A Survey on Optimizing Resource Allocation for Railway Construction and Renovation: A Cost Minimization Model

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Abstract: *The growing demands of urban transport systems, particularly in developing countries, necessitate efficient human resource management to optimize workforce allocation and project execution within limited resource constraints. This paper explores the application of Operations Research techniques, with a particular focus on Linear Programming, for manpower optimization in the rail construction industry. By analyzing various worker categories including skilled, medium-skilled, and unskilled labor and their associated costs and availability, the study identifies critical workforce requirements across key projects such as railway construction, maintenance, and station renovation. The findings highlight the importance of aligning manpower allocation with project requirements while minimizing operational costs. Through the development of a comprehensive Linear Programming model, the proposed work aims to provide actionable insights and strategies that improve decision-making processes in resource management, ultimately contributing to the operational efficiency and sustainability of urban transport systems.*

Keywords: **Operations Research, Linear Programming, Optimization, Manpower Optimization**

1. INTRODUCTION

Urban transportation systems play a crucial role in fostering economic growth and enhancing the quality of life in rapidly developing cities. As populations continue to expand and urbanization intensifies, the demand for efficient and reliable transportation networks has never been more critical. Among various modes of transport, rail systems stand out due to their ability to carry large volumes of passengers over considerable distances with relatively low environmental impact. However, the effective management of these systems, particularly in developing countries with limited resources, poses significant challenges. Human resource management is a fundamental component of operational efficiency in rail transportation. Proper allocation of manpower is essential to ensure that operations meet increasing demand while adhering to budget constraints. Inefficiencies in workforce allocation can lead to increased operational costs, diminished service quality, and ultimately, reduced passenger satisfaction. Therefore, optimizing manpower resources is paramount for improving the overall effectiveness of urban rail systems. Operations Research (OR) techniques, particularly Linear Programming (LP) and Integer Programming (IP), offer powerful tools for addressing the complexities associated with workforce allocation and scheduling in rail transportation. These methodologies facilitate the development of models that can analyze various constraints, including labor availability, project deadlines, and operational costs, thereby enabling decision-makers to make informed choices regarding resource deployment. By applying these techniques, organizations can enhance their capability to respond to fluctuating demands and ensure efficient utilization of available manpower. This paper aims to explore the application of Operations Research techniques, focusing on manpower optimization within the rail construction and operation sectors. It will provide a comprehensive overview of relevant strategies, models, and practical applications that enhance decision-making processes across the industry. Through this investigation, the research seeks to contribute valuable insights into the importance of effective workforce management in achieving operational efficiency and sustainability in urban rail transportation systems.

2. LITERATURE SURVEY

Employee or labor scheduling is a complex problem involving the allocation of an appropriate number of workers to tasks while balancing factors such as fluctuating labor availability, job requirements, and cost constraints. [2] presents a methodical approach to solving this challenge using linear programming techniques. The proposed model identifies and analyzes tasks, estimates workforce needs in terms of size and quality, and calculates expected labor expenses. It also considers the dynamic nature of labor availability, including part-time and full-time workers, and adapts schedules weekly to align with changing service demands. By systematically organizing tasks and optimizing labor costs while accommodating worker preferences, the study provides a logical framework for efficient workforce management in construction companies. This approach not only ensures the smooth running of projects but also minimizes labor costs and maximizes operational efficiency, making it a valuable tool for addressing labor scheduling problems in resource-constrained environments.

Chen et al. demonstrates the ability of mixed integer programming models coupled with problem decomposition techniques to develop an algorithm that is capable of for manpower supply planning under mixed deterministic and stochastic demands [5].

Espiritu et al. (2020) expand on the use of LP by focusing on energy consumption optimization within rail transportation systems. Their research highlights how LP can be employed not only for labor management but also for enhancing overall operational efficiency through energy savings. By optimizing energy use, rail systems can reduce operational costs while improving sustainability, thereby supporting the dual goals of efficiency and environmental responsibility [4].

The integration of advanced methodologies in project management is explored by Kanakaris et al. (2020), who combine machine learning with OR techniques. Their study underscores the potential for predictive analytics to enhance decisionmaking in resource allocation, indicating a future direction for research in manpower optimization. By leveraging data-driven approaches, organizations can refine their labor management strategies and respond more effectively to changing operational demands [6].

Agarana et al. (2020) focus on the application of OR techniques in optimizing urban rail transportation, specifically in emerging countries. Their research emphasizes the unique challenges faced by these systems, including resource limitations and fluctuating demand patterns. By utilizing OR methodologies, they demonstrate how organizations can improve resource allocation and scheduling to enhance service delivery [1].

Liu et al. (2024) introduce a cost and passenger-responsible optimization method for planning additional high-speed train operations during peak periods. This study emphasizes the importance of aligning manpower resources with passenger demand to improve service quality and operational efficiency. By incorporating passenger dynamics into operational planning, the research highlights the necessity for adaptable workforce strategies in response to peak demand situations [7].

Qi et al. (2023) present an integer linear programming model for integrated train stop planning and timetabling, addressing time-dependent passenger demand. Their findings reinforce the need for flexible scheduling practices that accommodate varying demand levels, which directly impacts manpower requirements. This model provides a comprehensive approach to ensuring that train services align with passenger needs, thereby optimizing labor allocation [8].

Zhao et al. (2023) delve into fluctuating demand-oriented optimization of train line planning, further illustrating the impact of demand variability on operational practices. Their study highlights the necessity for adaptable labor management strategies to respond effectively to changing passenger volumes, reinforcing the importance of integrating demand forecasting into workforce planning [10].

The optimization of railway systems has been a critical focus of research due to the increasing demands for efficiency and sustainability. In high-speed railways, strategies such as integrating train-stop planning and timetabling have demonstrated the potential to enhance operational efficiency by responding dynamically to passenger demands through mixedinteger linear programming model [12]. This approach not only minimizes travel time and unfulfilled passenger demand but also highlights the significance of data-driven decisionmaking in complex transport systems. Building on this, the present study extends the principles of optimization to workforce management in the railway construction and maintenance sectors. By employing Linear Programming techniques, it explores how aligning manpower allocation with project requirements can minimize operational costs while addressing resource constraints. This interconnected focus on optimizing both service delivery and resource management underscores the importance of Operations Research in advancing urban and high-speed railway systems.

M.C. Agarana et al. highlights the benefits of optimizing urban rail transportation in emerging countries using operational research techniques. The results highlight the effectiveness of Linear Programming (LP) to optimize the systems leading to lower costs, carbon emissions as well as economic development and eradication of poverty in emerging countries. [14].

The transportation model applied to Covenant University [9] leverages Linear Programming to address inefficiencies in students' daily commutes between hostels and lecture rooms, a critical aspect of campus logistics. The study employs a structured approach using methods such as the North-West Corner, Least Cost, and Vogel's approximation techniques to determine an initial feasible solution, followed by the MODI method to optimize it further. This step-by-step application of linear programming ensures that the total time spent traveling is minimized, thereby enhancing the overall efficiency of campus transportation.

A novel integrated approach by Qi et al. (2023) toward the training of stop planning and timetabling with time-dependent passenger demand through an Integer Linear Programming model resulted in neglecting time-dependency, which led to more than 30% of passengers leaving outside preferred time intervals. [15]

The study [13] supports the ideas presented in the paper by emphasizing the importance of optimizing resource allocation under constraints, particularly in dynamic rail transportation environments. It focuses on manpower optimization in railway projects and extends these principles by demonstrating how resource optimization, including labor and operational assets, can adapt to fluctuating demands. It validates the necessity of flexible planning techniques by applying similar operations research methodologies to manage limited resources efficiently, showcasing how cost minimization and efficient allocation principles can be operationalized in dynamic contexts.

The integer programming optimization model can be used to simplify practical problems in public transportation services as demonstrated by Zhou et al. The numerical study motivated by real-life case of the Hong Kong mass transit railway (MTR) shows that an effective model can be used to improve the utilization and quality of practical applications [11].

Finally, Chhabra (2020) provides a historical perspective on operational research, detailing its significance during World War II. While not directly focused on rail transportation, this paper contextualizes the evolution of OR methodologies and their foundational role in contemporary applications, including manpower optimization in various sectors [3].

3. PROPOSED METHODOLOGY

1. Define the Objective Function

As in the previous methodology, start by clearly defining the objective of the optimization problem, which is typically to minimize costs or maximize efficiency. The objective function can be formulated as follows:

Minimize:

$Z = \sum (C_i \cdot H_i)$

Where:

- $\mathbf{Z}$ = total cost
- $\mathbf{C_i}$ = cost per hour of each job role (e.g., Train Operators, Maintenance Crew)
- $\mathbf{H_i}$ = total hours worked by each job role

2. Identify Constraints

Establish the constraints based on the data available. The following constraints may be relevant:

- **Availability Constraints:** Total hours worked for each job role cannot exceed the available staff hours.

$H_i \leq \text{Available Staff Hours}_i \ \forall i$

- **Minimum Hours Required:** Each job role must meet its minimum required hours.

$H_i \geq \text{Minimum Hours Required}_i \ \forall i$

- **Maximum Hours Allowed:** Each job role cannot exceed the maximum hours allowed per day.

$H_i \leq \text{Maximum Hours Allowed}_i \ \forall i$

- **Project Requirements:** Total hours allocated to each job role must meet the project-specific requirements.

$H_i \geq \text{Required Hours}_j \ \forall j$

3. Formulate the LP Model

Once the objective function and constraints are defined, the next step is to formulate the complete Linear Programming (LP) model as follows:

Objective Function:

$\text{Minimize } Z = \sum (C_i \cdot H_i)$

Subject to:

$H_i \leq \text{Available Staff Hours}_i \ \forall i$

$H_i \geq \text{Minimum Hours Required}_i \ \forall i$

$H_i \leq \text{Maximum Hours Allowed}_i \ \forall i$

$H_i \geq \text{Required Hours}_j \ \forall j$

4. Optimize using HiGHS solvers

1) Algorithm Selection by HiGHS:

• HiGHS automatically chooses the best algorithm based on problem characteristics: – Interior Point Method (IPM):

- Moves through the interior of the feasible region, effective for complex problem structures.
- Dual Simplex: Navigates along the edges of the feasible region, suitable for problems with bound constraints or close to feasible solutions.

• This selection optimizes performance without requiring user input on algorithm choice.

2) Iterative Optimization Process:

• HiGHS adjusts decision variables in each iteration to improve the objective while ensuring constraints are met.

• Updates are calculated based on the direction and step size that lead toward an optimal solution, with methods recalculating feasibility at each step.

3) Convergence to Optimal Solution:

• The solver iterates until it meets convergence criteria, such as minimal improvements in the objective function or reaching a maximum number of iterations.

• Convergence indicates the solution is optimal or near-optimal within the constraints, where further improvements are negligible.

5. Analyze the Results:

After solving the LP model using Karmarkar's algorithm, analyze the results: Examine the optimal hours allocated to each job role. Review total costs and compare them to previous allocations. Check whether all constraints have been satisfied.

6. Sensitivity Analysis

Conduct a sensitivity analysis to understand how changes in costs, availability, or project requirements impact the optimal solution. This analysis will provide insights into the robustness of the solution.

7. Communicate Results

Communicate Results to the firm.

4. DATASETS

A. Dataset 1: Manpower Requirements and Train Scheduling Constraints

This dataset includes two components:

Manpower Requirements:

Details the required and available staff for various job roles (Train Operators, Maintenance Crew, Customer Service, Engineers, and Security Personnel). Each role specifies the required number of staff, available staff, cost per hour, and work hour constraints.

Train Scheduling Constraints:

Provides scheduling details for three train lines, including peak and off-peak hours, and the number of required operators during those periods.

B. Dataset 2: Manpower Availability and Project Requirements

This dataset includes:

Manpower Availability:

Lists worker types (Engineers, Train Operators, Maintenance Crew, and Security Personnel) with available hours, cost per hour, and maximum hours per project.

Project Requirements:

Details projects (Railway Construction, Maintenance, and Station Renovation) with required hours, deadlines, and priority levels.

C. Dataset 3: Manpower Categories and Project Requirements

This dataset consists of two sections:

Manpower Categories: Provides details on the available hours and cost per hour for different skill levels, including Skilled, Medium-Skilled, and Unskilled labor categories. Project Requirements: Specifies the required hours for each skill category across various projects, including Railway Construction, Maintenance, and Station Renovation.

5. EQUATIONS

Objective Function 1:

Minimize

$$Z = c_1 (x_{k_1,RC} + x_{k_1,MT} + x_{k_1,SR}) + c_2 (x_{k_2,RC} + x_{k_2,MT} + x_{k_2,SR}) + c_3 (x_{k_3,RC} + x_{k_3,MT} + x_{k_3,SR}) + c_4 (x_{k_6,RC} + x_{k_6,MT} + x_{k_6,SR})$$

Legend:

- $\mathbf{x_{k_1,RC}, x_{k_1,MT}, x_{k_1,SR}}$ → Hours allocated to skilled labor (K1) for tasks RC, MT, and SR.
- $\mathbf{x_{k_2,RC}, x_{k_2,MT}, x_{k_2,SR}}$ → Hours allocated to medium-skilled labor (K2) for tasks RC, MT, and SR.
- $\mathbf{x_{k_3,RC}, x_{k_3,MT}, x_{k_3,SR}}$ → Hours allocated to medium-skilled labor (K3) for tasks RC, MT, and SR.
- $\mathbf{x_{k_6,RC}, x_{k_6,MT}, x_{k_6,SR}}$ → Hours allocated to unskilled labor (K6) for tasks RC, MT, and SR.
- $\mathbf{c_1, c_2, c_3, c_4}$ → Cost coefficients per hour for K1, K2, K3, and K6, respectively.

Constraints:

Labor Requirements for Projects:

- $x_{k_1,RC} + x_{k_2,RC} + x_{k_3,RC} + x_{k_6,RC} \geq 300$
- $x_{k_1,MT} + x_{k_2,MT} + x_{k_3,MT} + x_{k_6,MT} \geq 200$
- $x_{k_1,SR} + x_{k_2,SR} + x_{k_3,SR} + x_{k_6,SR} \geq 150$

Labor Availability:

- $x_{k_1,RC} + x_{k_1,MT} + x_{k_1,SR} \leq 2000$
- $x_{k_2,RC} + x_{k_2,MT} + x_{k_2,SR} \leq 3000$
- $x_{k_3,RC} + x_{k_3,MT} + x_{k_3,SR} \leq 2500$
- $x_{k_6,RC} + x_{k_6,MT} + x_{k_6,SR} \leq 3500$

Non-Negativity:

All x variables must be ≥ 0.

Objective Function 2:

Minimize

$$Z = c_5 (x_{E,RC} + x_{E,MT} + x_{E,SR}) + c_6 (x_{TO,RC} + x_{TO,MT} + x_{TO,SR}) + c_7 (x_{MC,RC} + x_{MC,MT} + x_{MC,SR}) + c_8 (x_{SP,RC} + x_{SP,MT} + x_{SP,SR})$$

Legend:

- $\mathbf{x_{E,RC}, x_{E,MT}, x_{E,SR}}$ → Hours assigned to Engineers (E) for tasks RC, MT, and SR.

- **xTO,RC, xTO,MT, xTO,SR** → Hours assigned to Train Operators (TO) for tasks RC, MT, and SR.
- **xMC,RC, xMC,MT, xMC,SR** → Hours assigned to Maintenance Crew (MC) for tasks RC, MT, and SR.
- **xSP,RC, xSP,MT, xSP,SR** → Hours assigned to Security Personnel (SP) for tasks RC, MT, and SR.
- c_5, c_6, c_7, c_8 → Cost coefficients per hour for E, TO, MC, and SP, respectively.

Constraints:

Labor Requirements for Projects:

- xE,RC + xTO,RC + xMC,RC + xSP,RC ≥ 300
- xE,MT + xTO,MT + xMC,MT + xSP,MT ≥ 200
- xE,SR + xTO,SR + xMC,SR + xSP,SR ≥ 150

Labor Availability:

- xE,RC + xE,MT + xE,SR ≤ 2000
- xTO,RC + xTO,MT + xTO,SR ≤ 3000
- xMC,RC + xMC,MT + xMC,SR ≤ 2500
- xSP,RC + xSP,MT + xSP,SR ≤ 3500

Non-Negativity:
All x variables must be ≥ 0.

Objective Function 3:

Minimize
$Z = c_9 x_1 + c_{10} x_2 + c_{11} x_3 + c_{12} x_4 + c_{13} x_5 + c_{14} x_6$

Legend:

- x_1 → Regular hours for Train Operators.
- x_2 → Overtime hours for Train Operators.
- x_3 → Hours for Maintenance Crew.
- x_4 → Hours for Customer Service.
- x_5 → Hours for Engineers.
- x_6 → Hours for Security Personnel.
- c_9, c_{10}, c_{11}, c_{12}, c_{13}, c_{14} → Cost coefficients per hour for x_1 to x_6.

Constraints:

Labor Requirements for Projects:

- $x_1 + x_2 + x_3 + x_4 \geq 300$
- $x_5 + x_6 \geq 200$

6. APPLICATIONS

The optimization of manpower in urban rail transportation has several critical applications, including:

- **Cost Reduction:** By optimizing the allocation of manpower, the project aims to significantly reduce operational costs associated with labor, ultimately enhancing the financial sustainability of urban rail systems.
- **Improved Operational Efficiency:** The methodologies developed in this project facilitate better scheduling and resource allocation, ensuring that the right personnel are available at the right times to meet service demands.
- **Aiding in Planning:** By ensuring adequate manpower levels, the project contributes to improved human resource management and proactive resource allocation, especially within a limited budget.
- **Data-Driven Decision Making:** The application of Operations Research techniques provides a structured framework for decision-making, allowing transportation authorities to make informed choices based on empirical data.
- **Scalability and Adaptability:** The developed optimization models can be adapted to different urban environments and scaled according to the specific needs of various rail projects, making them widely applicable across different contexts.

7. CONCLUSION

This study has demonstrated the importance of manpower optimization in the context of urban rail transportation, with a specific focus on developing countries where resource constraints are significant. Utilizing Operations Research techniques, particularly **Linear Programming** and **Karmarkar's Algorithm**, we formulated a model that minimizes labor costs while ensuring operational requirements are met efficiently.

The proposed solution optimizes manpower allocation across various roles, ensuring that the appropriate number of workers is assigned to each task while adhering to cost and time constraints. By implementing this approach, urban rail systems can achieve **substantial cost savings, improved service quality, and enhanced decision-making capabilities**.

The methodology outlined in this study is flexible and can be applied across different projects, including railway construction, maintenance, and station renovation. Additionally, it provides a framework for data-driven decisions, promoting efficient resource management.

In conclusion, **optimizing manpower in urban rail systems is a crucial step toward enhancing the operational and financial efficiency of transportation networks**. Future research could explore the integration of **machine learning techniques** for dynamic adjustments and improved real-time resource allocation based on fluctuating demand patterns.

8. First-order Headings

While this project has proven to be an efficient tool for streamlining the hiring process, there are several areas where it could be further improved in future iterations:

- **Flexibility:** Future versions of this project could incorporate a **dynamic model** capable of adapting to real-time changes in labor availability and costs, providing even more robust solutions for large-scale projects.
- **Additional Constraints:** Incorporating external factors such as **weather conditions, equipment availability, and political influences** into the model could enhance its real-world applicability and improve decision-making.
- **Expansion to Other Industries:** The optimization model could be extended beyond urban rail systems to other sectors, including **road construction, energy infrastructure, and manufacturing**, where labor allocation remains a key challenge.
- **Enhanced Dashboard Features:** Further integration with **Looker Studio** or similar platforms could improve **data visualization and predictive analytics**, enabling more proactive project management and strategic decision-making.

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