



METAHEURISTIC OPTIMIZATION OF RESOURCE PLANNING AND BUSINESS PROCESS MANAGEMENT IN RAIL TRANSPORT

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Abstract – Modern rail transport operates under increasing requirements for capacity, reliability, safety and resource efficiency. The planning of rolling stock, locomotive crews, maintenance activities and infrastructure resources is a complex optimization problem involving multiple constraints and interrelated business processes. Traditional optimization methods often fail to provide solutions within an acceptable timeframe for large-scale problems, which motivates the use of metaheuristic algorithms. This article proposes a conceptual model for optimizing resource planning in rail transport by applying metaheuristic methods. The possibilities of using genetic algorithm, anthill colony optimization, particle swarm optimization, simulated annealing, and taboo search have been explored to optimize schedules, locomotive allocation, crew planning, and maintenance resources. A business process model is proposed, integrating optimization algorithms into operational planning and resource management. The expected results include reduced operating costs, better use of resources, increased reliability of the transport process and improved quality of services, providing a basis for the deployment of intelligent systems to support solutions in rail transport.

Keywords – rail transport, metaheuristic algorithms, optimization, resource planning, business processes, genetic algorithm.

1. INTRODUCTION

The digitalization of rail transport, together with the increasing complexity of modern rail networks, increases the need for efficient planning and use of resources such as locomotives, rolling stock, teams and infrastructure capacity. Rail operators solve various challenges in coordinating business processes, such as scheduling, rolling stock allocation, crew composition and maintenance planning, while satisfying operational, technical and safety constraints [1].

The growing volume of freight and passenger traffic, combined with ageing infrastructure and limited investment budgets, is forcing operators to extract more value from existing assets rather than relying solely on capacity expansion. This necessitates the replacement of manual, experience-based planning practices with data-driven, quantitative tools to support decisions capable of addressing the scale and interdependence of modern rail operations.

In this context, efficient resource planning becomes a key factor for the sustainability of rail services, as it allows for better alignment between capacity, demand and technical reliability. Integrating operational data into the decision-making process is important because it allows for a faster response to schedule deviations, accidents or

resource shortages. Metaheuristic methods offer an applicable toolkit for solving complex problems where traditional approaches are limited by the large number of possible combinations and interdependent constraints [2, 4].

The study presents a developed model for optimizing resource planning and management of business processes in railway transport through the application of metaheuristic algorithms. The processes in railway transport and the available resources are considered. A suitable metaheuristic optimization algorithm has been chosen.

2. ANALYSIS OF BUSINESS PROCESSES IN RAILWAY TRANSPORT

2.1. Main processes

Business processes in railway transport are a specific integrated system of management, operational and support activities that ensure safe, reliable and cost-effective train movement. They are characterised by the simultaneous interaction between infrastructure, rolling stock, human resources, information systems and external regulatory requirements. Rail transport operates under strict schedules, limited infrastructure capacity and a high degree of dependency between individual solutions.

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Therefore, business process analysis should be considered not only as a description of sequential operations, but as a basis for formalizing an optimization model for resource planning and management [2, 3].

Business processes can be grouped into three groups, strategic, tactical and operational. At strategic level, long-term network development objectives, infrastructure investments, rolling stock renewal and quality of service policies are defined. The tactical level includes planning schedules, allocation of locomotives and wagons, formation of train compositions, determination of repair windows and allocation of personnel. The operational level covers day-to-day traffic management, dispatching decisions, response to deviations, resource redeployment, delay control and coordination between stations, depots and control centres [2, 3, 4, 5, 6, 7].

Table 1. Diagram of the main business processes in rail transport

Input data	Main processes	Management decisions	Results
Search for transport Graph Available resources Infrastructure capacity	Transport planning and timetables	Determination of routes, train routes and priorities	Optimised schedule and higher accuracy of movement
Locomotives Wagons Depas Technical condition	Rolling stock management	Allocation of locomotives and wagons to trains	Better use of assets and lower costs
Machinist Teams Working hours Qualification	Personnel management	Composition of shifts and crews under regulatory restrictions	Balanced workload and compliance with labor rules
Wear data Accidents Repair windows	Infrastructure and rolling stock maintenance	Prioritize repairs and plan resources	Increased reliability, safety and availability

Each process in the rail system has its own purpose, but at the same time it affects the other processes. For example, a change in timetable may lead to the need for a new allocation of locomotives and crews, as well as the relocation of previously planned maintenance activities. Isolated optimization of individual processes cannot achieve effective management. A coordinated approach based on a common information base and uniform evaluation criteria is needed [2, 3, 4].

From the point of view of optimization, the main business processes can be described through variables, constraints, and performance criteria. Variables include choosing a locomotive for a specific train, appointing a driver, setting a departure time, choosing a route, length

of stay and time to carry out repair work. The limitations stem from the technical compatibility between the locomotive and the route, the available capacity of the infrastructure, the regulatory requirements for working hours, safety requirements, permissible delays and resource limits. Efficiency criteria include minimizing operating costs, reducing delays, increasing the usability of locomotives and wagons, optimal staff workload, and limiting unplanned disruptions [2, 5].

The maintenance process is of particular importance, as it both ensures safety and limits the available traffic capacity. Maintenance of railway infrastructure must be planned based on data, asset criticality and coordination with the train schedule. This management model allows repairs to be carried out in appropriate time windows without significantly disrupting the operational process. Such an approach is compatible with the digitalisation of the rail sector and with the use of asset management systems, dispatch systems and decision support modules [2, 4, 5, 11, 12].

The number of possible combinations between trains, locomotives, routes, crews and repair works increases significantly as the scale of the network increases. This makes classic manual planning methods insufficient under complex and dynamic conditions.

The main resources subject to optimization are locomotives, wagons, train drivers, maintenance teams, railway infrastructure, time and energy resources. Underutilization of these resources increases operating costs, while overuse increases the risk of delays, safety incidents, and reduced quality of service.

3. THEORETICAL BASIS OF METAHEURISTIC METHODS

3.1. Classical optimization methods

Classical optimization approaches, such as linear programming, integer programming, dynamic programming, and constraint-based methods, have traditionally been applied to transport and rail planning tasks. The mathematical model must be well structured, the constraints must be clearly defined, and the size of the problem allows you to find the exact optimal solution in a reasonable time. In real rail systems, the number of variables and constraints is rapidly increasing due to the need to simultaneously accommodate timetables, locomotives, crews, infrastructure capacity and repair windows. This leads to high computational complexity and practical difficulties in using accurate methods. For this reason, classical methods are often used as a basis for formulating the model, while the search for practically applicable solutions is supported by heuristic and metaheuristic approaches [8, 9, 10].

3.2. Metaheuristic methods

Metaheuristic methods are general search strategies

that combine local improvement and a higher level of demand management to avoid prematurely hitting a local optimum. These include Genetic Algorithm (GA), Simulated Annealing (SA), Ant Colony Optimization (ACO), Particle Swarm Optimization (PSO), Tabu Search (TS) and others, applicable to complex combinatorial and nonlinear problems. Their main strength is that they do not require a mandatory analytical description of all the properties of the target function and can work with discrete, continuous and mixed variables. In rail transport, this is important because timetable, routing, locomotive allocation and staff planning tasks often involve multiple interrelated constraints and conflicting objectives. Therefore, metaheuristics are seen as an effective alternative to precise methods for large-scale tasks, where it is more important to obtain a high-quality solution in an acceptable time than a formally proven global optimum [2, 3, 9, 10].

3.3. Advantages

The main advantages of metaheuristic methods include their ability to find near-optimal solutions within an acceptable computational time [9,10]. They are flexible when working with multiple constraints, different types of variables and several simultaneous performance criteria, which makes them suitable for real transport systems [2, 10]. For rail transport, this means the possibility of simultaneously optimising timetables, the use of locomotives, staff workload, delays and maintenance [2, 3]. It is possible to combine the use of a metaheuristic algorithm with mathematical programming or specialized rules for the specific subject area [9]. On this principle, an adaptive decision support system can be built, which can be adjusted according to the operational priorities of the railway operator, the current state of the network and the level of digital maturity of the organization [4, 10, 11].

4. PROPOSED OPTIMIZATION MODEL

Input data

The proposed model takes into account the following inputs: train timetable, available locomotives, available drivers, operational and technical constraints, maintenance windows and rolling stock specifications.

Target function

The target function to be minimized is defined as follows (formula 1):

$$F = \alpha C + \beta T + \gamma D + \delta R \rightarrow \min \quad (1)$$

Where:

C is the operating value,

T is the rest time (unused),

D is the delay,

R is the amount of unused resources,

α , β , γ and δ are weighting factors reflecting the relative importance of each component and can be adjusted according to the operator's priorities.

Limitations

The model is subject to restrictions related to the legal regulations on the working hours of the teams, the technical requirements of the rolling stock, the capacity limitations of the infrastructure, the operational restrictions and the safety requirements.

1. $0,60 \leq U \leq 0,90$
2. $0,75 \leq W \leq 0,95$
3. $5 \leq d \leq 20$
4. $g \geq 0$
5. $C, T, D, R \geq 0$
6. $\alpha, \beta, \gamma, \delta \geq 0$
7. $\alpha + \beta + \gamma + \delta = 1$

U - use of railcars, W - load of drivers, d - average delay
g - Cost reduction

The first three limits set the permissible limits for the use of rolling stock, the workload of drivers and the average delay. The condition $g \geq 0$ means that the optimised solution must not lead to an increase in operating costs compared to the baseline scenario. The constraints $C, T, D, R \geq 0$ guarantee non-negativity of the components of the target function, and the condition $\alpha + \beta + \gamma + \delta = 1$ normalizes the weighting factors and allows comparability between the individual criteria.

5. OPTIMIZATION ALGORITHM

The evolutionary algorithm has been proposed as the main method of optimization, as recent experimental studies of the railway timetable show high efficiency in terms of solution quality, convergence rate and infrastructure capacity utilization. The proposed algorithm follows the standard EA procedure, illustrated in Fig. 1:

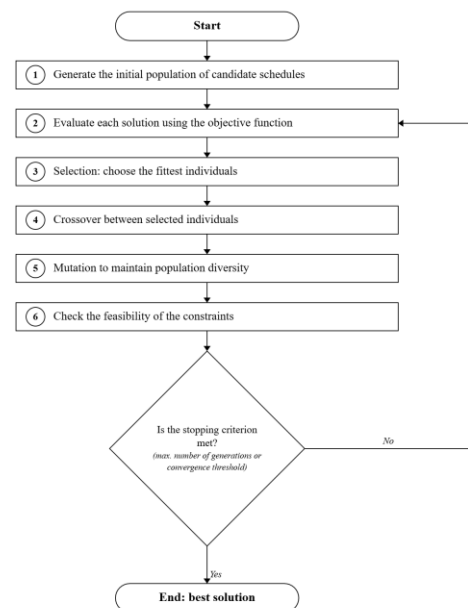


Fig. 1. Flowchart of the genetic algorithm for schedule optimization

6. EXPERIMENTAL SETUP

Case study

To evaluate the proposed model, a case study based on a regional railway network is considered, including 25 trains (railcars), 150-200 train drivers, 25 daily trains and 100 stations, technicians and maintenance 150, service personnel (conductors) 250, administration and management 100.

Scenarios

Three scenarios are compared: classical planning used as a basis; planning based on a standard genetic algorithm and planning based on a hybrid genetic algorithm combined with local search improvement in order to evaluate the benefits of the proposed approach.

The implementation is planned in Excel, Solver. The input data for the case study (timetable, availability of locomotives and crews, support windows) are defined on the basis of typical operational models of the regional rail network, in the absence of access to the live data of a specific operator at this stage of the study.

7. RESULTS ANALYSIS

The comparison focuses on operating costs, locomotive utilization, staff load, delays, calculation time, and resource utilization rates. The results will be visualized through charts, comparison tables, and Gantt charts, allowing for a clear assessment of the improvements made by the metaheuristic approach to the baseline scenario.

Based on the results reported for similar applications of genetic algorithms in transport planning, the hybrid scenario is expected to achieve the lowest operating costs and delays, at the expense of longer calculation times compared to the standard Genetic Algorithm. The classic planning scenario is expected to serve primarily as a starting point, illustrating the potential margin for improvement achievable through metaheuristic optimization. The proposed model can be applied to operational planning, locomotive fleet management, maintenance planning, human resource management, decision-making support for dispatchers, and integration with rail transport management systems (TMS) and corporate resource planning (ERP) systems used by railway operators.

8. CONCLUSION

This article presented a conceptual, integrated model for optimizing resource planning in rail transport by applying metaheuristic algorithms. The applicability of metaheuristic methods for managing interconnected

business processes – scheduling, locomotive allocation, crew planning and maintenance – is demonstrated. A methodology for improving the efficiency of the use of the locomotive, personnel and infrastructure is proposed. Future work will focus on experimental model validation on real operational data, comparison of alternative metaheuristic algorithms, and expanding the approach through the integration of digital twins and machine learning techniques for adaptive real-time resource management.

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