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Concept of Efficient Utilization of Railway Station Technical–Hygienic Maintenance Centers—A Case Study from Slovakia

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Abstract: The current technical condition of facilities designated for the technical–hygienic maintenance of railway rolling stock is unsatisfactory, as they are neither technologically nor technically equipped to meet the required quality standards. Maintenance is often carried out in open spaces or directly on the tracks of major railway junctions, which prevents year-round execution of these services and causes operational limitations. This article analyses and proposes solutions for the technical–hygienic maintenance center (THU) of railway rolling stock at the Nové Zámky railway station in Slovakia, focusing on improving the efficiency and quality of the provided services. The analysis includes an assessment of technological procedures, identification of operational deficiencies, and a comparison of current maintenance standards with the requirements for contemporary railway systems, such as automated diagnostic platforms, predictive maintenance modules, and modular cleaning infrastructure. The optimization of THU services considers the average time norms for selected technological procedures and the characteristics of train sets passing through the center. The proposed solution involves a more efficient scheduling of operations in line with the valid railway traffic timetable and train set circulation, utilizing a graphical planning method for modelling and optimizing the facility's service processes. The implementation of optimization measures can lead to increased capacity and efficiency of maintenance, reduced time required for individual procedures, and lower operational costs. The study's results provide practical recommendations for improving the quality of technical–hygienic maintenance at railway junction stations, contributing to greater railway transport reliability and an overall improvement in passenger comfort. Additionally, the findings offer a transferable framework that may inform the planning and modernization of maintenance facilities at other regional railway stations facing similar infrastructural and operational challenges.

Keywords: technical–hygienic maintenance; railway station; railway vehicles; effectiveness; services

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1. Introduction

Rail transport is a key component of public transportation and plays a significant role in the sustainable development of transport infrastructure [1,2]. In addition to its environmental and social benefits, rail transport is also a crucial driver of national economies, as it facilitates the mobility of people and goods and enhances regional connectivity. The availability and quality of transport services, supported by effective and integrated transport infrastructure, have a direct impact on economic productivity and the general well-being of citizens. This interdependence between transport development and socioeconomic performance has been emphasized in prior research, such as the analysis of passenger and freight volumes in rail and road transport in Poland between 2009 and 2019 [3].

However, the efficient operation of railway services requires regular, high-quality technical–hygienic maintenance of rolling stock to ensure reliability, safety, and passenger comfort [4,5].

Currently, the technical condition of maintenance facilities at railway stations in Slovakia is inadequate, as they are neither technologically nor functionally equipped to meet the required quality standards [6,7]. Most THU is performed outdoors or directly on station tracks, which are primarily intended for train stabling rather than servicing [8]. These stabling tracks typically lack the equipment necessary for comprehensive technical and hygienic maintenance, significantly limiting operational capacity—especially during the winter months [9,10].

In fact, maintenance services on open tracks can only be performed for 7 to 8 months per year, greatly reducing overall efficiency and highlighting the need for infrastructure modernization [11]. A typical example of this limitation occurs during winter, when maintenance crews are unable to service train sets due to frozen wastewater tanks and unheated working environments. This has led to train service delays and cancellations, directly undermining operational reliability and passenger satisfaction. Such failures underscore the critical need for adequately equipped, weather-resistant THU facilities that support year-round operations and prevent costly disruptions. Additionally, maintenance is often carried out across multiple dispersed locations, resulting in increased costs for external shunting and the management of multiple sites [12]. These added expenses are reflected in the overall operating costs of Železničná spoločnosť Slovensko, a.s. (ZSSK) [13], which must maintain rental agreements for several separate facilities. Many of these sites also rely on outdated or non-functional equipment that is only suitable for older rolling stock. New-generation railway units are equipped with advanced systems such as onboard diagnostics, electronic control modules, and sensitive electronic interfaces, all of which require specialized servicing procedures and dedicated equipment—further emphasizing the need to upgrade existing infrastructure [14,15]. Effective maintenance in modern railway operations thus requires ongoing investment in infrastructure, technological equipment, and innovative servicing processes to ensure reliability, safety, and long-term sustainability [16,17]. In the context of this study, effectiveness refers to the combined efficiency of service delivery with respect to time utilization, throughput capacity, and resource allocation. The term THU denotes a set of operational procedures that include routine maintenance, cleaning, waste disposal, water refilling, and technical inspections of railway vehicles. In this study, the effectiveness of THU is evaluated across three key dimensions, such as time efficiency (reduction in average service time per train set), capacity throughput (number of train sets serviced per day), and resource utilization (optimization of staff, track occupancy, and facility usage to minimize operating costs).

The aim of this study is to propose an operational model for a new THU at the Nové Zámky railway station, aligned with the current railway timetable and the anticipated start of full operations following construction. By establishing a well-equipped facility—including automated cleaning systems, dedicated tracks for technical inspections, and minor repair infrastructure—Železničná spoločnosť Slovensko (ZSSK) can significantly extend the service life of both newly delivered and modernized rolling stock. In selecting a suitable location for the new THU, it is important to consider both the historical development of Slovakia's railway network and the current operational demands. The placement of passenger servicing facilities is typically operator-independent and is primarily determined by the frequency and structure of train operations on individual lines.

Key factors influencing the siting of THU include the number of originating and terminating train services at a given station, the presence of suitable infrastructure or favourable conditions for construction without incurring additional technological mileage, and the potential to reduce external shunting costs by consolidating maintenance activities at a centralized location.

This study presents an innovative approach to the assessment and optimization of technical–hygienic maintenance processes in railway transport. The proposed methodology emphasizes efficient planning of THU procedures, the reduction of operational costs, and the deployment of targeted technological solutions—such as automated interior and exterior cleaning systems, digital diagnostics based on onboard sensors, and centralized dashboards for real-time condition monitoring. Beyond technical and operational dimensions, the study also considers the environmental implications of technical–hygienic maintenance, highlighting its role in supporting the ecological sustainability of rail transport. Enhancing the efficiency of these processes can lead to a measurable reduction in the environmental footprint of railway operations and contribute to the broader goals of sustainable mobility as promoted by the European Green Deal.

The structure of the paper Is organized as follows: Section 2 presents a review of relevant domestic and international literature on railway maintenance infrastructure and methodologies. Section 3 describes the research context and the current state of technical–hygienic maintenance at the Nové Zámky station. Section 4 introduces the proposed optimization methodology, detailing the steps of workload assessment, time analysis, and performance evaluation. Section 5 discusses the results of the application, including efficiency improvements, infrastructure utilization, and capacity analysis. Section 6 provides practical recommendations for implementation, and Section 7 concludes with a summary of key findings and directions for future research. The conclusion offers practical recommendations for the implementation of specific technologies in railway maintenance, including automated cleaning systems, predictive diagnostics, and digital platforms for tracking and managing maintenance tasks.

Although the proposed concept is demonstrated using Nové Zámky as a case study, it is also applicable to other key railway nodes in Slovakia—such as Bratislava, Zvolen, Žilina, Košice, and Humenné—where the volume of originating and terminating train sets is high, and the infrastructural preconditions for centralized maintenance are met.

2. Literature Review

This literature review is structured into four thematic areas:

- optimization of railway maintenance operations,
- predictive and automated maintenance systems,
- environmental sustainability in railway servicing, and
- international practices in depot design and modernization.

2.1. Optimization of Railway Maintenance Operations

Operational efficiency in railway maintenance remains a key concern for infrastructure managers and railway operators. Several studies have explored mathematical and heuristic approaches to scheduling, resource allocation, and cost optimization. For instance, [18] applied hybrid metaheuristics to large-scale preventive maintenance planning in the Dutch railway network, while ref. [19] employed probabilistic degradation models to support decision-making in substructure maintenance. Scheduling optimization is emphasized in [20], demonstrating that efficient slot allocation can significantly reduce downtime.

Additionally, the use of artificial intelligence for system-wide optimization was examined in [21]. Despite promising results, most of these studies focus on freight networks or isolated technical subsystems, offering limited insight into the specific requirements of passenger rolling stock maintenance—particularly regarding the integration of both hygienic and technical servicing. Furthermore, few contributions address the incorporation of such optimization models into station-level operational planning, which is essential for the practical deployment of centralized maintenance centers.

2.2. Predictive and Automated Maintenance

Recent advancements in predictive maintenance emphasize the adoption of smart diagnostics and real-time monitoring systems. Studies propose AI- and IoT-based frameworks for fault prediction and early warning, particularly in critical subsystems such as switches and braking components [22]. For example, [23] applied anomaly detection and remaining useful life models to interlocking log data in the Metro do Porto network, while [24] evaluated the effectiveness of onboard sensors in enabling condition-based maintenance strategies. These approaches show considerable promise in reducing unplanned downtime and improving overall system reliability. However, most of these technologies are focused on core mechanical components and fail to address service-level processes such as interior cleaning, waste disposal, or water refilling—elements that are equally essential to the operability of passenger rolling stock and to maintaining service quality and passenger comfort.

2.3. Hygiene and Environmental Aspects in Maintenance

Studies highlight the importance of hygiene in railway operations and its broader environmental implications [25]. Microbiological inspections conducted in [26] revealed that the effectiveness of disinfection procedures depends heavily on both the choice of cleaning agents and the frequency of application. Meanwhile, [27,28] investigated ecological approaches—such as water recycling and the deployment of low-emission infrastructure—as a means of reducing the environmental footprint of railway stations. Despite these insights, the systemic integration of hygienic and technical maintenance within a unified servicing strategy remains largely underdeveloped, particularly in Central and Eastern Europe. This gap is increasingly critical, as modern railway operations depend on high-frequency, quick-turnaround services that require not only mechanical reliability but also consistently high sanitary standards to meet passenger expectations and regulatory requirements.

2.4. International Best Practices in Maintenance Depot Design and Operations

In contrast to regional studies, several countries have established exemplary practices in the design and operation of railway maintenance centers, integrating advanced technology with high levels of process automation. In Germany, Deutsche Bahn's Zugbildungsanlagen and ICE maintenance depots—such as the Frankfurt-Griesheim facility—combine real-time train dispatching with modular diagnostic portals, ensuring seamless and efficient throughput. These depots serve as operational hubs for the ICE high-speed network and exemplify the benefits of centralized, data-driven maintenance management [29].

In France, SNCF's Technicentres, particularly the Le Landy facility near Paris, operate 24/7 and support the intensive maintenance needs of TGV, Thalys, and Eurostar trains. They utilize robotic inspection gates, automated cleaning systems, and digitalized workflows to ensure high throughput and compliance with safety-critical standards [30].

Japan offers a further evolved model through the Shinkansen General Rolling Stock Depot in Tokyo. This center employs a "pit-stop" maintenance concept, with parallelized procedures coordinated via digital dashboards and real-time fault monitoring systems.

Such design enables minimal turnaround times while upholding the Shinkansen's globally renowned standards for punctuality and safety [31].

In the United Kingdom, ref. [32] applied discrete event simulation to examine the interaction between rolling stock, depot operations, and scheduling protocols. Their study identified bottlenecks and assessed alternative servicing frequencies and layout designs, supporting data-driven decision-making. Similarly, ref. [33] introduced the Maintenance Scheduling and Location Choice Problem (MSLCP), applying logic-based Benders' decomposition to jointly optimize depot placement and scheduling under routing and capacity constraints—an approach particularly relevant for complex, multi-depot systems in dense railway networks. From an infrastructure standpoint, Transport for London's Old Oak Common depot—constructed for the Elizabeth Line—exemplifies sustainability-oriented depot design. It integrates renewable energy systems, energy-efficient construction, and real-time digital platforms for maintenance monitoring and asset management [34].

In China, CRRC-operated high-speed rail depots are characterized by full automation. These facilities implement robotized exterior washing, embedded diagnostic sensors, and AI-driven predictive maintenance modules, significantly enhancing operational foresight while minimizing downtime and manual labor [35].

Collectively, these international cases demonstrate that integrated planning, automation, and digitalization are essential for addressing increasing maintenance demands while preserving high service quality. By leveraging simulation-based planning, mathematical optimization, and smart infrastructure, Western European and Asian operators have achieved remarkable throughput and reliability in depot operations. In contrast, most Central and Eastern European (CEE) depots—including those in Slovakia—lack the necessary physical infrastructure, technological systems, and process integration to adopt such advanced practices. The absence of coordinated planning, limited investment in automation, and underutilization of digital tools continue to constrain their operational performance. This paper seeks to address this gap by proposing a practical and scalable concept for technical–hygienic maintenance, tailored to the functional and institutional context of regional Slovak stations. The model builds upon the foundational principles of international best practices but adapts them to the unique infrastructure, operational density, and resource constraints of the Slovak railway network.

Recent studies have increasingly highlighted the value of data-driven strategies for optimizing infrastructure in urban transport systems. For instance, [36] proposed a physics-informed method for load identification in rubber-tired railway transport, offering valuable insights into the integration of electric mobility with broader urban planning frameworks. Similarly, [37] developed an explicit LSTM-based neural network that incorporates velocity data to detect failures under non-stationary conditions, introducing new perspectives on predictive maintenance in electric transport systems. These findings support the broader trend toward integrating real-time diagnostics and data-informed infrastructure planning in public transport maintenance—an approach that also aligns with the future development trajectory of the proposed THU model. Although the existing literature provides a solid foundation in algorithmic optimization and predictive diagnostics, a comprehensive methodology that integrates hygienic servicing, resource scheduling, and infrastructure constraints at the station level is still lacking. Furthermore, comparative analyses between international high-performing systems and underdeveloped regional depots remain scarce.

The current state of the art is characterized by the implementation of automation, AI-based diagnostics, and simulation-driven planning in leading countries such as Germany, France, Japan, and China. These systems demonstrate high service reliability and reduced turnaround times through centralized, digitally managed depots. In contrast, Central and Eastern Europe—including Slovakia—lag in the adoption of such technologies, mainly due to fragmented infrastructure, limited investment, and the absence of integrated servicing models. This technological and methodological gap highlights the need for scalable, context-sensitive solutions tailored to medium-sized stations.

This study contributes to addressing that gap by proposing a methodology that bridges both the theoretical and practical aspects of implementing integrated THU in medium-sized stations, using Nové Zámky as a representative case study.

3. Methodology

This study introduces a systematic methodology for evaluating and optimizing THU processes at the Nové Zámky railway station. Based on empirical data on service times and a comprehensive workload analysis, the methodology enables the development of targeted optimization strategies aimed at reducing operational delays, increasing process efficiency, and improving the quality of maintenance services in passenger rail transport. The need for such a methodology arises from the current condition of THU operations at Nové Zámky, which reveals capacity bottlenecks, fragmented procedures, and outdated maintenance practices. In response, the proposed framework focuses on improving the efficiency of technological operations while optimizing the planning and coordination of train servicing, movement, and track utilization. It comprises five sequential steps, each addressing a key component of the THU process.

The first step involves a detailed workload analysis, which includes identifying critical operational bottlenecks, evaluating the daily train turnaround schedule, and assessing occupancy rates across available tracks. This provides a baseline understanding of resource utilization and service capacity.

The second step focuses on designing the operational workflow within the THU. It aims to optimize train routing and improve the use of specialized tracks and facilities for technical inspections, cleaning, and waste management. By planning these procedures in an integrated manner, the methodology reduces the number of unnecessary train movements and minimizes idle time between operations.

The third step is dedicated to evaluating the efficiency of servicing processes. It involves calculating the average time required for each major maintenance task—such as cleaning, diagnostics, and waste disposal—and comparing actual values with performance benchmarks to identify areas for improvement.

The fourth step introduces optimization measures. These may include automation of cleaning and diagnostic procedures, adjustments to train arrival and departure schedules, and the implementation of sustainable technologies, such as water recycling systems or the use of renewable energy in facility operations.

The fifth and final step focuses on performance monitoring and continuous improvement. Key performance indicators (KPIs) are defined and regularly tracked to evaluate maintenance efficiency, track utilization, and the effectiveness of implemented technologies. This step enables data-informed strategic adjustments in response to evolve operational needs.

Through the application of this methodology, THU at Nové Zámky can become more streamlined, cost-effective, and environmentally sustainable. The increased servicing capacity reduces operational costs, and higher reliability will support the long-term competitiveness of railway transport. The structure and logical flow of the methodology are illustrated in Figure 1.

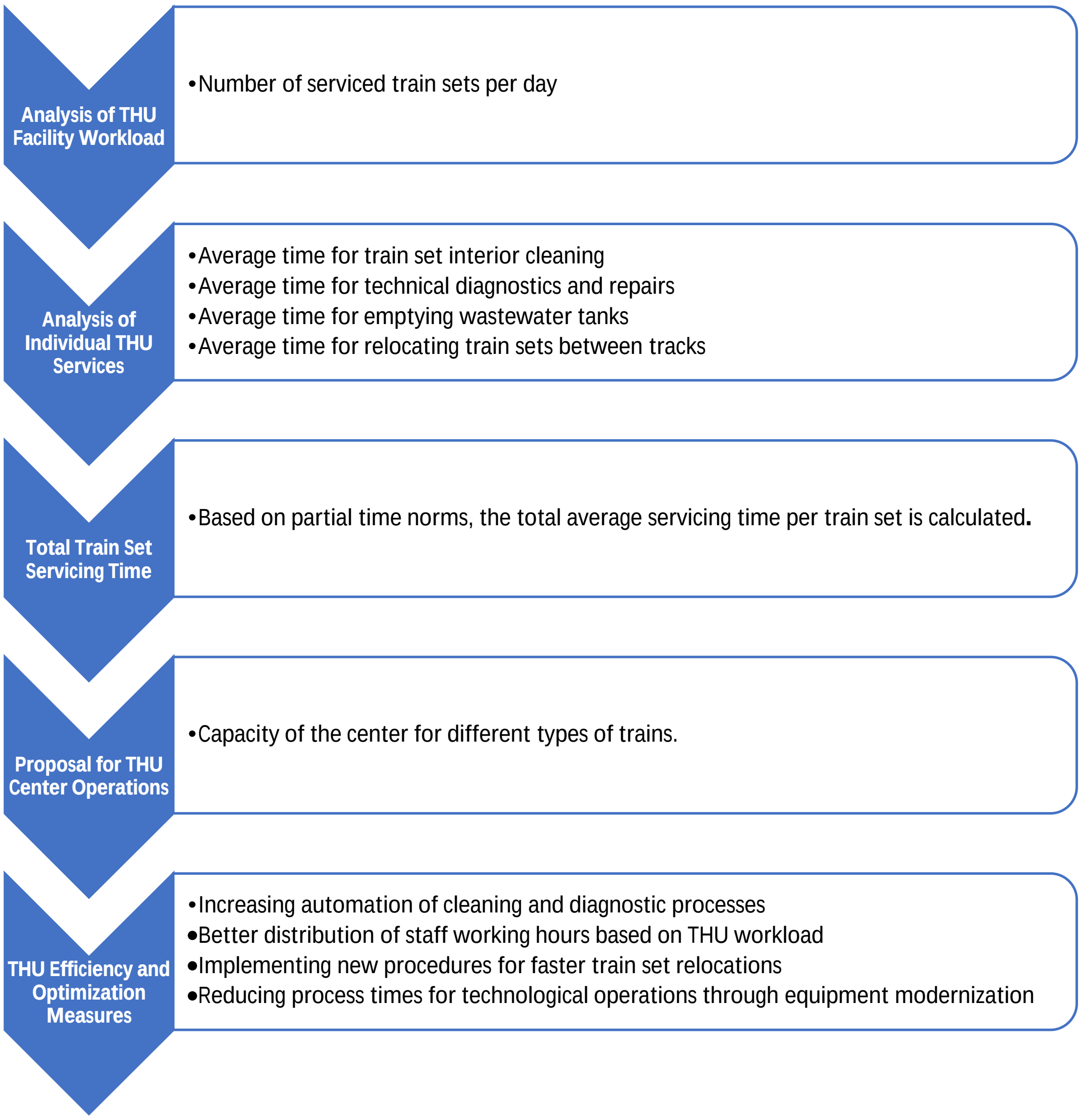


Figure 1. Methodology for evaluating and optimizing technical–hygienic maintenance processes at the railway station.

3.1. Step 1. Analysis of THU Facility Workload

The assessment of facility efficiency begins with the analysis of the workload of individual sections within the center. This includes the following:

- The number of train sets serviced per day.
- Time norms for technological operations.
- Limiting factors (track capacity, shunting time, staff availability).

Calculation of the number of serviced train sets per day:

$$N_{THU} = \frac{T_{operating}}{T_{total}} \tag{1}$$

where $T_{operating}$ is total available operating time per day (min), and T_{total} is average servicing time per train set (min).

3.2. Step 2. Analysis of Individual THU Services

The evaluation of the efficiency of individual services within the THU includes the calculation of average time norms for key technological operations.

Average time for train set interior cleaning:

$$T_{cleaning} = \frac{\sum_{i=1}^{n} T_{clean,\ i}}{n}\ (\text{min}) \quad (2)$$

where $T_{clean,i}$ are the measured values of cleaning times for individual train sets, and n is the number of observations.

Average time for technical diagnostics and repairs:

$$T_{diagnostics} = \frac{\sum_{i=1}^{n} T_{diag,i}}{n}\ (\text{min}) \quad (3)$$

where $T_{diag,i}$ are the measured values of diagnostics times for individual train sets, and n is the number of observations.

Average time for emptying wastewater tanks:

$$T_{waste} = \frac{\sum_{i=1}^{n} T_{waste,i}}{n}\ (\text{min}) \quad (4)$$

where $T_{waste,i}$ are the measured values of wastewater tank emptying times for individual train sets, and n is the number of observations.

Average time for relocating train sets between tracks:

$$T_{transfer} = \frac{\sum_{i=1}^{n} T_{transfer,i}}{n}\ (\text{min}) \quad (5)$$

where $T_{transfer,i}$ are the measured values of train set relocation times, and n is the number of observations.

3.3. Step 3. Total Train Set Servicing Time

The total average servicing time per train set is used for workplace capacity planning and optimization of time reserves. Based on partial time norms, the total average servicing time per train set is calculated as follows:

$$T_{total} = T_{cleaning} + T_{diagnostics} + T_{waste} + T_{transfer}\ (\text{min}) \quad (6)$$

3.4. Step 4. Proposal for THU Operations

The servicing of train sets in the THU is planned based on the available facility capacity, the current railway timetable, and train set circulation. The total daily number of train sets is distributed among different types of trains.

Facility capacity for different types of trains:

$$N_{THU} = N_{EC} + N_{Ex} + N_{REX} + N_{Os} + N_{Sv} \quad (7)$$

where N_{EC} is the number of EuroCity trains, N_{Ex} is the number of Express trains, N_{REX} is the number of Regional Express trains, N_{Os} is the number of Passenger trains, and N_{Sv} is the number of train sets (empty stock movements).

3.5. Step 5. THU Efficiency and Optimization Measures

To improve workplace efficiency, various optimization measures can be implemented, including the following:

- Increasing automation of cleaning and diagnostic processes.
- Better distribution of staff working hours based on THU workload.
- Implementing new procedures for faster train set relocations.

- Reducing process times for technological operations through equipment modernization.

Optimization is evaluated by comparing the previous and optimized values of the total average servicing time using Formula (8):

$$\Delta T_{total} = T_{original} - T_{new} \text{ (min)} \quad (8)$$

where $T_{original}$ is the original total servicing time per train set, and T_{new} is the new total servicing time after optimization. If $\Delta T_{total} > 0$, it indicates an improvement in workplace efficiency.

Although the proposed methodology is grounded in empirical analysis and direct measurement, its structure supports further development using formal modelling techniques. For example, the optimization of train set scheduling, track utilization, and resource allocation could be formulated using Mixed Integer Linear Programming (MILP) models. In addition, discrete event simulation (DES) may provide a more detailed analysis of bottlenecks, queuing dynamics, and the interaction of concurrent servicing operations under stochastic conditions. These advanced modelling approaches would enhance the generalizability of the methodology to other railway stations with varying infrastructural or operational characteristics.

While the current methodology primarily assesses effectiveness in terms of reduced total servicing time, a broader conceptual framework is required to evaluate THU within a multidimensional context. Future evaluations should extend beyond time efficiency to include additional performance dimensions, including the following:

- Operational costs, including energy and water consumption, waste disposal, and wear and tear on cleaning systems.
- Energy efficiency, particularly in comparing manual versus automated procedures and the role of renewable energy sources.
- Human resource utilization, considering staffing structures, shift optimization, and the extent to which automation can reduce labor dependency.

Such a framework allows for a more comprehensive understanding of the trade-offs and synergies among technical, economic, and environmental objectives. Although detailed quantification of these indicators is beyond the scope of this case study, their conceptual integration strengthens the scientific validity and transferability of the proposed approach. Table 1 presents a schematic evaluation matrix designed to support multidimensional assessment of THU efficiency.

Table 1. Evaluation matrix for assessing THU efficiency.

Dimension	Criteria	
Time	Service time	
Costs	Operational costs	
Energy Staffing	Energy	Workforce utilization

The proposed methodology for optimizing THU operations (see Figure 1) comprises five steps focused on workload analysis, service duration measurement, capacity evaluation, and the implementation of improvement measures. These steps are not assessed solely through time-based indicators but are conceptually integrated with a multidimensional efficiency framework (see Figure 2), which encompasses time, operational costs, energy consumption, and workforce allocation. For instance, while calculating average servicing time directly supports improved scheduling (time efficiency), the automation of diagnostic procedures influences both cost structures and staffing requirements. This conceptual linkage enables broader applicability of the methodology and provides a foundation for future enhancements that incorporate quantified trade-offs across different efficiency dimensions.

4. Research Background

The Nové Zámky railway station is situated at kilometer 145.385 on the double-track electrified Slovak Railways (ŽSR) Line No. 130 (Bratislava–Štúrovo), at kilometer 35.424 on the single-track electrified line Komárno–Nové Zámky, and at kilometer 0.000 on the single-track line Nitrianske Pravno–Nové Zámky, which is electrified in the Šurany–Nové Zámky section. All mentioned lines operate on a standard track gauge of 1435 mm [38]. Nové Zámky serves as both a starting and home station for passenger train sets operating in the southwestern region of the Slovak railway network [39]. Accordingly, inspections are conducted at this hub for both arriving and departing trains. At present, these activities are distributed across three facilities: the Inspection and Repair Centre (SPO), the Carriage Repair Facility for Major Repairs (OV), and the locomotive depot [38]. THU services are performed on a variety of train set types, including conventional coach sets, electric double-deck units (EPJs), diesel multiple units (DMJs), and motor units (MJs) with trailer cars. These services support not only Nové Zámky-based operations but also units from adjacent stations [40]. However, the current THU infrastructure does not meet the technical and hygienic maintenance requirements of the modern vehicles acquired by ZSSK in recent years. At present, maintenance procedures are carried out either in open-air spaces or directly on the stabling tracks of major junction stations, without the availability of a dedicated track group for THU purposes. As a result, Nové Zámky lacks centralized THU capacity. Inspections are performed on a limited basis at three separate remote facilities located in Štúrovo, Komárno, and Levice. Since none of these facilities is equipped to provide full-spectrum, high-quality maintenance for all train types in a single location, a comprehensive solution is urgently needed [38].

4.1. Analysis of Technical–Hygienic Maintenance Services

The primary purpose of the THU center for railway rolling stock in passenger transport is to perform the full scope of THU operations, as well as minor and medium-level wagon repairs. The facility is therefore designed to carry out all necessary maintenance procedures required to ensure operational readiness and passenger comfort. To fulfil these functions, the center is organized into distinct operational sections. These include two groups of entry and exit tracks (Tracks No. 701–705 and No. 601–606), a designated waste disposal track (referred to as FK, Track No. 607), an Operational Servicing Hall (HPOS, Tracks No. 608–610), and a track equipped with a stationary hall washer (SHU, Track No. 611). Additional infrastructure includes two pull-out tracks (Track No. 110a at the Bratislava junction and Track No. 705a leading to the locomotive depot), a bypass track (No. 612), and various interconnecting tracks linking THU groups and connecting the THU with the main Nové Zámky railway station. The operational preparation of complete train sets involves a series of THU services, including both maintenance and hygienic readiness procedures. From a safety and service reliability perspective, these procedures are considered mandatory for all passenger train sets. However, certain technical preparation tasks—such as onboard electronics diagnostics, vacuum toilet system servicing, air conditioning checks, Wi-Fi module testing, and other technologically advanced maintenance procedures—are not required for older vehicle types, particularly older MJ units used in regional services [38].

4.2. Hygienic Preparation of Railway Rolling Stock

The procedures carried out at maintenance facilities follow standardized operational preparation protocols and are scheduled at defined intervals—after each journey at the originating station, at the end of daily operation, and on a weekly or monthly basis. Standard hygienic preparation includes routine interior cleaning after every journey, reduced cleaning at the end of daily operation, and comprehensive operational cleaning performed once per week. Additionally, deep cleaning is carried out monthly or as needed, depending on vehicle condition and usage intensity. Machine washing of exterior surfaces is performed either weekly or monthly, in accordance with operational standards. Waste-free toilet systems are emptied after daily operation, and a variety of other hygienic tasks are completed, such as garbage disposal, interior and toilet disinfection, descaling, internal sanitation, and the refilling of water tanks and other consumable supplies. Table 2 summarizes the regularity of cleaning procedures applied to railway vehicles, categorizing them by frequency and maintenance scope.

Table 2. Cleaning operations for railway vehicles based on regularity.

Cleaning Operations	After Each Ride	Daily	Weekly	Monthly
Dust Wiping	yes	yes	yes	yes
Floor Washing	no	If it is necessary	yes	yes
Vacuuming	no	no	yes	yes
Waste Removal	yes	yes	yes	yes
Toilet Suction	no	yes	yes	yes

The inspection of required tasks and verification of vehicle readiness for operation are performed by train personnel or designated staff responsible for accepting the train set prior to the commencement of service. While the general standards for operational preparation are consistent, certain procedures may vary depending on the specific type of rolling stock.

4.3. Technical Preparation of Railway Rolling Stock

The technical preparation of railway vehicles includes mandatory inspections of key components such as the braking system, bogies, bearings, electrical circuits, air conditioning and heating units, as well as window and door locking mechanisms. These tasks constitute the minimum required scope of technical readiness for all vehicles entering service. In addition to routine pre-operational checks, vehicles are also subject to scheduled maintenance once they reach predefined mileage thresholds, in accordance with applicable maintenance regulations. Table 3 provides an overview of technical maintenance operations, categorized by their frequency and scheduling intervals.

Table 3. Technical operations for railway vehicles based on regularity.

Maintenance, Testing, and Inspection	After Each Ride	Daily	Weekly	Monthly
Brake System Inspection	yes	yes	yes	yes
Lighting System Check	yes	yes	yes	yes
Air Conditioning/Heating Check	yes	yes	yes	yes
Passenger Door Lock Inspection	yes	yes	yes	yes
Testing of Electronics and Communication Systems	no	no	yes	yes
Window Closure Inspection	no	no	yes	yes
Water Replenishment	yes	yes	yes	yes

After each journey, a technical inspection of railway vehicles is performed at both the originating and turnaround stations. This inspection includes light maintenance tasks, ongoing safety checks, minor inspections, and brake system testing. At the end of daily operation, a more comprehensive inspection is conducted, involving detailed safety checks and functional assessments. These activities include testing of electrical systems, lighting, air conditioning and heating units, full brake system diagnostics, and interior condition assessments. Minor interior repairs may also be carried out without detaching the vehicle from the train set. If necessary, short-term detachment for essential repairs is permitted, provided the vehicle is reintegrated into the train set before its next scheduled departure. In addition to daily inspections, scheduled technical maintenance is based on mileage thresholds. Diesel multiple units (DMJs) undergo inspections every 5000 km and 25,00 km, while electric multiple units (EJs) are inspected every 10,000 km and 60,000 km. These intervals determine the frequency of regular maintenance activities based on daily mileage. For example, a DMJ operating under standard conditions may require approximately 29 inspections per year at the 5000 km interval and 6 inspections at the 25,000 km interval. Specialized maintenance procedures include descaling, verification of water and sanitary system functionality, lighting and air conditioning performance checks, electronic system diagnostics, aggregate testing, and seasonal procedures such as vehicle preheating or internal temperature regulation during winter [41–43]. Table 4 provides an overview of technical and hygienic activities included in the scope of THU operations.

Table 4. Overview of THU activities.

	Passengers' Wagons	**THU**	**Railway Vehicles Periodic Maintenance**	**THU**
Technical Inspections of Railway Vehicles	Initial Technical Inspection	yes	THU	yes
	Final Technical Inspection	yes	Minor Inspection	yes
	Electrical Equipment Technical Inspection	yes	Regular Technical Inspection	yes
	Safety Technical Inspection	yes	Railway Vehicle Repairs	
	Technical Control	yes	Major Inspection	no
Maintenance and Repairs of Railway Vehicles	Regular Maintenance Without Detachment	yes	Overhaul Repair	no
	Regular Maintenance with Detachment	partial	Regular Technical Inspection	no
	Intermediate Repair	partial	Scheduled Repair	no
	Overhaul Repair	no	Unscheduled Repair	no

If a vehicle fails to meet operational and safety requirements following a technical inspection and requires major repairs that necessitate its detachment from the train set, it is replaced by a standby or reserve unit. The defective vehicle is then transferred to a designated repair facility located at a hub station, where it undergoes further diagnosis and servicing. These facilities are responsible for handling unplanned repairs, scheduled maintenance tasks, operational modifications, and damage restoration. Table 5 presents an overview of maintenance and technical preparation activities conducted after daily operation. The table includes all relevant vehicle types, such as classic wagons, EPJs (Electric Double-Decker Units), EJ-PPs (Electric Push–pull Units), power units (locomotives), trailer wagons, and inserted intermediate wagons.

Table 5. Maintenance and technical preparation of railway vehicles after daily operation.

Type	Technical Inspection and Maintenance						Cleaning		
	Brake Inspection	Lighting Inspection	Air Conditioning	Door and Window Closure	Window Inspection	Water Replenishment	Dust Wiping	Vacuuming	Waste Removal
All Types of Wagons	yes	yes	yes	yes	yes	no	yes	yes	yes
EPJs	yes	yes	yes	yes	no	yes	yes	yes	yes
EJ-PPs	no	yes	yes	yes	yes	yes	yes	yes	yes
Power Units	yes	yes	no	yes	yes	yes	yes	yes	yes
Trailer Wagons	yes	yes	no	yes	yes	yes	yes	yes	yes
Inserted Wagons	yes	yes	no	yes	yes	yes	yes	yes	no

4.4. Entry and Exit Track Group

The entry and exit track group represents a critical component of the THU infrastructure, serving as the primary zone for manoeuvring train sets during arrival and departure and constituting a key capacity-limiting factor for the entire facility. The VOS 600 and VOS 700 track groups meet the operational requirements in terms of train set turnover, allowing for the execution of technological operations upon entry to or prior to departure from the THU center, with an average dwell time of approximately 40 min per train set. These track groups are also dimensioned to accommodate a peak throughput of up to six train sets per hour. The THU itself will not include dedicated stabling tracks. However, the VOS 600 and VOS 700 tracks may be used for short-term storage of train sets, provided this does not interfere with the facility's core servicing operations. The VOS 600 track group is specifically designed to facilitate efficient transfers between the Nové Zámky railway station and the THU. It supports a range of operational activities, including shunting, temporary stabling, maintenance, and minor repairs.

4.5. Waste Disposal Track

The waste disposal track (FK) will be situated adjacent to the Operational Servicing Hall (HPOS) and connected at one end to the HPOS junction and at the other to the Bratislava junction of the THU center. Waste from gravity and vacuum toilet systems will be extracted using a central suction system, which will be linked to all designated waste-handling equipment along the FK track and within the HPOS hall. In addition to its primary function, the FK track will also support both operational and deep cleaning activities. A covered platform will be installed along the FK, directly connected to the HPOS, to facilitate these processes. The track will also be equipped to handle emergency emptying of vacuum toilet systems when necessary. The FK is expected to be the most intensively utilized component of the THU, with an estimated servicing capacity of up to 35 train sets per day.

4.6. Shunting Operations in the THU

Shunting operations within the THU will include movements between the VOS 600 and VOS 700 track groups, FK, HPOS, and SHU. These operations will be conducted as unsecured accompanied shunting, managed through a simplified interlocking system with remote-controlled turnout operations. The system will not include continuous track occupancy monitoring; only the position of switch points will be tracked. Turnouts will be operable both locally and centrally, with automatic switching enabled as train sets approach the switch tip. Shunting operations will be handled by a single shunting locomotive, and the entire THU will function as one shunting zone. In periods of increased traffic demand, a second locomotive may be deployed, allowing for the division of the area into two shunting zones—for example, between VOS 600 and HPOS. All personnel will be coordinated via radio communication, and shunting crews will operate in accordance with the Z1 railway regulations, which define standard procedures for train movement and shunting on the Slovak railway network [44]. Electric and diesel multiple units (EJs and MJs) will perform shunting movements under their own power. In contrast, classic wagons and electric multiple units being moved into HPOS will be maneuvered using a shunting cart. A dual-mode battery-powered shunting vehicle is proposed for flexible use within the THU, including track alignment tasks at HPOS and SHU interfaces. Shunting through the SHU hall will be performed using a cable traction system, ensuring sufficient clearance with the overhead traction system and compatibility with the working length of the equipment.

5. Results

As there is currently no dedicated track layout designed for THU operations at the Nové Zámky railway station, the establishment of such a facility within the existing yard configuration is not feasible. This necessitates the construction of a new track layout specifically tailored to the functional and spatial requirements of the THU. The current infrastructure—including buildings, stabling yard capacity, and associated engineering networks—is inadequate to support the existing or projected future volume of technical–hygienic maintenance activities. Furthermore, the existing site does not offer the spatial flexibility required for expansion. The new THU service center will be constructed within the enclosed area of the Nové Zámky railway station, on ŽSR-owned land currently occupied by a decommissioned locomotive depot. The selected location includes partially preserved infrastructure, specifically the former coal storage area, which will be repurposed for the new facility. The track layout will be integrated into the existing railway network via connections to the station's operational junctions and the locomotive depot. The western boundary of the new center will be adjacent to the main station yard and the locomotive depot, which already contains ground structures and technical infrastructure. This strategic location enables seamless connectivity to the existing passenger station yard, contributing to improved operational efficiency. On the eastern side, the THU will have direct access to the public road network, facilitating logistical support and potential supply deliveries. The facility will also be bordered by residential areas (visually and acoustically separated by an existing greenbelt), as well as by mixed-use urban and suburban developments and an industrial-transport zone within the city of Nové Zámky. Figure 2 presents a visual representation of the proposed THU within the spatial context of the Nové Zámky railway station.

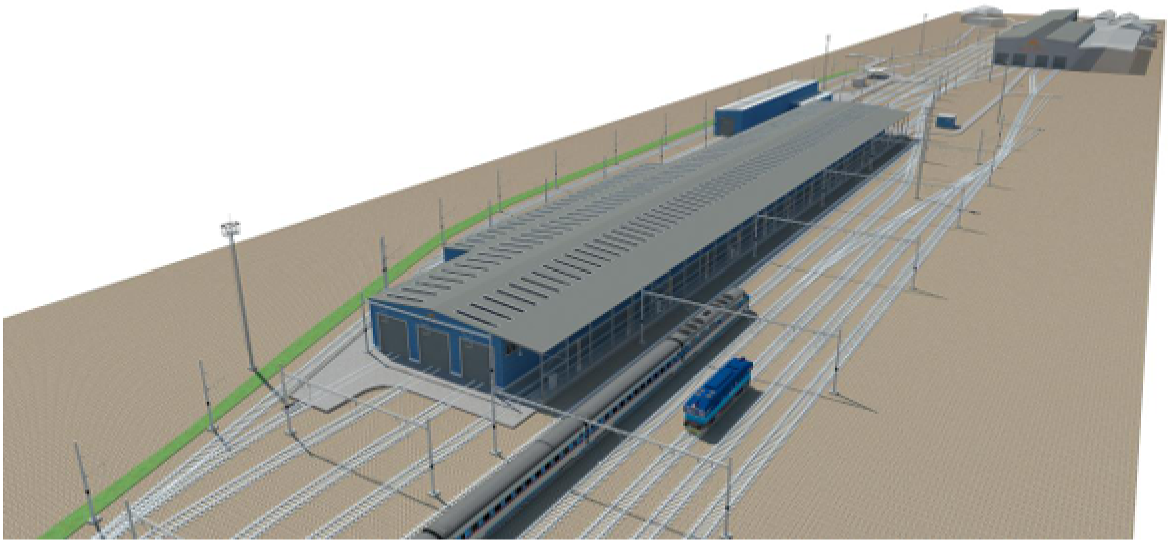


Figure 2. Visualization of the THU in Nové Zámky [45].

Following the construction of the THU, all technical and hygienic maintenance activities—including interior and exterior cleaning of railway rolling stock and routine technical inspections—will be centralized at a single location. These operations will be conducted within HPOS, SHU, and on specialized tracks designated for servicing carriages equipped with closed toilet systems. The modernization of the site will include the installation of new utility networks and the deployment of advanced technologies for technical–hygienic servicing. These technologies will include automated washing units, centralized waste disposal systems, water recycling modules, and sensor-based diagnostic equipment. The THU will be equipped with a Category 3 electronic railway interlocking system, which will allow for more efficient train movements, reduced process durations, and improved operational safety. Track occupancy will be monitored using integrated safety systems, while axle counters will control turnout sections. Train set movements will be guided by light-controlled shunting signals. All turnouts will be equipped with electromotor-operated switch machines with centralized control. The entire interlocking system will be monitored and managed from a centralized control station located in the HPOS building, where key operational data will be continuously displayed and recorded. The newly constructed THU facility will be located within the Nové Zámky railway station area, specifically between kilometers 144.3 and 145.2, ensuring seamless integration with the existing infrastructure. The track layout will connect the facility to station track No. 110 toward Bratislava (Šurany) and, on the opposite side, to the depot yard leading toward Štúrovo (Komárno), thereby facilitating efficient routing and servicing of train sets. From the Bratislava direction, the tracks will branch into the following:

- The entry and exit track group (VOS) near HPOS (tracks No. 601–606).
- Tracks passing through the Operational Servicing Hall (HPOS) (tracks No. 608–609).

Additional track designations:

- Track No. 607 will serve as FK.
- Track No. 611 will pass through SHU.
- Track No. 612 will be designated as the bypass track.

Beyond the HPOS hall, the track layout will branch into the VOS 700 group (Tracks No. 701–705), from which train sets will be distributed to the operational halls. The THU will comprise the VOS yard, HPOS, SHU, and FK, arranged in parallel to ensure efficient process flow. The VOS yard will be directly connected to the main railway line via five tracks (No. 602–606), with lengths ranging from 180 to 400 m and usable lengths between 144 and 277 m. Three of these tracks will measure approximately 250 m, aligning with the typical length of standard passenger train sets. All tracks will be electrified. The HPOS track yard will be situated between VOS 600 and VOS 700 and will include three through tracks designated for servicing classic coach sets, electric multiple units (EJs), including double-decker units (EPJs), and diesel multiple units (MJs). HPOS will be connected to the Bratislava junction via pull-out track No. 110a, enabling shunting movements between the VOS 600 and VOS 700 groups. The HPOS hall itself will be located on Tracks 608, 609, and 610, while FK will be on Track No. 607. Track No. 611, equipped with SHU, will also be positioned between VOS 600 and VOS 700. This track will be linked to the Bratislava junction via pull-out track No. 110a and connected with VOS 700, enabling seamless vehicle transfer. Track No. 611 will be outfitted with a cable shunting system (LPZ), which allows the movement of wagons without direct coupling, improving efficiency and reducing mechanical strain. The LPZ will be dimensioned to service the SHU, enabling positioning of the entire train set with support on a single axle, eliminating the need for repeated detachment and reattachment. The overhead traction system (TV) on Track No. 611 will be partially electrified, with both ends powered to allow electric units to move under their own traction to the LPZ. The SHU washing facility will have an estimated daily capacity of 25 railway vehicles, assuming standard wagon lengths of 27 m. The total length of the SHU hall will be 72 m. Figure 3 shows scheme of track layout and functional zoning of the THU at Nové Zámky station.

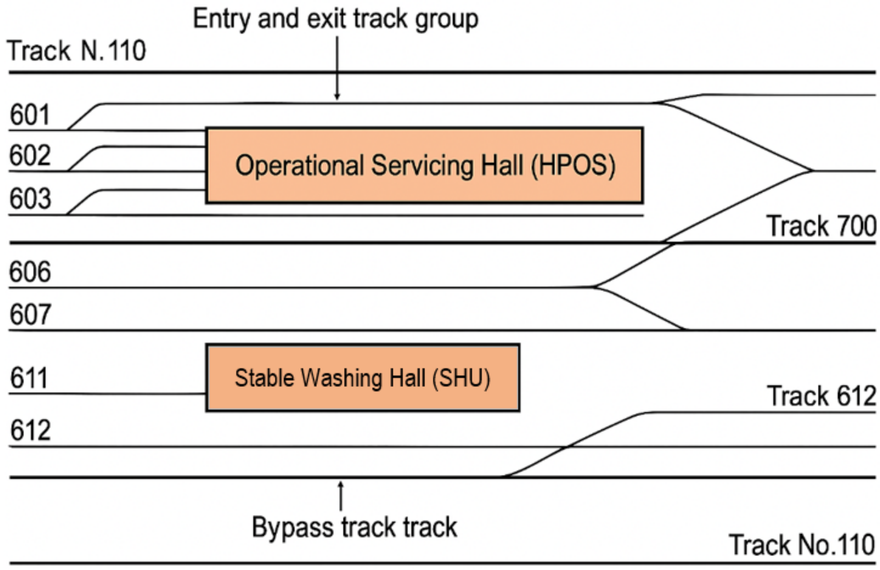


Figure 3. Track layout and functional zoning of the THU at Nové Zámky station.

5.1. Calculations for THU at Nové Zámky Railway Station

The data used for evaluating servicing times and track occupancy were collected through field observations conducted at the Nové Zámky railway station between March and May 2024. Measurements included cleaning duration, diagnostic inspections, waste disposal time, and train relocation intervals. In total, 62 train sets were observed across six service categories (EC, REX, Os, Sv, MV 812, DMJ 861).

Each servicing activity was measured multiple times under varying operational conditions. The calculated average times are accompanied by standard deviation (σ) to reflect process variability. For example, the interior cleaning of Os train sets averaged 24.5 min (σ = 3.2 min), while waste disposal ranged from 18 to 36 min (mean = 26.7 min, σ = 4.5 min).

Although the sample size is limited to a single station, the diversity of train types and the consistency of servicing procedures ensure that the dataset is sufficiently robust for supporting optimization recommendations. Additional measurements from other stations would further enhance the generalizability of the proposed model.

Analysis of THU facility utilization:

The number of train sets serviced per day is calculated using Formula (1).

$T_{operating}$ = 1080 min (in the case of an 18 h operational regime of the center)

T_{total} = 90 min

$$N_{THU} = \frac{1080}{90} = 12 \text{ train sets/day} \tag{9}$$

The THU center can service 12 train sets per day.

Analysis of individual THU services:

The average time for train set interior cleaning is calculated using Formula (2).

Operational cleaning is performed once every 24 h (duration 45 min); deep cleaning is performed once per month (duration 120 min); general cleaning is performed once per year (duration 180 min); and reduced cleaning is performed during quick turnarounds (duration 30 min).

$$T_{cleaning} = \frac{45 + 120 + 180 + 30}{4} = 93.75 \text{ min}$$

5.2. Calculation of Average Time for Technical Diagnostics and Repairs

The average time for technical diagnostics and repairs is calculated using Formula (3).

Operational service for one shift lasts 8 h; minor periodic inspection for two shifts lasts 16 h.

$$T_{diagnostics} = \frac{(480 + 960)}{2} = 720 \text{ min}$$

The average time for emptying wastewater tanks is calculated using Formula (4).

Tank emptying is performed once every 24 h (duration 20 min); toilet disinfection and descaling are performed once per year (duration 60 min).

$$T_{waste} = \frac{(30 + 60)}{2} = 40 \text{ min}$$

The average time for relocating train sets between tracks is calculated using Formula (5). Average relocation time within the THU is 10 min; average relocation time between the THU and the locomotive depot is 20 min; average relocation time between the THU and the station track 15 min.

$$T_{transfer} = \frac{(10 + 20 + 15)}{3} = 15 \text{ min}$$

The total servicing time per train set is calculated using Formula (6):

$$T_{total} = 93.75 + 720 + 40 + 15 = 868.75 \text{ min} = 14.48 \text{ h}$$

These calculations indicate that approximately 14.5 h must be allocated per train set for the complete maintenance process.

The capacity of the THU for different train types we calculated according to Formula (7).

N_{EC}—2 (EuroCity)
N_{Ex}—3 (Express Trains)
N_{REX}—2 (Regional Express Trains)
N_{Os}—4 (Passenger Trains)
N_{Sv}—1 (Empty Train Set Movements)
The THU can service up to 12 trains per day.

5.3. Optimized Processing Times After Modernization

$T_{cleaning}$—70 min (automated cleaning systems)
$T_{diagnostics}$—18 min (improved diagnostic systems)
T_{waste}—12 min (more efficient wastewater pumping stations)
$T_{transfer}$—8 min (better train relocation management).
The optimization effectiveness is evaluated using Formula (8).

$$\Delta T_{total} = 126.4 - (70 + 18 + 12 + 8) = 126.4 - 108 = 18.4 \text{ min}$$

By implementing the proposed optimization measures, the average servicing time per train set can be reduced by approximately 18.4 min, thereby improving the overall efficiency of THU operations and enabling an increased number of trains sets to be serviced within a given timeframe. At the THU located at Nové Zámky railway station, a comprehensive technical–hygienic maintenance process is performed for passenger rolling stock. Each train set undergoes a sequence of operations, including interior and exterior cleaning, wastewater disposal, technical inspections, and temporary stabling on designated tracks prior to being dispatched for its next scheduled service. The servicing plan is categorized by train type and includes EuroCity (EC) and Express (Ex) trains, Regional Express (REX) trains, Passenger (Os) trains, and Empty (Sv) train sets. A detailed breakdown of scheduled operations for each train category is presented in Tables 5–11. To support the design and optimization of train servicing procedures at the THU, a graphical scheduling method is applied. The visual representation of the servicing process is provided in Figure 4a,b, illustrating the temporal distribution of maintenance tasks and the use of individual tracks.

Table 6. Proposal for the service of EC and Ex train sets.

Train	THU Used (FK607)	THU Used (HPOS)	THU Used (SHU)	THU Duration [Approx.]	Operation Days
R 800 Poľana	Yes	Yes	No	~2 h	Sat + Holidays
R 801 Poľana	Yes	Yes	No	~5 h	27.12–8.1.
EC Metrop. 293	Yes	No	Yes	~2 h	Daily
EC Metrop. 282	No	No	No	No	Daily (No THU in NZ)

Table 7. Proposal for the servicing of REX train sets.

Train	THU Services Used	Estimated Duration	Special Features	Operation Days/Restrictions
REX 1865	EPZ, TP, Stabling	~3 h	Full daytime cycle	Weekdays until 30.11.
REX 1867	EPZ, TP, Waste Disposal	~3 h	Waste disposal included	Weekdays until 30.11.
REX 1879	TP, Waste Disposal, Stabling	~5 h	Evening + overnight cycle	Weekdays until 30.11.
REX 1883	Cleaning, Waste Disposal, Stabling	~6.5 h	Short train set, overnight staging	Weekdays only
Sv 4692	SHU, Waste Disposal, Stabling	~4 h	Train set 951, special routing	Limited dates (e.g., 6.4., 4.7., 31.8. . .)
Os 4635	Cleaning, Waste Disposal, TP, Stabling	~6 h	Complex servicing overnight	Weekdays only, restricted 26.12–5.1.

Table 8. Proposal for the servicing of passenger (Os) train sets.

Train	Main THU Activities	Estimated Duration	Continues as	Operation Days/Notes
Os 4639	Washing, Cleaning, Sewage Disposal	~1.5 h	Os 4600	Daily except 24., 25., 31.12.
Os 4704	Overnight Stabling	~2.5 h	Os 4704	Selected Saturdays and holidays (e.g., 24.12.–7.1.)
Os 4600	Only Stabling	N/A	Os 4600	Daily
Os 4727	Cleaning, Stabling	~3 h	Os 4708	Operates on 24. and 31.12.
Os 4708	Early Morning Stabling	~1 h	Os 4708	Operates on 24. and 31.12.
Os 4731	Cleaning and Sewage Disposal	~0.5 h	Os 4600	Operates on 24. and 31.12.

Table 9. Proposal for the servicing of Os train sets with regular 951 push–pull formation.

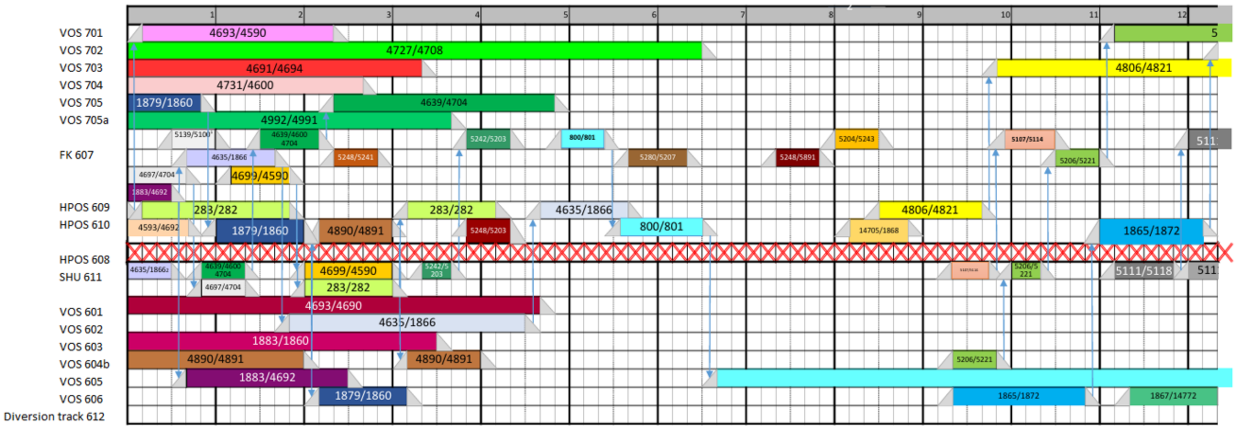
Train	Main THU Activities	Estimated Duration	Washing (SHU)	Departure as	Operation Days/Notes
Os 4806	Technical Inspection, Cleaning, Stabling	~5 h	No	Os 4821 (14:01)	Weekdays except 27.12–5.1.
Os 4826	Cleaning, Stabling	~2.5 h	No	Os 4835 (21:01)	Weekdays except 24.12–8.1.
Os 4832	Cleaning + SHU Unit Washing	~1.5 h	Yes	Os 4939 (23:14)	Daily, except 24., 31.12.
Os 14705	Quick Cleaning and Waste Disposal	~0.5 h	No	REx 1868 (09:14)	Weekdays except 27.12–5.1.
Os 14729	Quick Cleaning and Waste Disposal	~0.5 h	No	Os 4640 (21:05)	Weekdays except 27.12–5.1.

Table 10. Proposal for the servicing of Os train sets with regular DMJ 861 formations.

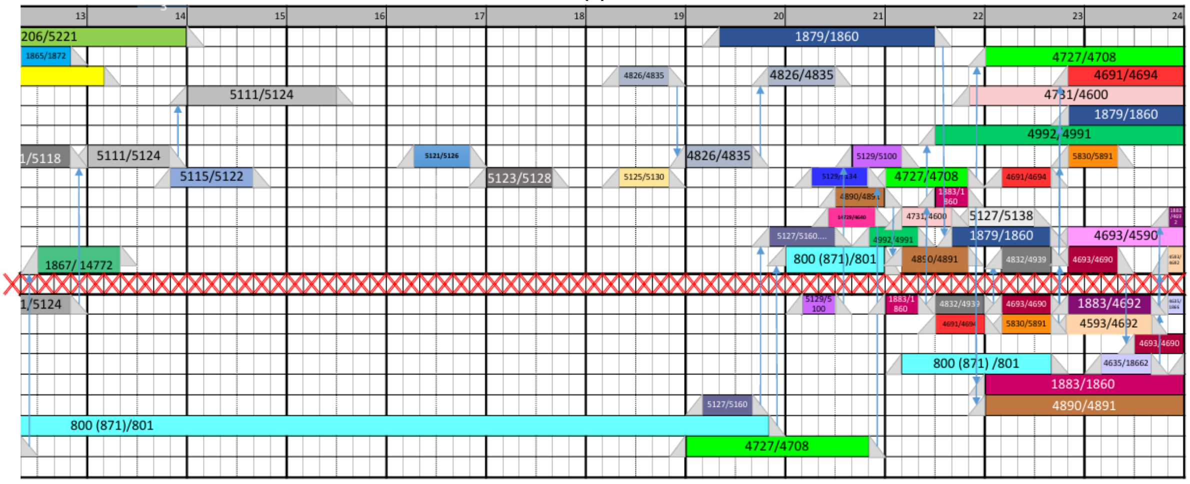
Train	Main THU Activities	Unit Washing	Approx. Duration	Next Train	Operation Days/Notes
Os 5107	Washing, Cleaning, Water	Yes	~1.5 h	Os 5114 (11:15)	Weekdays, not 24.12–8.1
Os 5111	Washing, Cleaning, Water	Yes	~2 h	Os 5118 (13:15)	Daily
Os 5115	Cleaning, Water	No	~1 h	Os 5122 (15:15)	Weekends, holidays, 24.12–8.1
Os 5121	Cleaning, Water	No	~0.5 h	Os 5126 (17:15)	Weekends, holidays, 24.12–8.1
Os 5123	Cleaning, Water	No	~0.5 h	Os 5128 (18:03)	Weekends, holidays, 24.12–8.1
Os 5125	Cleaning, Water	No	~0.5 h	Os 5130 (19:15)	Weekends, holidays, 24.12–8.1
Os 5127	Cleaning, Stabling, Water	No	~1.5 h	Os 5160/5110	Conditional, depends on rotation
Os 5129	Cleaning, Water	No	~0.5 h	Os 5134 (21:15)	Weekdays, not 24.12–8.1
Os 5139	Cleaning, Water	No	~0.5 h	Os 5100/5114	Conditional, depends on rotation

Table 11. Proposal for the servicing of Os train sets with regular MV 812 formations.

Train	Main THU Activities (1–2 Stages)	Approx. Duration	Final Departure	Operation Days/Notes
Os 5204	Cleaning, Sewage Disposal, Water	~1 h	09:03 AM (to Šurany)	Weekdays, not 24.12–8.1
Os 5206	Parking, Washing, Cleaning, Sewage Disposal, Water	~3 h	02:15 PM	Weekdays, not 24.12–8.1
Os 5248	Refueling, Turnaround Parking, Cleaning	~5 h	03:33 AM (Os 5241)	Weekdays, not 24.12–8.1
Os 5280	Refueling, Overnight Stabling, Full Cleaning Cycle	~12 h	07:03 AM (Os 5207)	24.12, 31.12. only
Os 5830	Washing, Cleaning, Stabling	~10 h	08:22 AM (Sv 5891)	24.12–8.1. only



(**a**)



(**b**)

Figure 4. (**a**) Proposal for train servicing at the THU in Nové Zámky. (**b**) Proposal for train servicing at the THU in Nové Zámky.

The servicing of EuroCity (EC) and Express (Ex) train sets is presented in Table 6, which provides an overview of train servicing at Nové Zámky railway station. It details arrival times, the start and duration of individual operations, such as technical inspections (TP), cleaning, and connection to EPZ (External Power Supply). An important aspect is the relatively long stabling time for some trains, especially Express 800 Poľana, where the train set remains connected to EPZ until the evening. For EC 293 Metropolitan, a key operation is intensive cleaning in SHU, which lasts one hour, followed by additional cleaning and water refilling in HPOS.

Table 5 summarizes the use of THU services by selected EC and Ex train sets. It identifies which operations are performed (waste disposal, technical inspection, washing) and estimates total service duration. The table also indicates limitations in operation days. This abstraction helps identify how different categories of trains utilize the THU facility, which informs scheduling and capacity planning.

Table 7 provides a summarized overview of THU operations for selected REX and Os train sets. It indicates which servicing modules are used (cleaning, waste disposal, technical inspection, stabling), estimated total servicing duration, and relevant operational restrictions.

Table 8 summarizes night-time or early morning technical–hygienic servicing of regional passenger (Os) trains. Each entry lists the primary THU activities, estimated servicing duration, the subsequent train operation, and any operational constraints. The simplified view facilitates comparison of process types and identifies efficient reuse of rolling stock within station rotation plans.

Table 9 presents a summary of THU activities for regional push–pull train sets (type 951). The simplified view outlines the key servicing operations (technical inspection, cleaning, waste handling), whether unit washing is performed, total estimated time, and the next train operation. Operational restrictions are also indicated, reflecting limited circulation around the holiday season.

Table 10 summarizes the THU activities for Os train sets operating with DMJ 861 diesel multiple units. It indicates the primary service activities (cleaning, water refilling, washing), estimated duration, and the next scheduled departure. The table highlights operational patterns, such as short service windows and variable circulation based on weekday/weekend schedules and seasonal restrictions.

Table 11 presents a simplified servicing overview for Os train sets formed by motor vehicle type MV 812. The summary highlights key maintenance activities (refueling, cleaning, washing), staging periods, and the outbound train rotation. Different turnaround patterns are visible based on whether the units are serviced during daytime or stored overnight. Operating constraints reflect holiday-affected deployment.

Table 12 summarizes servicing procedures for Sv train sets, which typically involve empty, repositioning, or non-revenue moves. These units are serviced overnight and undergo multiple operations such as cleaning, waste disposal, unit washing, and technical inspections. The average servicing time ranges from 3 to 5.5 h. Departure times reflect the next operational use of the train set. Operation is limited to specific dates or weekdays, and several units operate on an irregular or ad hoc basis.

Table 12. Proposal for the servicing of train sets.

Train	Main THU Activities (Stages 1–2)	Approx. Duration	Final Action	Departure	Operation Days/Notes
Sv 4593	Washing + Cleaning, Disposal, Stabling	~4 h	Stabling on station	03:05 AM	Selected Mondays, not 26.11., 2.1., etc.
Sv 4691	Washing + Cleaning + Disposal, Stabling	~4 h	Stabling (track 703)	03:34 AM	Same as above
Sv 4693	Washing + Disposal, Stabling	~3.5 h	Stabling (track 601)	03:00 AM	Irregular, as required
Sv 4697	Cleaning, Disposal + EPJ Washing, Stabling	~5 h	Stabling	05:14 AM	Saturdays, some public holidays
Sv 4890	Cleaning, Disposal + Tech. Inspection ×2	~5.5 h	Technical check	05:50 AM	Mondays, not 26.12., 2.1., etc.
Sv 4992	Cleaning + Tech. Inspection + Stabling	~5.5 h	Stabling	04:20 AM	Working days with multiple exceptions

6. Discussion

The optimization of technical–hygienic maintenance processes in railway transport is a crucial factor in enhancing operational efficiency, reducing downtime, and ensuring the reliability of railway rolling stock. The analysis of servicing times and maintenance procedures at the THU in Nové Zámky provides valuable insights into the current state of operations and the potential for optimization through the implementation of automated cleaning systems, digital diagnostic tools, and improved scheduling and workflow coordination.

This section discusses the key findings derived from the conducted analyses, comparing the current servicing practices with the proposed optimization measures. It assesses the impact of modernization on servicing efficiency, the utilization of existing infrastructure, and the THU's capacity to accommodate various train categories. Furthermore, the analysis highlights operational bottlenecks, potential improvements in staff allocation, and the benefits of integrating automated systems to streamline maintenance activities. By evaluating the effectiveness of train set movements, the achieved reductions in servicing time, and the feasibility of further capacity expansion, this section provides a comprehensive assessment of the THU's operational performance and its contribution to a more sustainable and efficient railway network. A graphical representation of track capacity utilization at the THU is provided in Figure 5a,b. These visualizations reflect the approximate duration of individual servicing operations, recognizing that each train set requires a different amount of time depending on its specific maintenance needs. In the case of stabling, the diagram considers only the net track occupancy time for each individual train. However, during overlapping operations such as wastewater disposal or vehicle washing, it is possible to service multiple train sets within the same time window. The graphical layout uses color coding to differentiate between various activities, enhancing clarity and allowing for an intuitive understanding of capacity usage and operational sequencing as follows:

- Gray represents times when train sets are stabled on tracks.
- Brown indicates wastewater disposal operations.
- Yellow highlights activities performed in HPOS, primarily technical inspections of train vehicles.
- Blue is used for operations in the SHU, where a distinction is made between normal and intensive cleaning.
- Orange marks operations on VOS, including the connection of train sets to EPZ.

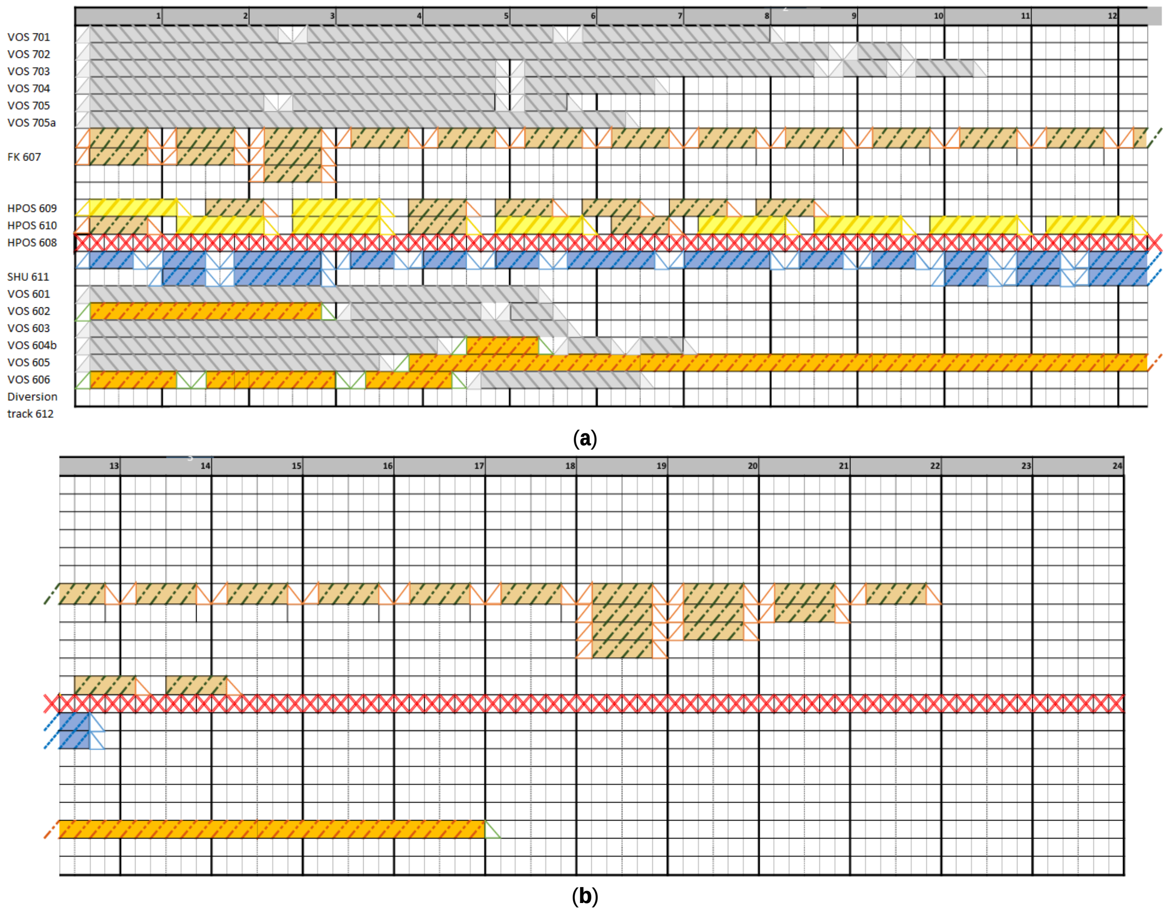


Figure 5. (**a**) Track capacity utilization in the THU. (**b**) Track capacity utilization in the THU.

Track No. 701 exhibits a total technological occupancy time of 470 min, during which three train sets are processed within a 24 h period. Although the track typically accommodates only one train set at a time, parallel servicing is technically feasible if operationally required. The occupancy time includes an estimated 60 min for transfers between the THU, the railway station, and the locomotive depot. The actual stabling duration accounts for 410 min, while the remaining 970 min remain unused. The resulting track occupancy rate is 32.64%.

Track No. 702 shows a total occupancy time of 580 min per day, with two train sets processed. Like track 701, only one train is physically present at a time, but the track supports overlapping operations when necessary. Of the total, 40 min are assigned to transfer operations, and 540 min to stabling. The remaining 860 min are unutilized, resulting in an occupancy rate of 40.28%.

Track No. 703 has the highest occupancy rate among the evaluated tracks, with a daily technological occupancy of 630 min and four train sets processed. While only one train set is typically present at any given time, the track supports parallel operations if required. The transfer time accounts for 80 min, and stabling occupies 550 min. The unutilized time totals 810 min, yielding an occupancy rate of 43.75%.

Track No. 704 is utilized for 410 min daily, with two train sets rotated across a 24 h period. Of this, 40 min are allocated to transfer operations and 370 min to stabling. The unutilized time amounts to 1030 min, resulting in an occupancy rate of 28.47%. Although parallel processing is not standard, it remains a feasible option.

Track No. 705 shows the lowest occupancy, with 350 min of technological use per day and two train sets serviced. While this track is not routinely used for simultaneous servicing, it can accommodate overlapping operations when required. Transfer activities consume approximately 60 min, with 290 min allocated to stabling. The remaining 1090 min are unutilized, producing an occupancy rate of 24.31%.

The capacity utilization analysis of additional tracks reveals occupancy rates ranging between 22.92% and 71.53%. The highest utilization was recorded on track No. 605, which reached an occupancy rate of 71.53%. On this track, two train sets are serviced within a 24 h period, with a total technological occupancy time of 1030 min. Of this, 40 min are allocated for train transfers and connection to EPZ, while 200 min are dedicated to stabling. In contrast, track No. 606 exhibits an occupancy rate of 27.78%, with approximately 400 min of daily technological activity. As with other tracks, it is technically possible to conduct simultaneous servicing of multiple train sets if operationally required. When evaluating the operational efficiency of the THU, it is necessary to assess not only the total occupancy times of individual tracks but also the effectiveness of technological processes carried out within the facility. Well-coordinated train movements and maintenance scheduling can minimize idle time, thereby enhancing the overall throughput and capacity of the center. Based on the conducted analysis, it may be concluded that the THU currently possesses adequate capacity to accommodate existing operational requirements. However, with the projected growth in train set volume, further optimization strategies may become necessary. Tracks operating above a 50% occupancy rate may represent potential capacity bottlenecks, which could limit flexibility during peak periods or unplanned service events. It is therefore essential to implement continuous monitoring and dynamic adjustment of track utilization and maintenance scheduling to maintain optimal operational performance. Table 13 summarizes the occupancy rates of individual tracks based on the graphical analysis presented in Figure 5a,b, offering a detailed overview of infrastructure usage at THU in Nové Zámky.

Table 13. Track occupancy based on graphical processing.

	T_{obs} (Min)	n (Train Set)	n_{total} (Train Set)	T_{obs_act} (Min)	T_{depon} (Min)	T_{medz} (Min)	So_1 (%)
VOS 701	470	3	3	60	410	970	32.64
VOS 702	580	2	2	40	540	860	40.28
VOS 703	630	4	4	80	550	810	43.75
VOS 704	410	2	2	40	370	1030	28.47
VOS 705	350	2	2	60	290	1090	24.31
VOS 705a	390	1	1	20	370	1050	27.08
FK 607	942	32	22	1320	x	498	65.42
HPOS 609	520	8	8	520	x	920	36.11
HPOS 610	820	12	12	820	x	620	56.94
HPOS 608	1440	x	x	1440	x	x	100.00
SHU 611	770	18	13	770	x	670	53.47
VOS 601	330	1	1	20	310	1110	22.92
VOS 602	340	3	3	220	120	1100	23.61
VOS 603	350	1	1	20	330	1090	24.31
VOS 604b	430	4	4	130	300	1010	29.86
VOS 605	1030	2	2	830	200	410	71.53
VOS 606	400	4	4	290	110	1040	27.78
Track 612	0	0	0	0	0	1440	0.00

Table 12 provides essential data for strategic decision-making regarding the capacity of THU Nové Zámky and enables the identification of areas where improvements can be made in the organization of technological processes and track utilization. It includes various parameters that characterize the overall track occupancy, the number of serviced train sets, technological times, and utilization [46]:

- T_{obs} (min) is total technological track occupancy time in minutes. This value represents the sum of the time during which the track is actively used for technological operations such as cleaning, diagnostics, repairs, and waste disposal.
- n (train sets) is number of train sets serviced daily on the given track.
- n_{total} (train sets) is total number of train sets serviced throughout the day.
- T_{obs_act} (min) is time allocated for technological operations, such as the transfer of train sets between THU, the railway station, and the locomotive depot.
- T_{depon} (min) is time during which train sets are parked on the track without undergoing technological operations.
- T_{medz} (min) is time during which the track is neither occupied by technological operations nor by parked train sets.
- So_1 (%) is track occupancy rate, calculated as the proportion of occupied time relative to the total time within a 24 h period.

The THU in Nové Zámky demonstrates the capacity to efficiently service train sets across a variety of track types, with the highest utilization observed on the waste disposal track (FK 607) and tracks located within the HPOS facility. In contrast, other tracks—such as VOS 705—are only partially utilized, revealing opportunities for further optimization and more effective train movement planning. A track utilization rate exceeding 50% may pose operational limitations in the future, particularly during peak servicing hours or in the event of unforeseen disruptions. Therefore, it is essential to implement continuous monitoring of track occupancy and to apply flexible scheduling adjustments to technological processes to maintain operational fluidity. The high occupancy rate of the waste disposal track (FK 607) underlines the critical importance of efficient sanitary service coordination. Without appropriate management, this track could become a bottleneck that restricts the overall servicing capacity of the center. Furthermore, optimization of train movements between the THU, the main railway station, and the locomotive depot represents a key opportunity to reduce transfer-related time losses and enhance the overall throughput and productivity of the facility.

As part of the economic evaluation, the proposed construction and operation of the THU at the Nové Zámky Railway Station introduces a shift in the cost structure of railway vehicle maintenance services. This transition from decentralized maintenance facilities in Štúrovo, Levice, and Komárno to a centralized site brings multiple economic benefits as well as new operational demands. Due to limited availability of precise data, all estimates were prepared based on a 2018 project study [47], adjusted using indexation and refined through expert estimates in consultation with railway station staff.

The changes in the cost structure after commissioning the THU are summarized in Table 14 and include the following categories:

- Material costs—Expected to increase due to higher consumption of cleaning agents and technical supplies required for new technological processes.
- Personnel costs—Projected to rise due to an increase in staff numbers to 127 and the need for employee training. The proposed staffing structure includes administrative and management staff (8), technical maintenance personnel (62), hygienic maintenance staff (45), support operations (8), and warehouse staff (4).
- Energy costs—Will increase due to the operation of washing lines, wastewater treatment facilities, and heating of maintenance halls.
- Rental expenses—Expected to decrease after the cancellation of certain leased premises.
- Supply and production overhead—Will slightly increase due to in-house diagnostics and spare parts storage.
- Other services—A reduction is expected in external servicing and support, replaced by internal capacities.
- Equipment repair and maintenance—These costs will include regular service cycles of technologies and buildings.
- External shunting—Costs will decrease as most shunting operations will be carried out internally.
- Cleaning costs—Will remain at similar levels, but with significantly improved output quality.

Table 14. Estimated operating costs of the THU in Nové Zámky; authors, according to [47].

	Estimated Costs Based on the Project Study (EUR)	**Estimated Costs After Commissioning of the THU (EUR)**
Material Costs	618,685	649,619
Personnel Costs	1,178,717	1,428,190
Energy Costs	95,593	224,490
Rental Expenses	216,629	115,500
Supply and Production Overhead	345,336	376,416
Other Services	226,316	269,239
Equipment Repair and Maintenance	129,343	156,922
Operating Expenses of the Facility	2,838,200	3,215,113
External Shunting	239,479	137,500
Cleaning Costs	462,114	462,114
Other Operating Expenses	701,594	599,614
Total Operating Expenses	3,512,214	3,819,992

Despite the increase in total operating costs from EUR 3.51 million to EUR 3.82 million annually, improvements in service quality, enhanced cleaning standards, optimized train movements, and reduced dependence on external providers are expected. Investments in the cable-based shunting system (LPZ), automated washing line, and diagnostic panels are estimated in the range of several hundred thousand euros, with a projected return on investment (ROI) within 5–7 years, primarily due to labor time savings and the elimination of outsourced services.

The proposed technologies are assessed at Technology Readiness Levels (TRL) 7–9, indicating that they are already deployed in pilot projects or standard operations abroad. Potential risks include staff training requirements, the availability of spare parts, maintenance demands, and the need for integration with ZSSK's existing operational systems.

The economic analysis confirms that, despite an increase in certain operating cost categories, the centralized THU model in Nové Zámky is economically sustainable in the long term. The investments in technical infrastructure are expected to be recovered within a reasonable timeframe while delivering higher service quality and operational reliability.

While this study focuses on the specific case of the Nové Zámky station with a defined traffic pattern and train set rotation, the proposed THU concept is designed to be scalable and adaptable. The modular structure of servicing zones (SHU, FK, HPOS) allows for reconfiguration based on local operational needs and available space. For smaller regional stations, a reduced version of the THU could focus on basic cleaning and waste disposal, while major junctions may benefit from integrating advanced diagnostics and real-time monitoring systems. Future studies could validate this framework at other stations with different demand profiles to further generalize the findings.

Although this research is focused specifically on the conditions of the Nové Zámky railway station, the proposed concept of a centralized THU may be applicable to other medium-sized railway nodes, provided that several critical factors are considered. To improve the general relevance and transferability of the findings, it is essential to outline the infrastructural and operational parameters that influence the applicability of the proposed solution. The implementation of the THU concept requires a station layout that includes enough through tracks, shunting sidings, and service-specific tracks (for cleaning, inspection, and waste disposal). Stations must allow parallel handling of multiple train sets and have adequate spatial conditions for the construction or adaptation of facilities such as the SHU (washing unit) and HPOS (technical inspection hall). The proposed model is particularly suitable for stations with moderate to high daily turnover—approximately 20 to 50 train sets per day. It is most effective where rolling stock remains idle for a few hours between arrivals and departures, enabling staged servicing activities without disrupting circulation. Effective implementation requires access to a stable energy supply (for EPZ), waste and water treatment systems, and compatibility with the station's timetable planning processes. The ability to connect to digital platforms for diagnostics and scheduling is also a key enabler for automation and performance tracking. The model presumes sufficient availability of internal shunting resources or the use of self-propelled multiple units (electric or diesel). Stations that rely entirely on external shunting (by ŽSR locomotives) may face operational delays unless coordination mechanisms are optimized. In contrast, small terminal or regional stations with fragmented track layouts, low traffic intensity, or non-electrified lines may not justify full-scale THU implementation. For such locations, a simplified model focusing on basic hygienic services—such as waste disposal and minimal cleaning—may be more appropriate and cost-effective.

Future research in the field of technical and hygienic maintenance of railway vehicles should primarily focus on improving the efficiency of technological processes, implementing digital solutions such as predictive maintenance platforms, real-time monitoring systems, and automated diagnostics, as well as enhancing sustainability through water recycling systems and energy-efficient infrastructure. Future research should focus on the development of mathematical models to simulate and predict track utilization, thereby enhancing maintenance planning based on actual operational conditions. In addition, further studies could explore the application of artificial intelligence (AI) and machine learning for predictive scheduling and optimization of maintenance workflows within THUs. The integration of the Internet of Things (IoT) into servicing processes could also enable automated data collection on component wear, service intervals, and system diagnostics. Another promising area of investigation involves strategies for reducing the consumption of water and cleaning agents in the washing of railway vehicles—such as the use of wastewater recycling systems and closed-loop technologies. Likewise, the potential deployment of renewable energy sources, such as photovoltaic systems, could help reduce the facility's energy demand and operational costs, contributing to a more sustainable maintenance model. An additional avenue for research involves evaluating the feasibility of hybrid or fully electric shunting locomotives, which offer the potential to reduce emissions and noise pollution associated with traditional diesel-powered units. Altogether, the integration of advanced analytics, automation, AI-driven systems, and ecological technologies represents a promising direction for improving the quality, efficiency, and sustainability of railway maintenance practices—ensuring a more resilient, cost-effective, and environmentally responsible transport system.

7. Conclusions

This study introduced the design and analysis of a centralized THU for passenger rail transport at the Nové Zámky railway station. Based on operational analysis, capacity visualizations, and servicing time calculations, several key findings were identified that confirm the efficiency of the proposed model and its potential for broader application. Track utilization analysis revealed that the most heavily used tracks are Track No. 608 (HPOS) and No. 605 (VOS), with occupancy rates exceeding 70%. The waste disposal track (FK 607) is also highly utilized, servicing up to 32 train sets per day. These results indicate that while the current capacity of the THU is sufficient, operational bottlenecks may arise if the number of serviced train sets increases. Notably, optimization of technological processes could reduce the average servicing time per train set by 18.4 min, thereby enhancing overall throughput. The most effective and innovative element of the proposed concept is the use of Track No. 611 with a cable shunting system (LPZ), which reduces manual movement requirements and shortens unproductive time. In addition, relocating long-stay train sets to the station yard tracks (VOS) frees up capacity in the THU halls. Segmenting the maintenance processes (cleaning, inspection, stabling) ensures a more balanced workload distribution across service points.

The proposed technologies—automated washing systems, digital diagnostics with onboard sensors, and a centralized control system—correspond to TRL 7–9, meaning they have already been proven in operational environments. Investments are estimated in the range of several hundred thousand euros, with an expected return on investment within 5–7 years based on time savings and elimination of external services. The cost comparison with a project study from 2018 confirms the long-term economic viability of the concept, even with an increase in some operational cost categories. The model is designed to be scalable and replicable. Provided that certain operational and technical conditions are met—such as sufficient train set turnover, available land, and railway infrastructure integration—it can be implemented at other key nodes like Bratislava, Zvolen, Žilina, Košice, or Humenné. To ensure sustained high performance, the following measures are recommended: regular monitoring of track occupancy to identify capacity bottlenecks in advance, optimization of train movements and scheduling to prevent conflicts, gradual implementation of automated cleaning and diagnostic technologies, and infrastructure expansion (e.g., extending the FK track or duplicating the busiest tracks) in response to future growth in service demand. By integrating these measures, the Nové Zámky

THU concept demonstrates how strategic infrastructure design, synchronized operations planning, and technological modernization can support growing maintenance needs while maintaining high service quality. Its replicability for other regional stations positions it as a scalable model for enhancing the reliability and sustainability of Slovakia's rail transport.

Future research should explore formal modelling and simulation (e.g., discrete event simulation or MILP models) to validate the proposed methodology under varying infrastructural and operational conditions. For broader adoption of the THU concept, feasibility assessments must be conducted at each candidate station to account for spatial, technical, and organizational criteria. This ensures that the model is adapted to local contexts while retaining its core benefits: efficiency, quality of service, and cost optimization. The research findings confirm that the Nové Zámky THU concept has high potential not only to improve maintenance efficiency and service quality, but also to serve as a reference model for the modernization of maintenance centers in passenger rail transport across Central Europe.

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