Multiobjective Timetable Development Tool for Railway Strategic Planning in Norway

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ABSTRACT

Strategic planning is critical in helping railways develop optimal programs for improving their business by making service more attractive and efficient. Preparing a strategic plan requires comparing multiple alternatives and options, each requiring time-consuming planning, evaluation, and analysis. To improve this process Jernbanedirektoratet, Norway's Railway Directorate, began a research project to develop a state-of-the-art railway timetable generation tool that could be integrated into the agency's existing timetable planning process. The new tool, called Automatic Timetabler with Multiple Objectives (ATMO), is designed to transform conceptual passenger and freight service requirements into working timetables, while ensuring robustness and minimizing time losses. It is designed to bridge the gap between less detailed (macroscopic) models used in timetable development and detailed (microscopic) traffic simulation models. More specifically, it is a mesoscopic model, simplifying some infrastructure elements while using more detailed representations of others (e.g., using specific track allocations in stations). In practice, the tool quickly provides planners with many feasible and good timetables using high-level timetable requirement data. This ability is very useful for strategic planning because it enables planners to quickly evaluate alternative timetable concepts. This paper describes the new timetable generator tool, its development, and results of a case study application.

INTRODUCTION

The Norwegian Railway Directorate (Jernbanedirektoratet) was created in 2017. It serves as the government's coordinating agency for railway affairs. Its responsibilities include providing input for Norway's National Transportation Plan (NTP) and procuring passenger rail service through open tenders.

Norway separated railway operations from infrastructure ownership in 1996 consistent with European Union railway regulations. Norway's railway infrastructure owner is Bane NOR SF, a state enterprise.

Norway's passenger rail tenders are geographically separated, although they overlap in the area around Oslo. The first tender was awarded in 2018, and the first three tenders have been awarded to the private company Go-Ahead Norge AS, the Swedish state-owned SJ Norge AS and the Norwegian state-owned Vy Tog AS. Freight service is operated commercially, with temporary public support to strengthen environmentally friendly freight transport by rail.

Jernbanedirektoratet prepares strategic plans for railway service improvements and capital investments as input for the NTP. Norway has adopted an ambitious set of objectives for achieving climate neutrality by 2050. One of these objectives directly affecting Jernbanedirektoratet's strategic planning is transferring 30 % of all long-distance road freight transport to rail and sea by 2030 and eliminating private car traffic growth in metropolitan areas. (*1*)

An important strategy for achieving the objective of increasing railway's mode share is increasing customer attractiveness by adding service and adopting regular interval timetables. These timetables, also known as clock-face schedules, are easy for the customers to remember and have successfully increased passenger ridership in Norway and other European countries.

A key planning constraint is Norway's geography of high mountains combined with a long and jagged coastline. While beautiful, it leaves little flat space for settlements and transport lines, making it very difficult to build passing tracks where they would be most useful to increase service and operate clock-face schedules.

Preparing and analyzing timetables is a fundamental part of railway strategic planning. Railway strategic planning is a complicated balancing of train scheduling (timetabling) with available rolling stock and infrastructure. This is often referred to as the timetable-rolling stock-infrastructure planning triangle where any changes to one element impacts the other two. In the short-term planners have limited options, in the long-term new rolling stock and infrastructure can be built to support increased service (operating more trains). Timetable simulation is used to identify train operating patterns (timetables) that can squeeze more capacity out of a given rolling stock-infrastructure state. More efficient methods of simulation allow planners to explore more possible alternative timetables and thereby identify better timetables (e.g., operate more trains, increase reliability). This type of strategic planning using simulation is even more important in Norway since the country's highly constrained geographic setting makes it difficult to add new infrastructure.

Therefore, in 2020, Jernbanedirektoratet began a research program to develop a state-of-the-art timetable generation tool that could be easily integrated into the agency's existing timetable planning process. The new tool applies state-of-the-art mathematical optimization techniques to railway timetable planning and is called the Automatic Timetabler with Multiple Objectives (ATMO). This paper describes the new ATMO tool, its development, and results of a case study application.

SIMULATION AND RAILWAY PLANNING

Simulation is used to assess the complex interactions between infrastructure, rolling stock, signaling, timetables, customer demand and passenger behavior. As such it is a critical tool in the railway strategic planning process. There are several commercially available railway simulation programs including Trenissimo, LUKS, RailSys, Rail Traffic Controller, and OpenTrack. For a comprehensive review of simulation tools, the reader is referred to Medeossi and De Fabris *(2)*, Jordi et al. (*3*)*,* and Nash and Huerlimann (*4)*.

Railway simulation in the past has been limited to detailed analysis of small networks or more general analysis of large networks. The continuing development of more powerful computers and efficient software are now making it possible to model much larger networks at increasing levels of detail.

Simulation is used to identify and understand a timetable's limits and problems (e.g., bottlenecks). Many existing timetabling software applications can update running times and quickly check for timetable conflicts, and a few provide limited automatic timetabling functions such as local optimization of already planned timetables, but there are currently no commercial tools supporting timetable generation from scratch. In short, most timetabling software programs today function as computer-aided timetable editors, but timetable design itself remains an intricate puzzle where multiple conflicting objectives must be manually balanced.

The Train Timetabling Problem is a major research topic in Mathematical Optimization research. Several approaches have been proposed including those by Cacchiani et al. *(5)*, Lamorgese et al. *(6)*, and Kroon e. al. *(7)*. These approaches often combine exact formulations with metaheuristics, and aim at a single objective. In some papers *(8)*, this single objective may have multiple components. Specific multiobjective approaches exist in the literature. They often rely on the so-called $\mathcal{E}$-constraint method, in which one objective is alternatively optimized while bounds are set for the others. A solution of the Pareto front results from each optimization. Examples of these approaches are by Ghoseiri et al. *(9)* and Yan et al. *(10)*. The multiplicity of optimization executions typically imply rather long solution times, and this multiplicity increases with the number of objective functions considered. Despite the relevance of the existing approaches, their current functioning implies that a common shortcoming is their difficulty in handling real-size problems with a multiobjective focus.

Another key problem in using simulation to analyze timetables is that a timetable must be designed before simulating it. Normally, the timetable creation process is a labor-intensive design-simulate-check loop in which several simulation/timetable adjustment iterations are performed using macroscopic modelling before converging on a definitive timetable that will be analyzed in detail through microscopic modeling. Mathematical optimization can help improve this process by quickly identifying a "good" starting set of timetable drafts for the microscopic modelling process.

Therefore, Jernbanedirektoratet began a research project to develop a tool for improving timetable design using mathematical optimization. This research is outlined in the next section.

JERNBANEDIREKTORATET AUTOMATIC RAILWAY TIMETABLING RESEARCH

The goal of Jernbanedirektoratet's research in the field of automatic railway timetabling was to develop a state-of-the-art tool to transform conceptual railway service requirements into working timetables, while ensuring robustness and minimizing time losses (i.e., stopped, or delayed trains). More specifically, Jernbanedirektoratet wanted to develop a tool that bridges the gap between less detailed (macroscopic) models used in the timetable development process and the detailed (microscopic) models used for traffic simulations.

Traffic simulations analyze a given timetable on a given infrastructure, in this project the goal is identifying a large number of optimized timetables using a less detailed infrastructure model. The tool should automatically aggregate detailed infrastructure data (the digital twin) into a form where it can be used in strategic timetable planning. Specifically, the tool should use a mesoscopic model, in which details such as signal positions or precise interlocking system characteristics are neglected. Nonetheless, the model should represent train movements and network capacity utilization in detail: parallel tracks, sidings and multiple station platforms should be fully considered, together with the impact of their use on train movements. For example, if a train using a particular platform in a station has to run at lower speed through switches, depending on the specific track topology, this will have an impact on travel time and platform utilization times.

Jernbanedirektoratet issued a public tender to select a software developer for the new tool in September 2020. The tender specified that the tool shall use mathematical optimization, because existing simulation software is not sufficient to develop optimized timetables for large and complex networks, not even with today's powerful computers. Mathematical optimization allows software to quickly select and continue the most fruitful explorations. This enables planners to evaluate a far higher number of alternatives, compared to using traditional software computer-aided planning tools. The tender did not specify the type of mathematical optimization timetabling algorithm to be embedded into the tool.

Jernbanedirektoratet specified that the tool must be designed for integration into the agency's existing strategic planning process because human planners will continue to play a vital role in timetable development. The ATMO tool should perform detailed calculations and leave human planners free to concentrate on actual strategic planning including designing the input service concepts, adjusting service parameters, evaluating results, and comparing output solutions. In addition, the new tool should be directly linked to existing tools and data sources to minimize costs and potential transition delays.

Finally, as its name suggests, the Automatic Timetabler with Multiple Objectives was required to handle multiple objectives for assessing timetable optimality, such as travel time (minimizing time losses), fixed-interval services (minimizing deviations), reliability (maximizing robustness) and capacity (maximizing the number of trains that can be operated).

The tender evaluation criteria were:

- Understanding of the task and description of the solution
- Experience and competence in mathematical optimization
- Experience and competence in the railway operations
- Progress plan and project management
- Staffing and resource availability
- Price

The price of the bid counted for 20 % in the evaluation, with the other criteria together making up the remaining 80 %.

In November 2020 Jernbanedirektoratet awarded a contract to the Trenolab/Université Gustave Eiffel team to develop the new ATMO tool, within the research project number 202000783 "Tools for mathematical optimization of strategic railway timetable models". Trenolab is a railway software and consulting company based in Gorizia, Italy and Université Gustave Eiffel is a scientific research institution including a team specialized in railway transport in Lille, France.

STRATEGIC TIMETABLING ALGORITHM DESCRIPTION

The ATMO tool developed in this research uses a multiobjective approach to identify timetables that best utilize available capacity to operate a specified traffic pattern. The tool uses an algorithmic framework based on a novel Multiobjective Ant Colony Optimization (MOACO) algorithm and on a Mixed Integer Linear Programming (MILP) formulation. The MOACO algorithm quickly performs a wide-ranging exploration of the possible solutions' space. An overview of these types of algorithms is presented in Stützle and Hoos *(11)* and López-Ibáñez and Stützle *(12)*.

The timetables found by the MOACO are then refined using a MILP formulation. More specifically, a commercial MILP solver is used to identify possible local improvements to the timetables. Although ACO algorithms have already been applied in, e.g., the train routing problem *(13)*, the algorithmic framework proposed in this research is, to the best of our knowledge, a novel and original contribution in the field of mathematical optimization applied to the entire routing-scheduling problem.

The combination of MOACO and MILP takes optimal advantage of each method's strengths providing users with an approximated Pareto Optimal Set (POS) of possible timetables in a reasonable computation time. Providing a set of timetables rather than single timetables is especially useful in the strategic timetable and network capacity planning, where comparing alternatives is a crucial step.

Finally, the Paretian multiobjective approach has a major practical advantage over methods where multiple objectives are blended using weights to create a single objective function to be optimized. These single objective functions are often significantly sensitive to the weights' values, thus requiring a careful tuning to obtain sound results. Furthermore, many of the monetary value estimates for our multiple objectives have, often significant, error margins.

The algorithmic framework generates timetables while attempting to optimize them according to a number of objective functions. ATMO can deal with virtually any objective function fulfilling a set of conditions. For example, these functions must be quantifiable in linear (or linearizable) terms. The possibility of assessing objective functions for partial solutions is a benefit for the algorithm performance but it is not compulsory. In the default version of the framework, the following five objective functions are implemented: minimize total travel time of all trains, minimize total energy consumption, maximize timetable stability, maximize the number of optional trains that can be scheduled, minimize the number of residual traffic conflicts (optional, user can also choose to be provided with conflict-free timetables only).

This multiobjective approach makes the ATMO especially useful for strategic planning because it supports planners in solving several types of problems including saturation studies, strategic exploration of draft timetables, fine-tuning of previously developed timetables, and capacity assessment of infrastructure alternatives.

The first step in using the ATMO is entering a mesoscopic model description of infrastructure and operations into the software. The infrastructure data is based on a multigraph, where nodes are stations and edges are line sections connecting consecutive stations. Each edge is characterized by a set of data specifying, for each rolling stock type, minimum run times, technically possible headways, and energy consumption. Multiple parallel tracks imply the presence of multiple edges connecting a pair of nodes. Each station node is characterized by a set of tracks with associated minimum run times for each rolling stock type. These data are automatically calculated via microsimulation.

Next, planners enter operations data for the desired traffic pattern. This conceptual timetable data describes fixed, movable, and optional trains. Fixed trains must be run at the specified time and route, while movable trains can be scheduled freely within given time constraints (minimum/maximum arrival, departure and stopping times) and spatial constraints (allowed station routes). It is also possible to define whether the train must pass or stop at a station, or whether the algorithm can choose between these two event types to improve the objectives (e.g., to solve conflicts). Finally, optional trains are trains which the tool can choose to schedule or not.

Trains can be organized into train groups based on a quasi-periodic pattern (i.e., trains approximately every 2-hours). For train groups, a periodicity tolerance, greater than or equal to zero, is defined in each location, denoting how much each train of the group can deviate from the group's strict periodic pattern.

Periodicity tolerance is a useful parameter for strategic planning. On one hand, strict periodicity is more attractive for passengers because precise clock-face schedules are easier to remember. On the other, strict periodicity consumes extra capacity and therefore reduces the number of trains that can be operated especially for single track lines *(14,15*). Furthermore, taking advantage of the flexibility possible using this "hybrid cyclicity" has been shown to better serve high density demand *(16)*.

Strategic planning consists of analyzing and comparing various combinations of infrastructure and timetable concepts. Therefore, several different infrastructure models and timetables are entered into the tool. Once all the input data has been entered, the planner chooses which objective functions should be considered in developing the optimized timetables. Finally, the tool is used to create many timetables that meet the selected criteria.

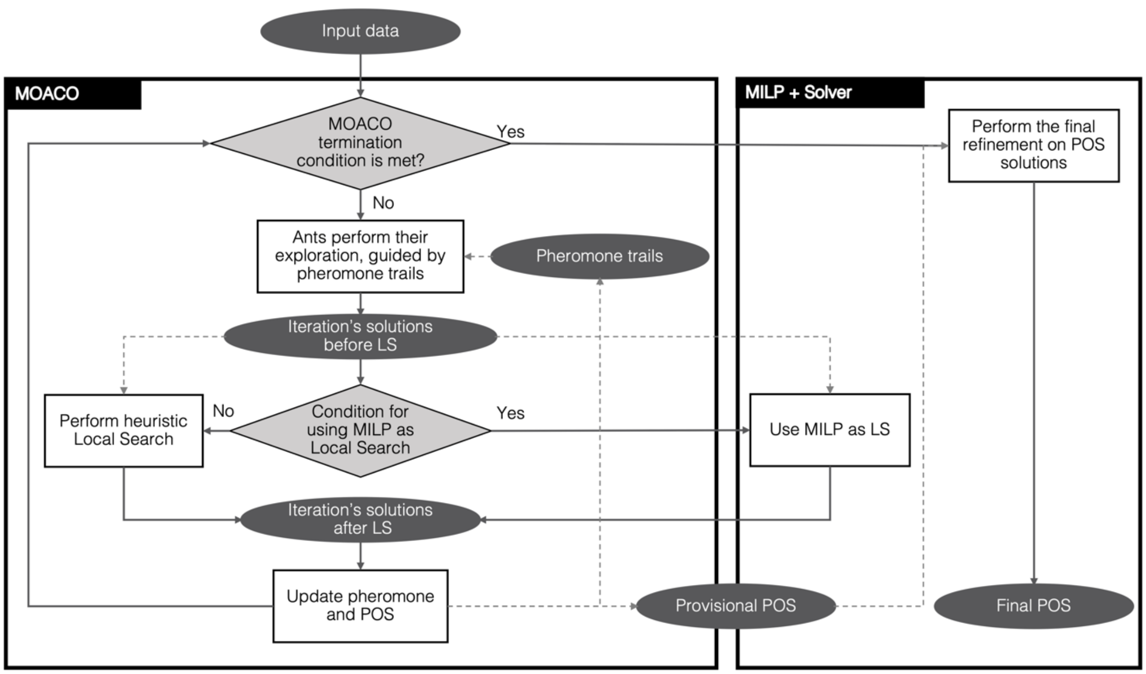

Figure 1 Algorithm Framework Architecture – Dark grey ovals represent data contents, white rectangles processes and light gray diamonds conditional switches. Solid arrows show the operations flows, dashed arrows show data flows (Source: (17)).

Figure 1 illustrates the proposed algorithmic framework architecture. Starting with input data, the MOACO is run through multiple iterations each time maintaining and updating a provisional Pareto Optimal Set (POS) of timetables. The best-so-far solutions of the POS are used to guide the ACO search during subsequent iterations via the pheromone trails.

The MILP formulation improves the solutions in two ways. First, it can be used as a local search tool to refine POS solutions during the MOACO search process (alternatively local search can be performed using a simpler heuristic). Users can define how the local search process is performed. For example, MILP local search can be performed once every ten iterations.

The second way the MILP formulation improves solutions is by refining all the solutions in the POS after the MOACO algorithm stops according to a termination criterion. In this step, the MILP formulation is used to further optimize timetable solutions using selected objective criteria before the timetables are presented to the user. This illustrates one of the key features in the proposed approach: the MILP formulation constraints are slightly different from those used by the MOACO algorithm.

The MOACO algorithm rigidly enforces regular intervals between trains of the same train group. This dramatically speeds-up the exploration process but does not take advantage of train group periodicity tolerances (outlined above). Therefore, in the MILP stage, the train paths provided by the MOACO solution can be adjusted based on the periodicity tolerances, if any. This flexibility is used to solve conflicts and improve other objective functions.

In the MOACO algorithm, conflict constraints (both for line stretches and for station tracks) are relaxed to improve the algorithm's searching capability. They are treated as soft constraints, minimizing their violation in the objective function. This mechanism pushes solutions towards a low number of residual conflicts. Any residual conflicts at the end of the MOACO process are solved in the MILP stage, which finds the optimal solution in the neighborhood of the MOACO solution by considering conflict constraints as hard. If no feasible conflict-free solution exists in a neighborhood, the original MOACO solution is dropped. Otherwise, the MILP refined solution is assessed for addition to the provisional Pareto Optimal Set of timetables.

CASE STUDY APPLICATION OF THE ATMO TOOL

The ATMO tool was applied in an infrastructure planning case study exercise for the Bergen-Oslo railway line. The case study considered the 370 km single-track railway line between Bergen and Hønefoss. The existing infrastructure was designated as scenario zero (S0) and two infrastructure improvement scenarios were defined each of which added 50 km of double track along the line. In scenario 1 (S1) three double track sections were placed equally spaced along the line. In scenario 2 (S2) a single long double track stretch was placed approximately in the middle of the line.

The case study objective was to develop conflict-free timetables that maximizes the number of freight trains that could be scheduled in a 24-hours day (starting at midnight) and minimizes additional total travel time required due to trains waiting at passing tracks for opposing trains, given a specified passenger train timetable. Therefore, two algorithm objectives were activated, namely minimization of additional travel time and maximization of number of scheduled optional trains. This illustrates how the tool's multiobjective approach enables planners to easily study the relationships between multiple objectives (in this case two objectives).

Three base service concepts were defined in the case study:

- FR: line capacity should be saturated with up to 37 freight trains.
- LH+FR: 10 quasi-periodic long haul passenger trains (5 in each direction) must be scheduled; the remaining capacity should be saturated with up to 37 freight trains.
- R+LH+FR: In addition to the long-haul passenger trains, 30 periodic regional trains (15 in each direction) must be scheduled following a clock-face headway pattern between Bergen and Myrdal in the time window 7:00 AM to 10:00 PM, the remaining capacity should be saturated with up to 37 freight trains.

In addition to the base service concepts, the case study also tested the influence of tolerances in the periodic pattern of passenger trains. To test the impact of periodicity the following two sets of service concepts were constructed to be overlaid on the base service concepts:

- "X" concept where strict periodicity is required (no periodicity tolerance).

- "T" concept where a tolerance of ±15-minutes for long-haul trains and ±5-minutes tolerance for regional trains is allowed at all stations.

The infrastructure alternatives and service concepts were defined for the ATMO tool using the Treno suite of railway timetable planning software *(18*) currently used by Jernbanedirektoratet. A dedicated interface was developed as part of the research to provide seamless data transfer between Treno and the ATMO tool and vice-versa. The infrastructure as well as the base service concepts are illustrated schematically in **Figure 2**.

In the case study the saturation testing was performed by setting freight trains as optional, this means the algorithm can choose whether to schedule them or not. This enables the ATMO to search for the best trade-off between number of scheduled trains and additional travel time.

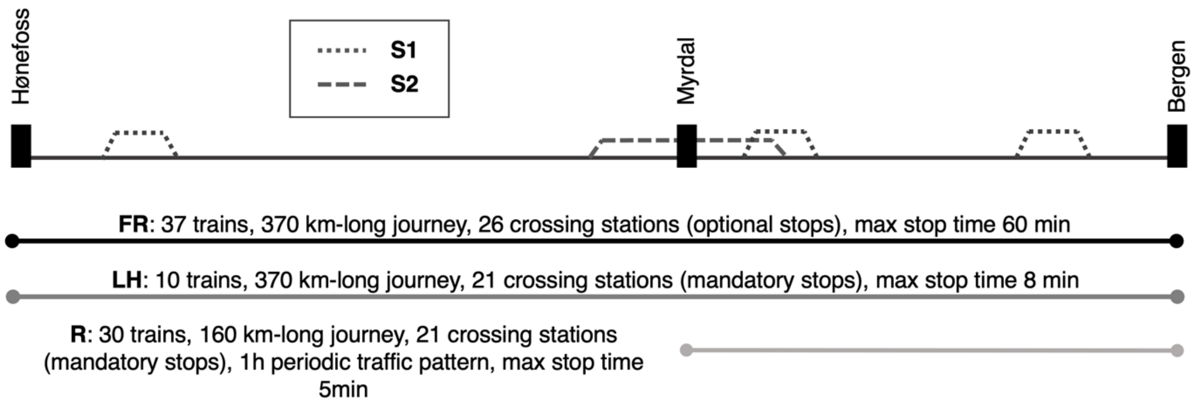

Figure 2 Case Study Infrastructure and Service Concepts.

The combination of three infrastructure alternatives and six service concepts led to 18 scenarios. The ATMO tool was applied to all 18 scenarios. The following termination criteria were set to the algorithmic framework. The MOACO algorithm was stopped after a 30-minute time limit. Then the MILP formulation was applied to all the timetables in the provisional POS. The MILP formulation was solved using a commercial solver, which stopped when a 2% MIP gap (an indicator which measures how far the current solution is from its estimated optimum) or a 5-minute time limit was met. In the 85 % of the experiments for which the MILP formulation returned a feasible solution, the MIP gap termination condition was met. The algorithm framework was developed in Java 8 and the experiments were carried out on a MacBook Pro with 2.6 GHz Intel Core i7 6 core processor and 16 GB RAM.

Figure 3 presents the results as approximations of the Pareto fronts relevant to the X scenarios (no periodicity tolerance allowed). The points composing the fronts (lines) represent actual conflict-free timetables produced by the algorithm. Each point on the line quantifies the key performance indicators (KPIs) selected for this case study, namely the number of scheduled freight trains and the total additional travel time due to trains waiting at passing tracks. Each point on a line is Pareto optimal, in other words it is the maximum possible number of freight trains for the given additional travel time.

The lines display the best trade-off between the objectives (KPIs) for each infrastructure / service concept scenario. This means that timetables falling under and to the right of the Pareto front lines can be designed, but do not use capacity optimally (more freight trains could be operated with the same total additional travel time). Similarly, timetables falling in the sector over and to the left of the Pareto front lines cannot be designed without causing traffic conflicts. In particular, the figure shows that an upper bound exists for the number of freight trains which it is possible to schedule in each scenario, no matter how much additional travel time is scheduled.

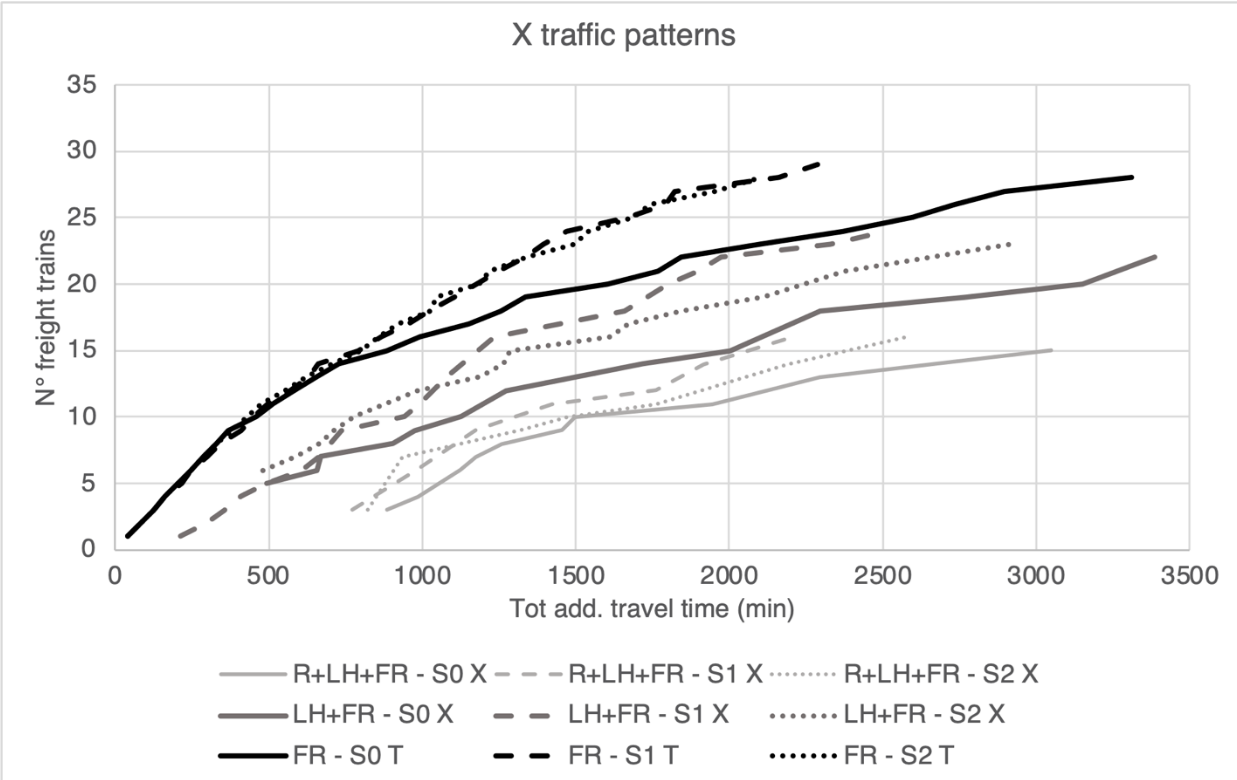

Figure 3 Approximated Pareto Fronts Representing Capacity Utilization Trade-off for Analyzed Scenarios. Colors refer to the three service concepts considered in the case study. The solid lines represent the infrastructure baseline S0, the dashed lines represent alternative S1, and the dotted lines alternative S2.

In terms of strategic planning the results presented in **Figure 3** can be used to make the following conclusions regarding the case study:

- The difference between infrastructure scenarios S1 and S2 only arises when passenger trains are scheduled. In this case, S1 performs better than S2. When only freight trains are considered, there is no difference between S1 and S2.
- The presence of passenger trains strongly affects the maximum number of freight trains that can be scheduled. In LH+FR scenarios, the maximum number of schedulable freight trains is 18.8 % lower than in the FR scenarios (based on 3 FR scenario average). In R+LH+FR scenarios, this percentage increases to 44.7 %. Or, looked at another way, total additional travel time increases significantly when passenger trains are added to timetable with a specified number of freight trains.
- Adding double track increases the number of freight trains that can be operated under all service scenarios for a given additional travel time. Double tracks reduce the time trains spend waiting on passing tracks for trains travelling opposing direction. In particular, considering the upper-right extremities of the Pareto fronts, in scenarios S1 an average travel time reduction of 36.3 % can be achieved compared to scenarios S0 (average value over the three service concepts). For scenarios S2, the average reduction is equal to 26.8 %.

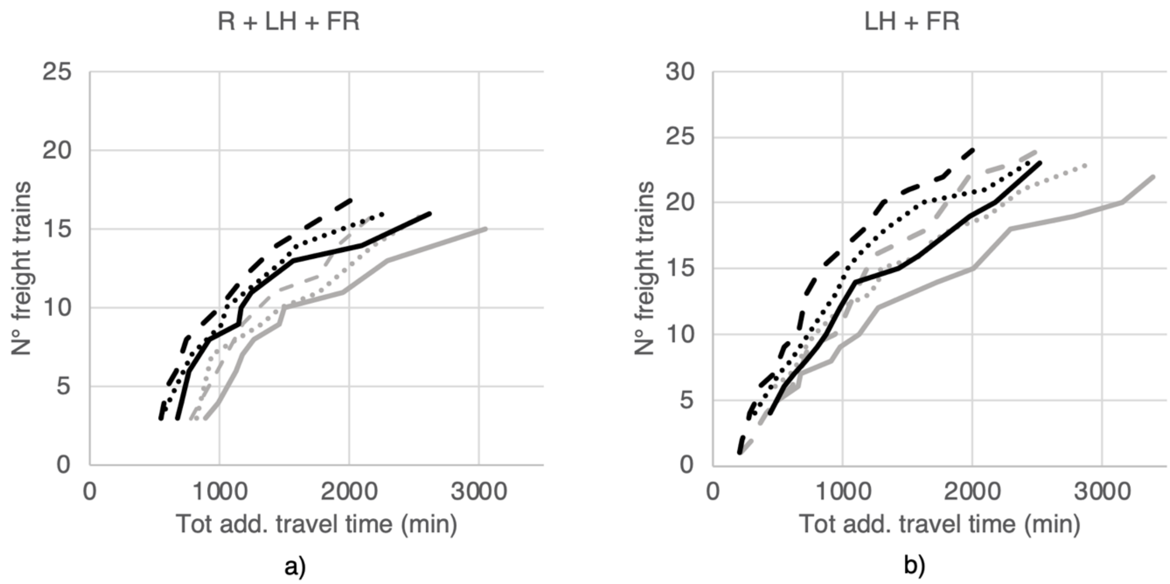

Figure 4 Influence of Periodicity Tolerances. Grey lines refer to the X traffic pattern (strict periodicity) and black to the T traffic patterns (with periodicity tolerances). Solid lines refer to the S0 baseline, the dashed lines represent S1, and the dotted lines represent the S2 infrastructure alternatives.

Figure 4 illustrates the influence of periodicity tolerances in the passenger train traffic patterns ("T" scenarios). As shown, relaxing the constraint requiring strict periodicity (by introducing periodicity tolerances) is an effective measure for reducing the time losses. This scheduling flexibility allows the algorithm to adjust the timetable so that train meets occur in double track sections, thus reducing the time trains spend waiting at passing tracks for trains travelling in the opposite direction. The general findings for the infrastructure alternatives are the same both in "X" and "T" scenarios.

This case study highlights the benefits of the new ATMO tool. Using a multiobjective optimization and Pareto fronts, it provides planners with much more information than a classic timetabling approach which produces just one timetable at time. Essentially, the tool enables planners to to enter general timetable requirements into the tool and several hours later receive many good timetables to evaluate, making it ideal for strategic planning.

Furthermore, the tool also can produce these timetables efficiently. **Figure 5** illustrates the computation time required to produce the relevant Pareto front approximation as well the number of timetables returned as an output for each of the nine "X" scenarios analyzed in the case study. The figure shows how the use of a multiobjective metaheuristic combined with a MILP-based refinement can be used to produce a significant number of timetables in a relatively small computation time. In total, the case study required approximately 8.5 hours of computation time (it was run overnight) and produced 539 timetables.

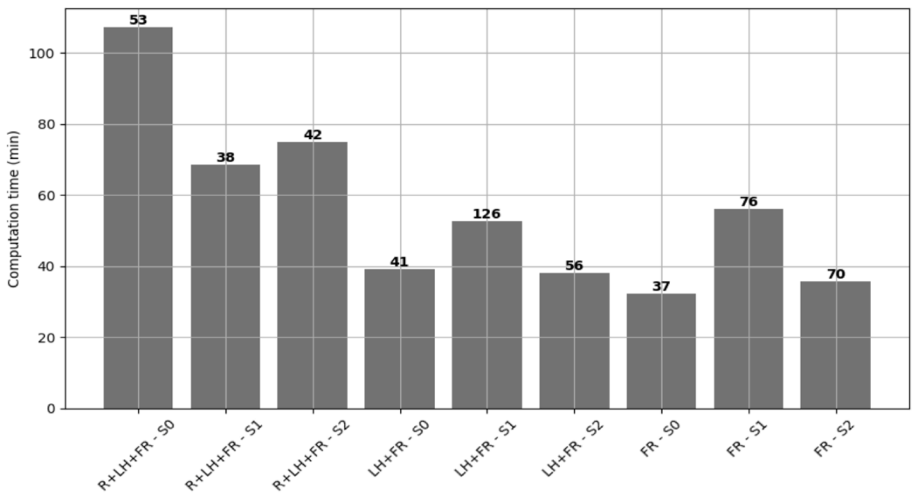

Figure 5 Computation Time (minutes) for each Analyzed Scenario ("X" traffic patterns) . The number on the top of each bar specifies the number of timetables used to create the relevant Pareto front.

In summary, the case study showed how the ATMO tool can be used to improve the strategic planning process for real medium-sized Norwegian networks by efficiently creating many feasible timetables for comparing infrastructure – service concept scenarios all of which are fully compliant with Jernbanedirektoratet requirements. As illustrated in the case study, the ATMO tool results, although based on aggregated KPIs, are effective as a first step during strategic capacity analysis of timetable planning. They provide planners with a quick overview of the main trends for the KPIs.

The results also help planners identify problem areas to be studied in detail. More specifically, each point on a POS line represents an actual timetable that can be further analyzed using microscopic timetable-planning software. This detailed study would use the standard methods, i.e., an iterative loop of manual adjustments and traffic simulations, to design-test-analyze the specific issues of interest.

The next steps in tool development will be to improve it to handle larger and more complex networks. The tool has already been tested for larger networks, but its performance must be improved before it can be applied efficiently in the planning process. This work is ongoing.

CONCLUSIONS AND RECOMMENDATIONS

Norway has adopted ambitious goals for increasing the mode share of railway transport for both freight and goods as part of its program for fighting climate change. Achieving this objective means using railway capacity as efficiently as possible and adding new capacity precisely where it is needed to meet service plans. Strategic planning using simulation is a key tool in this process.

Therefore, Norway's Railway Directorate (Jernbanedirektoratet) is supporting research to improve the strategic planning process by developing a new tool that quickly creates a set of timetables optimized for multiple objectives. Having many timetables to compare helps planners understand strategic trade-offs (e.g., between train capacity and infrastructure investments) and identify the best timetable alternatives for detailed analysis.

The new tool, called Automatic Timetabler with Multiple Objectives (ATMO), uses numerical methods, specifically a Multiobjective Ant Colony Optimization (MOACO) algorithm to quickly explore a large solution space of potential timetables and then develops optimized timetables using mixed integer linear programming (MILP). It considers several aspects of infrastructure and operations in detail while using abstractions of others. As such, it bridges the gap between the less detailed (macroscopic) models used for timetable development and the more detailed (microscopic) models used for traffic simulations. The new tool is designed to be used with data from digital twins and has been tested successfully.

One of the key project objectives was integrating academic work on improving simulation modelling into Norway's real railway strategic planning processes. The case study showed that the tool can be used effectively in real railway planning processes, and it is being used in several ongoing studies. In the coming years the methodology and tools will be improved so they can be applied to more types of planning projects and larger networks.

Recommendations for further research include improving the algorithmic framework (e.g., to efficiently solve larger network problems) and examining new ways of using the ATMO tool's results. An example of this is extending the software to help planners identify the optimal locations for new infrastructure (e.g., passing tracks) under various scenarios (a suggestion from one of the paper's anonomous peer reviewers) and to help support more aspects of the strategic planning process.

Moreover, future research will be devoted to the extention of the MILP formulation proposed in this paper, to make it capable of solving instances independently of MOACO. The use of such an extended formulation will constitute a benchmark to assess the absolute performance of the ATMO tool, as, to the best of our knowledge, none of the approaches appearing in the literature deal with the mesoscopic model of interest here.

Another recommendation for further research is developing automated methods to analyze the fundamental structure of timetables more precisely, a task nearly impossible to perform manually on such a large number of timetable alternatives. The next step in this research will be developing automatic techniques for more deeply analyzing these timetables to identify and understand specific capacity bottlenecks.

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AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study conception and design: N. Coviello, G. Medeossi, T. Nygreen, P. Pellegrini, J. Rodriguez; data collection: N. Coviello, G. Medeossi, T. Nygreen; analysis and interpretation of results: N. Coviello, G. Medeossi, A. Nash, T. Nygreen; draft manuscript preparation: N. Coviello, A. Nash, T. Nygreen. All authors reviewed the results and approved the final version of the manuscript.

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