



A METHODOLOGY FOR TASK IDENTIFICATION AND SELECTION FOR THE OPTIMIZATION OF INVESTMENTS IN RAILWAY NETWORKS

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Abstract

Effective strategic planning for the development of transport systems, which constitutes a class of optimization problems known as the Network Design Problem (NDP), currently requires the use of complex, multi-criteria models. Tools such as evolutionary algorithms can analyze intricate dependencies and support decision-making processes. However, their practical application encounters a barrier in the form of the curse of dimensionality, especially when the analyzed system is extensive, and the set of possible actions is very large. The number of potential combinations of investment variants, including, for example, modernizing existing infrastructure to various standards and constructing new links between defined transport zones, grows exponentially. This leads to a search space with a large number of decision variables, making it impossible to find a near-optimal solution within an acceptable computation time. Therefore, a key challenge before the actual optimization is reducing the problem's complexity. The presentation focuses on a methodology for limiting the number of decision variables through preliminary identification, classification, and selection of investment needs. The goal of this approach is to filter the set of potential projects, narrowing it down exclusively to those that demonstrate the highest potential for effectiveness. This process utilizes input data and results derived from transport macrosimulation models (including various types of matrices). Such a hierarchical approach, involving the intelligent selection of candidates before initiating the main optimization algorithm, is a necessary condition for the practical application of advanced computational methods in the strategic planning of complex transport networks.

Keywords: network design problem, railway infrastructure, macroscopic transport model, curse of dimensionality

1 Introduction

1.1 Strategic infrastructure planning

Strategic planning for transport infrastructure development is a highly complex process that involves significant economic and social responsibilities. Investment decisions regarding the construction of new railway lines or the modernization of existing transport corridors are long-term, and their impacts shape regional mobility for decades. Given limited financial resources and increasing demands for sustainable development [1, 2], the use of advanced decision-support tools is essential for planning the development of transport systems. In the literature, this problem is most commonly named as the Network Design Problem (NDP) [3]. It consists of finding an optimal network configuration (a set of investments) that minimizes total system costs, such as travel time, operating costs, and capital expenditures, while satisfying specific technical and budgetary constraints. The NDP is classified as NP-hard.

The primary challenge in solving real-world NDPs is their scale. When analyzing a national network, the number of potential infrastructure projects can reach several thousand. Applying classical metaheuristic algorithms, such as the genetic algorithm (GA), directly to such a broad spectrum of variables makes finding a near-optimal solution within a finite time impossible [4]. Although evolutionary techniques are effective in searching for discontinuous solution spaces, their efficiency decreases drastically as the length of the variable vector increases [5]. In such cases, these algorithms tend to get trapped in local optima, and the convergence process becomes unacceptably long. Therefore, reducing the number of variables is a prerequisite for a successful optimization process. Modern transport planning relies on digital macroscopic network models. These models serve as computational tools that provide data on demand and supply [6]. The example of such a model for the Polish national transport system is the Passenger Transport Model (PMT) [7]. It enables multi-scenario traffic forecasting on a national scale and the precise determination of the impacts of infrastructure modifications.

1.2 Research question and scientific contribution

Despite the extensive literature on NDP, there is a lack of practical frameworks that effectively bridge the gap between high-fidelity macroscopic simulations and heuristic optimization for large-scale national networks. The research question of this paper is: How can a preliminary, multi-stage definition and filtration of investment projects based on transport potential reduce the search space without losing near-optimal solutions? The scientific contribution of this work lies in the development of a hierarchical methodology for defining and selecting potential projects that integrates demand-side potential from macroscopic models directly into the decision-variable reduction process in large-scale railway network design.



Figure 1 Passenger Transport Model with the railway network and transport regions, horizon 2040 [7]

2 Multi-stage method of preselection of investment projects

The objective of the proposed multi-stage preselection method for investment projects is to reduce the search space in the NDP optimization process. On a national network scale, this problem involves a vast number of investment projects. Without preliminary selection, the evolutionary algorithm would have to analyze variants that contain clearly inefficient solutions, such as constructing high-parameter lines for negligible demand. Through this selection, the algorithm can optimize only those investment projects with a proven minimum transport potential. The method is divided into three independent stages, in which the following categories of investments are analyzed:

- improvement of parameters on existing lines (stage 1)
- new sections of conventional railway lines (stage 2)
- new High-Speed Rail (HSR) lines (stage 3).

The entire project selection procedure, leading from the input data to the identification of the optimal investment portfolio, is illustrated in the diagram below (figure 2). In the presented method, projects are evaluated not based on current traffic flows, but through the lens of their total potential within a selected time horizon. This is possible due to the “Rail-as-PrT” (Rail as Private Transport) procedure. It involves modelling traffic assignment in rail transport using assignment algorithms typical for private transport. In this approach, the railway network is treated as a pure connectivity graph, where impedance results solely from physical parameters and the technical design speed of the sections. This procedure intentionally ignores constraints resulting from the timetable, such as rigid transit line offerings, service frequencies, transfer times, or intermediate stops, which are characteristic of public transport travel modelling. Consequently, it is possible to isolate the impact of infrastructure on travel attractiveness. This allows for observing how passengers would move under conditions of “ideal” rail service supply.

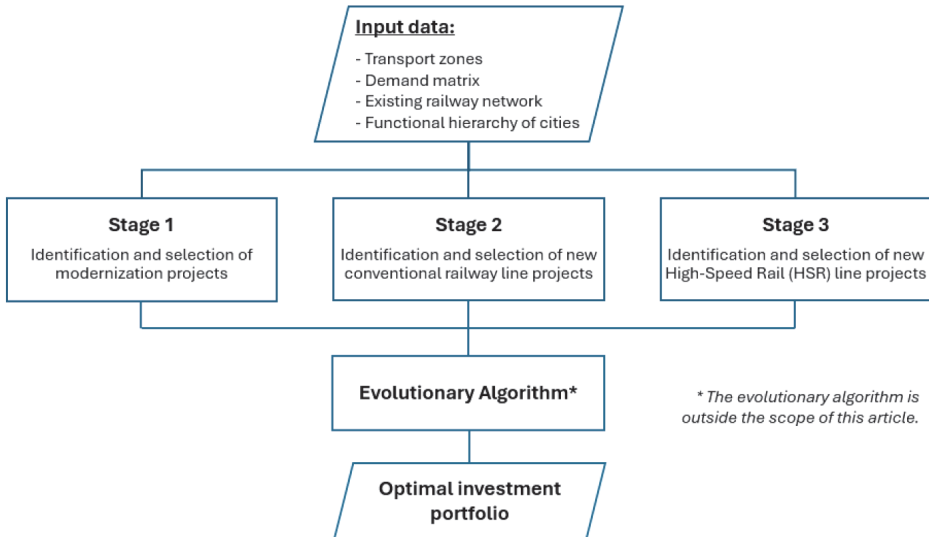


Figure 2 Block diagram of a multi-stage method for preselection and optimization of investment projects

The preselection method yields a set of projects that may include complementary tasks. In such cases, the implementation of one project can enhance the effectiveness of another (e.g. the modernization of conventional lines increases demand on a HSR line). Conversely, some tasks may be mutually exclusive in practice (e.g. modernizing an existing line and constructing a new one). Utilizing an evolutionary algorithm as the final selector ensures that the best possible combination of projects is selected from the prepared pool, maximizing benefits while accounting for constraints and the interactions between investments.

3 Procedure for identifying modernization needs (stage 1)

3.1 Concept of potential traffic flow assignment

The first stage of the proposed methodology is to identify a set of existing railway network sections for which modernization will yield the greatest benefits for the entire system. Here, modernization is defined specifically as increasing the maximum speed on a given section, rather than improving other technical parameters or constructing additional tracks. To identify sections with the highest potential, the concept of potential traffic flow assignment was applied. This method proposes conducting traffic assignments for the full demand matrix while bypassing the modal split procedure, thereby accounting for traffic that may be shiftable from private transport, aviation, and bus services. Due to the limited spatial coverage and accessibility of the railway network, only trips originating from and destined for transport zones with direct rail access are realized. The “Rail-as-PrT” procedure is used for this purpose.

3.2 Identification of the modernization potential of sections

For each link in the railway network, the time gain parameter multiplied by the number of potential beneficiaries (passengers) is analysed. To ensure an objective evaluation of modernisation efficiency, a normalised unit efficiency index W_e was introduced, defined as:

$$W_e = Q_e (1/V_{curr} - 1/V_{target}) \quad (1)$$

where:

- Q_e – potential passenger flow on link
- V_{curr} – current maximum speed on the section
- V_{target} – maximum speed on the section after modernization.

It allows the identification of locations where relatively short modernization projects can yield significant improvements for a large number of travelers. Due to the strategic and macroscopic level of the analysis, a simplifying assumption was made that modernization increase the maximum speed on a given railway section by 20 km/h. It should be noted that a relatively simple modernization will not yield such results in every case. This limitation may arise from terrain conditions, environmental factors, or existing land use. Accounting for these dependencies constitutes a separate research problem related to railway track geometry, which is outside the scope of this study. The final selection of sections designated for modernization is performed using the Jenks Natural Breaks optimization algorithm, which allows for the objective determination of cut-off thresholds based on the actual data structure. This algorithm aims to minimize intra-group variance and maximize inter-group differences by identifying gaps in the distribution of the W_e index. In the analytical process, the set of all sections is divided into four efficiency classes. Sections with the lowest modernization potential are rejected.

4 Procedure for generating new line proposals (stage 2)

4.1 Topological rules and reference points

The second stage of the methodology involves constructing a project library of new infrastructure sections. Unlike modernization, new investments alter the network topology, which requires strict generation rules to maintain model consistency. To maintain order within the macroscopic model, a unified principle for defining zone reference points (R_i) was adopted. For zones with existing infrastructure access, the point is the station node nearest to the centroid. For zones without direct access to the rail network, the point R_i becomes the centroid, where a new network node is generated, including a railway stop and a connector linking it to the transport zone.

4.2 Railway network construction (Delaunay triangulation)

The first step is to create a dense grid of potential connections between transport zones lacking rail access. For this purpose, the Delaunay triangulation algorithm is used, which connects adjacent zone centroids to form a coherent network of triangles. This approach avoids unnaturally long connections and prevents lines from crossing without creating nodes. The resulting grid of connections is then integrated into the existing railway network nodes. A uniform maximum speed and very high capacity are assigned to these new potential lines. A maximum speed of 50 km/h was adopted to ensure that, in the subsequent simulation and traffic assignment steps, these new sections do not serve as an attractive alternative to existing high-category railway lines.

4.3 The process of iterative shaping of the potential network

The vast railway network resulting from this process is analyzed and reduced in the subsequent step. The previously discussed “Rail-as-PrT” traffic assignment is executed for the full demand matrix, bypassing the modal split procedure to account for traffic potentially shiftable from other modes of transport at this stage as well. Following the traffic assignment, the bottom 10% of the least-loaded network sections, with traffic flows below 1,500 passengers per day, are removed. The entire process of network analysis and shaping is iterative. The procedure follows the loop below:

- executing the traffic assignment according to the “Rail-as-PrT” procedure
- checking the load on all new potential sections
- removing the group of sections with the lowest potential traffic flow
- returning to step 1: re-executing the traffic assignment.

The process terminates when all remaining new sections in the model reach the target load of 1,500 passengers/day, representing the estimated break-even point.

5 Procedure for generating HSR projects (stage 3)

5.1 Topological rules and reference points

The functional hierarchy of cities in Poland (figure 3) was used to develop the potential High-Speed Rail (HSR) network. Cities classified from tier I (national-level metropolis) to tier IV (sub-regional centers) were identified as candidates for inclusion in the national HSR network.

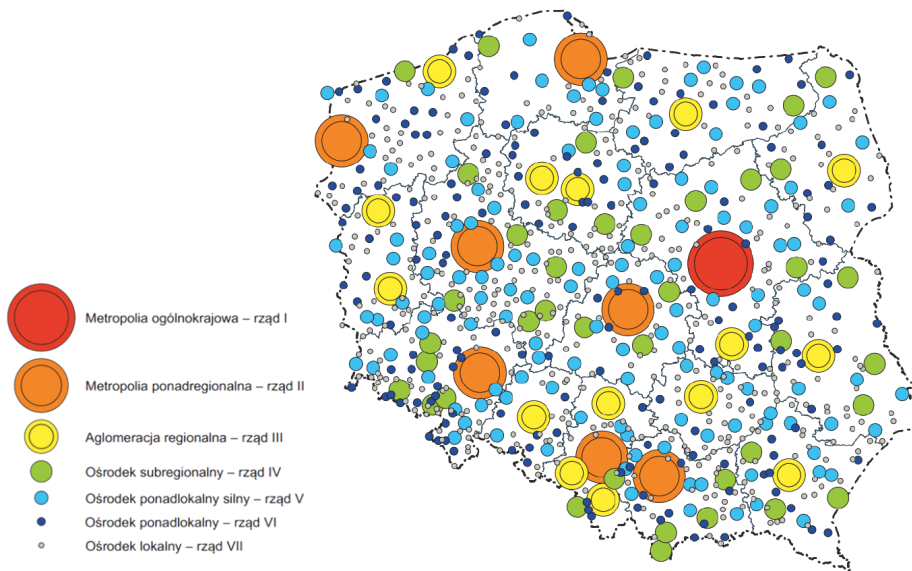


Figure 3 Functional hierarchy of cities in Poland [8]

Furthermore, the planned “Y” line (Warsaw – Łódź – Poznań/Wrocław) was assumed to be implemented. The selected cities and existing rail border crossings served as network vertices; subsequently, a Delaunay triangulation was conducted to establish a complete potential HSR network. The generated sections were assigned a maximum speed of 300 km/h.

5.2 The process of iterative shaping of the potential HSR network

In this stage, the demand matrix is filtered to exclude trips shorter than 50 km, measured as the distance between transport zone centroids. For this filtered demand matrix, the “Rail-as-PrT” traffic assignment is performed, bypassing the modal split procedure again. The entire process of analyzing and shaping the HSR network is iterative. The procedure follows the loop below:

- executing traffic assignment according to the “Rail-as-PrT” procedure
- for each link in the potential HSR network, the efficiency index is calculated according to equation (1)
- from the sections that have not reached the assumed load threshold of 25, 000 passengers per day, the 10% of sections with the lowest values are removed
- returning to step 1; in the subsequent step, the demand from the removed sections is redistributed across the remaining edges, forming major transport corridors; the process terminates when all remaining new sections in the model reach the target load of 25, 000 passengers/day.

6 Conclusion

This article presents a comprehensive methodology for preselecting investment needs within the NDP, integrating macroscopic transport models with algorithmic rules for project generation and filtering to reduce the problem’s dimensionality. The proposed process, covering modernization, new conventional rail and HSR sections, ensures that only projects with proven economic potential are passed to the final optimization. The selection of investment projects conducted in advance reduces computational time in later stages.

Instead of performing optimization over the full space of all theoretically possible investment combinations, the algorithm focuses on a limited set with high potential. While the proposed methodology offers a robust framework, certain limitations must be noted. Firstly, reliance on macroscopic transport models implies simplification. These models are suitable for long-term strategic decisions. They do not account for small-scale projects and cannot cover more specific, operational constraints. Secondly, at this stage, the focus is primarily on transport potential, while real investment feasibility is assumed. Future research could integrate operational parameters and spatial conditions to enhance the quality of the results. The methodology can be transferred to other national networks. However, its application at the regional or urban scale might require methodological adjustments and more detailed data to address local specificities. Nevertheless, similar decision-support frameworks for other transport systems can be inspired by this approach.

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