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OPTIMISING LOCOMOTIVE SCHEDULING IN RAILWAY OPERATIONS: TECHNIQUES, CHALLENGES, AND A FRAMEWORK FOR INDIAN RAILWAYS

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Abstract

Locomotives are one of the significant capital-intensive components in a railway system. A systematic locomotive assignment has a high potential for productivity enhancement and cost savings. The locomotive scheduling problem in railways involves optimally allocating and managing locomotives to ensure efficient train operations. Due to the scale of the problem and the large number of practical constraints, finding an optimal assignment is a complex problem. Researchers have attempted to tackle this problem in different railway systems worldwide. This paper presents an overview of the techniques used and the state-of-the-art in this domain. In the Indian context, the publications in this domain are scarce. The literature review underscores the importance of systematic locomotive assignment for productivity enhancement and cost savings in railway operations. Mathematical models and algorithms, including heuristics, linear programming, and integer programming, are the usual solutions methodologies used to balance these conflicting needs and restrictions and increase the overall efficiency of railway operations. We also present a framework for locomotive scheduling for Indian Railways considering the maintenance constraints. This framework tries to accommodate the unique challenges faced by the Indian railway system, such as diverse locomotive types and varying operational conditions. By adopting and implementing the discussed structured mathematical models or heuristic techniques, Indian Railways can potentially enhance its operational efficiency and reduce costs.

Keywords: Railway Operations Management, Productivity, Locomotive Scheduling

INTRODUCTION

RAILWAY OPERATIONS MANAGEMENT

In order to maintain infrastructure, coordinate multiple tasks, and ensure the safe and effective movement of trains, railway operations management entails planning, coordinating, and supervising railway services. Effective railway operations management involves planning and scheduling resources for seamless and efficient service delivery. This process includes the allocation and scheduling of infrastructure and movable assets such as rakes and locomotives. Managing limited track capacity, outdated infrastructure, integrating technology, environmental concerns, and security issues are some of the major challenges. To increase efficiency, safety, and customer satisfaction, effective railway operations management integrates several departments and makes use of technology and innovation.

Some techniques used in the context of railway operations management include such Scheduling techniques, Mixed Integer Linear Programming (MILP), Simulation, Heuristics and evolutionary algorithms. Rodenas et al. [1] utilized MILP for real-time train platforming management.Routing algorithms, like Dijkstra's algorithm can be utilized for optimizing train routes. Bozejko et al. [2] discussed the use of Dijkstra's algorithm for scheduling and routing in rail freight transportation. Simulation methods, including Discrete Event Simulation and Agent-Based Simulation model network behaviour to identify potential improvements. Michala et al. [3] addressed the challenge of integrating additional freight movements into a constrained railway network using a simulation modeling platform called RailNet. Additionally, machine learning algorithms predict equipment failures and demand patterns, boosting overall system performance and sustainability. Malekjafarian et al. [4] employed a machine-learning-based approach for railway track monitoring using acceleration data from an in-service train. Swapnesh et.al [5] presented a heuristic for allocation of arriving rakes to facilities in Indian Railways, focusing on maintenance activities and operational constraints. The study proposed a two-phase heuristic algorithm for creating maintenance and parking schedules at terminuses, aiming to automate the planning process and save man-hours, though it did not consider local routing and shunting requirements. Zhang et.al [6] examined the interplay between train timetabling, platforming, and network maintenance scheduling. Their study on high-speed rail networks showed that integrated optimization of these factors could reduce the weighted running cost by 9.08% to 22.16%. The study used a 0–1 binary integer programming model that minimizes the total train weighted running cost and any deviation from ideal maintenance task start times. Above case studies showcases best how to deploy different optimization techniques for effectively managing railway operations.

India's railway network has relied on various locomotives, from historical steam engines to modern electric and hybrid models, to meet its operational needs. These advancements in locomotive technology enhance efficiency and sustainability, reflecting the adaptability of Indian Railways to its vast and diverse transportation demands. A locomotive is a rail vehicle that provides the power for a train and is responsible for pulling or pushing the train along the tracks. Locomotives can be powered by various energy sources, mainly diesel and electricity. Research in locomotive assignment problems is increasingly important. According to Kroon et al.[7], planning challenges for a passenger railway operator can be classified in various ways. One approach considers the planning horizon, encompassing strategic, tactical, and operational phases. Another approach focuses on the physical location of planning issues, differentiating between local problems, like deciding which train should depart from which platform at a station, and global problems that impact the entire railway network.

The locomotive scheduling problem involves allocating locomotives to a network of trains, adhering to various practical constraints while minimizing the overall cost. Rail planners need to assign locomotives to thousands of different trains. These problems are highly complex due to the large scale of the problem and the various constraints involved. Given the capital investment and impact on operational efficiency, developing an effective solution to the locomotive scheduling problem is crucial. Optimizing locomotive allocation ensures that the available assets are used to their fullest potential, reducing the need for excess locomotives and minimizing idle times. An optimized schedule enhances the reliability and punctuality of train services, improving customer satisfaction.

REVIEW OF OPTIMIZATION TECHNIQUES USED IN LOCOMOTIVE SCHEDULING PROBLEMS

Railway firms face challenges in locomotive assignment and scheduling, which involve distributing locomotives across trains and developing efficient schedules. The main objective of these problems is to minimize operating costs while meeting various constraints, including track availability, maintenance schedules, and locomotive resources. Solutions to these optimization problems often involve different methods depending on the problem scale and requirements. Integer Linear Programming (ILP) is frequently used for precise optimization, while heuristic approaches such as genetic algorithms and greedy algorithms are employed for practical applications. Metaheuristic techniques like Tabu Search and Ant Colony Optimization are also utilized for exploring broader solution spaces. Additionally, reinforcement learning—a type of machine learning technology—has been explored to enhance decision-making using historical data. Effective solutions for railway operations require the careful design of objective functions and constraints, comprehensive data collection, and iterative refinement of strategies.

Due to the limitations of exact mathematical methods for solving large-scale problems, researchers have increasingly turned to evolutionary techniques for modeling and solving these challenges. These methods range from simple heuristics to advanced simulations and evolutionary algorithms. For instance, Booler [8] proposed a heuristic algorithm for the basic locomotive assignment problem, which involves assigning a single type of locomotive to each train. This algorithm starts with a feasible allocation and iteratively refines it using dual information derived from assignment problems. In contrast, more complex scenarios involving multiple locomotive types and train segments are modeled as multi-commodity flow problems. Florian et.al [9] pioneered the use of Benders decomposition for this complex problem, though their method struggled with convergence issues for small problems. Ziarati et.al [10] addressed large-scale strategic problems by breaking them into overlapping sub-problems and solving these using a Dantzig-Wolfe decomposition method. Their approach achieved a 6% improvement in locomotive utilization when compared to existing solutions. In tackling cyclic locomotive assignment problems, the Genetic Algorithm demonstrated significant potential. By using data from the Canadian Railway Company, this approach improved operational efficiency from 30% to 39% despite a 20-hour computation time. The heuristic nature of this algorithm suggests its applicability to similar problems across different contexts [11].

Ahuja et.al [12] studied locomotive scheduling at CSX Transportation using a mixed-integer programming formulation with 197,000 variables and 67 constraints. Their solution technique, which combined problem decomposition and large-scale neighbourhood search, successfully solved the problem in 30 minutes and saved over 400 locomotives, resulting in annual savings exceeding one hundred million dollars compared to CSX's in-house software. Kasalica et.al [13] focused on the optimization of cyclic locomotive assignments considering train delays. The model aimed to determine the minimum number of locomotives needed assuming all trains were delayed, and it demonstrated that timetable optimization could improve locomotive usage significantly. This research, conducted on the Serbian and

Montenegrin Railway Networks, showed that as the probability of delays increased, the number of required locomotives grew by 7.14%, while the coefficient of locomotive time utilization decreased by 3.14%.

Su et.al [14] proposed a model for the Multi-Locomotive Scheduling problem specifically for 30kt heavy-loaded trains. By converting the multi-locomotive problem into a single-locomotive problem and solving it with the Hungarian algorithm, the model reduced locomotive usage by over 100 units. The model also improved schedule balance by adjusting minimal technological times at stations.To achieve high-quality solutions for large real-world instances within low computation times, Frisch et.al [15] employed a heuristic solution approach, utilizing both the Overlapping Rolling Horizon Approach and a Two-Stage Matheuristic Approach. Kang et.al [16] explored the integrated TRLA (Train Rescheduling and Locomotive Assignment) problem during the COVID-19 pandemic, using the Beijing-Tianjin intercity railway as a case study. The study developed a tailored approach to manage fluctuating travel demands during the pandemic by incorporating flexible time windows and minimizing locomotive idle time, which helped in decision-making for train scheduling and locomotive utilization. Although the model did not account for refined passenger travel demands due to their unpredictability, it emphasized efficient locomotive use to maximize operational benefits and reduce costs. Using Deep Reinforcement Learning, specifically the Proximal Policy Optimization (PPO) algorithm, Cheng et al. [17] have effectively optimized the transportation capacity for heavy-haul railway scheduling, achieving superior performance compared to traditional methods.

Lazarev et.al [18] analyzed the freight train make-up and routing problem by proposing a polynomial algorithm for constructing order delivery schedules for a single locomotive across three railway stations.Yaghinia et.al [19] adapted a BPR (Business Process Reengineering) methodology to redesign the process of locomotive distribution, aiming to balance logistical needs with economic benefits. The approach sought to improve operational efficiency and optimize freight distribution by aligning locomotive allocation with financial considerations.

Table:-1: Research Objectives and outcomes of previous studies

Authors	**Research Objectives**	**Outcomes**	**Region of Study**
Ziarati et al.[11]	Solve cyclic locomotive assignment problems and thereby improve operational efficiency.	Operational efficiency improved to 39% from 30%	Canada
Ahuja et al.[12]	Solve locomotive scheduling problem faced by CSX Transportation, a major US railroad company	Researchers obtained a savings of over 400 locomotives compared to the in-house solution by CSX	US
Kasalicaet al.[13]	Optimize cyclic locomotive assignment problem considering train delays at the time of preparing the timetable	Raising train delay probabilities from 20% to 90% increases the number of locomotives needed by 7.14%.Model gave optimum number of locomotives required considering delays.	Serbia and Montenegro
RuiyeSut al.[14]	Optimise Multi Locomotive Scheduling problem for 30kt heavy loaded trains to minimise the total number of locomotives used	The use of 100+ locomotives can be reduced	Serbia and Montenegro
Frisch et al.[15]	Minimize the total costs of	High-quality solutions for	Austria

	locomotive operations including active locomotive costs, deadheading costs, light travel costs, consist-busting costs, and penalties for single locomotive consists, with considerations for maintenance jobs and CO2 emissions reduction.	large real-world instances within low computation times	
Kang et al.[16]	Train Rescheduling and Locomotive Assignment problem during the COVID-19 outbreak until full recovery, focusing on operating costs	Was able to minimize the number of locomotives utilized and their total idle time.	China
Cheng et al.[17]	Optimization of transportation capacity heavy-haul railway Scheduling	Achieved effective optimization of transportation capacity and outperform traditional methods.	China
Lazarev et al.[18]	Construction of orders delivery schedule for one locomotive plying among three railway stations	Was able to minimize the total completion time of locomotives plying among three railway stations.	Russia
Yaghinia et al.[19]	To optimize locomotive distribution for improved financial benefits and efficient freight transportation, prioritizing destinations appropriately.	To overcome the consequences of the problems, the locomotive operation management process has been reengineered.	Iran

Research objectives and outcomes from Table-1 clearly suggest that locomotive assignment problems are vital as they significantly influence the efficiency and cost-effectiveness of railway operations. Optimal locomotive assignment maximizes resource use, reduces fuel consumption, and ensures timely transport of goods and passengers. Additionally, it enhances operational reliability, lowers maintenance costs, and improves overall sustainability and service quality. From Table-1 it is clear that research on locomotive assignment problems in India is limited, revealing a crucial gap that could greatly improve railway operations. Greater focus and study in this area could lead to significant advancements in the performance and sustainability of Indian Railways.

Table-2:- Overview of solution methodologies used for Locomotive Scheduling

Authors	**Year**	**Solution Approach**	**Technique Used**
Ziarati et al.[11]	2005	Evolutionary Algorithm	Genetic Algorithm
Ahuja et al.[12]	2015	Combinatorial Optimization Algorithm	Hungarian Algorithm

Kasalica et al.[13]	2013	Simulation	Software package developed in Microsoft Visual Basic, ver. 6.0
RuiyeSu et al.[14]	2002	MIP+Simulation	Problem decomposition,
			Integer programming, and very large-scale neighbourhood search
Frisch et al.[15]	2021	Heuristic solution approach	Overlapping Rolling Horizon Approach and a Two-Stage Matheuristic Approach
Kang et al.[16]	2022	Mixed Integer Linear Programming	2 stage algorithm
Cheng et al.[17]	2023	Deep Reinforcement Learning	Proximal Policy Optimization (PPO) algorithm
Lazarev et al.[18]	2013	Approximation technique	Polynomial Algorithm
Yaghinia et al.[19]	2012	Management Strategy	Business Process Reengineering

Type of optimization techniques previously used by researchers in locomotive assignment problems are mentioned in Table-2. In our study a network flow model will be suggested for efficient utilization of locos. Network flow models have several advantages over other optimization techniques in railway operations management. They efficiently handle large and complex networks, making them ideal for extensive railway systems. Their clear graphical structure simplifies problem formulation and implementation. Network flow models optimize resource allocation and routing, improving utilization and reducing costs. They are robust and adaptable to various constraints and objectives, and integrate well with other optimization methods and decision-support systems. Furthermore, they manage dynamic changes, such as disruptions or demand fluctuations, enhancing overall operational resilience.

AN INTEGRATED FRAMEWORK FOR EFFICIENT LOCOMOTIVE UTILISATION

For competitive railway operations, efficient locomotive utilisation that reduces operational costs and improves service reliability is essential. Locomotive circulation plans in many railway systems, including Indian Railways, are manually generated by railway personnel through iterative processes. This manual process is time-consuming and complex, often failing to achieve optimal asset utilization due to the vast scale and network size. An automated solution is essential to address this challenge.

We present an integrated framework that encompasses maintenance planning and locomotive circulation. Our framework accounts for the specific requirements of long-distance trains in India, considering maintenance replenishment needs after specific time intervals or travel distances and facility capacity constraints. This approach facilitates decision-making on loco linking to minimize locomotive requirements. Automating the process of generating locomotive links can result in substantial savings in staff hours and enhance the quality of the solutions. This framework will be particularly advantageous when introducing new services or modifying the existing locomotive links.

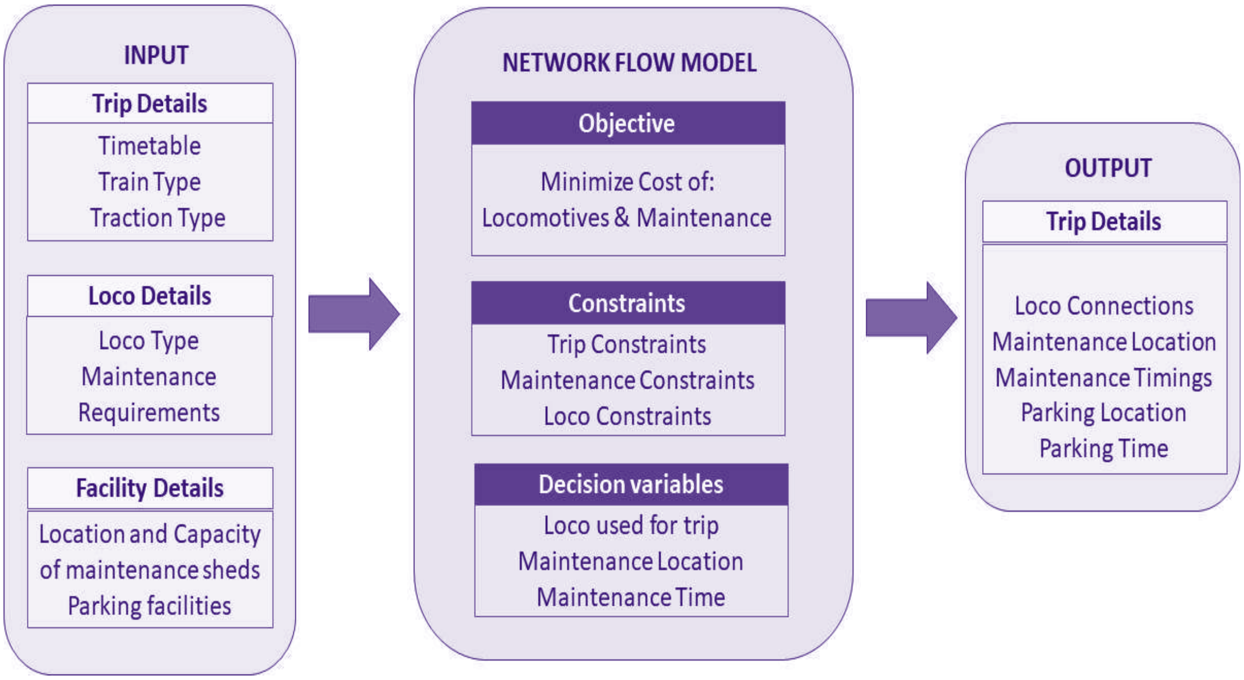
India's vast and complex railway network relies heavily on multiple locomotives for its smooth operation. These locomotives have evolved over the years and incorporate technological advances to meet the growing and changing needs of the system. Indian Railways operates various models of diesel locomotives, which are mainly divided into diesel-electric and diesel-electric types. The introduction of electric locomotives marked a major advance in Indian railway technology. With a focus on efficiency, speed and environmental sustainability, electric locomotives have become increasingly dominant, especially on high-traffic and long-distance routes. Different types of trains, whether passenger or freight, have their own locomotive requirements and models are tailored to meet those needs.

Planning at a locomotive maintenance station includes:

1. Allocating maintenance facilities to locomotives according to established norms.
2. Assigning parking slots for locomotives when not in use or undergoing maintenance.
3. Scheduling the shunting operations.

The primary objectives of locomotive optimization in Indian Railways include maximizing utilization by ensuring locomotives are used to their full potential without idle time, minimizing costs by reducing fuel consumption, maintenance expenses, and operational costs, and enhancing reliability to avoid delays and cancellations.

Figure 1: A framework for optimizing locomotive assignment



We present a structured framework to address the locomotive assignment problem using a network flow model. This model optimizes the allocation and utilization of locomotives across a railway network, aiming to minimize costs associated with operations and maintenance. The inputs include trip details, which include the timetable, train type, and traction type; locomotive details, mainly the type of locomotives and their maintenance requirements; and facility details, which detail the location and capacity of maintenance sheds and parking facilities. By organizing these inputs, the model ensures that all necessary information is available for accurate decision-making.

Network flow models with flow and capacity constraints are helpful for modeling and optimizing the movement of movable assets like locomotives and rakes in railway operations management. The network flow model is a mathematical representation used to optimize the flow of resources through a network. It consists of nodes representing sources, destinations, intermediate points, and edges representing the paths connecting these nodes. Each edge has an associated capacity, which limits the amount of flow it can handle, and a cost represents the expense of sending flow through that edge. A network flow model aims to determine the optimal flow through the network that minimizes the total cost while satisfying the constraints.

These constraints ensure that the flow is within the capacity of the tracks and stations, thereby maintaining smooth operations. The network flow model processes these inputs with the primary objective of cost minimization, considering constraints related to trip schedules, maintenance needs, and locomotive capabilities. Trip constraints ensure that locomotives are allocated according to the timetable without causing delays. Maintenance constraints account for the regular servicing schedules and the capacity of maintenance facilities, while loco constraints handle the availability of locomotives and the type of locomotive to be used. Decision variables within the model include:

- The assignment of locomotives to specific trips.
- Selection of appropriate maintenance locations.

- Precise scheduling of maintenance activities to minimize disruptions.

The output section provides detailed and optimized locomotive allocation, including the connections between locomotives and trips, designated maintenance locations, scheduled maintenance timings, and parking locations and duration. This approach ensures that railway operations are efficient, reliable, and cost-effective. By integrating various operational constraints and requirements, the model helps make informed decisions that enhance the overall performance of the railway network, leading to improved service quality and reduced operational costs.

CONCLUSION

This paper presents an overview of the locomotive optimization problem, the evolution of literature in this domain, and the tools and techniques commonly used to solve this problem. We also provide a framework that can be used to solve this problem in the context of Indian Railways. Finding efficient solutions to the locomotive optimization problem is crucial for a railway system's sustainable, efficient, and cost-effective operation. For Indian Railways to perform better, an integrated framework that includes maintenance planning and locomotive circulation has been proposed. Automation of the process of loco link generation can lead to significant savings in the number of staff hours and improve the quality of the solution. The framework will be useful when introducing new services or for analyzing the effectiveness of the existing locomotive linkages. Research could also explore the integration of real-time data and advanced predictive analytics to further refine locomotive assignment and maintenance scheduling, offering even greater optimization potential.

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