improving the level of interaction between production and transport-technological systems of railway transport – which constitute essential elements of the transport and logistics system – was conducted by Rakhmangulov A.N. and Baginova V.V. [18].

In railway transport, the activity of the station duty officer plays a key role in ensuring the timely and efficient movement of trains and shunting operations. However, in the absence of clear orders, regulations or automated programmes defining the order of wagon supply and distribution, the duty officer has to rely on his own experience, intuition and subjective assessments.

This approach, while it may be effective in non-standard or crisis situations, carries a number of significant risks. Firstly, the subjectivity of decisions may lead to deviations from the optimal plan, which in turn may increase time and material costs. For example, incorrect distribution of wagons can disrupt the rhythm of the technological process, cause train delays or create conflicts between different departments.

Secondly, decision-making based on personal preferences or interests of the station duty officer may become a factor of corruption or abuse of authority, which contradicts the principles of transparency and equality in customer service.

Third, the lack of a centralised control system and standard algorithms leads to a significant increase in the workload of operational staff, which increases the likelihood of errors under stress or time pressure.

**METHODS**

From a scientific point of view, this problem highlights the need to implement modern automated traffic control and shunting systems based on optimisation algorithms and big data processing. Such systems can take into account a wide range of factors, including the current state of infrastructure, customer priorities, weather conditions and other parameters, ensuring decision-making based on objective data.

In addition, the formalisation and standardisation of wagon allocation procedures should be accompanied by regular training of station duty officers in modern methods of planning and working with automated systems. This will minimise the influence of the human factor, increase the reliability of railway traffic and improve the overall quality of transport process management.

The variants of the sequence of wagon group feeding depending on the number of freight objects and shunting locomotives are subject to the theory of mathematical combinatorics [6,12,19]. According to the theory of mathematical combinatorics, the number of variants of transferring groups of wagons going to n objects with k shunting locomotives obeys the following law [6,19]:

(1)

|  |  |
| --- | --- |
|  | number of freight facilities, n=10; |
|  | number of shunting locomotives, k=6. |

Formula combinations: 

Thus, if locomotives can feed objects in any order and it only matters which 6 out of 10 objects are selected for maneuvers, the total number of combinations is 210.

Based on the condition that 6 locomotives work for 10 objects, then in the first feed we express the following combination: locomotives work on 1 2 3 4 5 6 objects while in the second feed of this combination locomotives will work on 7 8 9 10 objects, and so on, for all subsequent 209 combinations. The minimum wagon waiting time for the second feed is required.

The station has 10 freight facilities and 6 shunting locomotives. The waiting time for wagon-hours depends on the number of wagons to each freight facility and the minimum duration of wagon delivery time.

The time cost of supplying and removing wagons to each of the freight facilities is determined by the technological schedule and can be represented in parametric form as follows:

 times characterising the process of wagon delivery and removal for each of the objects, starting from the first and ending with the tenth.

The number of wagons allocated for delivery to freight objects on the station tracks is denoted in the following parametric form:

 number of wagons from the first to the tenth object, respectively.

The station duty officer should distribute shunting locomotives in such a way as to minimise the waiting time (car-hours) for groups of wagons to which no locomotive has been assigned, while performing operations of supplying and removing groups of wagons to freight facilities.

In this case, the wagon groups with the longest waiting time (wagon-hours) for first delivery should be dispatched first. The groups of wagons, assigned and not assigned to locomotives, at first delivery to freight facilities can be represented in the form of the following set theory:

  (2)

The waiting time when wagons are delivered to freight facilities depends on the following elements:

 (3)

The objective function for minimising the waiting time for wagons (wagon-hours) of groups from set theory will be as follows:

 (4)

It is required to reach the minimum value of the target function. For the target function to reach the minimum value, the sum below must reach the minimum value:

 (5)

(6)

|  |  |
| --- | --- |
|  | - number of wagons in the second set; |
|  | - the shortest time of wagon delivery and removal from the first set of wagons. |

**RESEARCH RESULTS**

The results of researches, received at implementation of the modelled formula at the station of JSC “Uzmetkombinat” “Zavodskaya”, are as follows: 30 wagons in the train are accepted to the station “Zavodskaya”, distribution of these wagons for 10 cargo objects on transfer and export forms 210 combinations according to.

Based on the conditions of the modelled formula, wagons distributed in descending order (e.g. in the sequence 1:2:4:6:8:7 or 3:5:9:10), when distributed to the freight facilities with the highest number of wagons and feed-to-collection times, have a downtime of 93 minutes.

To automatically calculate the sequence of wagon deliveries to freight points with the goal of minimizing the total idle time of wagons, a program should be developed to automate planning, improve the efficiency of wagon and freight point utilization, reduce costs by minimizing idle time, and promptly respond to changes in the transportation process. The program should include the following functional capabilities:

1. Calculation of the optimal wagon delivery sequence:

An algorithm determines the order of wagon deliveries, minimizing idle time and taking into account time constraints for operations. Multi-criteria optimization: ability to consider additional parameters such as shipper priorities, cargo types, or wagon conditions. Support for various operation scenarios: calculations considering schedule changes, delays, and other force majeure situations.

2. Integration with traffic management systems:

Import of data on wagon availability, track conditions, and freight point schedules. Consideration of freight point characteristics: throughput capacity, loading/unloading time, and restrictions by wagon and cargo types. Idle time modeling: calculation of potential waiting time for each wagon based on the current workload of freight points and available resources.

3. Automatic plan updating:

Recalculation of the sequence when input data changes (e.g., wagon delay or schedule modification). Manual adjustment capability: the operator can manually modify the delivery order of wagons, considering specific conditions or unforeseen situations. Idle time forecasting: evaluation of possible delays and their impact on the overall process.

4. Delay notifications:

Alerts about risks of exceeding permissible idle time. Flexible settings: the ability to define user parameters (for example, weights for various optimization criteria).

5. Report generation:

Provision of data on delivery time, wagon idle time, and operational efficiency. Result analysis: comparison of planned and actual delivery times to assess calculation accuracy and identify bottlenecks.

6. Support for large data volumes:

Operation with large stations that have multiple tracks and freight points. Integration with ERP systems: data exchange with enterprise resource management and logistics platforms.

**CONCLUSIONS**

Automation of train traffic control and shunting operations is a prerequisite for improving the efficiency of railway stations. The absence of centralised systems leads to subjectivity of decisions, which increases time and material costs, as well as increases the workload of personnel. The application of mathematical methods, including set theory and combinatorial analysis, makes it possible to formalise the process of wagon allocation, optimising their supply and minimising waiting time. The implementation of optimisation algorithms helps to reduce the probability of errors, ensure the rhythm of the technological process and increase the transparency of operations. Experimental studies conducted at Zavodskaya station confirmed the effectiveness of the proposed approach, which demonstrates the prospects of its application to improve the management of transport processes in the railway industry. As a result of implementing a software tool for the automatic calculation of the sequence of wagon deliveries to freight points at JSC “Uzmetkombinat,” it will become possible to improve resource utilization efficiency and reduce wagon idle time by decreasing technological operations related to wagon placement at freight fronts by an average of 11%.

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